Strategies for Sustainability

Peter A Khaiter
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Sustainability Perspectives: Science, Policy and Practice

A Global View of Theories, Policies and Practice in Sustainable Development

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Strategies for Sustainability

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Preface

The concept of sustainable development is a multifaceted global problem which was recognized, introduced, and articulated over the course of several decades. Nevertheless, the concept still requires a thorough and comprehensive investigation. It is obvious that the entire scope of the sustainability issues cannot be addressed by a single book.

This volume appears in the "Strategies for Sustainability" series focusing on implementation strategies and responses to sustainability problems – at the organizational, local, national, and global levels. The main objective of the series is to encourage policy proposals and prescriptive thinking on topics such as sustainability management, sustainability strategies, lifestyle changes, regional approaches, organizational changes for sustainability, educational approaches, pollution prevention, clean technologies, multilateral treaty-making, sustainability guidelines and standards, sustainability assessment and reporting, the role of scientific analysis in decision-making, implementation of public-private partnerships for resource management, regulatory enforcement, and approaches to meeting inter-generational obligations regarding the management of common resources.

The book presents original research papers on the state of the art in sustainability, and it is intended for a broad audience, primarily from the academia, environmental authorities, industry, forestry, agriculture, and land and water management, and can be of interest for researchers, graduate students and practitioners in the areas of sustainable development and environmental sciences, business managers and analysts, and policy- and decision-makers, who will find valuable sources of information for their professional activities.

The contributions received for the book reflect geographically disperse locations from New Zealand to Nepal and from Australia to the United States. Thus, the book sets out a worldwide perspective of the science, policy, and practice of sustainability in North and South Americas, Europe, Asia, Australia, and Oceania. It is a clear indication of a growing interest toward the issues of sustainability – locally, internationally, and globally. The chapters in the volume also explore country-specific development and applications of sustainability principles. We would like to thank all the researchers who responded to the call for chapters and submitted manuscripts to this project for their hard work under tight deadlines and high quality of the contributed papers.

The high scientific quality of the material was also assured by a rigorous reviewing process by the leading researchers and practitioners in respective fields from Argentina, Australia, Austria, Canada, India, New Zealand, Palestinian Territories, Qatar, Russia, Saudi Arabia, United Arab Emirates, and the United States. We are grateful to our reviewers whose names are not listed in the volume due to the confidentiality of the process. Their voluntary service and insightful comments helped the authors to improve the quality of the manuscripts as well as assisted the editors in decision-making on each chapter.

We would like to express our appreciation to the entire team of Springer Nature with very special thanks going to the series editor of Strategies for Sustainability, the publishing editor Dr. Fritz Schmuhl, and his editorial assistant, Catalina Sava. We are grateful to the Project Coordinator (Books) Prasad Gurunadham and Project Manager AbdulBari Ishrath Ara of SPi Technologies for their enthusiastic support and exceptional editorial and proofing work on behalf of the team of authors.

Toronto, ON, Canada

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Introduction

For this book, we invited contributions on methodological and applied aspects of sustainability and sustainable management from different countries and regions around the globe. The chapters discuss approaches to sustainability assessment and demonstrate how ideas of sustainability and sustainable management are incorporated into public policies and private actions at local and national levels. The book presents the current directions of scientific thinking and success in the field of sustainable development. The conceptual ideas and case-based implementations showcase how the theory of sustainability and its approaches can be applied to public policy development and actual realization in local and regional sustainable practices. The authors focus on promoting greater sustainability in natural resource management, energy production and storage, housing design, coastal planning, land use, and business strategy, including sustainability indicators, environmental damages, and relevant theoretical frameworks. The chapters reflect environmental, economic, and social issues in sustainable development, challenges encountered, and lessons learned as well as solutions proposed.

Structurally, the book is divided in three parts. Part I is dedicated to scientific or theoretical foundations of sustainability. At the same time, the authors discuss and demonstrate practical applications of their thoughts. The opening chapter, by the editors, provides an introduction to the fundamentals of sustainability, including a brief historic overview of the concept. The idea of sustainability is articulated on the basis of ecosystem services and formalized in a theoretical framework in terms of a meta-modeling approach. In moving the concept of sustainability toward design and implementation, the architecture of the environmental software modeling framework is presented. Syaifudin and Wu (Chap. 2) discuss sustainable development in Indonesian regions where significant economic growth over the past several decades has been achieved at the cost of environmental degradation. Currently, the Government of Indonesia views sustainability as an important goal in the country's long-term development planning. The chapter presents a study aimed at measuring and analyzing sustainability at the provincial level in Indonesia by developing composite indices, so that they reflect four aspects of sustainability: economic, environmental, social, and institutional pillars. Prato (Chap. 3) presents a framework that identifies a preferred sustainable management action and its application to sustainable fuel treatment of forests in the United States. The proposed framework has been applied in a case study that determines which fuel treatment strategy is preferable for US Forest Service Land in Flathead County, Montana, over a 50-year planning period. The objectives in the study express sustainability goals through minimizing expected residential monetary losses from wildfire, minimizing expected deviation of forest ecological conditions from their historic range and variability, and maximizing expected net returns from timber harvesting associated with fuel treatment. Trofimchuk (Chap. 4) explores sustainability of water ecosystems as self-organizing systems. The existing approaches to the assessment of water quality may not provide control of thousands of new pollutants into the water bodies. Through the results of many years of experimental work, the chapter describes the criteria of ecosystem stability and functioning on the basis of thermodynamic parameters.

Part II deals with promoting sustainability through policies. The opening chapter in this part by Eaves et al. (Chap. 5) investigates how precautionary policy planning can shape sustainable land use development in the coastal environment of New Zealand. There is an evolving risk and exposure to hazards that are perpetuated by sea level rise and extreme storm events that manifest from a changing climate. It is proposed that a sustainable dynamic adaptation to these hazards through a managed process can create a long-term resilience for communities. Tyaglov et al. (Chap. 6) is focused on measures aimed at remediation of environmental damages accumulated from the past and the necessity to formulate them in the form of regional and federal policies as a means of promoting sustainability. Viewing from environmental and economic perspectives, the analysis reveals the main components of the restoration process including environmental objects, stakeholders, tools, institutions responsible for policy implementation, and enforcement mechanisms. Thomson et al. (Chap. 7) document the development of an outcome-based platform for assessment of sustainability performance of commodity crop agriculture in the United States. The multi-stakeholder development process is described showing co-design of the platform with farmers and industrial stakeholders, including brand and retail companies. As sustainability programs in agriculture are increasingly focused on meeting environmental objectives, this case study provides useful lessons regarding scientific metrics and key environmental performance indicators. Danilenko et al. (Chap. 8) present assessment and forecast of surface water quality as the key elements of effective water resource management given that the state of natural ecosystems, including aquatic ecosystems, has decisive importance for sustainable social and economic development. The authors argue for regional standards on the content of pollutants in water bodies taking into account specific local conditions of their formation for the development of ecologically justifiable water protection measures as the necessary premise for sustainable development of the territories. Braaten et al. (Chap. 9) explore the use of indicators for water management by drawing on the Australian National Water Account dataset, specifically their applicability and usefulness as well as limitations for water sustainability reporting and potential utilization by environmental authorities. It is assessed which indicators provide the most insight into water sustainability, best suitability for addressing contemporary sustainability issues, and how indicators could/should be applied by decision- and policy-makers. Banjade and Paudel (Chap. 10) provide a historical account of how the concept of sustainability has been advanced over time in Nepal where the Himalayan environmental degradation has forced to revisit the approaches to forest sector governance of highly vulnerable hill areas to integrate environmental, social, and economic dimensions. The authors examine the concept of sustainability in relation to these three dimensions and analyze existing forest sector policies and programs in relation to increased market interface and in the context of climate change threats and food security crises.

Part III is focused on implementing the ideas of sustainability in practice. In the first chapter of this part, Scarpati and Capriolo (Chap. 11) analyze seasonal precipitation trends over a 40-year period in 16 drainage basins of the Buenos Aires Province, one of the main crop production areas in Argentina. The results show a decreasing tendency over many areas and call for a high need of irrigation during the entire year. This information is important to plan for irrigation measures in support of sustainable agricultural production in the region taking into account that climate changes are also likely to challenge existing spatiotemporal patterns of plant species, cultivated crop systems, and their management. Cakici et al. (Chap. 12) discuss the recent developments of low-cost and highly efficient storage devices and their role in supporting sustainable energy supply. The authors argue for novel techniques which will produce multifunctional well-defined nanostructured hybrids consisting of carbons and conjugated polymers that have potential for applications in sustainable energy storage devices (e.g., supercapacitors, batteries, fuel cells, solar cells, and photoanodes). Paudel and Imteaz (Chap. 13) present an experience with a prudent and optimal government rebate for rainwater tank installation with a case study for an Australian coastal city, Adelaide. It is found that payback periods widely vary depending on region, tank, roof, and demand scenario. Accordingly, a variable rebate scheme is recommended to optimize government's spending. Shekhovtsov et al. (Chap. 14) deal with incorporating the principles of sustainable development in long-term socioeconomic planning at regional and municipal levels in a large industrial and agricultural area – Rostov region, Russia. The authors investigate the best practices of strategic planning of sustainable initiatives based on the thorough analysis of the dynamics of sustainability indicators, major stakeholders, and organizations involved in the due process and formulate appropriate recommendations. Tahir et al. (Chap. 15) highlight the most recent approaches to resilience and sustainability of water supply in the Middle East where countries heavily depend on desalination for freshwater procurement. The authors evaluate the possible vulnerabilities and the ways of technological diversification to ensure that constant water supply can be maintained without relying on fossil fuel-based plants. A review of the national programs in the region looks promising as they implement ongoing projects, such as Mega Reservoir, and research programs in solar desalination and pretreatment techniques. Kumar et al. (Chap. 16) present an Indian nation-scope study of the current status of forest fringes and their role in sustainable development. The recent phenomenal increase in human population and cattle size and the lack of effective management have led to overexploitation of forest resources and diminished supply of goods and services. The authors emphasize that forest fringes demand an urgent quantitative assessment and site-specific prioritized intervention to improve livelihood as well as ecological health in addressing the goals of sustainable development.

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Part I
Scientific Foundations of Sustainability

Chapter 1
Perspectives of Sustainability: Towards Design and Implementation

Peter A. Khaiter and Marina G. Erechtchoukova

Abstract The idea of sustainability is approached on the basis of ecosystem services which are widely recognized as a key notion for sustainable development. Utilization of this interpretation of sustainability requeres a mechanism whereby all the goods and services generated by ecosystems are adequately quantified, valuated and incorporated in the decision-making process. A theoretical framework for sustainable management consists of five layers: "Ecosystem", "Monitoring", "Modeling", "Valuation" and "Management" and it is expressed in terms of a meta-modeling approach. A sophisticated information system which implements the main elements of the meta-modeling framework allows to transform it into a tool of a practical use by the policy- and decision-makers as well as by the wider categories of the interested stakeholders, thus moving the concept of sustainability towards design and implementation. The architecture of the environmental software modeling framework (ESMF) follows the main structural solutions of the multi-layered designs and the principle of platform independence. As a result, the logic of the ESMF is distributed across four tiers: Client tier, EMMVM tier, Data Source (DS) tier and Data Warehouse/Database (DW) tier. A particular parameterization of the underlying techniques and selection of the targeting variables in each tier are determined by a given domain and problem at hand.

Keywords Sustainability · Ecosystem services · Environmental management · Software tool · Decision-making · Meta-modeling framework

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1.1 Introduction

The interplay between environmental conditions and economic prosperity had been noticed long time ago. For example, the relationships between forests and the hydrological cycles on the adjacent territories were understood as early as the ancient Greece and Rome. Definitely, this link was recognized by Plato who noted that disappearance of forests (i.e. deforestation in our modern language) on the Attic peninsula, a historical region of Greece, had led to soil erosion and drying of springs. In general, the collapse of ancient societies often followed the deforestation of their land, what is reflected in an old saying that "forests proceed civilization; deserts follow" (Thiele 2013).

Nowadays, the issues of rational use of the environmental objects continue to attract public attention world-wide, especially in connection with increasing man-produced impact. The scale of anthropogenic alteration of the planet's ecosystems is a substantial and growing factor to be regarded in policy- and decision-making procedures. Human society and its economic development cause adverse side effects, such as habitat destruction, over-harvesting and pollution of environmental niches (i.e., air, soil, fresh waters, oceans, etc.). According to Saier (2006), the rate of biological species extinction due to human activities is about 8000 per year.

There are even growing concerns on the part of various environmental stakeholders and general public in relation to the on-going global climate change and natural resources depletion as well as a common demand for a harmonized type of relationships between the societal development and the environment which crystalized in the concept of environmentally-friendly sustainable development. In the most generic sense, sustainability can be understood as maintaining natural capital and resources (Goodland 1995). The frequently cited Brundtland report defined sustainability as "development that meets the needs of present [generations] without compromising the ability of future generations to meet their needs" (WCED 1987).

The 2005 World Summit on Social Development (UNGA 2005) expressed the paradigm of sustainability in three dimensions or "pillars": "economic development", "social development" and "environmental protection" (also known as the "Triple Bottom Line" approach). Inherent in the definition of sustainability is the recognition of the importance of the three pillars (NRC 2011) and their interdependency, so that the economy is a subsystem of human society, which is itself a subsystem of the biosphere (Porritt 2006). This can be visualized by a diagram with the three nested circles in which both economy and society are constrained by environmental limits (Scott 2009). Therefore, the environmental pillar is a key aspect of sustainable development which, to a greater extend, will determine the future of humanity because everything that humans require for their survival and well-being depends, directly or indirectly, on the natural environment (NRC 2011; Marsh 1864).

Fig. 1.1 17 sustainable development goals (UNDP 2015)

In 2015, the United Nations General Assembly adopted the 2030 Agenda for Sustainable Development in which 17 Sustainable Development Goals (SDGs) (Fig. 1.1) have been set and spelled them out in 169 associated targets aimed at addressing "the global challenges we face, including those related to poverty, inequality, climate, environmental degradation, prosperity, and peace and justice" (UNGA 2015). All UN Member States agreed that solving the global problems is impossible without addressing climate change and working to preserve the nature at all the levels.

A methodology linking together the three pillars of sustainability is rooted in the concept of *ecological-economic-social* (EES) systems and ecosystem services they produce (Khaiter 1986, 1993a, 1996, 2005a; Gorstko and Khaiter 1991). Corresponding theoretical framework expressed in terms of a meta-modeling approach is presented in the second section of this chapter. In order to move the concept of sustainability towards design and implementation, a transformation of the theoretical framework into a sophisticated software tool is required. Environmental software modeling framework (ESMF) is discussed in the third section of the chapter. The ESMF applies the key structural solutions of the multi-layered designs and the principle of platform independence and demonstrates the ways of how the task of sustainable development can be formulated in terms of optimal control theory.

1.2 Methodology for Sustainability Assessment: Theoretical Framework

An approach to managing the economic and societal development with a view of ecosystem goods and services they produce for humankind had been suggested and developed mainly for forested territories since late 1980s (Khaiter 1986, 1991, 1993b; Khaiter and Erechtchoukova 2013). Nowadays, there is an obvious broad consensus that ecosystem services are an important integral part and even cornerstone of sustainability studies, even if the term ecosystem services is not always explicitly mentioned in policy documents (Geijzendorffer et al. 2017; Griggs et al. 2013; Liu et al. 2015; Wu 2013).

At the same time, Geijzendorffer et al. (2017) explored two international policy documents: the SDGs (UNGA 2015) and the Conventional of Biological Diversity (CBD) Aichi Targets (CBD 2013), both having global coverage and containing objectives on sustainable development, to analyze to what extent the ecosystem services have been incorporated in global sustainability policies. It was found that 12 goals (out of 17 SDGs) and 13 targets (out of 20 Aichi Targets) relate to ecosystem services. Therefore, it should be taken as imperative that the very idea of sustainable management can be discussed in practical terms only if all the goods and services generated by the affected ecosystems are properly quantified, valuated and incorporated into the decision-making process at its various stages (Khaiter and Erechtchoukova 2010a).

The UN-led Millennium Ecosystem Assessment Report (MEA 2005) has categorized ecosystem services into four broad groups: *provisioning*, such as the production of food and water; *regulating*, such as the control of climate and diseases; *supporting*, such as nutrient cycles and crop pollination; and *cultural*, such as spiritual and recreational benefits. However, the main methodological problem is that the quantifying of ecosystem benefits is a non-trivial task. In most of the cases, the corresponding measures can only be obtained through modeling of the phenomena in question (Khaiter 1993a, 2005b).

Quantitative assessment of the ecosystem services in the scenarios of sustainable development requires, at the very minimum, the following elements: (1) an adequate theoretical understanding of an ecosystem and its various services; (2) an adequate model of an ecosystem describing internal physical, chemical and biological processes and their interrelationships, structure and components of the ecosystem, laws of its functioning and generation of the services under natural conditions; (3) understanding of the principles governing responses/reactions of the ecosystems to exogenously caused stresses including the ability to produce services under the stress; and (4) a model predicting the ecosystem behaviour under the anthropogenic impacts and the quantities of the services it can so deliver (Khaiter and Erechtchoukova 2009a, 2010a).

As a means of coupling the concepts and ideas of sustainable development, a theoretical framework has been suggested. While the initial steps in developing the framework were mostly concerned with the four above tasks of quantifying

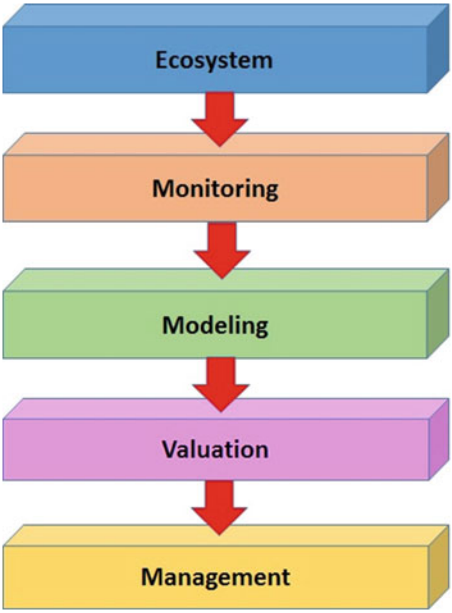

Fig. 1.2 Layers of the theoretical framework for sustainable assessment (Khaiter and Erechtchoukova 2014)

the ecosystem services (Khaiter and Erechtchoukova 2010a, b), as a further development, the framework has been extended to include the modules implementing valuation and decision-making activities at the upper structural levels (Khaiter and Erechtchoukova 2012) to finally consist of five layers: "Ecosystem", "Monitoring", "Modeling", "Valuation" and "Management" (Fig. 1.2) briefly reviewed below. A detailed description of the internal operations of each layer can be found elsewhere (Khaiter and Erechtchoukova 2018).

1.2.1 "Ecosystem" Layer

Based on general systems theory (von Bertalanffy 1969) as well as classical and systems ecology (Dale 1970; Mueller 1997; Odum 1983; Tansley 1935), it has been suggested (Khaiter and Erechtchoukova 2018) a five-set tuple description of an ecosystem (E), which includes a set $\{C\}$ of biotic and abiotic constituents (i.e., ecosystem composition), a set $\{S\}$ of their particular assemblages reflecting interrelationships of ecosystem elements (i.e., ecosystem structure), a set $\{P\}$ of ecosystem parameters designating quantitative values to the characteristics of ecological processes, a set $\{In\}$ of environmental inputs and a set $\{Out\}$ of ecosystem outputs:

$$E = \langle \{In\}, \{C\}, \{S\}, \{P\}, \{Out\} \rangle . \qquad (1.1)$$

1.2.2 "Monitoring" Layer

The objective of the "Monitoring" layer is to supply sustainable decision-making with required observation data collected in a standardized way and in conformity with a certain monitoring program. The latter can be defined in terms of monitoring indicators, sampling designs and a set of observation sites (Erechtchoukova et al. 2013). It will also specify laboratory analyses and procedures, and include recording of monitoring data, data analysis and interpretation as well as reporting and follow-ups (WQTG 2006). The aims of a monitoring system can be: (1) assessment of trends in indicators; (2) attainment of environmental quality standards; (3) assessment of environmental impact; and (4) general surveillance (Whitfield 1988).

1.2.3 "Modeling" Layer

The "Modeling" layer consists of a module responsible for modeling natural dynamics, another one modeling anthropogenic dynamics and a module for quantifying the ecosystem services. The aim of as well as steps and challenges associated with modeling of ecosystem natural dynamics have been recently summarized by Khaiter and Erechtchoukova (2018). The outcome of the first module is a model for evolution of the studied ecosystem under the natural conditions, which, in a unified notation by Ide et al. (1997), can be written as follows:

$$M\left[t, \mathbf{in}(t), \mathbf{x}(t), \mathbf{p}(t), \mathbf{F}\right] = 0, \tag{1.2}$$

with the initial conditions $\mathbf{x}(0) = \mathbf{x}_0$. Here M is the model dynamics operator; t is the time variable; $\mathbf{x}(t)$ is the vector of model state variables quantifying elements of the set $\{C\}$, i.e. both biotic and abiotic constituents of the ecosystem; $\mathbf{p}(t)$ is the vector of model parameters; and $\mathbf{in}(t)$ is the vector of inputs of environmental factors, i.e. elements of the set $\{In\}$. The vector-function of ecosystem processes $\mathbf{F}$ expresses an interplay of environmental inputs, state variables and parameters. The structure $\{S\}$ of the modelled real-world ecosystem is revealed through the values of the state variables and parameters and a particular mathematical form of functions $f_i\left(i = \overline{1, n}\right)$ in $\mathbf{F}$.

Exogenous perturbations denoted as vector $\mathbf{u}(t)$ caused by anthropogenic impacts may affect and change different components of the real-world ecosystem as expressed by its mathematical model (1.2). Therefore, the task of the module of anthropogenic dynamics is to predict ecosystem behaviour in response to each type of stress. Following classical papers by Holling (1973) and Odum (1983), it has been demonstrated that there are common patterns in the ecosystem reaction to anthropogenic stress and five possible scenarios determined: (i) resistance; (ii) deformation; (iii) resilience; (iv) degradation; and (v) shift (Khaiter and Erechtchoukova 2007). Considering the evolution model (1.2) as the base model level 0 (*BaseModel*0), ecosystem anthropogenic dynamics can be interpreted as a meta-model level 1 of the base model:

$$MetaModel1 = BaseModel0\left[\mathbf{u}(t)\right]. \tag{1.3}$$

Building the transformations (1.3) requires extensive data of empirical observations on the behaviour of the ecosystem components as they respond to each kind of anthropogenic stress or a certain combination thereof. Provided that these data are supplied by the "Monitoring" layer of the framework, the impact can be factored through the corresponding transformation functions for each affected state variable and for each type of the influence (Khaiter 1991), i.e.:

$$x_i^A = TF_{i,k} * x_i^U, \quad 0 \le TF_{i,k} \le 1, \forall i = 1, .., n, \forall k = 1, ..K, \tag{1.4}$$

where x_i^U and x_i^A are the *i*th state variable before and after the influence of the *k*th type factor, respectively; $TF_{i,\,k}$ is the transformation function of the *k*th type factor on *i*th state variable. A compounding effect of multiple factors can be expressed through the resulting transformation function (*TFR*) built using different approaches, e.g. either from the ecological Liebig's law of the minimum of limiting factors (1.5) or in the multiplicative form (1.6):

$$TFR = \min_{k=1,\ldots,r}\left\{TF_k\right\}, \tag{1.5}$$

$$TFR = \Pi_{k=1}^{r}\left\{TF_k\right\}. \tag{1.6}$$

A sample view of the transformation functions *TF*s is given in Fig. 1.3.

Ecosystem services can be interpreted as derivatives or by-products of ecosystem existence and functioning. Then, their quantitative values appear as the outputs of the ecosystem dynamic model. In the case of natural (undisturbed) dynamics, *BaseModel*0 will be applied while in the case of anthropogenic dynamics, *MetaModel*1 will be used. In either case, an operator that quantifies ecosystem services is a meta-model level 2 (i.e. *MetaModel*2). It should be noted that there is no analytic expression for *BaseModel*0, *MetaModel*1 or *MetaModel*2. In most cases, they can only be formalized by building complex process-based simulation or data-driven models. As Costanza and Folke (1997) noted, "one way to get at these values would be to employ systems-simulation models that incorporate the major linkages in the system at the appropriate time and space scales."

For example, to quantify the water regulating (hydrological) service of a forest ecosystem, an approach has been suggested (Khaiter 1993a) that is based on a simulation model "Forest hydrology" (SMFH) of the processes of moisture transformation in a forested watershed. The SMFH simulates the processes of forest hydrology to produce as outputs the values of the water balance components and provides a quantitative assessment of the hydrological service of the forest under different management scenarios.

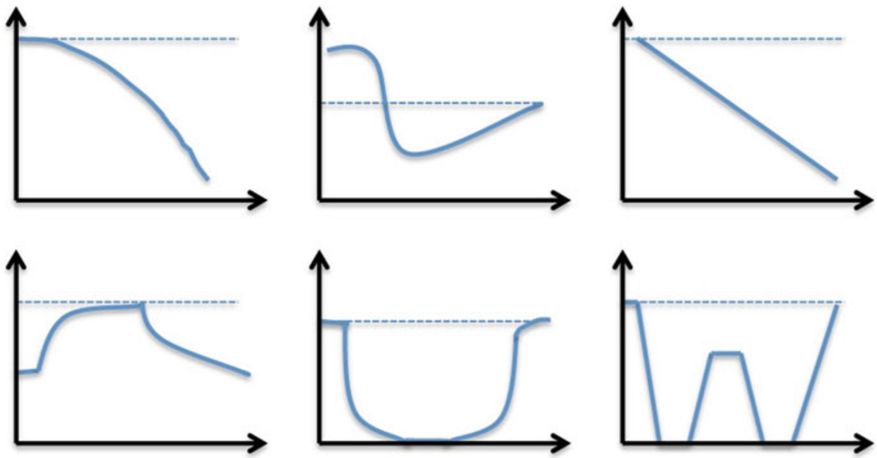

Fig. 1.3 View of *TF*s [x-axis is time; y-axis represents coordinates of $\mathbf{x}(t)$] (Khaiter and Erechtchoukova 2012)

1.2.4 "Valuation" Layer

One of the ways to incorporate ecosystem services in the practical sustainability is by attributing to them some monetary values due to the necessity to choose from a set of possible alternatives and determine which one is preferable. Goulder and Kennedy (1997) noted in this connection that it always "requires to indicate which alternative is deemed to be worth more." The output produced by the "Valuation" layer is an integral monetary value of a set of compatible services V_O, which depends on a chosen management strategy of exploitation u_k, i.e.

$$V_O = V_O\left(u_k\right). \tag{1.7}$$

In terms of the meta-modeling steps, it constitutes meta-model level 3 (i.e. *MetaModel*3).

1.2.5 "Management" Layer

Given a number of potential alternatives for managerial actions, a criterion of sustainability on the basis of ecosystem services can be formulated through the notion of ecological stability and expressed in terms of optimal control theory. One of the articulations allows to restrict anthropogenic impact on the ecosystem in study to maintain a minimal level of critical services, so that ecosystem rehabilitation abilities were not exceeded, and it could operate within a certain structural domain, thus, preventing the ecosystem from critical transitions leading to ecosystem deterioration or destruction (Khaiter and Erechtchoukova 2009b).

Environmental objects are characterized by the long timespans. It is, therefore, more realistic to assume that the management strategy may not stay unchangeable over the whole period of consideration (t_0, T) but rather an appropriate strategy should be re-evaluated and determined for shorter time intervals, for which the best management actions are found from the criterion of maximizing the overall integral value of ecosystem services $V_O(\mathbf{u})$, from the condition:

$$\mathbf{u}^* = Arg \max_{u_k \in \mathbf{U}} \sum_{j=0}^{T-1} v_0 \left(u_k \left(t_j \right) \right). \tag{1.8}$$

Solving the problem (1.8) on the basis of meta-models presented in the "Modeling" and "Valuation" layers is the core purpose of the "Management" layer forming meta-model level 4 (i.e. *MetaModel*4). It is important to note that said articulation of sustainable management is fully consistent with Brundtland's definition of sustainability (WCED 1987) clearly enabling trans-generation well-being.

1.3 Designing for Implementation of Sustainability

A practical utilization of the meta-modeling framework requires a sophisticated information system which implements the main elements of the framework in corresponding software components. In other words, it calls for a transformation of the theoretical framework into an environmental software framework to allow for its practical use by the policy- and decision-makers as well as by the wider categories of the interested stakeholders.

In general, software frameworks help define the software architecture of applications by: (1) providing a reusable design which guides software development in partitioning functionality into units, commonly referred to as components, classes or modules; and (2) specifying how units communicate and manage the thread of execution (Lloyd et al. 2011). Most modern architectural solutions for large-scale information systems employ multi-layered designs, such as the Core J2EE architecture (Alur et al. 2003) and the PCBMER architectural model (Maciaszek and Liong 2005), but none of them concerns the environmental problem domain.

In the proposed environmental software modeling framework (ESMF) the key structural solutions of the multi-layered designs and the principle of platform independence were applied. As a result, the logic of the ESMF is distributed across four tiers: Client tier, EMMVM tier, Data Source (DS) tier and Data Warehouse/Database (DW) tier as shown in Fig. 1.4.

The EMMVM tier is the backbone of the ESMF implementing its application logic in response to the users' requests placed through the Client tier. It also communicates with the DW tier to retrieve or store any required data sets. As

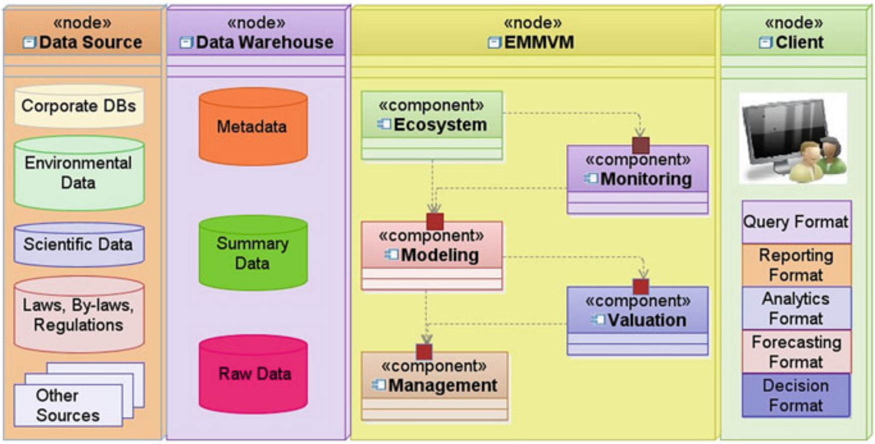

Fig. 1.4 Architecture of the ESMF (Khaiter and Erechtchoukova 2018)

seen in Fig. 1.4, the tier is structured in five hierarchical layers: Ecosystem, Monitoring, Modeling, Valuation and Management which fully address all aspects of the theoretical framework.

Particular environmental issues may require designing the software tools suitable for specific characteristics of the case at hand. For example, biological invasion of nonnative species is recognized as one of the major threats to sustainable development and as a major danger to marine and terrestrial biodiversity (Hughes and Worland 2010; Molnar et al. 2008). As observed by Mazza et al. (2014), alien species are one of the primary means for human-accelerated global change: they pose a threat to biodiversity, re-work domestic ecosystem structure, functions and services, and induce huge economic costs and serious health complications to humans. The effects of having no control in place for invasive species could be costly in terms of both direct monetary values and the negative consequences for human life (Andersen et al. 2004).

The problem of biological invasion calls for the ecosystem scope of study because alien species produce substantial negative effects on the composition, structure and functioning of the invaded ecosystems (e.g., Higgins et al. 1996; Wangen and Webster 2006). The introduction of non-native species is a stress onto invaded ecosystems, and this stress, in most of the cases, will be compounded with, and possibly amplified by, other natural and anthropogenic influences (Khaiter and Erechtchoukova 2017). The impacted ecosystem and its components will react to the stress in different ways altering their functioning. A typology of ecosystem stresses (e.g. Khaiter and Erechtchoukova 2009a; Gutiérrez et al. 2014) enables differentiation between specific categories of stress, on the one hand, and the distinct functions and ecosystem components (biotic and abiotic) being influenced, on the other. It is important to predict a particular scenario in the ecosystem stress dynamics in terms of five common patterns (Khaiter and Erechtchoukova 2007).

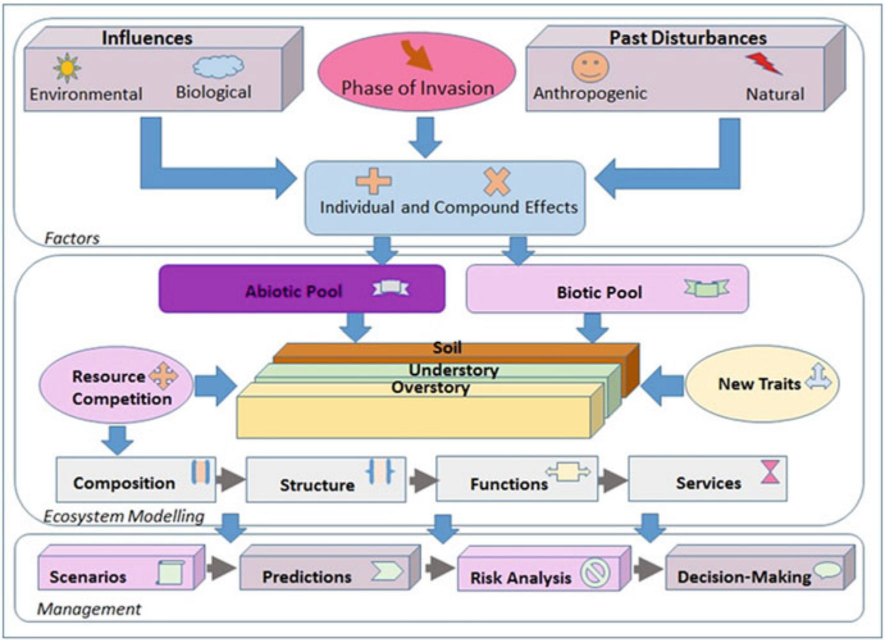

Fig. 1.5 The EMDMIC architectural design (Khaiter and Erechtchoukova 2017)

Managerial actions directed at the protection and restoration of native ecosystems are associated with considerable difficulty and expense, and their effect is not easily foreseeable due to the multifactorial and multiattribute complexity as well as substantial non-linearity of the contributing factors and processes. A software tool for environmental modelling and decision making in managing of invasive cases (EMDMIC) is aimed at integrating relevant knowledge and acting as a supporting expert (Fig. 1.5).

The EMDMIC facilitates the efforts of decision-makers and environmental practitioners in managing the invasive cases by generating possible scenarios of interventions to cope with the invasiveness. Once the set of scenarios is formed, it executes predictions of ecosystem components, their short- and long-term dynamics, ecosystem persistence capacity and restoration capabilities in response to each potential managerial effort while taking into account the mechanisms of invasion, typology of stresses and the common patterns in the ecosystem stress behaviour.

Given the uncertainty and likely significant cost associated with the implementation of controls in view of scarce budgeting resources, a risk analysis becomes a necessary step of the decision-making process. Specific features of risk analysis in application to the cases of biological invasion have been examined by Andersen et al. (2004) and Bartell and Nair (2004). The outcome of the EMDMIC is a set of recommended measures addressing the intervention of alien species in the most efficient way and suggesting resilient solutions for the impacted ecosystems.

1.4 Conclusions

Traditionally, sustainability appraisal was conducted on the basis of annual estimates of the 50 core indicators formulated by the UN at country- and continent-levels (UN 2007). These indicators are categorized into themes and can be used to select the relevant measures for natural environments and human impacts. However, the analysis of these core indicators demonstrated that they require data of various granularity, collected from diverse sources and by different authorities (Erechtchoukova and Khaiter 2014). Furthermore, it is important to stress out that the granularity of these indicators does not allow for the assessment of a planned policy or an undertaking at the local levels taking into account the specifics of potential anthropogenic impacts it may cause. The proposed ESMF framework applies the systemic approach to the assessment process with a focus on impacted ecosystems, their potential reactions to perturbations and evaluation of the consequences of management actions. It supports an 'end-to-end' integration of the activities corresponding to the entire decision-making process including the identification of the most appropriate strategies of operations. Therefore, the framework is a tool promoting sustainability by outlining underlying methodology, necessary data, algorithms and technology enabling the inclusion of sustainability appraisal into practical sustainable management.

The generic nature of the presented ESMF framework allows for a wide range of computational techniques utilized at different structural tiers and their internal components. The techniques can be based on different modelling paradigms reflecting specific features of an investigated environment, type of the potential impact and available data. A particular parameterization of the underlying techniques and selection of the targeting variables are determined by a given domain or problem at hands. Chapters in this volume describing various areas and case studies provide foundation for further elaboration on specific modelling components and tools required to evaluate sustainable decisions.

It is evident that the concept of sustainability is multifaceted by default and requires inter- and multi-disciplinary approaches for its investigation and designing the practically viable solutions. In view of the growing interest to formalization and systematization of knowledge in relevant subject areas and integration across spatial and temporary scales, the outlook is favourable: sustainability emerges in a practical discipline, being increasingly spelled out in policies and management decisions, thus becoming a driving force of societal development.

References

Alur D, Crupi J, Malks D (2003) Core J2EE patterns: best practices and design strategies, 2nd edn. Prentice Hall, Englewood Cliffs

Andersen MC, Adams H, Hope B, Powell M (2004) Risk analysis for invasive species: general framework and research needs. Risk Anal 24(4):893–900

Bartell SM, Nair SK (2004) Establishment risk for invasive species. Risk Anal 24(4):833–845
CBD (2013) Decision document UNEP/CBD/COP/DEC/X/2; Quick guides to the Aichi biodiversity targets, version 2. CBD
Costanza R, Folke C (1997) Valuing ecosystem services with efficiency, fairness, and sustainability as goals. In: Daily GC (ed) Nature's services: societal dependence on natural ecosystems. Island Press, Washington DC, pp 49–68
Dale MB (1970) Systems analysis and ecology. Ecology 51:1–16
Erechtchoukova MG, Khaiter PA (2014) Sustainability indicators for water resource assessment: compatibility and data requirements. In: Ames DP, NWT Q, Rizzoli AE (eds) Proceedings of the 7th international congress on environmental modelling and software (iEMSs 2014). International environmental modelling and software Society, San Diego, pp 948–954
Erechtchoukova MG, Khaiter PA, Khaiter DP (2013) Freshwater quality monitoring systems: ways towards improvements. IAHS Publ 361:278–285
Geijzendorffer IR, Cohen-Shacham E, Cord AF, Cramer W, Guerra C, Martín-López B (2017) Ecosystem services in global sustainability policies. Environ Sci Policy 74:40–48
Goodland R (1995) The concept of environmental sustainability. Annu Rev Ecol Syst 26:1–24
Gorstko AB, Khaiter PA (1991) On a question of economic assessment of forest resources. Econ Math Meth 27(3):522–526
Goulder LH, Kennedy D (1997) Valuing ecosystem services: philosophical bases and empirical methods. In: Daily GC (ed) Nature's services: societal dependence on natural ecosystems. Island Press, Washington DC, pp 23–47
Griggs D, Stafford-Smith M, Gaffney O, Rockström J, Öhman MC, Shyamsundar P, Steffen W, Glaser G, Kanie N, Noble I (2013) Policy: sustainable development goals for people and planet. Nature 495:305–307. https://doi.org/10.1038/495305a
Gutiérrez J, Jones CG, Sousa R (2014) Toward an integrated ecosystem perspective of invasive species impact. Acta Oecol 54:131–138
Higgins SI, Richardson DM, Cowling RM (1996) Modeling invasive plant spread: the role of plant-environment interactions and model structure. Ecology 77(7):2043–2054
Holling CS (1973) Resilience and stability of ecological systems. Annu Rev Ecol Evol Syst 4:1–23
Hughes KA, Worland MR (2010) Spatial distribution, habitat preference and colonization status of two alien terrestrial invertebrate species in Antarctica. Antarct Sci 22(3):221–231
Ide K, Clourtier P, Ghil M, Lorenc AC (1997) Unified notation for data assimilation: operational, sequential and variational. J Meteorol Soc Jpn 75(1B):181–189
Khaiter PA (1986) Problems of simulating the ecological-economic system of a forestry complex. In: Proceedings of the 10th conference on mathematical modeling in the problems of rational environment use, Novorossijsk. RGU Press, Rostov-on-Don, USSR, pp 74–75
Khaiter PA (1991) Modeling of the anthropogenic dynamics of forest biogeocenoses. Znaniye, Kiev, Ukraine
Khaiter PA (1993a) Mathematical modeling in the study of the hydrological regime in a 'Forest-watershed' system. In: Proceedings of the 9th international conference on computational methods in water resources (CMWR), Boulder, Colorado. CMP, Southampton, UK, pp 789–794
Khaiter PA (1993b) Decision support system 'Forest management'. In: Adey RA (ed) Proceedings of the 7th international conference on artificial intelligence in engineering. CMP, Southampton, pp 581–589
Khaiter PA (1996) Optimal control on the basis of a simulation system for environmental applications. In: Cerrolaza M, Gajardo C, Brebbia CA (eds) Numerical methods in engineering simulation. Proceedings of the 3rd international conference on numerical methods in engineering and applied sciences, Mérido, Venezuela, 1996. CMP, Southampton, pp 297–302
Khaiter PA (2005a) Valuing the ecological and socio-economic services in management of headwater ecosystems. In: Proceedings of the international conference on hydrology, ecology and water resources in headwaters 6 (HeadWater 2005), Bergen, Norway. NVE (Norwegian Water Resources and Energy Directorate), Oslo, pp 1–10

Khaiter PA (2005b) Simulation modeling in quantifying ecosystem services and sustainable environmental management. In: Zerger A, Argent RM (eds) Proceedings of the 16th international congress on modeling and simulation (ModSim'05), Melbourne, Australia. Modelling and Simulation Society of Australia and New Zealand, pp 347–353

Khaiter PA, Erechtchoukova MG (2007) Environmental assessment of anthropogenic impact through the patterns of ecosystem reactions. Int J Environ Cult Econ Soc Sustain 3(4):181–190

Khaiter PA, Erechtchoukova MG (2009a) Model aggregation and simplification in sustainable environmental management. Int J Environ Cult Econ Soc Sustain 6(1):227–242

Khaiter PA, Erechtchoukova MG (2009b) The notion of stability in mathematics, biology, ecology and environmental sustainability. In: Anderssen B et al. (eds) Proceedings of the 18th IMACS world congress – MODSIM09 international congress on modelling and simulation, Cairns, Australia, pp 2265–2271

Khaiter PA, Erechtchoukova MG (2010a) A model-based quantitative assessment of ecosystem services in the scenarios of environmental management. In: Swayne DA, Yang W, Voinov AA, Rizzoli A, Filatova T (eds) Proceedings of the 5th international congress on environmental modelling and software (iEMSs 2010), Ottawa, Canada. International environmental modelling and software Society, pp 272–279

Khaiter PA, Erechtchoukova MG (2010b) Simulating the hydrological service of forest for sustainable watershed management. Int J Environ Cult Econ Soc Sustain 6(3):227–240

Khaiter PA, Erechtchoukova MG (2012) Quantitative assessment of natural and anthropogenic factors in forest carbon sequestration. In: Seppelt R, Voinov AA, Lange S, Bankamp D (eds) Proceedings of the 6th international congress on environmental modelling and software (iEMSs 2012), Leipzig, Germany. International Environmental Modelling and Software Society, pp 2075–2082

Khaiter PA, Erechtchoukova MG (2013) Ecosystem services in environmental sustainability: a formalized approach using UML. In: Piantadosi J, Anderssen RS, Boland J (eds) Proceedings of the 20th international congress on modelling and simulation (ModSim'13), Adelaide, Australia. Modelling and simulation Society of Australia and New Zealand, pp 1805–1811

Khaiter PA, Erechtchoukova MG (2014) Environmental software development with UML. In: Ames DP, Quinn NWT, Rizzoli AE (eds) Proceedings of the 7th international congress on environmental modelling and software (iEMSs 2014), San Diego, California, USA. International Environmental Modelling and Software Society, pp 1289–1296

Khaiter PA, Erechtchoukova MG (2017) Designing a software tool for environmental modelling and decision making in managing of biological invasion cases. In: Denzer R, Schimak G, Hřebíček J (eds) Environmental software systems. Springer, Berlin, pp 209–222

Khaiter PA, Erechtchoukova MG (2018) Conceptualizing an environmental software modeling framework for sustainable management using UML. J Environ Inf. https://doi.org/10.3808/jei.201800400

Liu J, Mooney H, Hull V, Davis SJ, Gaskell J, Hertel T, Lubchenco J, Seto KC, Gleick P, Kremen C, Li S (2015) Systems integration for global sustainability. Science 347(6225):1258832-1–1258832-9. https://doi.org/10.1126/science.1258832

Lloyd W, David O, Ascough JC II, Rojas KW, Carlson JR, Leavesley GH, Krause P, Green TR, Ahuja LR (2011) Environmental modeling framework invasiveness: analysis and implications. Environ Model Softw 26(10):1240–1250

Maciaszek LA, Liong BL (2005) Practical software engineering: a case-study approach. Addison-Wesley, Harlow

Marsh GP (1864) Man and nature; or, physical geography as modified by human action. Belknap Press of Harvard University Press, Cambridge, MA

Mazza G, Tricarico E, Genovesi P, Gherardi F (2014) Biological invaders are threats to human health: an overview. Ethology Ecology & Evolution 26(2–3):112–129

MEA (Millennium Ecosystem Assessment) (2005) Ecosystems and human well-being: synthesis. Island Press, Washington, DC

Molnar JL, Gamboa RL, Revenga C, Spalding MD (2008) Assessing the global threat of invasive species to marine biodiversity. Front Ecol Environ 6(9):485–492
Mueller F (1997) State-of-the-art in ecosystem theory. Ecol Model 100(1–3):135–161
NRC (National Research Council) (2011) Sustainability and the U.S. EPA. The National Academies Press, Washington, DC. https://doi.org/10.17226/13152
Odum EP (1983) Basic ecology. Saunders College Publishing, Philadelphia
Porritt J (2006) Capitalism as if the world mattered. Earthscan, London
Saier M (2006) Species extinction. Environmentalist 26:135–137
Scott CM (2009) Green economics. Earthscan, London
Tansley AG (1935) The use and abuse of vegetation concepts and terms. Ecology 16:284–307
Thiele LP (2013) Sustainabily. Polity Press, Malden
UN (ed) (2007) Indicators of sustainable development: guidelines and methodologies, 3rd edn. United Nations, New York. http://www.un.org/esa/sustdev/natlinfo/indicators/guidelines.pdf
UNDP (United Nations Development Program) (2015). http://www.undp.org/content/undp/en/home/sustainable-development-goals.html
UNGA (United Nations General Assembly) (2005) 2005 world summit outcome, resolution A/60/1, adopted by the general assembly on 15 September 2005. www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_60_1.pdf
UNGA (United Nations General Assembly) (2015) Transforming our world: the 2030 agenda for sustainable development. http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E
von Bertalanffy L (1969) General systems theory: foundations, development, applications. G. Braziller, New York
Wangen SR, Webster CR (2006) Potential for multiple lag phases during biotic invasions: reconstructing an invasion of the exotic tree *Acer platanoides*. J Appl Ecol 43:258–268
WCED (United Nations World Commission on Environment and Development) (1987) Our common future. Oxford University Press, Oxford
Whitfield PH (1988) Goals and data collection designs for water quality monitoring. J Am Water Resour Assoc 24(4):775–780. https://doi.org/10.1111/j.1752-1688.1988.tb00928.x
WQTG (Water Quality Task Group) (2006) A Canada-wide framework for water quality monitoring. PN 1369. http://www.ccme.ca/files/Resources/water/wqm_framework_1.0_e_web.pdf
Wu J (2013) Landscape sustainability science: ecosystem services and human Well-being in changing landscapes. Landsc Ecol 28:999–1023. https://doi.org/10.1007/s10980-013-9894-9

Chapter 2
Framework for Identifying Preferred Sustainable Management Actions with Application to Forest Fuel Treatment

Tony Prato

Abstract A conceptual framework is presented for identifying preferred feasible and sustainable management actions for a coupled human and natural system. The framework involves: (1) determining operationally and financially feasible management actions; (2) selecting and estimating management objectives for those actions; (3) using the weak or strong sustainability criterion to identify feasible management actions that are sustainable; (4) assigning weights to management objectives; and (5) ranking feasible and sustainable management actions. Management actions, objectives, and weights are selected by the manager. Management actions are ranked using a multiple objective evaluation method and utility values estimated with the utility function $U(\sum_{i=1}^{n} w_i V_{ij})$, where i designates management objective, j designates management action, w_i is the weight assigned to the ith management objective, V_{ij} is the estimated value of the ith management objective for the jth management action, and $\sum_{i=1}^{n} w_i = 1$. Management objectives are simulated or estimated using biophysical and economic data and models. An empirical application of the framework is presented that uses the Stochastic Efficiency with Respect to a Function method and utility values to rank three preselected fuel treatment strategies and determines preferred treatment strategies for U.S. Forest Service land in Flathead County, Montana for two risk attitudes (i.e., almost risk neutral and strongly risk averse).

Keywords Preferred · Sustainable · Management actions · Forest · Fuel treatment

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2.1 Introduction

Managers of coupled human and natural systems (CHANS) face the daunting task of managing those systems in a sustainable manner over space and time. CHANS are complex socio–ecological systems for which natural and human elements interact (Liu et al. 2007). For example, preparing or updating a general management plan for a U.S. national forest requires forest managers to identify and evaluate the operational and financial feasibility of management actions (MAs) and the sustainability of feasible MAs based on the extent to which they attain forest management objectives and satisfy sustainability criteria. Evaluating the feasibility and sustainability of MAs requires a conceptual framework that quantifies expected outcomes of MAs in terms of management objectives, determines the importance of those objectives to managers, and ranks the sustainability of feasible management actions based on expected outcomes.

In the context of forest management, which is the area to which this study applies the proposed framework, several studies have evaluated management strategies to increase the resilience and sustainability of forest ecosystems (e.g., Deuling et al. 2000; Summerfield et al. 2004; Millar et al. 2007; Malmsheimer et al. 2008; Evans and Perschel 2009; Puettmann et al. 2009). These studies focus on how changes in just one natural or human driver of forest sustainability influence a single management objective (e.g., how landscape fragmentation resulting from residential development degrades wildlife habitat or how increases in temperature resulting from climate change influence the distribution of tree species). Few studies have evaluated how multiple sustainability objectives are influenced by multiple socioeconomic, biophysical, and other drivers of forest sustainability. For the most part, this deficiency stems from the lack of an integrated conceptual framework that forest managers can use to evaluate the impacts of multiple forest ecosystem drivers on the sustainability of MAs.

This chapter proposes an integrated, multiple objective, conceptual framework for evaluating and ranking the sustainability of MAs for CHANS, and determining preferred sustainable MAs. An empirical application of the framework is made that demonstrates how the framework is used to determine preferred fuel treatment strategies (FTSs) for a U.S. national forest in northwest Montana. The framework consists of five sequential elements: (1) determining operationally and financially feasible management actions; (2) selecting and estimating management objectives for those actions; (3) using the weak or strong sustainability criterion to identify feasible management actions that are sustainable; (4) assigning weights to management objectives; and (5) ranking feasible and sustainable management actions (FSMAs).

2.2 Methodology

This section describes the elements of the proposed conceptual framework and the methods used in the empirical application of that framework. Figure 2.1 summarizes the sequence of elements in the conceptual framework.

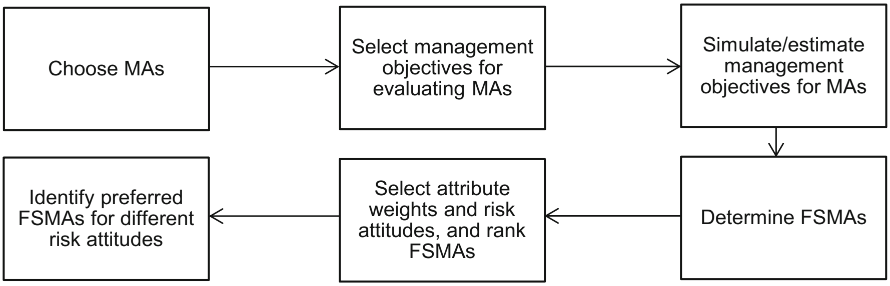

Fig. 2.1 Flow chart of proposed conceptual framework

2.2.1 Feasibility of Alternative Management Actions

The proposed framework evaluates two kinds of feasibility: whether an MA is operationally feasible; and whether an MA is financially feasible. An MA is operationally feasible if it is feasible to use that MA in the CHANS. For example, clearcutting involves harvesting most, but not all, of the standing trees in an area at the same time. Clearcutting is likely to be a more feasible harvesting method for a stand of Douglas fir because it supports the growth of new seedlings that require direct sunlight for growth, whereas selective harvesting methods, such as thinning, are more feasible for stands of shade–tolerant tree species because it allows trees to regenerate naturally (Oregon Forest Resources Institute 2018). Therefore, in terms of fostering natural tree regeneration, clearcutting is more operationally feasible in Douglas fir stands, and selective cutting is more operationally feasible in stands of shade–tolerant species. Of course, clearcutting and selective cutting have other benefits and costs that influence their overall acceptability.

Financial feasibility is evaluated by comparing the expected total cost of implementing a particular management action to the manager's expected budget for management actions. If expected total expenditures for an MA exceed the expected budget, then that MA is not financially feasible. In the example used above, selective cutting of certain tree stands may not be and clearcutting may be financially feasible. This is likely to occur because clearcutting is generally the most efficient and economical method of harvesting tree stands (Oregon Forest Resources Institute 2018). A harvesting method can be: (1) operationally feasible, but financially infeasible; (2) operationally infeasible, but financially feasible; (3) operationally and financial feasible; or (4) operationally and financial infeasible. For purposes of the proposed framework, sustainability of MAs is evaluated only for operationally and financially feasible MAs.

2.2.2 Selecting and Estimating Management Objectives

The proposed framework requires the CHANS manager to select a set of management objectives with which to evaluate and rank FSMAs and estimate the values of those objectives for FSMAs. Management objectives for a CHANS typically vary with land ownership/management. For example, if the CHANS is a national forest in the U.S. (i.e., a forest that is publicly owned and managed by the U.S. Forest Service), then the Multiple Use and Sustained Yield Act of 1960 requires the Forest Service to manage that forest for multiple objectives, including outdoor recreation, range, timber, watershed, and fish and wildlife with no use greater than any other. In other words, a U.S. national forest must be managed for multiple objectives that are equally important. In contrast, if the CHANS is a privately–owned industrial forest, then the primary management objective is to maximize net returns from the sale of timber harvested from tree stands subject to legally–mandated best management practices, such no logging within a certain distance of water bodies.

The proposed framework estimates the values of management objectives for feasible MAs using biophysical simulation models, revenue and cost estimation methods, land use change simulation models, and expert opinion. For instance, the empirical application, which determines preferred FTSs for tree stands in the Flathead National Forest (study area), required simulating the volume, location, and method of timber harvesting for each stand. That was done using a modified version of the Fire BioGeoChemical (FireBGCv2) model. FireBGCv2 is a mechanistic, individual tree succession model that includes a spatially explicit model for fire ignition and spread, and their effects on ecosystem components (Keane et al. 2011). Simulated volume of harvested timber, forecasted timber prices, and estimated harvest costs for forest stands were combined to estimate expected net returns from timber harvesting (*ENRT*) for each stand. *ENRT* is one of the three management objectives used to evaluate and rank MAs for Flathead National Forest.

2.2.3 Identifying Sustainable Management Actions

The proposed framework evaluates the sustainability of feasible management actions based on a set of sustainability conditions chosen by the manager. Sustainability conditions are statements about the level of management objectives that need to be achieved by feasible MAs to make them sustainable. Having the manager select sustainability conditions does not imply that stakeholders' opinions about sustainability are ignored because those conditions can be selected in collaboration with stakeholders.

Because the proposed framework evaluates the sustainability of feasible MAs in terms of multiple objectives, sustainability conditions need to be specified for all objectives. Sustainability literature differentiates between weak and strong sustainability (Dietz and Neumayer 2007; Prato 2015). A CHANS system is weakly sustainable when some, but not all, of the estimated values of the management objectives satisfy their respective sustainability conditions. The form of the weak sustainability condition depends on whether there are single or multiple estimated values of management objectives for MAs, and whether a management objective is positive (i.e., more is preferred to less) or negative (i.e., less is preferred to more). Two cases of weak and strong sustainability are described. In the first case, a single value is estimated for each management objective and feasible MA, whereas in the second case multiple values are estimated for each management objective and feasible MA. Both cases are described in terms of three management objectives (i.e., $\hat{O}_1$, $\hat{O}_2$, and $\hat{O}_3$).

For the first case of weak sustainability, the jth feasible MA (i.e., MA_j) is weakly sustainable with respect to positive objective i if $\hat{O}_{ij} \geq O_{imin}$ and not weakly sustainable if $\hat{O}_{ij} < O_{imin}$ where $\hat{O}_{ij}$ is the estimated value of positive objective i for MA_j and O_{imin} is the minimum acceptable value of O_i. Conversely, MA_j is weakly sustainable with respect to negative objective i' if $\hat{O}_{i'j} \leq O_{i'max}$ and not weakly sustainable if $\hat{O}_{i'j} > O_{i'max}$ where $\hat{O}_{i'j}$ is the estimated value of negative objective i' for MA_j and $O_{i'max}$ is the maximum acceptable value of $O_{i'}$.

For the second case of weak sustainability, MA_j is weakly sustainable with respect to positive objective i if $\Pr\{\hat{O}_{ij} \geq O_{imin}\} \geq 1 - \varphi$, and not weakly sustainable if $\Pr\{\hat{O}_{ij} \geq O_{imin}\} < 1 - \varphi$, where $0 \leq \varphi \leq 1$, and $1 - \varphi$ is the reliability level for the probability statements. Conversely, MA_j is weakly sustainable with respect to negative objective i if $\Pr\{\hat{O}_{ij} \leq O_{imax}\} \geq 1 - \varphi$, and not weakly sustainable if $\Pr\{\hat{O}_{ij} \leq O_{imax}\} < 1 - \varphi$. Evaluation of these probability statements requires specifying probability distributions for the estimated values of management objectives. This can be done, for example, by using the best–fitting probability distributions for the estimated values of management objectives.

A problem with applying the weak sustainability condition is that there is no generally accepted rule for how many estimated management objectives need to satisfy their respective sustainability conditions for the system to be weakly sustainable. One way to deal with this problem is for the manager to establish a decision rule, such as the system is weakly sustainable if at least two–thirds of the estimated management objectives satisfy their respective sustainability conditions.

An MA is strongly sustainable if every estimated management objective for that MA satisfies its respective sustainability condition. For the first case of strong sustainability, MA_j is strongly sustainable if $\hat{O}_{ij} \geq O_{imin}$ for all positive objectives and $\hat{O}_{ijt} \leq O_{imin}$ for all negative objectives. For the second case of strong sustainability, MA_j is strongly sustainable if $\Pr\{\hat{O}_{ij} \geq O_{imin}\} \geq 1 - \varphi$ for all positive objectives and $\Pr\{\hat{O}_{ij} \leq O_{imax}\} \geq 1 - \varphi$ for all negative objectives. For both cases, if even one of the sustainability conditions is violated, the MA_j is not sustainable.

Values of O_{imin}, O_{imax}, and φ are chosen by the manager. The sustainability conditions stated above assume φ is the same for positive and negative objectives. However, the manager can select different values of φ for positive vs. negative objectives, and different values of φ for different positive objectives and/or different negative objectives.

Table 2.1 Derivation of consensus weights for management objectives for a three–member management team

Objective	Member			Sum	Consensus weights[a]
	1	2	3		
O_1	0.2	0.3	0.4	0.9	0.9/3 = .3
O_2	0.3	0.2	0.3	0.8	.8/3 = .267
O_3	0.5	0.5	0.3	1.3	1.3/3 = .433
Sum	1	1	1	3	1

[a]Sum of weights for each objective divided by the sum of weights for all objectives

2.2.4 Assigning Weights to Management Objectives

Calculation of utility values for FSMAs (see Sect. 2.2.5) requires the manager to assign weights to management objectives, such that the sum of the weights equals one. Weights indicate the relative importance of management objectives to the manager or, if collaborative decision making is being practiced, the manager and stakeholders. For example, suppose there are three management objectives and the assigned weights are .20 for the first objective and .40 for the second and third objectives. These weights imply the first objective is half as important as the second and third objectives, and the second and third objectives are equally important. If weights are independently determined by members of a management team, then consensus weights for the team are used to calculate utility values. For example, suppose the weights assigned to management objectives by three members of a management team are as shown in Table 2.1. In this example, consensus weights for the team are .3 for O_1, .267 for O_2, and .433 for O_3.

2.2.5 Deriving Preferred Management Actions

Preferred management actions are determined by ranking FSMAs. Ranking requires: (1) selecting an outcome that the manager desires more of, designated as *c*; (2) defining a utility function on c, namely U(*c*); (3) using U(*c*) to calculate utility values for FSMAs; (4) using utility values to calculate certainty equivalents (CEs) for FSMAs; and (4) ranking FSMAs based on their CE values. In this study, a CE is the payoff amount that a manager is willing to receive in exchange for accepting the variability in utility associated with a particular FSMA (adapted from Prato et al. 2010). Studies of risky alternatives (e.g., Hardaker et al. 2004; Qiu and Prato 2012) typically define *c* as wealth or income. In this study, *c* is defined as the following index of the values of the multiple objectives achieved by an FSMA, namely $c_j = \sum_{i=1}^{n} w_i V'_{ij}$, where $i = 1, \ldots,$ n is an index for objectives, $j = 1, \ldots,$ m is an index for FSMAs, w_i is the weight assigned to the *i*th objective, V'_{ij} is the estimated normalized and/or adjusted value of the *i*th objective for the *j*th FSMA, and $\sum_{i=1}^{n} w_i = 1$. FSMAs are risky alternatives because w_j and V'_{ij}, and hence c_j are stochastic. Estimated values of management objectives need to be normalized when the raw values of objectives are measured in different units. Estimated values of negative management objectives need to be adjusted (i.e., converted from negative objectives to positive objectives) to ensure that c_j is a monotonically increasing function of the values of objectives or equivalently that all objectives in the utility function are positive (i.e., increasing the objective increases utility).

Use of the above utility function requires information about its exact shape, or equivalently the manager's risk attitudes. Such information can be obtained by eliciting the managers' risk attitudes (e.g., Charness et al. 2013). Alternatively, hypothetical risk attitudes can be used (Prato 2008). This study employs the Stochastic Efficiency with Respect to a Function (SERF) method (Hardaker et al. 2004) to rank FSMAs for an absolute, relative, or partial risk aversion coefficient $r(c_j) \in [r_L(c_j), r_U(c_j)]$, where $r_L(c_j)$ is the selected lower bound and $r_U(c_j)$ is the selected upper bound of the coefficient. In particular, the discrete approximation of the utility function is $\mathrm{U}\left[c_j, \mathrm{r}\left(c_j\right)\right] = \sum_{i=1}^{m} \mathrm{U}\left[c_i, r\left(c_i\right)\right] \mathrm{p}\left(c_{ij}\right)$, where $\mathrm{p}(c_{ij})$ is the probability of the ith outcome for the jth FSMA. This approximation provides utility values for discrete values of $r(c_j)$. Because the partial ordering of FSMAs based on $\mathrm{U}[c_j, r(c_j)]$ and CE values is the same (i.e., $\mathrm{CE}[c_j, r(c_j)] = \mathrm{U}^{-1}[c_j, r(c_j)]$, where $\mathrm{U}^{-1}[c_j, \mathrm{r}(c_j)]$ is the inverse utility function), the CE values calculated using the SERF method were used to rank FSMAs.

2.2.6 Empirical Application

The western U.S. continues to experience increasing wildfire–related losses, particularly for residential properties located near public lands (USDA and USDI 2001; Union of Concerned Scientists 2013). Such losses result from the accumulation of fuel loads due to decreased logging, especially in national forests, population growth in the wildland–urban interface, warmer summers, reduced precipitation, and milder winters. Prato et al. (2014) state that residential losses due to wildlife in the 290,135–ha Flathead National Forest in Flathead County, Montana–the study area used here–are expected to increase from \$1.8 million in 2010 to an average annual present value of \$6.8 million in 2059. Figure 2.2 illustrates the location of Flathead County in Montana and industrial forest landownership in the study area.

Potential benefits of forest fuel treatment include a reduction in fuel loads and possibly wildfire intensity or severity (Pollet and Omi 2002; Graham 2003; Agee and Skinner 2005; Raymond and Peterson 2005; Cram et al. 2006; Prichard et al. 2010). For that reason, fuel treatment in forest ecosystems has become a high priority for reducing wildfire risk to human and natural resources (Healthy Forests Restoration Act of 2003; Rhodes and Baker 2008).

This section describes the methods used in the empirical application to evaluate and rank FTSs for Flathead National Forest. Several of the methods used in the empirical application come from a previous study of wildfire risk in Flathead County (Prato et al. 2014).

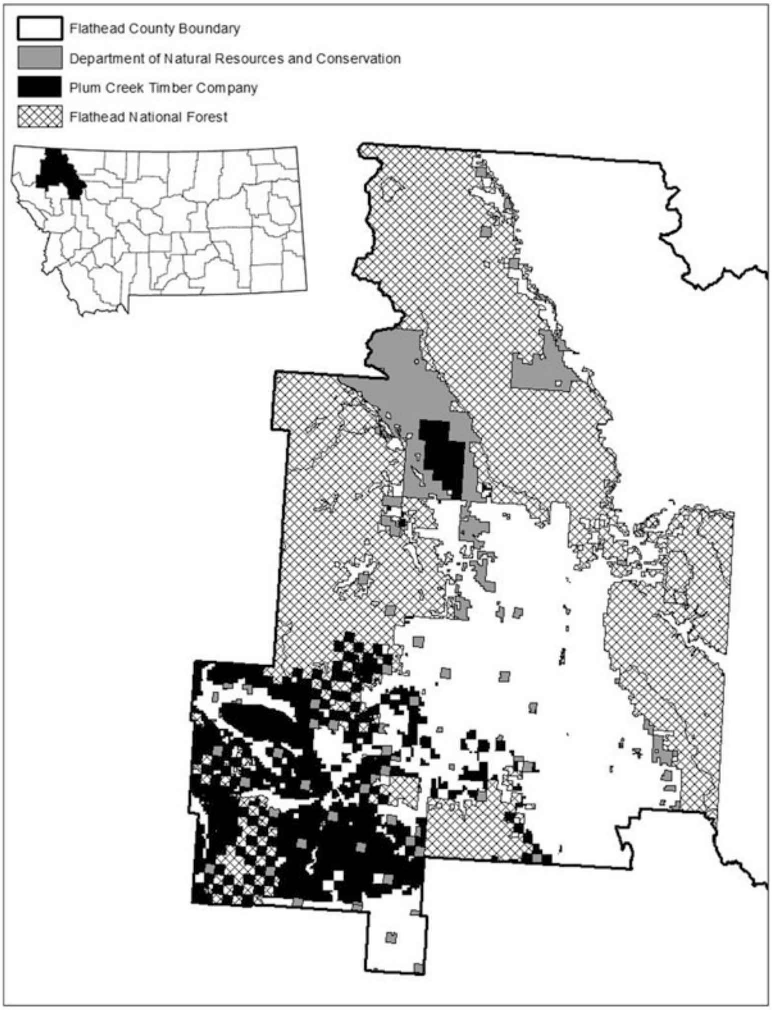

Fig. 2.2 Location of Flathead County, Montana and industrial forest landownership in the study area, 2010

2.2.6.1 Management Actions and Study Area

Three FTSs were evaluated and ranked: (1) Community Wildfire Protection Plan (CWPP) priority; (2) CWPP & Wildland–Urban Interface (WUI) priority; and (3) No priority. Each FTS specifies the forest stands prioritized for fuel treatment. Prioritization is appropriate because limited financial budgets and personnel restrict the forest area that can be treated in each subperiod. Such limits were taken into account by having officials of Flathead National Forest specify the maximum area that can be treated in each of five subperiods: 2010–2019; 2020–2029; 2030–2039;

2040–2049; and 2050–2059. Each FTS allows trees to be harvested using three practices: heavy partial thinning; light partial thinning; and/or prescribed burning.

The CWPP priority FTS is based on fuel treatment priorities established by local stakeholders in Flathead County, and "... is intended to outline the Flathead County's plans and activities targeted at reducing the risk of a catastrophic wildland and/or wildland–urban interface (WUI) fire event in Flathead County" (FireLogistics 2011, p. 7). Stands without a CWPP priority were not allowed to be treated unless all eligible CWPP priority stands were treated and the maximum area that can be treated per subperiod was not exceeded.

The CWPP & WUI priority FTS targets forest stands for fuel treatment based on whether they have a CWPP priority and/or are located in the WUI. The WUI generally refers to areas where human development is in close proximity to or interspersed with wildland vegetation. Procedures used to delineate the WUI are described in Paveglio et al. (2013) and Prato et al. (2014). Those procedures use site specific data and calculations, and spatial criteria to designate WUI areas that conform to state and federal policies. Stands without a CWPP & WUI priority were not allowed to be treated unless all eligible CWPP & WUI priority stands were treated and the maximum area that can be treated per subperiod was not exceeded.

The No priority FTS randomly selects eligible forest stands for treatment until the maximum area that can be treated per subperiod was attained or no more stands were eligible for treatment.

The empirical application assumes that the three FTSs are feasible and sustainable, only one FTS can be used per subperiod, and the same FTS is used across subperiods. The volume of wood harvested or burned in each stand and subperiod with each FTS and practice were determined using a modified version of the FireBGC model.

2.2.6.2 Specification and Estimation of Fuel Treatment Objectives

Empirical use of the utility function specified in Sect. 2.2.5 requires estimates of the values of the fuel treatment objectives for FSMAs, as well as the weighs for objectives. Three fuel treatment objectives were used to evaluate and rank FSMAs: (1) minimizing expected residential monetary losses from wildfire (*ERLW*); (2) minimizing expected deviation of forest ecological conditions from their historic range and variability (*EDRV*); and (3) maximizing expected net returns from timber harvesting associated with fuel treatment (*ENRH*). *ERLW*, *EDRV*, and *ENRH* are referred to as the attributes of fuel treatment objectives. These fuel treatment objectives are the same ones used in a previous study of wildfire risk in Flathead County, Montana (Prato and Paveglio 2017).

ERLW is a probabilistic metric of wildfire risk defined as

$$ERLW = ERLW_x + ERLW_n, \tag{2.1}$$

where:

$ERLW_x$ = present value in 2010 of expected wildfire losses for residential properties that existed in 2010; and

$ERLW_n$ = present value in 2010 of expected wildfire losses for new residential properties developed during the 50–year evaluation period.

Present values of *ERLW* were calculated using a nominal (i.e., unadjusted for inflation) discount rate of 6%. Properties containing residential structures in 2010 were identified using the Montana Computer Assisted Mass Appraisal (CAMA) parcel data for 2010 (Montana Cadastral 2010). For each subperiod, a new WUI was delineated that included existing and new residential properties as of the end of that subperiod.

$ERLW_x$ is defined as

$$ERLW_x = PV_{10}\left(ERLW_{x1}, ERLW_{x2}, ERLW_{x3}, ERLW_{x4}, ERLW_{x5}\right), \tag{2.2}$$

where PV_{10} stands for the present value in 2010. $ERLW_{xt}$ is the undiscounted expected wildfire losses during subperiod t for residential properties that existed in 2010 defined as

$$ERLW_{xt} = \sum\nolimits_{j=1}^{mx} pb_{jt}\left[\left(\sum\nolimits_{h=1}^{nxj} pS_{hjt} VS_{xhjt}\right) + \beta_{jt} TV_{xjt}\right](t = 1, \ldots, 5), \tag{2.3}$$

where:

m_x = number of parcels in the WUI containing residential properties in 2010;

n_{xj} = number of residential properties in parcel j in 2010;

pb_{jt} = probability that parcel j burns during subperiod t;

pS_{hjt} = probability that structures on property h in parcel j burn during subperiod t given parcel j burns during subperiod t;

VS_{xhjt} = total value of structure(s) existing in 2010 on residential property h in parcel j during subperiod t;

β_{jt} = average percentage loss in aesthetic value of residential properties in parcel j during subperiod t given parcel j burns during subperiod t; and

TV_{xjt} = total value of each 2010 residential property (structure and land) in parcel j during subperiod t.

m_x and n_{xj} are determined from the 2010 CAMA parcel data. Values of pb_{jt} for each FTS and subperiod were estimated by inputting into the FSim model (Finney et al. 2010) changes over subperiods in forest vegetation simulated using FireBGC. The latter were based on the Intergovernmental Panel on Climate Change's (IPCC's) A2 emissions scenario (IPCC 2007). pS_{hjt} and β_{jt} were simulated using the procedures described in Prato et al. (2014). VS_{xhjt} was estimated by $VS_{xhjt} = (1 + \lambda)^r\ VS_{xhjo}$, where VS_{xhjo} is the total value of structures located on residential property h in parcel j in 2010 determined from the 2010 CAMA parcel data, $\lambda = 0.035$, which is the annualized nominal growth in average property values in the US during the past 20 years (i.e., 1991 to 2009 (Federal Housing Finance Agency 2010) in decimal equivalent, and r equals 10 for $t = 1$, 20 for $t = 2$, 30 for $t = 3$, 40 for $t = 4$, and 50 for $t = 5$.

TV_{xjt} was simulated by $TV_{xjt} = (1 + \lambda)^r \, TV_{xjo}$, where TV_{xj0} is the sum of the assessed building and land values for residential properties located on parcel j in 2010, and r and λ are as defined above. VS_{xhjt} and TV_{xjt} are nominal values as of the end of each subperiod. $pS_{hjt}VS_{xhjt}$ is expected wildfire–related loss in the value of structures that existed in 2010 on residential property h in parcel j during subperiod t and $\beta_{jt}TV_{xjt}$ is expected wildfire–related loss in the aesthetic value of residential properties (including structures and land) that existed in 2010 on parcel j during subperiod t given parcel j burns during subperiod t.

$\mathrm{ERLW_n}$ is defined as

$$\mathrm{ERLW}_n = PV_{10}\left(\mathrm{ERLW}_{1n}, \mathrm{ERLW}_{2n}, \mathrm{ERLW}_{3n}, \mathrm{ERLW}_{4n}, \mathrm{ERLW}_{5n}\right). \tag{2.4}$$

$ERLW_{tn}$ is the present value as of subperiod t of expected wildfire losses between subperiods t and 5 for new residential properties added during subperiod t defined as

$$\mathrm{ERLW}_{t,t+k,n} = PV_t\left(\mathrm{ERLW}_{tn} + \ldots + \mathrm{ERLW}_{t+k,n}\right)(t = 1, \ldots, 5). \tag{2.5}$$

PV_t is the present value as of the end of subperiod t, k equals 4 for $t = 1$, 3 for $t = 2$, 2 for $t = 3$, and 1 for $t = 4$. $ERLW_{tn}$ is the expected wildfire losses for new residential properties added during subperiod t as of the end of subperiod t defined as

$$ERLW_{tn} = \sum\nolimits_{j=1}^{mnt} pb_{jt}\left[\left(\sum\nolimits_{h=1}^{fnjt} pS_{hjt}VS_{nhjt}\right) + \beta_{jt}TV_{njt}\right], \tag{2.6}$$

where:

m_{nt} = number of parcels in the WUI in which new residential properties are added during subperiod t;
f_{njt} = number of new residential properties added to parcel j during subperiod t;
pb_{jt} = probability that parcel j burns during subperiod t;
pS_{hjt} = probability that structures on property h in parcel j burn during subperiod t given parcel j burns during subperiod t;
VS_{nhjt} = total value of new structures added to residential property h in parcel j during subperiod t;

β_{jt} = average percentage of loss in aesthetic value of residential properties in parcel j during subperiod t given parcel j burns during subperiod t; and
TV_{njt} = total value of each new residential property added to parcel j during subperiod t.

The IMPLAN regional economic analysis model for Flathead County (Minnesota IMPLAN Group, Inc. 2011) was used with Bureau of Census data to estimate the number of new housing units required in each subperiod for a moderate economic growth scenario. The moderate economic growth scenario assumes an annual average rate of growth of 2.2%; the annual economic growth rate for the county between 2000 and 2008. The RECID2 model (Prato et al. 2014) was used to simulate m_{nt} and f_{njt} for six residential density classes as well as subdivision of residential parcels over subperiods based on total housing requirements estimated with the IMPLAN model and the 2010 land use policy scenario for Flathead County. The latter assumes or specifies: (1) no residential development on slopes greater than 30%; (2) no residential development in the 100–year floodplain; (3) the percentage of total housing units in six residential density classes (i.e., 3% in high density, 18% in urban, 42% in suburban, 7% in rural, 18% in exurban, and 12% in agricultural); (4) a 6.1 m setback of houses from wetlands and water bodies; and (5) residential development at the high, urban, and suburban density classes are only allowed on parcels having sewer access.

pS_{hjt} and β_{jt} were simulated using the procedures described in Prato et al. (2014). $pS_{hjt}VS_{nhjt}$ is the expected wildfire–related losses in the value of new structures in residential property h added to parcel j during subperiod t given parcel j burns during subperiod t. $\beta_{jt}TV_{njt}$ is the expected wildfire–related losses in the aesthetic value of residential properties (structure and land) added to parcel j during subperiod t given parcel j burns during subperiod t.

The historic range and variability (HRV) is an envelope of historical ecological conditions that can be used as reference point for evaluating the ecological benefits of management prescriptions (Aplet and Keeton 1999; Keane et al. 2009). *EDRV* measures the extent to which ecological conditions in forest stands in Flathead National Forest deviate from the HRV. For example, if heavy thinning reduces the departure of ecological conditions from HRV more than light thinning, then *EDRV* would be lower for heavy thinning than light thinning. Hence, heavy thinning would be preferable to light thinning in terms of reducing *EDRV*. FireBGC was used to simulate HRVs in Flathead National Forest for three variables: basal area; leaf area index; and fuel load. Deviations between simulated HRVs for the three variables and the estimated values of the variables for each FTS and subperiod were used to estimate *EDRV*.

ENRH measures total expected net returns from timber harvesting (across the five subperiods) in Flathead National Forest associated with FTSs. *ENRH* is a function of: (1) number of tree stands harvested in all subperiods with FTSs; (2) merchantable cubic feet harvested in each stand and subperiod with each FTS, if any; (3) average annual mill–delivered log prices; and (4) cost per cubic foot of harvesting and hauling timber to the sawmill for each FTS, stand, and subperiod.

Table 2.2 Conversion of attribute ratings to attribute weights

Attribute	Rating[a]	Weight[b]
ERLW	5	0.42 (α_{ERLW})
EDRV	4	0.33 (α_{EDRV})
ENRH	3	0.25 (α_{ENRH})

[a]Very low = 1, low = 2, moderate = 3, high = 4, and very high = 5
[b]Attribute rating divided by the sum of the ratings

Average harvesting costs per cubic foot for FTSs were estimated using the Harvest Cost Model (Hayes and Morgan 2014). Average annual mill–delivered log prices are sawlog prices weighted by volume delivered to northwest Montana sawmills during the period 1989–2009 (Bureau of Business and Economic Research, University of Montana 2013). More detailed explanations of how the attributes were estimated are given in Paveglio et al. (2013) and Prato and Paveglio (2014, 2017).

2.2.6.3 Determination of Attribute Weights

Weights for the three attributes of management objectives (i.e., *ERLW*, *EDRV*, and *ENRH*) were determined using the results from a survey conducted in an earlier study (Prato et al. 2014). In the survey, officials from Flathead National Forest were asked to rate the importance of the three attributes. Attribute ratings and their conversion to attribute weights are listed in Table 2.2.

2.2.6.4 Calculation of Utility Values

Utility values for FTSs were calculated using the utility function U(c_{jt}), where $c_{jt} = \sum_{i=1}^{3} w_i V'_{ijt}$. w_i is the weight for the *i*th attribute and V'_{ijt} is the normalized and/or adjusted present value of the *i*th attribute for the *j*th FTS in the *t*th subperiod. In terms of this study: $c_{jt} = \alpha_{\mathrm{ERLW}}(100 - ERLW_{jt*}) + \alpha_{EDRV}(100 - EDRV_{jt}) + \alpha_{ENRH}(ENRH_{jt}{}^{*})$, where $ERLW_{jt*}$ and $ENRH_{jt}{}^{*}$ are normalized present values of the objectives. $ERLW_{jt}$ and $ENRH_{jt}$ were normalized so that their units of measurement would match those of $EDRV_{jt}$, namely values in the interval [0, 100]. Subtracting $ERLW_{jt*}$ and $EDRV_{jt*}$ from 100, which is referred to as adjusting the attributes, makes $100 - ERLW_{jt*}$ and $100 - EDRV_{jt*}$ positive attributes (i.e., increases (or decreases) in $100 - ERLW_{jt*}$ and $100 - ERDV_{jt*}$ cause increases (or decreases) in $\mathrm{c_{jt}}$). Since $ENRH_{jt*}$ is already a positive attribute, it was not necessary to adjust its value. Normalized and adjusted attribute values are interpreted as follows: $100 - ERLW_{jt*}$ is the reduction in normalized, expected present value of residential losses due to wildfire; and $100 - EDRV_{jt*}$ is the reduction in normalized, expected deviation of ecological conditions from their HRV. The weights α_{ERLW}, α_{EDRV}, and α_{ENRH} were derived from the ratings of $ERLW_{jt}$, $EDRV_{jt}$, and $ENRH_{jt}$, respectively (see Table 2.2).

2.2.6.5 Ranking Management Actions

FSMAs were ranked using the SERF method contained in the Simetar computer program (Richardson et al. 2017). The SERF method substitutes the five values of c_{jt} (i.e., one for each subperiod) and 25 risk aversion coefficients (r) values selected from each of two user–specified intervals for the absolute risk aversion coefficient (ARAC) (i.e., $r \in [-.005, .005]$ for almost risk neutral attitudes, and $r \in [.02, .04]$ for highly risk averse attitudes) into a user–selected utility function to derive 25 utility values for each FTS. The two intervals selected for ARAC are consistent with the range of intervals for almost risk neutral and strongly risk averse attitudes used in other studies of risky alternatives (Raskin and Cochran 1986). SERF uses the 25 utility values to calculate 25 CVs for each FTS and risk aversion coefficient.

The following exponential utility function was selected for calculating utility values: $U(c_{jt}) = (1 - e^{-rcjt})$, where $r = -U''(c_{jt})/U'(c_{jt})$. $U''(c_{jt})$ is the second derivative and $U'(c_{jt})$ is the first derivative of $U(c_{jt})$ with respect to c_{jt}. An exponential utility function implies r is independent of c_{jt}, or constant absolute risk aversion. Therefore, r does not vary with respect to c_{jt}. Simetar displays the resulting 25 CE values for each FTS in tabular and graphical forms. Figure 2.3 is an example of CE curves calculated with the SERF method.

The figure illustrates a problem with trying to rank FTSs based on CE curves: CE values for the CWPP priority and No priority FTSs (the two lowest curves in Fig. 2.3) have similar CE curves making it difficult to ascertain whether the CWPP priority FTS is superior to the No priority FTS or vice versa. To alleviate such ambiguities, this study used statistical tests to determine whether CE values for the

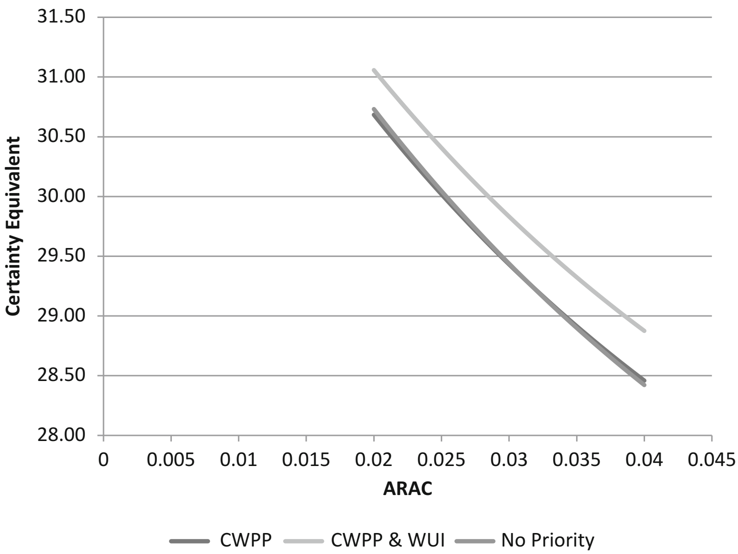

Fig. 2.3 Example of CE curves for three FTS calculated with the SERF method

three pairs of FTSs (i.e., CE_{CWPP} and CE_{NP}, $CE_{CWPP\&WUI}$ and CE_{NP}, and CE_{CWPP} and $CE_{CWPP\&WUI}$) were significantly different from one another. Normally, t–tests are used to test for significant differences in population means for a variable. The hypotheses in such tests are: (1) H_o: $\mu_{CWPP} = \mu_{NP}$ vs. H_a: $\mu_{CWPP} \neq \mu_{NP}$; (2) H_o: $\mu_{CWPP\&WUI} = \mu_{NP}$ vs. H_a: $\mu_{CWPP\&WUI} \neq \mu_{NP}$; and (3) H_o: $\mu_{CWPP} = \mu_{CWPP\&WUI}$ vs. H_a: $\mu_{CWPP} \neq \mu_{CWPP\&WUI}$, where μ is the population mean of CE. These tests would be valid if the CE values are normally distributed. This was not the case. Therefore, a nonparametric test was used to test for significant differences between CE values for the three pairs of FTSs.

Two nonparametric tests were considered for this purpose: Mood's Median Test; and Mann–Whitney U Test. The null and alternative hypotheses for both tests are H_0: $\eta_j = \eta_{j'}$ vs. H_a: $\eta_j > \eta_{j'}$, where η_j and $\eta_{j'}$ are the median CE values for the jth and j'th FTSs, respectively. Results of one–tailed tests were used to facilitate the ranking of FTSs. The Mann–Whitney U Test assumes the variances of the CEs are the same for the two FTSs being compared. Mood's Median Test does not make this assumption. Unfortunately, Mood's Median Test could not be used because there were not enough CE values greater than the median. Therefore, the Mann–Whitney U test was used to test the equality of median CE values for pairs of FTSs using an α–value, or type I error, of .05.

2.3 Results

Table 2.3 contains the raw and normalized and/or adjusted attribute values for the three FTSs. Raw *ERLW* values for all three FTSs increase during the first three subperiods and then decrease between the third and fifth subperiods. Changes in raw *ENRH* values are not consistent across subperiods. The raw *ENRH* value is negative for the CWPP priority FTS in subperiod 4 and the No priority FTS in subperiod 1. Raw EDRV values for all FTSs and subperiods are very high (100 is the maximum value), indicating that ecological conditions in the Flathead National Forest deviate substantially from their HRVs.

Total raw *ERLW* (i.e., the sum of raw *ERLW*s across subperiods) is lowest for the No priority FTS and highest for the CWPP priority FTS, but the difference is only 10%. Total raw *ENRT* is lowest for the No priority FTS and highest for the CWPP & WUI priority FTS, with a difference of 13%. Average *EDRV* is highest for the No priority FTS and lowest for the CWPP priority FTS, with a difference of 7%. If the three FTSs were ranked based on the total raw values of each of the three attributes, the first ranked FTS would be the No priority FTS based on minimizing raw *ERLW*, the CWPP & WUI priority FTS based on maximizing raw *ENRT*, and the CWPP priority based on minimizing *EDRV*. In other words, the preferred FTSs would be the No priority FTS based on minimizing *ERLW*, the CWPP & WUI priority FTS based on maximizing *ENRT*, and the CWPP priority based on minimizing *EDRV.* Hence, ranking FTSs based on only one management objective would give misleading information about the preferred FTS. In general,

Table 2.3 Subperiod raw and normalized and/or adjusted attribute values for FTSs

Attribute	Subperiod				
	1	2	3	4	5
	Raw and unadjusted attribute values				
	CWPP priority				
ERLW	\$371,677	\$1,242,245	\$1,972,854	\$1,434,784	\$1,077,629
ENRH	\$9,581,910	\$1,697,764	\$451,146	-\$1,775,674	\$1,813,348
EDRV	0.869	0.845	0.935	0.972	0.904
	CWPP & WUI priority				
ERLW	\$341,959	\$1,034,645	\$1,819,600	\$1,531,477	\$1,093,450
ENRH	\$3,271,970	\$3,368,976	\$3,076,553	\$1,516,979	\$1,209,313
EDRV	0.9570	0.9497	0.9773	0.9859	0.9753
	No Priority				
ERLW	\$449,672	\$864,919	\$1,692,502	\$1,326,331	\$1,189,675
ENRH	-\$309,844	\$1,678,596	\$3,510,581	\$2,888,701	\$3,209,873
EDRV	0.956	0.966	0.989	0.995	0.977
	Normalized and/or adjusted attribute values				
	CWPP priority				
$100 - ERLW_*$	93.91	79.63	67.65	76.48	82.33
$ENRH_*$	81.42	14.43	3.83	−15.09	15.41
$100 - EDRV_*$	13.07	15.48	6.54	2.83	9.57
	CWPP & WUI priority				
$100 - ERLW_*$	94.13	82.23	68.74	73.69	81.22
$ENRH_*$	26.29	27.07	24.72	12.19	9.72
$100 - EDRV_*$	4.30	5.03	2.27	1.41	2.47
	No priority				
$100 - ERLW_*$	91.86	84.34	69.36	75.99	78.46
$ENRH_*$	−2.82	15.29	31.98	26.31	29.24
$100 - EDRV_*$	4.42	3.43	1.11	0.51	2.31

this result supports the approach of ranking decision alternatives based on multiple management objectives.

Results of the Mann–Whitney U Test support rejection of the three null hypotheses at the 5% level of significance for managers having almost risk neutral and highly risk averse attitudes. These conclusions support the following preference orderings: CWPP Ƥ NP; CWPP & WUI Ƥ NP; and CWPP Ƥ CWPP & WUI, where Ƥ stands for ‘preferred to.’ Collectively, the three preference orderings imply CWPP Ƥ CWPP & WUI Ƥ NP. Therefore, the CWPP priority FTS is the preferred FTS for Flathead National Forest for both risk attitudes.

2.4 Discussion

The conceptual framework proposes using a multiple objective, exponential utility function to rank MAs for a CHANS. Other multiple objective/criteria decision frameworks can be used for this purpose, such as multiple objective/attribute value theory (Duarte and Reis 2006), ELECTRE (Roy 1968), Analytic Hierarchy Process (Saaty 1986), balancing and ranking method (Strassert and Prato 2002), and fuzzy Technique for Order Preference by Similarity of Ideal Solution (fuzzy TOPSIS) (Chen 2000; Prato 2009; Prato et al. 2010). An advantage of the utility function approach is that it allows management actions to be ranked for different risk attitudes, which allows evaluation of the sensitivity of the ranking of FTSs to variation in risk attitudes. Some of the other multiple objective/attribute decision–making methods do not require specification of a utility function. For example, the fuzzy TOPSIS method, which is a variation of the ideal point method (Anchen et al. 1997), evaluates and ranks decision alternatives based on how close (or how far away) the management objectives achieved by those alternatives are to the most (or least) desirable values of the positive (or negative) objectives. Use of fuzzy TOPSIS requires the decision–maker to rate the estimated values of the attributes for decision alternatives and importance of attributes using linguistic variables (e.g., low, moderately low, medium, moderately high, and very high). Fuzzy numbers assigned to the linguistic variables are then used to rank decision alternatives.

A potential drawback of the SERF method and some other decision frameworks is that they do not always yield a complete preference ordering for management actions. For example, suppose the results of the Mann–Whitney U test are: (1) H_0: $\eta_{CWPP} = \eta_{NP}$ is rejected relative to H_a: $\eta_{CWPP} > \eta_{NP}$; (2) H_0: $\eta_{CWPP\&WUI} = \eta_{NP}$ is not rejected relative H_a: $\eta_{CWPP\&WUI} > \eta_{NP}$; and (3) H_0: $\eta_{CWPP} = \eta_{CWPP\&WUI}$ is rejected relative to H_a: $\eta_{CWPP} > \eta_{CWPP\&WUI}$. These results imply CWPP Ƥ NP and CWPP Ƥ CWPP & WUI, which is not a complete preference ordering (i.e., it excludes a preference ordering between CWPP & WUI and NP). Lack of a preference ordering between CWPP & WUI and NP could be interpreted to mean that the manager is indifferent between the two FTSs. In cases where all three null hypotheses are not rejected, it is not possible to establish a preference ordering between the FTSs. Incomplete preference orderings for decision alternatives can also occur with other ranking methods, such as fuzzy TOPSIS (e.g., Prato 2009).

While the methods/approaches used in the empirical application can be used in other forested landscapes, their complexity is likely to dissuade most forest managers from using them. Some managers may be able to use these methods/approaches with assistance from professionals familiar with them. Another option is to utilize less complex models/approaches than the ones used here. For example, instead of using FireBGC to simulate the effects of MAs on intertemporal changes in forest vegetation, such dynamics can be simulated using the more tractable Climate–Forest Vegetation Simulator (Crookston 2014) or ENVISION model (Oregon State University 2012). Alternatively, vegetation changes over time for alternative MAs can be estimated using the Delphi method (Linstone and Turoff 1975). That method uses a panel of experts to estimate the effects of alternative decisions on management objectives. Similarly, instead of using the IMPLAN model to simulate the number of new housing units required in each subperiod, that number can be estimated by multiplying population projections for subperiods by the average number of persons per housing unit in the study area.

2.5 Conclusions

Intertemporal changes in complex, interacting biophysical and socioeconomic drivers influence the sustainability of CHANS. Managers of CHANS face the challenging task of understanding how these drivers influence CHANS and determining the best MAs for achieving sustainability. This task can be facilitated by developing conceptual frameworks that integrate the complex drivers of sustainability in a decision–making algorithm that managers can use to evaluate and rank feasible and sustainable MAs over time and space.

This study proposes one such conceptual framework that involves the following five elements: (1) determining operationally and financially feasible management actions; (2) selecting and estimating management objectives for those actions; (3) using the weak or strong sustainability criterion to identify feasible management actions that are sustainable; (4) assigning weights to management objectives; and (5) ranking feasible and sustainable MAs. Some of these elements are more difficult to accomplish than others. Specifically, elements 2 and 5 are more difficult to execute than elements 1, 3, and 4.

The empirical application uses the proposed framework to determine preferred FTSs for Flathead National Forest for forest managers having almost risk neutral and highly risk averse attitudes. Results indicate that: (1) ranking the three preselected FTSs based on only one management objective could give misleading information about the preferred FTS, which, in general, supports ranking decision alternatives based on multiple management objectives; and (2) there is a complete preference ordering for the three FTSs (i.e., no two FTSs have the same rank) that is the same for both risk attitudes. Although it would be challenging for CHANS managers to implement the proposed framework the way it was done here, the framework is general enough to be implemented using more simplified methods and techniques. Doing the latter would make it easier for CHANS managers to apply the framework.

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References

Agee JK, Skinner CN (2005) Basic principles of forest fuel reduction treatments. For Ecol Manag 211:83–96

Anchen Q, Linsen Z, Jianguo L, Weizhong L, Dinghua C (1997) Ideal point method applied in forest harvest regulation. J Forest Res 8:117. https://link.springer.com/article/10.1007%2FBF02864982. Accessed 1 May 2018

Aplet G, Keeton WS (1999) Application of historical range of variability concepts to biodiversity conservation. In: Baydack RK, Campa H, Haufler JB (eds) Practical approaches to the conservation of biological diversity. Island Press, New York, pp 71–86

Bureau of Business and Economic Research, University of Montana (2013) Forest economics. In: Montana quarterly log prices. http://www.bber.umt.edu/FIR/F_LogPrice.Asp

Charness G, Gneezy U, Imas A (2013) Experimental methods: Eliciting risk preferences. J Econ Behav Organ 87:43–51

Chen C-T (2000) Extensions to the TOPSIS for group decision–making under fuzzy environment. Fuzzy Sets Syst 114:1–9

Cram D, Baker T, Boren J (2006) Wildland fire effects in silviculturally treated vs. untreated stands of New Mexico and Arizona. USDA Forest Service, Rocky Mountain Research Station, Research Paper RMRS-RP-55, Fort Collins, CO

Crookston NL (2014) Climate–FVS version 2: content, user's guide, applications, and behavior. USDA Forest Service, Rocky Mountain Research Station, General technical report, RMRSGTR-319, Fort Collins, CO

Deuling MJ, Woudsma CG, Franklin SE (2000) Temporal analysis of habitat fragmentation: Integrating GIS, landscape ecology, and improved RS classification methods. In: 4th international conference on integrating GIS and environmental modeling (GIS/EM4): problems, prospects, and research needs. Alberta, CA, September 2–8

Dietz S, Neumayer E (2007) Weak and strong sustainability in the SEEA: Concepts and measurement. Ecol Econ 61:617–626

Duarte BPM, Reis A (2006) Developing a projects evaluation system based on multiple attribute value theory. J Comput Operat Res 33:1488–1504

Evans A, Perschel R (2009) A review of forestry mitigation and adaptation strategies in the Northeast US. Clim Chang 96:167–183

Federal Housing Finance Agency (2010) House price index news release. http://www.fhfa.gov/webfiles/15454/finalHPI22510.pdf

Finney MA, McHugh CW, Grenfell I, Riley KL (2010) Continental-scale simulation of burn probabilities, flame lengths, and fire size distribution for the United States. In: Viegas DX (ed) Proceedings of the VI international conference on forest fire research. University of Coimbra, Portugal, p 12

FireLogistics Incorporated (2011) Flathead County community wildfire protection plan. https://flathead.mt.gov/fireservice/documents/FlatheadCWPP2011.pdf. Accessed 1 May 2018

Graham RT (ed) (2003) Hayman fire case study. General technical report, RMRS-GTR-114, USDA Forest Service, Rocky Mountain Research Station, Ogden, UT

Hardaker JB, Richardson JW, Lien G, Schumann KD (2004) Stochastic efficiency analysis with risk aversion bounds: a simplified approach. J Agric Resour Econ 48:253–270

Hayes SW, Morgan TA (2014) Estimating harvesting costs. University of Montana, Bureau of Business and Economic Research, Missoula. http://www.bber.umt.edu/pubs/forest/prices/loggingCostPoster2011.pdf. Accessed 1 May 2018

Healthy Forests Restoration Act (HFRA) (2003). https://www.congress.gov/bill/108th-congress/house-bill/1904/text. Accessed 1 May 2018

Intergovernmental Panel on Climate Change (IPCC) (2007) Climate change 2007: synthesis report, summary for policymakers. http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf. Accessed 1 May 2018

Keane RE, Hessburg PF, Landres PB, Swanson FJ (2009) The use of historical range and variability (HRV) in landscape management. Forest Ecol Manag 258:1025–1037

Keane RE, Loehman RA, Holsinger LM (2011) The FireBGCv2 landscape fire succession model: A research simulation platform for exploring fire and vegetation dynamics. General technical report RMRS–GTR–255, USDA Forest Service, Rocky Mountain Research Station, Ft. Collins, CO

Linstone HA, Turoff M (1975) The Delphi method: techniques and applications. Addison-Wesley, University of Michigan, Reading

Liu J, Dietz T, Carpenter SR, Alberti M, Folke C, Moran E, Pell AN, Deadman P, Kratz T, Lubchenco J, Ostrom E, Ouyang Z, Provencher W, Redman CL, Schneider SH, Taylor WW (2007) Complexity of coupled human and natural systems. Science 317:1513–1516

Malmsheimer RW, Heffernan P, Brink S, Crandall D, Deneke F, Galik CS, Gee E, Helms JA, McClure N, Mortimer N, Ruddell S, Smith M, Stewart J (2008) Forest management solutions for mitigating climate change in the United States. J For 106:115–171

Millar CI, Stephenson NL, Stephens SL (2007) Climate change and forests of the future: managing in the face of uncertainty. Ecol Appl 17:2145–2151

Minnesota IMPLAN Group, Inc. (2011) IMPLAN System (data and software). Stillwater, MN. http://www.implan.com. Accessed 3 May 2018

Montana Cadastral (2010). http://svc.mt.gov/msl/mtcadastral. Accessed 1 May 2018

Oregon Forest Resources Institute (2018.) When is clearcutting the right choice? https://oregonforests.org/content/clearcutting. Accessed 1 May 2018

Oregon State University (2012) ENVISION version 6. http://envision.bioe.orst.edu/Documents/ENVISION%20Developers%20Manual.doc. Accessed 1 May 2018

Paveglio T, Prato T, Hardy M (2013) Simulating effects of land use policies on extent of the wildland-urban interface and wildfire risk in Flathead County, Montana. J Environ Manag 130:20–31. https://doi.org/10.1016/j.jenvman.2013.08.036. Accessed 1 May 2018

Pollet J, Omi PN (2002) Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. Intern J Wild Fire 11(1):10

Prato T (2008) Stochastic multiple attribute evaluation of land use policies. Ecol Model 219:115–124. https://www.sciencedirect.com/science/article/pii/S0304380008004043. Accessed 1 May 2018

Prato T (2009) Fuzzy multiple attribute evaluation of alternative land use futures. J Land Use Sci 4:201–213

Prato T (2015) Conceptual framework for assessing the sustainability of forest fuel reduction treatments and their adaptation to climate change. Sustainability 7:3571–3591. http://www.mdpi.com/2071-1050/7/4/3571. Accessed 1 May 2018

Prato T, Paveglio TB (2014) An integrated conceptual framework for adapting forest management practices to alternative futures. Inter J Forest Res 2014(1):1–13. https://doi.org/10.1155/2014/321345. Accessed 1 May 2018

Prato T, Paveglio T (2017) Multiobjective prioritization of preselected fuel treatment strategies for public forestland: a case study in Flathead County. Montana Forest Sci. https://doi.org/10.5849/FS-2017-007

Prato T, Qiu Z, Pederson G, Fagre D, Bengtson L, Williams J (2010) Potential economic benefits of adapting agricultural production systems to future climate change. Environ Manag 45:577–589. https://link.springer.com/article/10.1007%2Fs00267-010-9427-0. Accessed 1 May 2018

Prato T, Paveglio T, Barnett Y, Silverstein R, Hardy M, Keane R, Loehman R, Clark A, Fagre D, Venn T, Stockmann K (2014) Simulating future residential property losses from wildfire in Flathead County, Montana. In: Daniels JA (ed) Advances in environmental research, vol 33. Nova Science Publishers, Inc., Hauppauge, pp 1–40

Prichard SJ, Peterson DL, Jacobson K (2010) Fuel treatments reduce the severity of wildfire effects in dry mixed–conifer forest, Washington, USA. Can J For Res 40:1615–1626

Puettmann KJ, Coates KD, Messier CC (2009) A critique of silviculture: managing for complexity. Island Press, Washington, DC

Qiu Z, Prato T (2012) Economic feasibility of adapting crop enterprises to future climate change: a case study of flexible scheduling and irrigation for representative farms in Flathead Valley, Montana. Mitig Adapt Strat GL 17:223–242

Raskin R, Cochran MJ (1986) Interpretations and transformations of scale for the Pratt–Arrow absolute risk aversion coefficient: implications for generalized stochastic dominance. West J Agr Econ 11:204–210

Raymond CL, Peterson DL (2005) Fuel treatments alter the effects of wildfire in a mixed evergreen forest, Oregon, USA. Can J For Res 35:2981–2995

Rhodes JJ, Baker WL (2008) Fire probability, fuel treatment effectiveness and ecological trade-offs in western U.S. public forests. Open Forest Sci J 1:1–7

Richardson JW, Schumannm KD, Feldmanm PA (2017) Simetar: simulation and econometrics to analyze risk. College Station. http://www.simetar.com. Accessed 1 May 2018

Roy B (1968) Classement et choix en présence de points de vue multiples (la méthode ELECTRE). La Revue d'Informatique et de Recherche Opérationelle (RIRO) 8:57–75

Saaty TL (1986) Axiomatic foundations of the Analytic Hierarchy Process. Manag Sci 32:841–855

Strassert G, Prato T (2002) Selecting farming systems using a new multiple criteria decision model: the balancing and ranking method. Ecol Econ 40:269–277

Summerfield B, Johnson W, Roberts D (2004) Trends in road development and access management in the Cabinet–Yaak and Selkirk grizzly bear recovery zones. Ursus 15:115–122

U.S. Department of Agriculture, and U.S. Department of the Interior (USDA and USDI) (2001) Urban wildland interface communities within the vicinity of federal lands that are at high risk from wildfire. Federal Register, August 17, pp 43384–43435. https://www.federalregister.gov/documents/2001/01/04/01-52/urban-wildland-interface-communities-within-the-vicinity-of-federal-lands-that-are-at-high-risk-from. Accessed 1 May 2018

Union of Concerned Scientists (2013) Science connections: western wildfires and climate change. https://www.ucsusa.org/global-warming/science-and-impacts/impacts/infographic-wildfires-climate-change.html#.WujqM38h2Uk. Accessed 1 May 2018

Chapter 3
Sustainable Development in Indonesian Regions: Towards an Assessment

Noor Syaifudin and Yanrui Wu

Abstract Sustainable development has for a long time attracted the attention of economists and policy makers. Yet, there are few studies of sustainable development indicators, particularly in Indonesian regions. This paper presents an empirical assessment of sustainable development in Indonesia at provincial level. It contributes to the general literature. Firstly, the paper reviews the existing literature on the concepts and theory of sustainable development. It then applies a composite index method to examine relevant indicators of sustainable development in the Indonesian regions context. Various scenarios are considered in order to accommodate the different nature of Indonesian regions in terms of sustainable development aspects i.e. economic, social, environmental and institutional aspects. The findings confirm that the development in Indonesia emphasises the short term goal, by focusing on the economic and social aspects but ignores the environment aspect.

Keywords Sustainable development · Sustainable development indicators · Empirical assessment · Composite index · Indonesian regions

3.1 Introduction

Economic development, which does not aim for environmental preservation, may have negative impacts on the environment because of the limited capacity of the environment and may risk the economic future of a nation in the long term. Concern

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about economic growth and sustainability was first raised by Malthus (1798) when he addressed the limitation of natural resources to satisfy the vast growth of population in England (Fauzi and Oxtavianus 2014). Much later, Meadows et al. (1972) concluded that economic growth will be limited by the scarcity of natural resources and there will be no sustainable flow of services and goods.

This paper reviews the existing literature on sustainable development including the underlying economic theories, relevant indicators of sustainable development and economic models addressing sustainable development. The relevance of these issues in the Indonesian context is discussed and a composite index method is used to examine relevant indicators of sustainable development at the provincial level in Indonesia. Four different scenarios are used to capture the variations in various natures of Indonesian provinces in terms of four sustainable development aspects: economic, social, environmental and institutional.

3.2 Literature Review

Sustainable development was first addressed at the United Nations Conference on the Human Environment in Stockholm in 1972 (Rogers et al. 2006). The discussion focussed on how to boost the economy without harming the environment. The concept was explored further in the World Conservation Strategy prepared by the United Nations Environment Programme (UNEP), the International Union for Conservation of Nature and the Natural Resources (IUCN), the World Wide Fund for Nature (WWF) in 1980 and again at the UNEP summit in Nairobi, Kenya in 1982 (Elliott 2006). One key result was the establishment of a special council under the United Nations (UN), called the World Commission on Environment and Development (WCED). In 1987, the concept of Sustainable Development was formally defined in a WCED Report as "development which meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987).

Today, this definition of sustainable development continues to be debated. Several scholars argue that the definition is too general, ambiguous and difficult to implement (O'Riordan 1995; Mawhinney 2002; Holmberg and Sandbrook 1992; Lélé 1991). Others are still keen to operationalise the definition. Some of them look at it as an issue associated with the intergenerational environment and economic sustainability (Rogers et al. 2006; Elliott 2006), while others view it as an issue of equity and balance (Soubbotina 2004). Ene et al. (2011) suggest that sustainable development concurrently examines the presence of environmental fortification and economic improvement from a global and long-term position. From these different points of view, it can be concluded that sustainable development is related to equity, economic sustainability, and environmental protection in the long term.

Table 3.1 Aspects of sustainable development

Institutions	Economic	Social	Environmental	Institutional
OECD (2001)	√[a]		√	
UN (2007)	√	√	√	√
EU (2013)	√	√	√	√
Central Statistics Agency (2013)	√	√	√	√

[a]Socio-economic aspect

3.2.1 *Defining Sustainability*

Economists have different views of the meaning of sustainability. Before defining sustainability, they tried to distinguish the difference between growth and development. Daly (1990) correlated growth with physical characteristics and development with qualitative improvement. He saw growth as something caused by natural processes like assimilation or accretion, and development as something that expands capacity. Daly concluded that growth is not sustainable in the long term and suggested sustainable development. Asheim and Brekke (1993) stated that sustainable development requires sustainability of resource management over generations, and Pezzey (1997) noted that sustainability is attained when the human well-being trend is not decreasing. Alisjahbana and Yusuf (2003) also adopted the definition of sustainability as a non-declining welfare per capita of a human being, by using capital as the basis of the measurement.

More recently, the definition of sustainability has been extended to distinguish weak sustainability from strong sustainability. Two neoclassical economic scholars, Solow and Hartwick, introduced the term weak sustainability to explain how natural capital can be replaced by man-made capital (Davies 2013). In contrast, strong sustainability refers to man-made capital that cannot replace natural capital (Davies 2013; Neumayer 2003).

3.2.2 *Sustainable Development Indicators*

Different institutions have similar perspectives about the aspects that underpin sustainable development. The UN via Commission on Sustainable Development (CSD), European Union (EU) and Central Statistics Agency of Indonesia (UN 2007; EU 2013; Central Statistics Agency 2013) outlined four aspects of sustainable development: economic, social, environmental and institutional aspects. The OECD looked at only socioeconomic and environmental aspects (Table 3.1).

Any discussion of sustainable development without consideration of appropriate indicators remains incomplete. Sustainable development indicators (SDI) should be management tools (United Nations 2007), evaluation criteria (OECD 2001; United Nations 2007; Pintér et al. 2005), and a means to deliver ideas and values (United

Nations 2007; the European Union 2013). SDI should be supported by operational definitions (Rennings and Wiggering 1997), be related to policy priorities, and be flexible and communicable (The European Union 2013; Pintér et al. 2005).

The UN (2001) via CSD provides a framework for countries to determine their SDIs. This framework requires the themes and sub-themes of each SDI to be determined. There are six themes (equity, health, education, housing, security and population), three economic themes (economic structure, consumption and production patterns) seven environmental themes (atmosphere, land, oceans, seas and coasts, fresh water and biodiversity) and two institutional themes (institutional framework and institutional capacity).

Other institutions use different SDIs. The Department of Economic and Social Affairs of the United Nations Secretariat (UN-DESA) assesses 50 core SDIs (United Nations 2007). OECD (2001) considers two main sets of indicators – environmental and socio-economic. Pintér et al. (2005) proposed four main indicators covering institutional, economic, social and environmental factors. Institutional indicators comprised conflict, refugees and governance. The social indicators were represented by gender equality, HIV/AIDS and malaria, and the economic indicators by tariffs. The environmental indicators included the risk of soil degradation, vulnerability to climate change, and biodiversity weighted land use change. The EU (2013) uses 12 leading SDIs.

Consumption and production patterns are perceived as relevant in the economic aspect. While the UN and Indonesia agree that global economic partnership should be one of the themes, the OECD and the EU stress that productivity is more relevant. The OECD recognises that productivity should be more detailed to describe the SDI. However, the EU identifies that resource productivity as a sub-theme can represent the issue of productivity. While the OECD observes energy and transport as a theme in the economic aspect, the EU recognise these two sectors as a theme in the environmental aspects of SDI. According to the EU, renewable energy is valid to explain the climate change and energy issue in sustainable development. Furthermore, it is interesting that the OECD also includes waste as a theme, while the other institutions do not include it. In relation to the waste theme, the OECD identifies that waste generation and recycling should be considered as a sub-theme.

The social aspect is mostly represented by poverty and equity. This theme leads to the ability of people to maintain their level to adopt the economic and environmental changes. Demographics and poverty are seen by all institutions to represent social aspects. The OECD, which combines social and economic aspects of sustainable development, perceived that the social aspect will lead to the ability of society to produce and consume as well as enjoy the economic development. The EU's view is different from those of the UN and Indonesia about the demographics theme of sustainable development. The EU interprets the demographics as the employment rate of older workers, while the UN and Indonesia recognise demographics as the level of population as well as tourism. Institutional aspects of sustainable development represent governance. While the UN and Indonesia see governance as a focus on the level of corruption and crime, the EU perceives governance as the effectiveness of policy, public openness and economic instruments. The EU also looks at the institutional aspect as a focus on global cooperation, ODA particularly.

3.2.3 Studies of Sustainable Development Indicators in Indonesia

There are several studies of SDI in Indonesia. These include studies of the environmentally adjusted national income (EAAI), the system of integrated environmental and economic accounting (SEEA), genuine saving, Eco-Region Domestic Product (ERDP), and Composite Sustainable Development Index (CSDI). The EAAI was first introduced by Repetto et al. (1989). Supported by the World Research Institute (WRI), EAAI measures the SDI basically by determining the changes in the stocks of natural resources including oil, forestry, and soil into the capital and flow account. By subtracting the estimates of net natural resources depreciation from GDP for the three products, the study defines a net domestic product as the representative of SDI for Indonesia. The study with Indonesian data from 1970 to 1984 concluded that even though GDP growth from 1970 to 1984 was 7.4% but the net domestic product/growth rate only reached 4.0% annually. This is because GDP growth counts on the depletion of natural resources.

The SEEA (Gustami 2012) was compiled between 1997 and 2010 and was based on the methodology recommended by UNSD (United Nations Statistics Division). The study prepares the sustainability of Indonesia based on the asset account in terms of physical and monetary aspects of the selected environment assets such as timber, crude oil, and gas, coal, as well as other minerals (bauxite, tin, gold, silver and nickel) (Tasriah 2013). The system is broader than the previous study on national income in the sense that the national assets counted are more broad. The system provides information on the stock of environment assets, live assets and depletion of natural resources. The main result is to develop indicators which adjust the conventional GDP with a somewhat environmentally adjusted GDP. According to the result of the study for the period of 2007–2010, Net Domestic Product (GDP minus Depletion and Degradation) is reduced by about 10% from conventional GDP.

The study of Genuine Saving was conducted by Alisjahbana and Yusuf (2003). It adopted the weak sustainability concept which defines sustainability as non-declining welfare per capita. The study used genuine savings and change in wealth per capita as an indicator of sustainable development. It concluded that change in wealth per capita between 1980 and 2000 was not sustainable. The result showed that the shifting in the economy from oil and gas reliance to the secondary and tertiary sectors gives a positive impact in the long term. The study also found that economic crisis may reduce the savings rate and depletion of natural resources and hamper the positive trend of sustainability. Furthermore, the study recommended more appropriate management in mineral, forestry, and environmental degradation, because these three sectors will be an issue in the future.

The study to develop ERDP was conducted by Yusuf (2010) for 30 provinces in Indonesia for 2005. It is proposed that by calculating ERDP, the sustainable development indicator, which is represented by the ratio of ERDP over GRP, can be determined for each province. The study found the lowest ERDP value comes from provinces that are deeply reliant on natural resources. According to this paper, at least five provinces are not sustainable due to their reliance on the natural resources to support their economy. Thus, the policy implication is that the government should apply the sustainable development agenda as well as increasing economic productivity.

Studies of SDI for Indonesia were also conducted by applying a composite index which was initiated by OECD in 2008 (OECD 2008). The same approach was also applied by Indonesian scholars to determine the SDI in Indonesia. Examples include are Fauzi and Oxtavianus (2013), Oxtavianus (2014), and Fauzi and Oxtavianus (2014). The composite index is a set of indicators or sub-indicators which do not have measurement units. Each composite index can be regarded as a model, and formulated by following a series of steps.

In the study by Fauzi and Oxtavianus (2013), the CSDI was developed based on three different variables which are GRP (Gross Regional Product) for represent economic aspect/dimension, Human Development Indicator (HDI) for social dimension and Environment Quality Index for the environmental dimension. The study was conducted according to two scenarios. The first is an equal weight for each indicator, and the second is the same weight between dimensions of development. As a result, the study concluded that sustainable development in Indonesia reached about two-thirds of the maximum target. The significant progress in economic and social aspects was corrected by environmental degradation. However, progress in the economic and social aspects seems to put pressure on the environment.

There are two more recent studies concerning CSDI in Indonesia namely Fauzi and Oxtavianus (2013) and Oxtavianus (2014). Both studies apply descriptive analysis to get an overview of the early stage of development in Indonesia. These studies considered various aspects of the economic, social, environmental and institutional conditions. The initial overview indicates that development in Indonesia is still very oriented to economic and physical development. This is shown in the achievement of economic development being quite high, which is characterised by a fairly high level of GDP only a few years earlier. Also, the physical development showed reasonably good improvement, which can be seen from the rising value of the HDI. Both studies showed that an indicator is required to describe the condition of sustainable development in Indonesia. It is hoped that obtaining the appropriate indicator, will assist policy makers in determining the direction of development at a later stage.

Fauzi and Oxtavianus (2013) apply two scenarios i.e. (i) same weight among indicators and (ii) same weight among aspects. The first scenario was applied with the consideration that all indicators have the same impact on the level of sustainability in Indonesia; the second scenario assumes that the environmental and social aspects should be weighted to be equal with the economic aspect. Thus the indicators in the environmental aspect were weighted three times and the social aspect twice. The overall indicators in scenario two were divided by 6.

In a study by Fauzi and Oxtavianus (2013), each aspect of sustainable developments was constructed based on indicators that were provided by Central Statistics Agency, i.e. GRP for economic aspect, HDI for the social aspect and EQI for environmental aspect. In the study by Oxtavianus (2014), the indicators were selected based on the data availability and were constructed based on second-order confirmatory factor analysis. The analysis finally selected nine indicators to construct SDI. Fauzi and Oxtavianus (2013) found that the SDI in Indonesia in 2011 was 69.02 under scenario 1 and 68.81 under scenario 2. Oxtavianus (2014) was more optimistic and found that in 2011, SDI in Indonesia is 80.03 and became 82.42 in 2012. Both studies conclude that the developments in Indonesia are still an imbalance between economic, social, environmental and institutional aspects. It is also concluded that the level of sustainability in Indonesia is more about short-term perspectives and not the long-term ones. Moreover, development may also lead to a decline of social capital in more advanced provinces.

Based on those previous studies, it can be concluded that the previous composite index for sustainable development in Indonesia has several areas to be improved. First, the study by Fauzi and Oxtavianus (2013) did not include the institutional aspect of sustainable development. Second, Fauzi and Oxtavianus (2013) and Oxtavianus (2014) absorbed limited indicators in estimating a sustainable index. Fauzi and Oxtavianus (2013) only applied three indicators while Oxtavinaus (2014) applied nine indicators to construct the index. Third, both studies did not accommodate the difference between Java and Non-Java islands as well as the difference in impact of the provinces who have oil and gas and those who do not in their GRP.

Based on the above considerations, this study attempts to compose a sustainable development index at the provincial level in Indonesia by adopting a composite index method. Several adaptations were made, namely, 20 indicators are adopted, and several scenarios are considered to accommodate the difference between Java and Non-Java islands as well as the difference between total GRP and GRP without oil and gas.

3.3 Methodological Issues

In this study, a composite index (CI) approach is applied. CI is recognised for its practicality in presenting a performance indicator and providing a signal of required policy intervention (Jacobs et al. 2004). There are several advantages of applying CI (i) CI may focus on key policy matters (Jacobs et al. 2004; Michalos et al. 2011), (ii) it simplifies the presentation of major problems into a simple format (Jacobs et al. 2004; Michalos et al. 2011, Baptista, 2014), (iii) it is informative (Jacobs et al. 2004; Michalos et al. 2011; Baptista, 2014) and (iv) it provides trends for many different indicators for different times, regions and populations (Michalos et al. 2011; Baptista 2014).

Moreover, for technicality reasons CI is applied in this study due to two reasons. The first is that the CI approach has been widely applied and used in several empirical studies (Jacobs et al. 2004; OECD 2008; Kondyli 2010; Michalos et al. 2011; Fauzi and Oxtavianus 2013; Baptista, 2014 and Oxtavianus 2014). The second is that most of the data are available and collected in a book entitled "Indicators of sustainable development" (Central Statistical Agency 2004–2014). Thus, to construct the composite index, each of the indicators was grouped based on a theme and sub-theme following the UNCSD method (UN 2001). The indicator selection was also conducted based on the data availability. The indicators are grouped into four aspects as shown in Table 3.2. One important thing to understand is that the CI structure must always be checked and developed according to the situation and conditions over the period (Baptista 2014).

In this study, CI is estimated according to seven steps following a similar procedure adopted by OECD (2008), Kondyli (2010), Fauzi and Oxtavianus (2013), and Oxtavianus (2014). The seven steps include preparation of a theoretical framework, identification of indicators, imputation of missing data, normalisation of data, determination of weights, aggregation, presentation and dissemination.

3.4 Empirical Issues

In this study, normalisation is conducted by using the maximum-minimum method. References are used in determining the maximum and minimum values. For the normalised value between 0 and 100, the maximum and minimum use in this method also brings some consequences. The first consequence is that, while the indicator value may be below the minimum value, the normalised value is set at 0. Likewise, for indicators that exceed the maximum value, the normalised value is set at 100. There are two scenarios in determining SDI for Indonesia, with consideration of weighted Java Island and non-Java Island, and comparison between total GRP as well as GRP minus GRP from oil and gas.

Scenario 1: All indicators equally weighted

$$CSDI = \frac{1}{\mathrm{n}}\sum\nolimits_{i=1}^{n} xi; \quad \mathrm{n} = 20$$

where

x1 = Total GRP
x2 = % of population aged 15 years and over who worked
x3 = % of households that use LPG for cooking
x4 = Estimates of CO2 emissions from motorized vehicle
x5 = Environmental Quality Index
x6 = % of poor people
x7 = % dependency ratio

Table 3.2 Four aspects of CSDI in Indonesia

No.	Theme	Sub-theme	Indicators	References
Economic aspect				
1.	Economic development	Macroeconomic performance, sustainable public finance, employment, information and communication technologies, research and development, tourism	1. GRP per capita at constant price (with oil and gas; without oil and gas),	UN (2001, 2007), Central Statistics Agency (2014), Kondyli (2010), and Oxtavianus (2014)
			2. % of population aged 15 years and over who worked	UN (2001, 2007), Kondyli (2010), and Oxtavianus (2014)
Environmental aspect				
2.	Atmosphere	Climate change, ozone layer depletion, air quality	3. % of households that use LPG for cooking	Central Statistics Agency (2014)
			4. Estimates of CO2 emissions from motorized vehicle,	UN (2001, 2007), Central Statistics Agency (2014), Kondyli (2010), and Oxtavianus (2014)
			5. Environmental quality index	Oxtavianus (2014)
Social aspect				
3.	Poverty	Income poverty, income inequality, sanitation, drinking water, access to energy, living conditions	6. % of poor people,	UN (2001, 2007), Central Statistics Agency (2014), Kondyli (2010), and Oxtavianus (2014)
			7. % dependency ratio	UN (2007), Central Statistics Agency (2014), Kondyli (2010), Oxtavianus (2014)
4.	Health	Mortality, health care delivery, nutritional status, health status, and risks	8. % infant mortality,	UN (2001, 2007), Central Statistics Agency (2014), Kondyli (2010), and Oxtavianus (2014)
			9. % life expectancy,	UN (2001, 2007), Central Statistics Agency (2014), Kondyli (2010), and Oxtavianus (2014)

(continued)

Table 3.2 (continued)

No.	Theme	Sub-theme	Indicators	References
			10. % HH manages sanitation,	Central Statistics Agency (2014)
			11. % HH using clean water,	Central Statistics Agency (2014)
			12. % women using birth control,	UN (2001, 2007), Central Statistics Agency (2014), and Oxtavianus (2014)
5.	Education	Education level, literacy	13. % net enrolment rate of elementary school,	Central Statistics Agency (2014)
			14. % net enrolment rate of junior school,	Central Statistics Agency (2014)
			15. % net enrolment rate of high school,	Central Statistics Agency (2014)
6.	Demographics	Population, tourism	16. Total fertility rate	UN (2007), Kondyli (2010), and Oxtavianus (2014)
Institutional aspect				
7.	Governance	Integrating environment and development in decision-making, science for sustainable development, international legal instruments, and mechanisms, information for decision-making, strengthening the role of major groups	17. % houses connected to phone,	UN (1996)
			18. % HH accessing the internet within last 3 months,	UN (1996)
			19. Ratio women participation in the school to the men participation in the school,	Oxtavianus (2014)
			20. The ratio of women wages to men wages.	Oxtavianus (2014)

x8 = % infant mortality
x9 = % life expectancy
x10 = % HH manages sanitation
x11 = % HH using clean water
x12 = % women using birth control
x13 = % net enrolment rate of elementary school
X14 = % net enrolment rate of junior school
X15 = % net enrolment rate of high school
X16 = Total Fertility Rate
X17 = % houses connected to phone
X18 = % HH accessing the internet within last three months
X19 = Ratio women participation in the school to the men participation in the school
X20 = Ratio of women wages to men wages

Scenario 2: The Environmental and Social aspects of provinces in Java will be weighted more than Economic and Institutional Aspects. Non-Java Island will be weighted more on Economic than the other two aspects. In this scenario, the GRP is total GRP minus GRP from oil and gas.

$$\text{CSDI Indonesia} = (7 * \text{CSDI Java} + 26 * \text{CSDI non} - \text{Java})\,/33$$

$$\begin{aligned}\text{CSDI Indonesia} = \big[&7 * ((\text{Ecj} + 2\text{Socj} + 2\text{Envj} + \text{Insj})\,/6)\\ &+ 26 * ((2\text{Ecnj} + \text{Socnj} + \text{Envnj} + 2\text{Insnj})\,/6)\big]\,/33\end{aligned}$$

where

CSDI = sustainable development indicator composite index
CSDI Java = sustainable development indicator composite index – Java
CSDI non-Java = sustainable development indicator composite index – Non Java
Ecj = Economic aspect indicator for Java (GRP without oil and gas)
Socj = Social aspect indicator for Java
Envj = Environmental aspect indicator for Java
Insj = Institutional aspect indicator for Java
Ecnj = Economic aspect indicator for non-Java (GRP without oil and gas)
Socnj = Social aspect indicator for non-Java
Envnj = Environmental aspect indicator for non-Java
Insnj = Institutional aspect indicator for non-Java

The distinction between GRP total and GRP without oil and gas was recommended by Fauzi and Oxtavianus (2013), in order to know the magnitude of oil and gas in SDI. The latter scenarios are suggested by Oxtavianus (2014), in order to meet the same dimension among SDI variable (aspects), and weighting should also count the difference between Java and non-Java provinces. This is due to consideration that Java will be high on the economic aspect value but will be low in the environmental and social aspects; while in non-Java Island is otherwise. It is suggested that in the non-Java island, the environmental and social aspects will be high and economic aspect will be low. Thus, it is expected that the resulting index will be balanced. Meanwhile, Fauzi and Oxtavianus (2013) gave a weight of three for the social aspect and two for environmental aspect. This study gives a weight of two for social and environmental aspects of Java and two for economic and institutional aspects in non-Java. Under this scenario, it is assumed that the economic and institutional quality in Java will be better than that in non-Java, and the social and environmental quality in non-Java is considered to be worse than that in Java.

3.5 Sustainable Development Index (SDI) for Indonesian Regions

In general, based on two scenarios employed in this study, it shows an increasing tendency of sustainability index achieved among provinces in Indonesia over the period of study (2002–2013), but small numbers of provinces display the opposite trend. The other general finding is an imbalance in the increasing level of sustainability and the sustainability index itself. The high fiscal capacity will lead to a high level of sustainability. The high fiscal capacity mainly is drawn from a great transfer fiscal fund due to their high capacity in natural resources or the province with high locally-generated revenue. This confirms Wibowo (2011) that the poor provinces have difficulties in attaining their development target due to a limitation in economic development and natural resources. The scenarios also support Tusianti et al. (2013) and Fauzi and Oxtavianus (2013) that there was imbalance in each aspect of sustainable development. The conflicting and complementary interactions between the economic, social and environmental aspects of sustainable development are viewed as the main factors responsible for imbalanced development in Indonesia.

3.5.1 Scenario 1

In 2013 (Fig. 3.1), four provinces achieved a sustainable development index of more than 70. These are Riau Islands, East Kalimantan, Jakarta Special Region and South Sulawesi. In 2012 and 2013, those provinces were among the provinces that had the largest regional budget. Eight provinces had a sustainable development index below 60. Those provinces are West Nusa Tenggara, Papua, South East Sulawesi, West Sulawesi, Gorontalo, North Maluku, Maluku and East Nusa Tenggara. The low score of the sustainability is reflected by the low regional budget of those provinces.

Generally, based on scenario 1 (Fig. 3.2), all provinces experienced increasing trends in the level of sustainability, except Aceh and Papua. Those two provinces

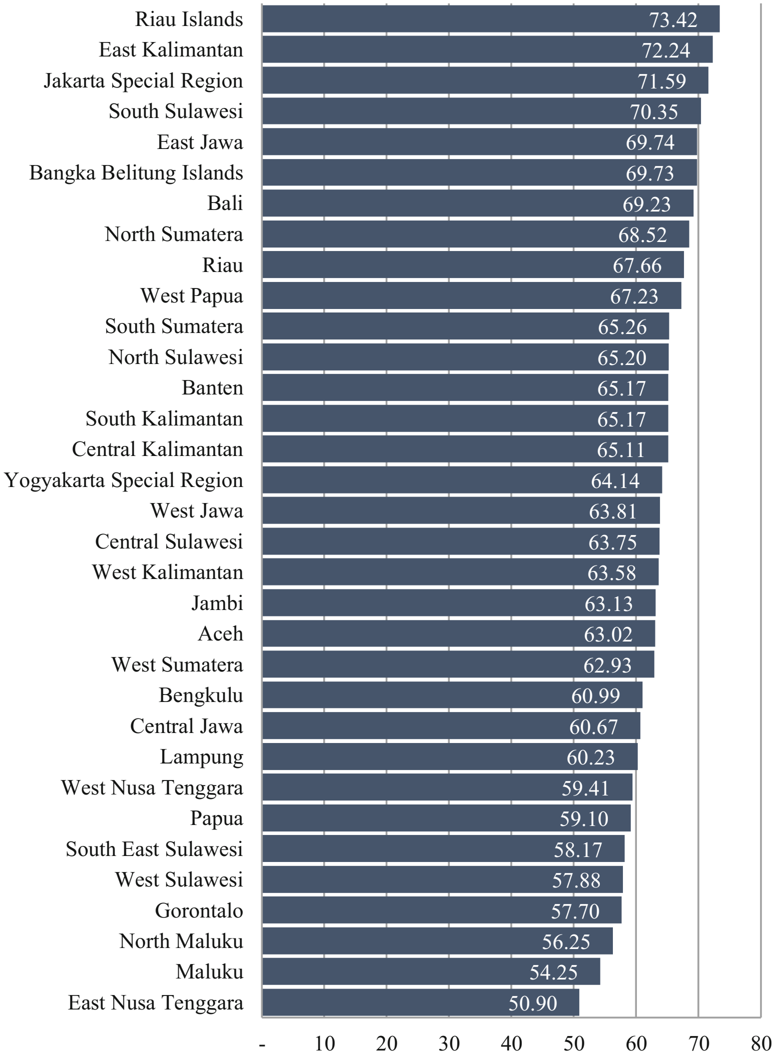

Fig. 3.1 Sustainability Ranking of Provinces in 2013. (*Source*: Authors' own estimates)

experienced a decreasing trend. From 2002 to 2013, Jakarta Special Region achieved the highest level of sustainability among provinces.

In Aceh, the sustainability was about 69 in 2002 and became 63 in 2013. The decreasing value was supported by the decrease in the economic and environmental aspects. These two aspects experienced a large decrease between 2002 and 2013. In 2002, the economic aspect reached 89% and became 76% in 2013, or a decrease of about −13%. The environmental aspect was 69% in 2002 and decreased to 53% in 2013.

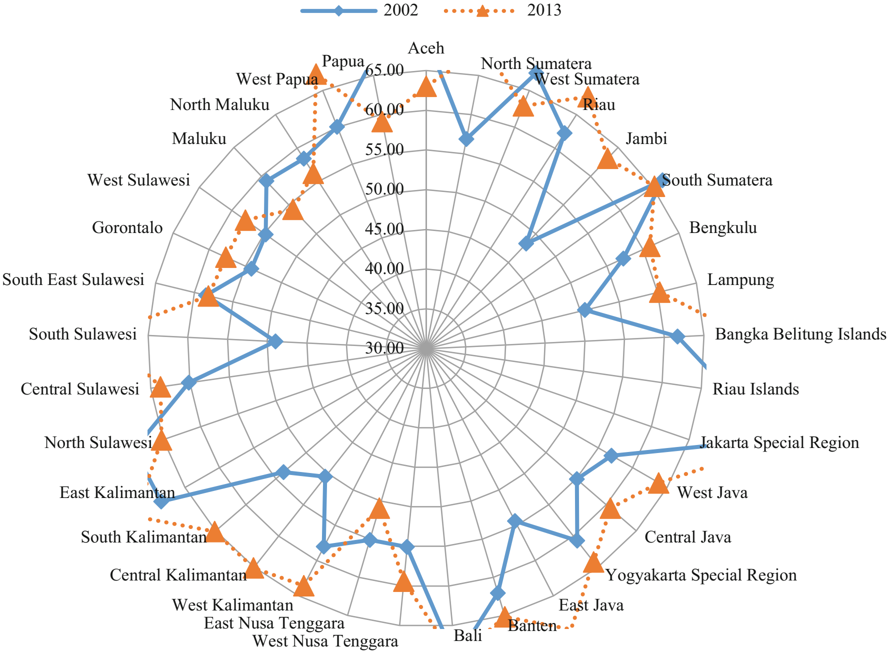

Fig. 3.2 SDI Based on Scenario 1 for 2002 and 2013. (*Source*: Authors' own estimates)

In Papua, three aspects support the decreasing trend of its sustainability i.e. economic, environmental and social aspects, while the institutional aspect shows an increasing trend. The economic aspect reached 93% in 2002 and decreased to 80% in 2013, or a decrease of about −13%. In 2002, the environmental aspect reached 68% and became only 50% by 2013. The social aspect was also decreasing, from 58% in 2002 to only 54% in 2013.

In this study, sustainability is grouped into three categories i.e. low, moderate and high. The low sustainability, represented by the blue colour on the map, was achieved when the sustainable development score was below average. Moderate (green) is above average and under ¾ of the highest score, and high (yellow) for more than ¾ of the highest score.

In 2002 (Fig. 3.3), there were nine provinces at the high level, six at a moderate level, and eighteen provinces in the low level. In 2013, there were seven provinces at the high level of sustainability, while ten provinces were at a moderate level and 16 provinces were at low sustainability levels. Among those high levels of sustainability provinces, only four maintained the level which was Jakarta Special Region, Bali, East Kalimantan and Riau Islands, while at the same time three provinces moved to high level i.e. East Java, Bangka Belitung Islands, and South Sulawesi.

Provinces which remained at high levels are generally rich provinces with natural resources, a tourist destination and also a national business centre. They had good

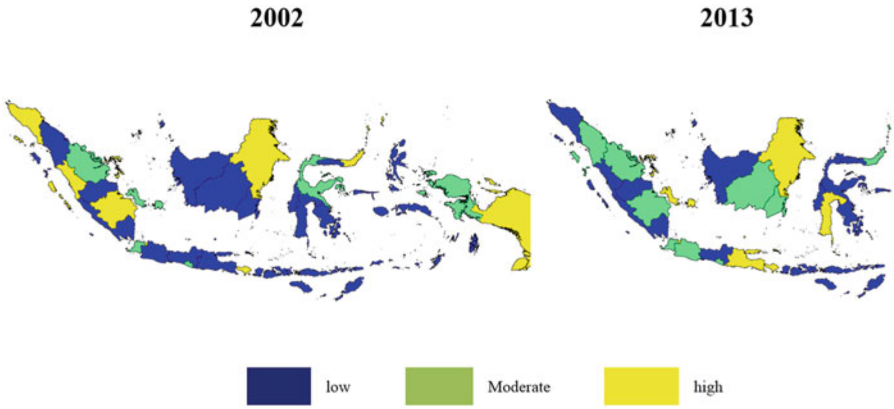

Fig. 3.3 SDI Based on Scenario 1 and Based on Group in 2002 and 2013. (*Source*: Authors' own estimates)

infrastructure which supports development in the social and institutional sectors. On the other hand, provinces that remained at the low level of sustainability are typically poor regions with low capacity in natural resources.

3.5.2 Scenario 2

In this scenario, GRP from gas and oil is excluded, while the weights of the economic and institutional aspects in non-Java islands are more than social and environmental aspects. At the same time, the social and environmental aspects in Java are weighted more than economic and institutional aspects. This scenario applied to give a more equal treatment to provinces in non-Java islands which have less capacity in economic aspects.

Figure 3.4 shows that in 2013 six provinces achieved sustainability index of more than 70 i.e. Riau Islands, Jakarta Special Region, East Kalimantan, East Java, Bangka Belitung Islands, and Bali. At the same time six provinces achieved below 60 of its sustainability index i.e. West Sulawesi, West Nusa Tenggara, Gorontalo, North Maluku, Maluku and East Nusa Tenggara. The results provide almost the same picture with the previous scenario, where the high economic capacity provinces achieved a higher index. The lower the economic capacity of provinces, the lower their sustainability level is.

Figure 3.5 depicts the dynamic of sustainability index between 2002 and 2013 among provinces in Indonesia. According to this scenario, three provinces had a decreased index, while the rest experienced an increasing value. Those three provinces are Papua at −6.35%, Maluku at −2.37%, and East Nusa Tenggara at −1.19%. There were several provinces that experienced increases in the index of

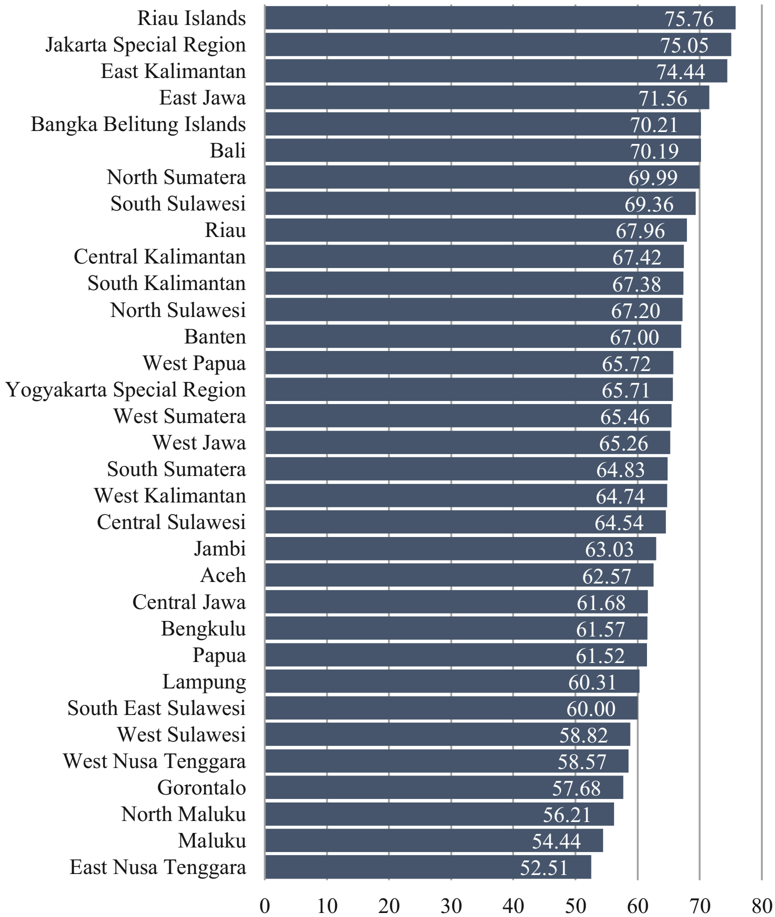

Fig. 3.4 Sustainability Ranking of Provinces in 2013. (*Source*: Authors' own estimates)

more than 10%: among others, they are South Sulawesi at 17.95%, Jambi at 16.17%, East Java at 15.12% and Central Kalimantan at 13.20%.

According to this scenario it appears that the level of sustainable index was shared quite evenly even though several provinces remained at the low level, this being due to very low economic capacity. Moreover, in this scenario several provinces achieved a high sustainability index increase with low resources and capacities such as Central Kalimantan and South Sulawesi. This proves that these two provinces applied policies that support the development of social and environmental aspects.

The distribution of the index according to this scenario can be depicted as follows: in 2002 the total index of seven provinces in Java islands was 426.62 or 60.95 on average, while in the non-Java islands the total index was 1516.06 or 58.31

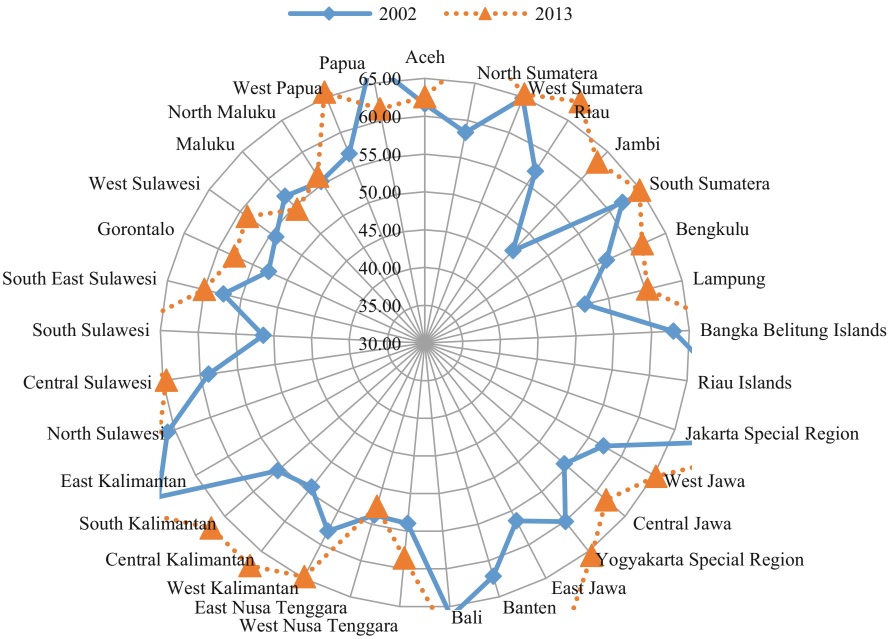

Fig. 3.5 SDI Based on Scenario 2 for 2002 and 2013. (*Source*: Authors' own estimates)

on average. Moreover, the highest index in Java island was achieved by Jakarta Special Region at 70.03, while the lowest was Central Java at 54.41. In non-Java islands, the highest was achieved by East Kalimantan at 70.66, and the lowest was achieved by Jambi at 46.85.

In 2013, in Java island the total index was 476.45 or 68.06 on average, with the highest level achieved by Jakarta Special Region at 75.05 and the lowest was Central Java at 61.68. During the same period the total index for non-Java islands was 1662.23 or 63.93 on average. The highest was achieved by Riau Islands at 75.76, and the lowest was East Nusa Tenggara at 52.51.

Furthermore, compared with the result from scenario 2, in 2002, the total index for Java island was 425.45 or 60.78 on average. The highest was reached by Bali at 69.32, and the lowest was East Java at 54.38. In the same year, in non-Java islands, the total index was 1521.01 or 58.50 on average. The highest was achieved by North Sulawesi at 68.88, and the lowest was by Jambi at 47.59. In 2013, the highest index was achieved by Riau Islands at 73.42 and the lowest was East Nusa Tenggara at 50.90. During this year the total index was 1631.26 or 62.74 on average. According to these findings, it can be concluded that the index under this scenario is more even among provinces both in Java and non-Java islands, even though the result shows that the high index was achieved by provinces with high economic capacity.

Figure 3.6 shows that there were 20 provinces which achieved a low level of sustainability in 2002, seven at high and the rest at moderate. This switched in

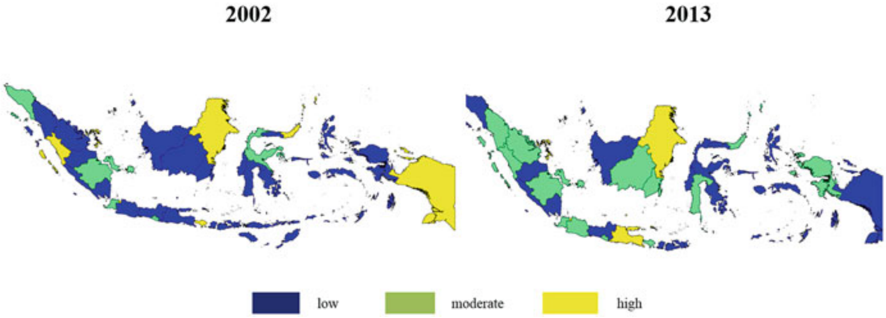

Fig. 3.6 SDI Based Scenario 2 and Based on Group in 2002 and 2013. (*Source*: Authors' own estimates)

2013 where there were 15 provinces at a low level, only four at a high level and 14 at a moderate level. Based on this scenario, East Java shifted from a low level in 2002 at 56.43 to reach a high level of sustainability in 2013 at 71.56. Papua decreased from high to low, from 67.87 in 2002 to 61.52 in 2013. Moreover, three provinces remained at a high level i.e. Jakarta Special Region, East Kalimantan, and Riau Islands. These provinces were characterised as provinces with high economic capacity. However, several provinces remained at the low level of sustainability: among others, East Nusa Tenggara, Maluku, Gorontalo and South East Sulawesi. In contrast with the high level, these provinces were characterised as provinces with weak economic capacity.

3.6 Conclusion

The need for the next generation to fulfill their necessities draws the notion of sustainability. Sustainability has several prerequisites to meet, namely, sustainability of resource management from time to time, sustainability of human well-being, the sustainable yield, and sustainability in natural capital. To measure the level of sustainability achievement, scholars have provided several indicators. Even though different authors have different methods in clustering the indicators, they share common arguments that the sustainable development indicators reflect four aspects, namely: economic, environmental, social and institutional aspects. Each aspect was then clustered into themes and sub-themes to construct the relevant indicators.

This study applies a composite index for 33 provinces in Indonesia by using 20 indicators from 2002 to 2013. First, the preliminary analysis shows high achievement in economic aspect, low achievement in institutional and social aspects and a decrease in the environmental aspect. This confirms that development only emphasises the short-term perspective, which focuses on the development of economic and infrastructure aspects at the expense of the environment and social development. Second, this study constructed a composite index based on two scenarios i.e. (i) the same weights among indicators where GRP is total GRP and (ii) the same weights among sustainable development aspects where GRP is total GRP minus GRP from oil and gas.

In general, according to the scenarios, most of the provinces showed an increasing trend between 2002 and 2013, even though a number of provinces experienced different tendencies. It is also shown that the increasing level of sustainability was not shared evenly among provinces. Moreover, all scenarios resulted in a high sustainable index for provinces with high fiscal capacity and vice versa. The high fiscal capacity in a province comes from its high transfer fiscal fund from central government due to its high capacity in natural resources or the province with high locally-generated revenue which may be a business centre or a tourist destination.

The findings also imply imbalance between sustainable development aspects. Development places emphasis on the improvement of the economic and social aspects but puts pressure on the environmental aspect. The results also point out the complexity in achieving balanced development in Indonesia due to conflicting and complementary interactions between the economic, social and environmental aspects of sustainable development. Furthermore, these results also confirm that there was inequality among rich and poor provinces. The poor provinces may have difficulties in attaining their development targets due to a limitation in economic development and natural resources.

References

Alisjahbana A, Yusuf AA (2003) Assessing Indonesia's sustainable development: long-run trend, impact of the crisis, and adjustment during the recovery period. MPRA Paper 1736. University Library of Munich. Germany

Asheim GB, Brekke KA (1993) Sustainability when Resource Management has Stochastic Consequences, Norwegian School of Economics and Business Administration, discussion paper no. 86, pp 01–32

Baptista SR (2014) Design and use of composite indices in assessments of climate change vulnerability and resilience. USAID, pp 4–5

Central Statistics Agency (various years) Indikator Pembangunan Berkelanjutan (Sustainable Development Indicators). Jakarta, Indonesia

Daly H (1990) Commentary: toward some operational principles of sustainable development. Ecol Econ 2:1–6

Davies GR (2013) Appraising weak and strong sustainability: searching for a middle ground. Consilience J Sustain Develop 10(1):111–124

Elliott JA (2006) An introduction to sustainable development (Routledge perspectives on development), 3rd edn. Taylor & Francis e-Library, New York, chapter 1, pp 7–43

Ene CM, Gheorghiu A, Gheorghiu A (2011) A theoretical approach for dynamic modelling of sustainable development. In: proceedings of recent researches in energy & environment, 6th IASME/WSEAS international conference on energy & environment 2011, Cambridge, pp 261–265

European Union (2013) Sustainable Development in the European Union. In: 2013 monitoring report of the EU sustainable development strategy. Publications Office of the European Union, Luxemburg, pp 20–25

Fauzi A, Oxtavianus A (2013) Pengukuran Pembangunan Berkelanjutan di Indonesia. Jurnal Ekonomi Pembangunan 15(1):68–83

Fauzi A, Oxtavianus A (2014) Background study RPJMN 2015-2019. In: Indeks Pembangunan Lingkungan Hidup. Study report. Ministry of National Development Planning, chapter 3, pp 14–35

Gustami (2012) Indonesia experience in developing sustainable development Indicator. Ministry of Environment, Geneva. https://www.unenvironment.org/ greeneconomy/Portals/88/documents/INDICATORS%20PPT/d3s3%20Gustami%20INDONESIAN%20EXPERIENCE%20IN%20DEVELOPING%20SUSTAINABLE%20DEVELOPMENT%20INDICATORs.pdf

Holmberg J Sandbrook R (1992) Sustainable development: what is to be done? In: Holmberg J (ed) Policies for a small planet, chapter 1. Earth Scan, London, pp 19–38

Jacobs R, Smith P, Goddard M (2004) Measuring performance: an examination of composite performance indicators, CHE technical paper series, vol 29. University of York, pp 93–95

Kondyli J (2010) Measurement and evaluation of sustainable development. A composite indicator for the islands of the North Aegean region, Greece. Environ Impact Assess Rev 30:347–356

Lélé SM (1991) Sustainable development: a critical review. World Dev 19(6):607–621

Malthus TR (1798) An Essay on the Principle of Population. Oxford World's Classics, Oxfordshire, England

Mawhinney M (2002) Sustainable development: understanding the green debates, chapter 1. Blackwell Science, Oxford, pp 1–22

Meadows DH, Dennis LM, Jorgen R, William WB III (1972) Limits to growth, chapter 1. New American Library, New York, pp 25–44

Michalos A, Smale B, Labonté R, Muhajarine N, Scott K, Guhn M, Gadermann AM, Zumbo BD, Morgan A, Moore K, Swystun L, Holden B, Bernardin H, Dunning B, Graham P, Brooker AS, Hyman I (2011) The Canadian index of wellbeing. Technical report 1.0. Canadian Index of Wellbeing and University of Waterloo, Waterloo, pp 9–14

Ministry of Finance (2013) Deskripsi dan Analisis APBD 2013. Direktorat Jenderal Perimbangan Keuangan, pp 1–99

Neumayer E (2003) Weak versus strong sustainability: exploring the limits of two opposing paradigms, chapter 6. Elgar, London, pp 169–187

O'Riordan T (ed) (1995) Environmental science for environmental management, chapter 1. Longman, Harlow, London, pp 1–13

OECD (2001) Environmental indicators: towards sustainable development. OECD, Paris

OECD (2008) Handbook on constructing composite indicators: methodology and user guide, part I. OECD, Paris, pp 19–40

Oxtavianus A (2014) Pembangunan Berkelanjutan dan Hubungannya dengan Modal Sosial di Indonesia. PhD thesis. Institute of Bogor Agriculture, chapter 5, pp 67–81

Pezzey JCV (1997) Sustainability constraints versus "optimality" versus intertemporal concern, and axioms versus data. Land Econ 73(4):448–466

Pintér L, Hardi P, Bartelmus P (2005) Sustainable development indicators: proposals for a way forward. Intl Inst Sustain Develop, New York, pp 1–43

Rennings K, Wiggering H (1997) Steps towards indicators of sustainable development: linking economic and ecological concepts. Ecol Econ 20(1):25–36

Repetto R, Magrath W, Wells M, Beer C, Rossini F (1989) Wasting assets: natural resources in the national income accounts. World Resources Institute, Washington, DC, pp 12–24

Rogers PP, Jalal KF, Boyd JA (2006) An introduction to sustainable development. The continuing education division, , chapter 2. Harvard University and Glen Educational Foundation, Cambridge, MA, pp 41–80

Soubbotina TP (2004) Beyond economic growth: an introduction to sustainable development, 2nd edn, chapter 1. World Bank, Washington, DC, pp 2–11

Tasriah E (2013) Indonesia's experiences in the compilation of environmental-economic. http://www.unescap.org/sites/default/files/5.Indonesia%27s%20Experiences%20In%20The%20Compilation%20of%20Environmental-economic%20Accounts.pdf

Tusianti E, Zuidema E, Prabatmodjo H (2013) Synergistic development performance in Indonesia: making sustainable development practical. Jurnal Perencanaan Wilayah dan Kota B SAPPK 2(3):403–416

United Nations (1996) Indicators of Sustainable Development: Framework and Methodologies. United Nations, New york

United Nations (2001) Indicators of sustainable development: guidelines and methodologies, 2nd edn. UN Sales Publication, New York, No.E.01.II.A.6

United Nations (2007) Indicators of sustainable development: guidelines and methodologies. United Nations, New York

Wibowo H (2011) Inequality and fiscal decentralization in Indonesia: evidence from the households expenditure data. PhD thesis. The University of Western Australia, chapter 3, pp 27–66

World Commission on Environment and Development (1987) Our common future, chapter 2. Oxford University Press, Oxford

Yusuf AA (2010) Estimates of the “Green” or “Eco” Regional Domestic Product of Indonesian Provinces for the year 2005. Working papers in economics and development studies (WoPEDS) no. 201004. University of Padjadjaran, Indonesia

Chapter 4
Sustainability of Water Ecosystems: From Theory to Practice

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Abstract Existing approaches to the assessment of water quality may not provide control of thousands of new pollutants into water bodies. To determine the scope of further exploitation of the hydrosphere, without irreversible changes to its functioning, there is a need for new methods evaluating the state of aquatic ecosystems as a holistic biogeochemical structures and scientifically based criteria of their evolution. This task cannot be solved on the basis of hydrochemical indicators or assessments of individual biotic structures of ecosystems – organisms, populations, communities. Objective assessment of aquatic ecosystems as holistic structures can be conducted only on the basis of state parameters representing a generalized response of aquatic ecosystems to external influences, regarding them as open self-organizing systems, using the principles of non-equilibrium thermodynamics, i.e., as a special case of dissipative systems, characterized by energy, exergy and entropy. Through the results of many years of experimental work, the chapter describes criteria of ecosystem stability and functioning on the basis of thermodynamic parameters. Their practical application will contribute to a more rational management of water resources and create a basis for sustainable existence of aquatic ecosystems.

Keywords Entropy · Exergy · Dissipative function · Primary production

4.1 Introduction

One of the central problems in ecology is the problem of ecosystem stability. “Life strives to maintain its own sustainability and optimal environment, so ecology is the science of sustainability of life and the environment. Life is a truly self-organizing

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system and manages not only chemical but also important physical processes in the space of life on Earth." (Kondratyev et al. 2003).

Sustainability limits determine the maximum loads on ecosystems, the excess of which can lead to irreversible degradation of ecosystems. The problem of sustainability is always faced with while considering the exploitation of natural resources. Since the use of natural resources cannot be abandoned by the society in order to maintain the balance of "use – reproduce", it must assess the limits of the impact that do not irreversibly violate this balance.

Since the middle of the last century, when it became evident that it was impossible to control thousands of newly created chemicals entering aquatic ecosystems and to predict their impact on the basis of hydrochemical methods, there was a need to directly assess the impact of pollutants on aquatic ecosystems. Many methods and approaches for assessing the state of aquatic ecosystems based on the response of individual biotic structures have emerged. However, they ignored the idea of the ecosystem as a whole living unity with emergent properties that are not a simple sum of the properties of its constituent elements. This was the reason that none of these approaches was able to predict the evolution of ecosystems under human impact, let alone to make a correct objective assessment of their state, even less to offer adequate methods of management and operation.

At the same time, it has become obvious that aquatic ecosystems poses all the properties of complex open systems, namely dissipative structures, whose specific features of functioning are largely studied (Anishchenko 1990; Gaponov-Grekhov and Rabinovich 1981; Glensdorf and Prigogine 1973; Zotin 1980, 1982; Zotin and Zotina 1987; Zotin and Zotin 1999; Klimontovich 1996; Knyazeva and Kurdyumov 1994; Malinetskiy and Potapov 2009; Nicolis and Prigogine 2008; Opritov 1999; Riznichenko and Rubin 2004; Rosen 1976; Trubetskov 2010). The nature of ecosystems as open self-organizing systems allows to describe their state by parameters expressed in energy terms. Thus, the problem of objective assessment of the state of ecosystems and to determine the measure of stability of a certain state can be solved on the basis of a holistic approach and thermodynamic interpretation of available observation data.

4.2 Methodology

4.2.1 Some Regularities of Functioning of Dissipative Structures

The concept of sustainability in the scientific literature is diverse and therefore somewhat ambiguous. The review (Grimm and Wissel 1997) analyses 163 definitions of environmental sustainability using 70 different concepts of sustainability. Having carried out an inventory of all these concepts and definitions, the authors quite reasonably come to a conclusion that "stability" is merely a general term that cannot be used as a classifier of specific ecosystem states. The main consequence of their study is expressed by the motto: "stability" is not a property of stability!" Different definitions of stability, the authors emphasize, may be sufficient "as a local terminology, i.e. within a single article, but for a proper understanding of the discussion of environmental stability they are an unnecessary obstacle because they cannot eliminate the ambiguity of the term "stability".

It is obvious that the ecosystem, existing in a relatively unchanged form for a long time, has the ability to resist disturbing environmental factors, including anthropogenic impacts. Stability in the conventional sense implies also the ability of the system to return to the previous state after perturbation (Margalef 1992).

There is a developed mathematical theory of stability, in which the definition of stability is given quite strictly. There are several concepts of stability of motion: Lyapunov stability, asymptotic stability, orbital stability, Poisson stability, Lagrangian stability, etc. Unfortunately for practitioners, this theory does not work with real objects themselves, but with their mathematical models (Khaiter and Erechtchoukova 2009). When studying models, we usually talk about the stability of some solution of the system of equations, i.e. either the stability of a state of the system or the stability of a particular regime of its functioning. For example, it is believed that the ecosystem is stable if the trajectory of its model in the phase space does not go beyond a given bounded region for some non-specific perturbations. It should be emphasized that in this case, we are talking about the model and the question of its adequacy to the real object remains aside (Svirezhev and Logofet 1978).

Mathematical models are often so abstract that they operate on variables that are in no way related to real systems. But despite this fact, the properties found in the investigation of abstract models can be useful for studying the evolution of the state of real ecosystems and determining the limits of stability.

Transformation in the nature have the character of irreversibility, i.e., they are non-equilibrium. Thermodynamically, living systems in the process of life and development pass through a number of non-equilibrium states, which is accompanied by appropriate changes in thermodynamic variables. In this regard, two classes of evolutionary processes are distinguished in open systems: (1) the temporal evolution towards a nonequilibrium but stationary state; (2) the process of evolution through a sequence of nonequilibrium stationary states of an open system. The change of stationary states is caused by the slow change of so-called control parameters. The emergence of a new system is associated with the loss of stability and the transition of the initial system to a new stable state.

The process of transition from one state to another is called bifurcation. In this case, the system structure changes. It is proved that the transition to a stable state can occur only through an unstable state, and the transition to order – through disorder. "Complex systems tend to disintegrate, reaching their developed state. Instability is dialectical. Stability grows out of instability, as a result of instability, because the beginning, the birth of a new structural formation is associated with randomness, chaos, instability. And stability, in the end, sooner or later, turns into instability" (Knyazeva and Kurdyumov 1994).

It is clear that in order for the same material substrate to form any new structure meeting the criterion of organization, the old structure must be destroying, breaking the intra-connections. In this case, the appearance of a new structure can be considered as a nonequilibrium phase transition (Klimontovich 1996). It should be emphasized here that in ecosystems the transformation process is primarily important to change intra-links. Elements of the old structure-the population, the community can continue to exist in a subordinate or oppressed state, giving way to the dominance of other elements. The qualitative certainty of the new system is formed randomly. According to the bifurcation theory, the past state of the system disappears abruptly due to the accumulation of fluctuations in the system (Buck 2013).

The bifurcation point acts as a point of maximum sensitivity of the system, both to external and internal impulses. For example, in the bifurcation point, the role of external factors affecting the system increases. The ecosystem can begin to react to small concentrations of pollutants, being in a stationary state indifferent to them (Prigogine and Stengers 1986). Near the bifurcation point, a highly nonequilibrium system is particularly sensitive to minor fluctuations of a process parameter. In the equilibrium state the effect of the second law of thermodynamics, will neutralize the effect of fluctuations, consistently forcing the system to return to the initial (stationary) state. Actually, the stable state of the system is called such a state when... active... disturbances fade in time", "leaving no traces in the system" (Nicolis and Prigogine 2008).

Since all living systems exist in a continuously fluctuating environment and since it is impossible to know which deviation will occur at the bifurcation point at the right moment, it is never possible to predict the future direction of the system. Insignificant deviations in the environment determine the choice of the branch on which this structure will follow. In addition, it is impossible to predict exactly when bifurcation will occur. Thus, all deterministic descriptions turn out to be untenable when the dissipative structure passes the bifurcation point. However, knowing the basic types of bifurcations, it is possible to predict the parameters of the movements that arise at the time of the transition, to find in the parameter space the region of their existence and stability (Trubetskov 2010).

Another important concept that fixes the specifics of dissipative structures is the attractor. It is defined as the mode (state) to which the system tends. In terms of content, this means that the attractor state acts as the desired and achieved (final in a particular frame of reference) phase of evolution (Nicolis and Prigogine 2008). In the study of the processes of self-organization was recorded the fact that among the possible branches of the evolution of the system are not all likely, "that nature is not indifferent, that it has "attraction" in relation to some states"; in this regard, the physics of" dissipative systems producing entropy calls the final states of these systems "attractors" (Nicolis and Prigogine 2008). The most important fact in this context is the fact that this state to which the system is evolving is not only a potential prospect of its development, but also as a really effective factor in this process. In fact, the attractor can be considered as a factor of order (an order parameter for a system in the process of self-organization) (Nicolis and Prigogine

2008). In the dynamics of open systems there are four types of attractors: stable focus (attractor-point), stable limit cycle, two-dimensional torus (two-dimensional torus surface) and chaotic, or strange attractor (Riznichenko 2003).

Living systems are characterized by periodic changes in different characteristics. In this case, the periodic change of values is one of the types of stationary behavior of the system. If the oscillations in the system have a constant period and amplitude, are set independently of the initial conditions and are maintained due to the properties of the system itself, and not due to the effect of periodic force, the system is called self-oscillating. In the phase space, this type of behavior corresponds to the attractor, called the limit cycle. The behavior of the system corresponding to the limit cycle has a characteristic specificity: small excitations do not destroy its stationary motion (Riznichenko 2003).

A more complex attractor has the form of a torus. This form corresponds to the movement, composed of two independent oscillations – the so-called quasi-periodic motion. The trajectory is wound on the torus in the phase space, one frequency is determined by the time of the revolution in a small circle of the torus, the other – in a large circle. For a combination of more than two rotations, the attractors can be multidimensional torus. An important distinguishing feature of the quasi-periodic movement is that, despite its complexity, it is predictable. Although the trajectory can never be repeated precisely (if the frequencies are incommensurable), the motion remains regular. Trajectories starting near one another on the torus remain close to one another, and the long-term forecast is guaranteed.

However, there may be non-stationary states of the system, i.e. those in which the equilibrium state does not have time to be established. The increase of nonlinearity in the system beyond a certain critical value leads the system to bifurcation again. The macroscopic coherence is replaced by the inconsistency of random fluctuations, which leads to ambiguous results: a small change in the initial condition over time leads to arbitrarily large changes in the dynamics of the system. In this situation, the system is characterized by instability with respect to its own initial parameters (Lyapunov instability) and an exponential trend towards divergence. Such behavior of systems was given the term dynamic or deterministic chaos.

The observed chaotic behavior is not due to external noise sources, a large number of degrees of freedom, or uncertainty under the laws of quantum mechanics. It is generated by the intrinsic dynamics of a nonlinear deterministic system (Beckman 2009). In the phase space such behavior of the system corresponds to a strange attractor. The deterministic chaos in the phase space is displayed by a continuous trajectory developing in time without self-intersection (otherwise the process would be closed in a cycle) and gradually filling a certain area of the phase space. Thus, any arbitrarily small zone of the phase space is crossed by an infinitely large number of segments of the trajectory. This creates a random situation in each zone – chaos. At the same time, despite the determinism of the process, the course of its trajectory is unpredictable, hence the name of the nature of the process – deterministic chaos. In other words, we are not able to foresee or at least roughly characterize the behavior of the system at a sufficiently large period of time, and primarily because there are no analytical solutions.

This trend, however, realizes itself within the boundaries of a fairly clearly limited scope of opportunity. Even systems described by strange attractors, i.e. chaotic, unstable systems, cannot be considered absolutely unstable. After all, for such systems, it is possible not to have any state, but only a state that gets into a limited deterministic region of the phase space. “Instability means random movements within a well-defined range of system parameters. Therefore, there is not a lack of determinism, but a different, more complex, even paradoxical regularity, a different type of determinism. ... the study of strange attractors (in particular, the construction of their phase portraits) is, in fact, the discovery of the laws and boundaries of instability” (Knyazeva and Kurdyumov 1994).

Since the normal functioning of a living system is possible only with a certain norm of randomness, which corresponds to a significantly non-equilibrium state, the deviations in both directions can be considered as a “disease” and, consequently, as degradation. However, not always, especially in biology, the transition to a more chaotic state should be considered as degradation. The consideration of deviations from the norm of randomness is essential (Beckman 2009).

Structure – attractors of evolution, considered as a holistic structure, according to Knyazeva and Kurdyumov (1994), relatively simple compared to the complex course of intermediate processes that form them. Based on this substantially simplifies the asymptotics and opportunity forecasting, “proceeding: a) ”of the purposes“ of the process (structure – attractors), b) ”on the whole,“ based on general trends in the deployment of processes into a holistic system”. For this purpose, the system, which is extremely complex, infinite-dimensional and randomized at the element level, should be described, like any non-linear system, by a small number of fundamental ideas and images, and subsequently, by mathematical models that determine the general trends of the system (Knyazeva and Kurdyumov 1994).

Depending on which attractor is present in the phase space, the system can implement various modes of dynamics – stationary, periodic (quasi-periodic), chaotic. Such modes of motion correspond to a stable point, a limit cycle and a strange attractor. With a slight change in the parameters, the stable point can shift in the phase space, change its shape and the period of the limit cycle or the invariant torus can be deformed. When the parameter is passed through some critical value, the system dynamics can change abruptly. A stable point can be transformed into a limit cycle, an invariant torus can arise from the limit cycle (Loskutov and Mikhailov 1990).

4.2.2 Some Extreme Principles as Criteria for the Evolution of the State of Open Systems

One of the key issues in solving the problem of ecosystem stability is the question of the criteria of state evolution. Simple logic suggests that to achieve success and dominance and ensure a stable state in a competitive relationship can only be the system that uses resources for its own reproduction more effectively than others. Accordingly, as criteria for the evolution of living systems may be some principles of extreme functioning. According to extreme principles, only states with an extreme value of the goal function are realized in nature. The formulation of the principle of extremity was given by the great philosopher of the Renaissance Giordano Bruno: “who wants to know the greatest mysteries of nature, let him consider and observe the minima and maxima of contradictions and opposites” (cite by Yugay 1985). Extreme principle is one of the fundamental principles of theoretical natural science, Yugay (1985) believes. Approaches based on extreme principles that allow us to overcome the difficulties associated with high dimensionality of the task of modeling ecosystems (“curse of dimensionality”) and to avoid the need of selection of hundreds of coefficients and the analysis of systems of many equations (Fursova et al. 2003).

Moiseyev (1987) formulated the principle of the minimum energy dissipation as follows: “if not the only state of the system (process) is permissible, but the whole set of states that agree with the conservation laws and relations imposed on the system (process), then its state is realized, which corresponds to the minimum dissipated energy, or the same, the minimum growth of entropy.”

Based on the reasoning of competitive mutual exclusion, Rosen (1976) formulated the principle of optimality of the living system as follows: “since the living organism has only a limited supply of energy, it can be considered that, all other things being equal, the optimal structure will be such that provides the lowest consumption of metabolic energy (sufficient at the same time for the needs of the entity)”. In other words, minimization of metabolic energy can be considered as a criterion for the evolution of living systems to the optimal state. At the same time, it is obviously necessary, firstly, to correlate the consumption of metabolic energy at least with the biomass of the living system (and more correctly to compare the process – the expense of metabolic energy with the process – the production of biomass), and, secondly, to keep in mind that the minimization cannot be unlimited. Most likely, it should be sufficient to implement the necessary level of competition. In other words, the use of energy by a live system is limited on two sides: on the one hand, the system needs necessary for self–maintenance and reproduction, on the other hand – competition for energy sources, i.e. the energy needs of competitors. It follows that the optimal ratio of metabolic energy expense and energy structured in the biomass of the system should lie within some apparently narrow limits.

Pechurkin (1982, 1988) formulated the energy principle of intensive development: “any living system of the supra-organizational level develops (evolves) in such a way that the flow of used energy per unit of biological structure (during the existence of this structure) increases”. It is obvious that in a competitive environment, this principle can be implemented by a living system only by increasing the efficiency of energy use.

Yugay (1985) is committed to the same views, arguing that “it is justified to consider the organization of living systems as the main criterion for the progress of their evolution, and the main criterion for the degree of their organization is the efficiency of energy use...Since the maintenance of the constancy of the organization of the living can be the most effective with a minimum of energy expense."

Rybin (1990), considering the factors of evolution, suggests that even with an unlimited supply of free energy in the environment in the form of sunlight, increasing the efficiency of the use of the mobilized energy was a factor of evolutionary selection. In the conditions of limited resources, this factor has become decisive in the competitive interspecies struggle for living space and food sources, in the struggle for existence.

We will mention a number of extreme principles that have found application in practical ecology.

The principle of maximum total breathing. Washida (1995) put forward a hypothesis according to which the system seeks in the development process to achieve the configuration at which the breath is maximum possible as early as possible.

Maximum empower and emergy. The emergence was proposed by Odum (1988), as a quality energy factor measuring how much initial solar energy is required to create a given product, i.e. energy of a given type. For example, the energy of fuel is of higher quality than solar energy. 10^4 calories of solar energy produce 10^2 calories of primary producers, which in turn produce 10 calories of predators. If you take the quality of solar energy per unit, 1 emjoule, the quality of higher trophic levels will be respectively 100, 1000, 10,000 emjoules.

The principle of maximum ascendency proposed by Ulanowicz (1986) in the theory of growth and development of the ecosystem. This principle considers the organization of the network as a result of the total flow of energy and the average joint information, including the individual flow and is described by the expression of the logarithm of various other flows and components of the organization.

The principle of maximum power. Odum and Pinkerton (1955) proposed the principle of maximum power, according to which the functioning of the ecosystem is so as to maximize power, i.e., the rate of change in the total system throughflow of energy, passing through the system.

A detailed description of the application of these and other principles in practice and specific ways of calculating indicators based on the relevant principles can be found in the original and review publications (Ray 2006; Fursova et al. 2003).

Thus, some of the stated principles, based on thermodynamic parameters, seem promising, in particular, to establish the state and solve the problem of sustainability of ecosystems. The question of the choice of parameters that can be determined by available methods in real ecosystems and are the basis for the calculations of ecosystem functioning regimes remains open.

4.2.3 From Models to Nature

Fedorov (1977) formulated the general requirements for variables to assess the state of ecosystems. The first requirement – the state of biological systems can be assessed only on the basis of indicators related to the processes with homeostatic mechanisms of regulation. The second requirement (subject to the first) is the need to select variables that characterize the non–specific response to external factors. The third requirement (subject to the first two) is that preference should be given to integral indicators and, above all, to those that can be measured quickly and reliably.

In recent years, the most widespread use of exergy for the assessment of the state of ecosystems. In a number of works, exergy is used as an indicator of the state of the environment, especially in anthropogenic impacts (Marques et al. 1997; Jørgensen et al. 1995, 1998, 1999, 2005, 2010; Fonseca et al. 2000; Marquez et al. 2003; Ulanowicz et al. 2006; Ludovisi and Jørgensen 2009; Ludovisi 2009; Silow and Mokry 2010; Zhang et al. 2003, 2010).

Exergy is the maximum work that can be done by a thermodynamic system in the transition from this state to the state of equilibrium with the environment. Thus, exergy is a measure of system efficiency. The value of exergy is determined by the degree of non-equilibrium of the system and its structure.

The concept of exergy entered into ecology in the late twentieth century thanks to the works of Jørgensen (Jørgensen and Mejer 1979; Jørgensen and Svirezhev 2004). Exergy is well-theoretically justified, connected with the theory of information and relatively easy to calculate. However, the exergy approach in its practical application for large-scale use in such tasks as assessment of the state of water ecosystems within the state observation network of Russia is significantly limited. To calculate the magnitude of exergy, it is necessary to collect primary data on the species comprising the ecosystem. This type of work requires efforts of highly qualified staff of hydrobiologists-taxonomists. The use of basic hydrobiological information in the calculation of eco-exergy also involves significant time spent on processing the material. Thus, the efficiency of the assessment of the state of aquatic ecosystems is significantly reduced, if not eliminated. The efficiency of assessment is dictated by timely management decisions to limit or stop negative human impacts and prevent damages to aquatic ecosystems. Another limitation of ecoexergy is due to the use of approximate averaged values of the parameter $\boldsymbol{\beta}$ a factor expressing roughly the quantity of information embedded in biomass (Marques et al. 1997) for the calculation of its value for a particular ecosystem. In addition, in our opinion, the calculation of any thermodynamic parameter (entropy, exergy) for the whole ecosystem by summing the values for individual communities contradicts the thermodynamic (holistic, macroscopic) approach.

It should be noted that all the above principles are described in terms of energy and organization and can be closely related. In particular, Patten (1995) showed that exergy, emergy, power, ascendency and indirect effects are interrelated microscopic dynamics. Ludovisi (2014) demonstrated, the relationship between entropy, exergy and respiration:

$$\frac{\text{Entropy generation rate}}{\text{Entropy of structure}} \approx \frac{\text{Resperation}/\text{T}}{\text{Free energy stored}/\text{T}} = \frac{\text{Resperation}}{\text{Biomass}}$$

where T is the absolute temperature.

The problem of ecosystem stability is not only an academic problem of interest exclusively for fundamental research. On the contrary, the determination of ecosystem sustainability limits is of great practical importance for the management and exploitation of natural resources. Therefore, the most promising approaches for practical implementation are those that, on the one hand, can be implemented by simple calculations based on instrumental measurements obtained manually or automatically, and the which use indicators that naturally generalize the interactions of the whole variety of abiotic and biotic structural elements on the other hand. These are photosynthetic production and destruction of organic matter representing complete variety of biotic relations and abiotic components forming an ecosystem refer to them. In other words, all processes occurring in an ecosystem are, in reality, separate stages of united process of solar energy transformation. It seems to us that the principle of the minimum specific dissipation combines the fundamental validity and the possibility of practical implementation and can serve as a criterion for the stability of ecosystem states.

This criterion is based on Prigogine's theorem, which is formulated as follows: in a stationary state, the production of entropy inside a thermodynamic system with constant external parameters is minimal and constant (Ray 2006). If the system is not in a stationary state, it will change until the entropy production rate, or the specific dissipative function σ of the system, takes the lowest value, i.e., the system will be in a steady state:

$$\frac{d\sigma}{dt} \le 0 \tag{4.1}$$

$$\sigma = \frac{T}{V}\frac{diS}{dt}, \tag{4.2}$$

where T is the absolute temperature, V is the volume of the system, diS/dt is the entropy production rate.

In living systems, the specific dissipative function, with a known approximation, is equated to the intensity of heat production, and, consequently, to the intensity of respiration and glycolysis (Zotin and Zotina 1987). Then the formula (4.2) can be written as

$$\sigma = \frac{T}{V}\frac{diS}{dt} \approx \dot{q}, \tag{4.3}$$

where $\dot{q}$ is the intensity of heat production. Therefore, the criterion of evolution for open thermodynamic systems can be written in the form of

$$\frac{d\dot{q}}{dt} \le 0 \tag{4.4}$$

The criterion (4) shows the direction of evolution of an open thermodynamic system associated with the transition of the system from a less probable unsteady state to a more probable stationary state (Zotin and Zotin 1999).

There are, however, theoretical objections to the use of the criterion (4) to describe the evolution of organisms, in particular during their growth, development and ageing. It is believed that the limitations imposed on the system by the thermodynamics of linear irreversible processes are not met during the development and growth of animals. Living systems are far from equilibrium or steady state, and it would seem that thermodynamics of linear irreversible processes cannot be used to describe their changes.

Leaving open the question of the limits of applicability of the principle of minimum of excess entropy production as a necessary and sufficient thermodynamic criterion for the evolution of complex living systems, it is believed that the complexity in nature cannot be reduced to a certain principle of global optimality, considering that in nature the search for stability plays an essential role (Nicolis and Prigogine 2008).

However, the condition of positivity of the excessive entropy production calculated in close proximity to standard nonequilibrium state can be regarded as sufficient conditions for the stability (Nicolis and Prigogine 2008; Opritov 1999).

Thermodynamics, as a general phenomenological theory of any processes and phenomena that occur in nature and are accompanied by processes of energy dissipation, i.e. entropy production, provides a key to the description of macroevolutionary changes in complex systems. Therefore, the science is faced with an alternative: either to abandon the thermodynamic description of the processes of life, or, to use the results already obtained in thermodynamics within reasonable limits and to continue the study of life on the basis of thermodynamics (Zotin 1980, 1982; Zotin and Zotina 1987; Zotin and Zotin 1999). It was shown that the application of modern thermodynamics to the phenomena of the development of organisms not only gives good experimental results, but also in principle the thermodynamics of linear irreversible processes in many cases can be used to describe these processes.

For strongly nonlinear systems, to which all living systems belong, Zotin postulates the principle of minimum dissipation, according to which in the stable state of any thermodynamic system the rate of energy dissipation in it is minimal. In such systems, the specific dissipative function is not necessarily constant and the criterion of evolution (4) can be written as

$$\frac{d\bar{\dot{q}}}{dt} \leq 0, \tag{4.5}$$

where $\bar{\dot{q}}$ is the average value of the heat production intensity of the system, achieves its minimum on a steady state in accordance with the principle of minimum dissipation.

Conclusions and reasoning of Zotin and his colleagues seem to us quite reasonable and sufficient and coincide with our views on the development and evolution of living systems. In practical terms, it is important that the thermodynamic criterion can be expressed in terms of the specific rate (intensity) of heat production, i.e. the amount of energy dissipated by a living system per unit of time per unit of biomass

$$\overline{\dot{q}} = \frac{T}{B}\frac{dQ}{dt}, \tag{4.6}$$

where Q is the heat production of the living system, B is the biomass, T is the absolute temperature. When determining the intensity of heat production of an individual organism or a fixed set of organisms, it is possible to take a biomass of a fixed value and easily determine, for example, by simple weighing. If we are talking about aquatic ecosystems, the definition of its biomass is practically impossible and unnecessary. The rate of energy dissipation can be logically linked to the rate of biomass growth, i.e. the ecosystem production, more precisely, with primary production, which are carried out in aquatic ecosystems mainly phytoplankton. Secondary products are not created again, and is the result of assimilation of primary products and therefore together with the breath of phytoplankton is the total dispersion of the ecosystem. The rate of energy dissipation for aquatic ecosystems is denoted as destruction (R), primary production (P). Then expression (4.6) can be replaced by

$$\overline{\dot{q}} = T\left(\frac{\dot{R}}{P}\right). \tag{4.7}$$

With regard to practical implementation to calculate specific dissipative functions of a real or full-scale model of aquatic ecosystems derivative of the relationship between destruction and production can be replaced with the average rate over the measurement period. Thus, we propose to approximate the specific dissipative function by the formula

$$\overline{\dot{\sigma}} = \overline{T}\Delta\overline{(R/P)}\,\Delta t^{-1} \tag{4.8}$$

As a result, we obtain the criterion of ecosystem state evolution, which can be easily calculated on the basis of traditional hydrobiological indicators – the destruction of organic matter and primary phytoplankton production.

In practice, when conducting full-scale experiments at a relatively stable temperature, the absolute temperature can be considered as a constant factor for all variants. Then, the dynamics of the approximation of the dissipative function will be determined by the

$$\overline{\dot{\hat{\sigma}}} = \Delta\overline{(R/P)}\,\Delta t^{-1} \tag{4.9}$$

4.3 Results and Discussion

In numerous experiments carried out in the period 1992–2009 on natural models of freshwater ecosystems (mesocosms) installed on various water bodies of the Don river basin, the response of ecosystems to toxic pollution was studied. Primary production and destruction of organic matter were determined by the difference in the content of dissolved oxygen in light and dark isolated vessels (Guidebook 1992) in the author's modification, which allows to take into account the production and destruction processes in bottom sediments and bottom microlayer of water (Trofimchuk et al. 2010). Cadmium (Cd^{2+}), mercury (Hg^{2+}), copper (Cu^{2+}), sodium lauryl sulfate (SLS) and others were used as pollutants.

One of the main objectives of the experiments was to study the regularities of response of production and destruction processes of aquatic ecosystems to toxic effects. Because the emphasis in research was placed on the ecosystem response to violating effects, in the majority of experiments used the same toxicant – a solution of sulfate of cadmium in various concentrations.

A priori, the higher the concentration of the toxicant, the greater the exposure and therefore the more distinct the response. In this regard, in one of the first experiments, a toxicant was introduced into the mesocosms based on the calculation of initial concentrations in the mesocosms from 250 to 750 $\mu g/dm^3$ $Cd2^+$. In subsequent experiments, lower concentrations of sulfate of cadmium were used.

The key point in the study of the thermodynamics of ecosystems is the question of whether there are stationary states in the dynamics of production and destruction processes in real aquatic ecosystems and if so, what are their parameters. The stationarity of the process is determined by the immutability of its rate, therefore, to identify the presence of stationary states in the dynamics of production and destruction processes and study their parameters according to field observation data, phase planes were built – graphs of the change in the time of the relationship of R/P and the rate of its change per day (Fig. 4.1). In other words, the analysis of the dynamics of production and destruction processes was carried out in the dynamic phase space. Determination of the rate of change in the parameters of the dynamic system is also necessary to identify such an important feature of the system, as bifurcation. After all, in the bifurcation points there is a change of modes of functioning of dissipative systems, therefore, without determining the point of bifurcation it is impossible to establish the moment of transition of the ecosystem from one state to another. This approach allowed us to present a qualitative picture of changes in the states of ecosystems by their phase portraits, without resorting to mathematical modeling.

Since the state of real living systems, including freshwater ecosystems, is always in dynamic equilibrium, the process parameters in these systems never take stable minimum values, and fluctuate around them. In this case, the steady state on the phase plane is a stable limit cycle (Nicolis and Prigogine 2008).

Phase portraits of ecosystems, built on the results of field experiments, clearly reveal the differences between the states of mesocosms, depending on the nature and

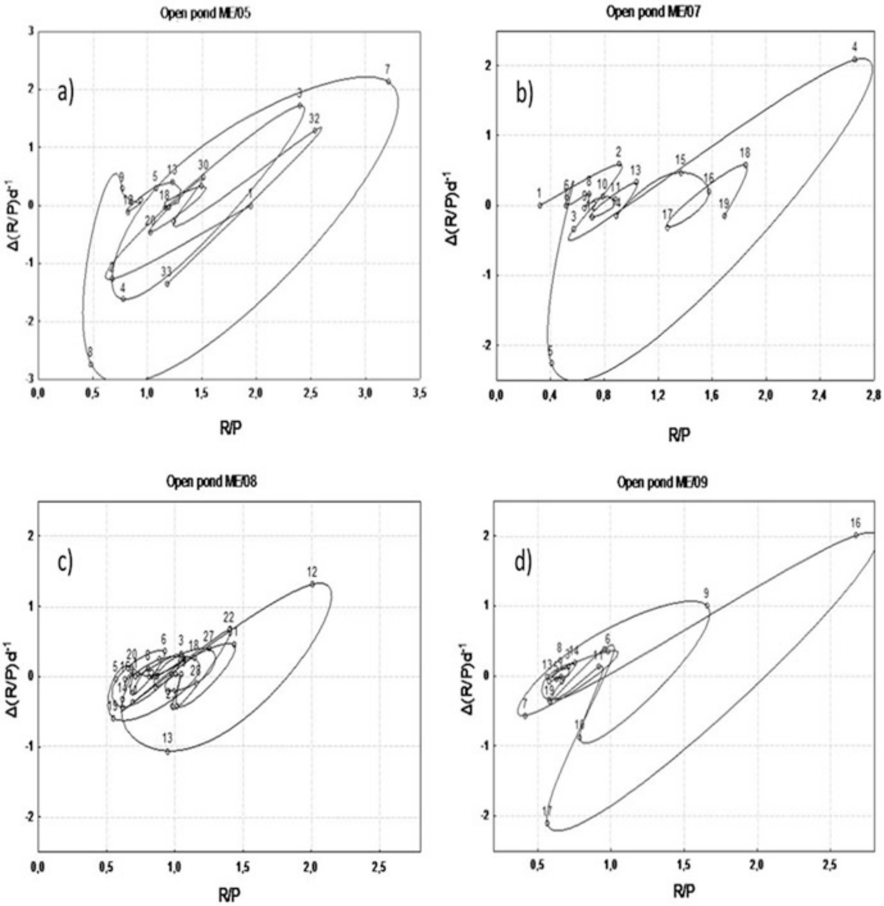

Fig. 4.1 The dynamics of the ecosystem characteristics in the open water body. Digits at the trajectories indicate the days of *P* and *R* measurements. (**a**) open pond (maternal ecosystem), 2005 year; (**b**) open pond (maternal ecosystem), 2007 year; (**c**) open pond (maternal ecosystem), 2008 year; (**d**) open pond (maternal ecosystem), 2009 year

strength of external influence. The parameters of the state of ecosystems describe cyclic trajectories – limit cycles, the number, area and relative position of which in the phase space may differ.

In maternal ecosystems, which served as reservoirs, not contaminated with toxic substances, during the period of experiments observed one (Fig. 4.1b) or several cycles (Fig. 4.1a, c, d). The cyclic trajectory can be completely or partially overlapping, in varying degrees, moving along the *R*/*P* – axis. In the case where the phase portrait of the ecosystem is represented by several cycles, one of them with a minimum area is allocated, from which unstable trajectories come out and to which they return. This limit cycle is a stable attractor (Fig. 4.1c, d). The depicting points representing the state of the ecosystem at a given time are located more compactly inside the attractor area.

Thus, the state of maternal ecosystems cannot be characterized as stationary over the entire time of observations. This behavior corresponds to the known trend of evolutionary processes observed in open systems in the general case, when stationary states are replaced by non-stationary periods of development. The change of stationary states is due to the slow change of so-called control parameters. The emergence of the new system is associated with the loss of stability and the transition of the initial system to a new stable state (Klimontovich 1996). Relatively stationary periods in the dynamics of production and destruction processes are observed for a short time, when the parameters of ecosystems lie within the cycles-attractors. These modes are replaced after bifurcations by bursts of parameters, during which the rate of change increases abruptly (exponentially). It should be noted that most of the bursts are directed towards increasing R/P, and the attractors, which are considered by us as an area of optimal ratio between the processes of dissipation and photosynthetic production, corresponding to the optimal conditions for the existence of the ecosystem, are located within the values of R/P equal to 0,6 – 1,0. Since we are talking about maternal ecosystems that are not subject to toxic load, and therefore whose condition is considered to be undisturbed, it must be recognized that some chaotic dynamics are inherent in the functioning of aquatic ecosystems and must be interpreted as the norm of functioning. "Stability grows out of instability, as a result of instability, because the beginning, the birth of a new structural formation is associated with randomness, chaos, instability. And stability, in the end, sooner or later turns into instability" (Knyazeva and Kurdyumov 1994).

Today it is accepted to distinguish between two "types" states of living systems – the norm that characterizes "health", and the pathology that characterizes the "disease". The norm is defined as the average value of some parameters established for a priory healthy living systems. Statistically significant deviations from this value are treated as pathology. The experiments have shown that extremely high values of production, destruction or their ratio can occur in the study of ecosystems that are not subject to any negative effects. Such values of production-destructive indicators may not be the result of measurement errors or ecosystem response to negative impact, but also the result of the processes of ecosystem self-development in case of changes in its state. Such "sudden outbursts" of trajectories, a kind of inversion loops, is a manifestation of unsteadiness of production and destruction processes, the transition period of the formation of a new ecosystem (new state), regardless of the reasons that caused this restructuring. Therefore, by themselves, they cannot be an indicator of negative effects and a sign of pathology. At the same time, the steady state of the ecosystem, by definition, describes the correspondence of environmental factors to this biotic structure, the "harmony" between the biota of the ecosystem and the environment. This state is characterized by the optimal (minimum possible) ratio of expenses on the exchange and production of biomass, energy dissipation and its accumulation in living matter.

Thus, there is a need to distinguish not only the pathology and normal functioning, but also the optimum functioning of the ecosystem, lying within the attractor.

As can be seen from the analysis of the state of undisturbed mother ecosystems, the normal state covers a large area of phase space, which includes the area of optimal parameters of functioning – the area of the attractor that displays the stable state of the ecosystem.

Regardless of the details of the state parameters dynamics, it is generally noted for the maternal ecosystems that individual phase points are distributed in the phase space less densely and more evenly than in the impact ecosystems. Thus, the main feature of the phase space of maternal ecosystems – its large uniformity and minimum density was revealed.

In mesocosms without toxicants (control) compression of the phase space occupied by the ecosystem occurs (Figs. 4.2a and 4.3a). In the case of a non-stationary initial state of the ecosystem, a cycle can be formed that lies within the maximum cyclic area, which in our opinion reflects the manifestation of the effect of a closed space and the change in the water exchange (Fig.4.3a). On the other hand, it shows that when the level of impact does not exceed the permissible level, the ecosystem "manages to stay" within the parameters of functioning close to the undisturbed state.

In exposed model ecosystems (M2/09 and M4/09) Cd^{2+} at toxic loads of 25 and 50 $\mu g/dm^3$ (Fig. 4.2b, d), further compression of the phase space is observed. Immediately after exposure, there is a shift of the limit cycle-attractor in the direction of increasing R/P to the average value of 0.9. Then, after bifurcation, a new stable cyclic attractor is formed in the region of R/P values equal to 0.7–0,8. The ecosystem is almost back to its initial state. With an increase in toxic load up to 125 $\mu g/dm^3$ Cd^{2+} (mesocosm M5/09), the shift of the initial cycle increases in the direction of increasing the value of R/P (Fig. 4.2c).

This level of toxic effect seems to be critical, i.e. exceeds the permissible for this ecosystem structure, which leads to an increase in the area of the initial cycle-attractor and compaction of the phase space of the second cycle to a state of a stable point in the phase space close to the initial one in the control mesocosm. It should be noted that the increase in the energy expense of the ecosystem for the restructuring of the structure in the first five days is "compensated" by the maximum energy saving to maintain the structure in the future. This is explained, apparently, by the accelerated use of limiting resources in the process of restructuring, which subsequently limit the rate of production and destruction processes by the type of feedback.

So far, we have observed the compaction of the phase space with an increase in the level of exposure to external factors, in particular toxic. In this case, there is a decrease in the density of the phase space in the initial cycle of the model ecosystem with an increase in the load. In the final limit attractor cycle, the density of the phase space is maximal and close to the limit. It can be assumed that under different toxic loads the transformation of the ecosystem structure occurs under different scenarios due to different sensitivity and different limits of resistance and tolerance of the populations forming the ecosystem. A five-and ten-fold excess of the MPC leads, perhaps, not to the destruction of the old structure, but to the oppression of its main functions. This is manifested in the change in the energy balance of the ecosystem

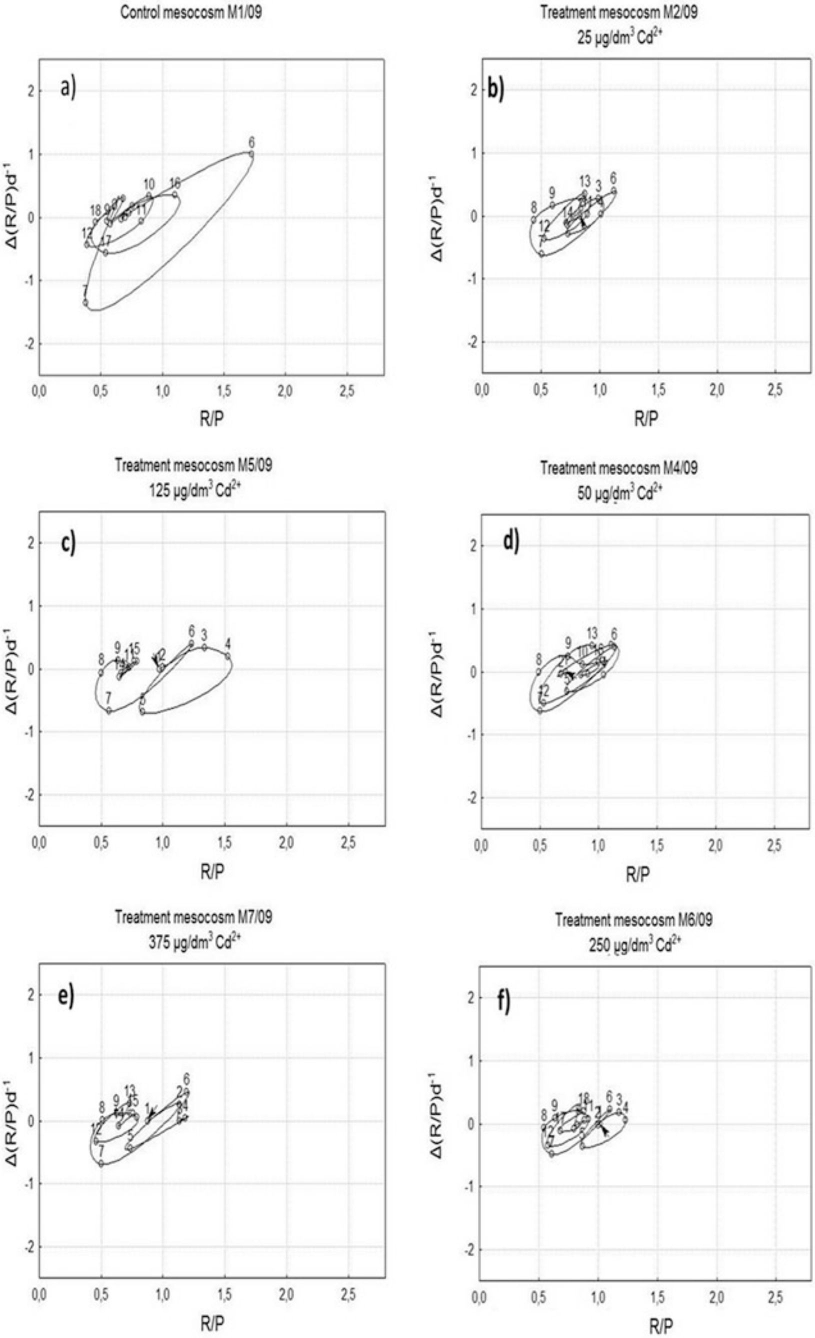

Fig. 4.2 The Dynamics of the ecosystem characteristics (experiment series of 2009). Solid arrows denote the days of toxicant adding (**a**) control mesocosm M1/09; (**b**) treatment mesocosm M2/09, 25 μg/dm^3 Cd^{2+}; (**c**) treatment mesocosm M5/09, 125 μg/dm^3 Cd^{2+}; (**d**) treatment mesocosm M4/09, 50 μg/dm^3 Cd^{2+}; (**e**) treatment mesocosm M7/09, 375 μg/dm^3 Cd^{2+}; (**f**) treatment mesocosm M6/09, 250 μg/dm^3 Cd^{2+}; (**g**) treatment mesocosm M3/09, 375 (25*15) μg/dm^3 Cd^{2+}

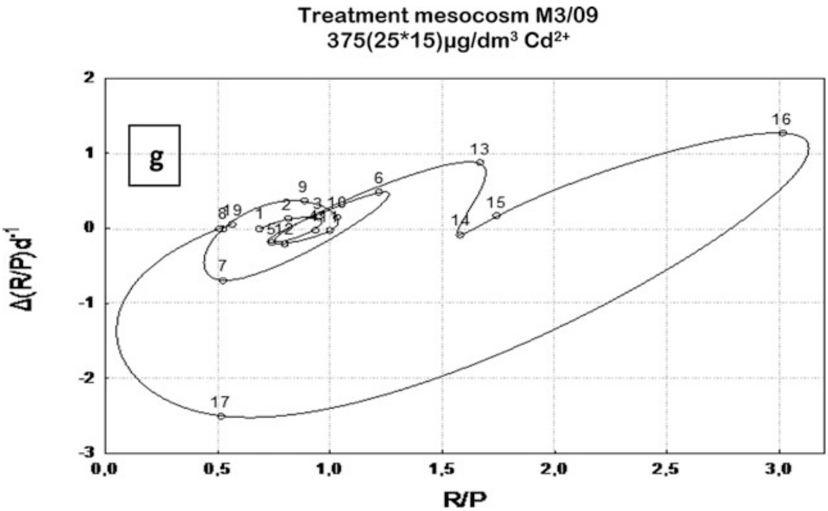

Fig. 4.2 continued

in the direction of increasing the expense of exchange (R) and reducing the rate of change of (R/P), which is manifested in the phase space by the compression of the attractor. The impact on the model ecosystem at the level of 125 μg/dm^3 Cd^{2+} may exceed the limits of its tolerance. In this case, the old structure of the ecosystem is destroyed and a new one is formed, which is accompanied by an increase in exchange expense and an increase in the rate of change of R/P. Thus, in this case, there is a nonlinear dependence of the production – destructive parameters of ecosystems on the magnitude of toxic effects.

The increase in the toxicant concentration in the mesocosm M6/09 to 250 μg/dm^3 Cd^{2+} leads to the compaction of the phase space of the model ecosystem (Fig. 4.2f) compared to the previous version. The topological similarity of the phase portrait with the phase portrait of the previous variant with the toxic load of 125 μg/dm^3 Cd^{2+} (two cycles separated in the phase space) is preserved. Phase portrait of model ecosystem M7/09 (Fig.4.2e) when exposed to 375 μg/dm^3 is generally similar to that in the previous version, occupying the same area of the phase space.

The temporal dynamics of thermodynamic parameters of ecosystems of different variants in a series of experiments remains almost the same. Thus, in a series of experiments in 2009, the initial cycles are formed in the 1st-sixth day, the first bifurcation occurs on the sixth day, the second cycle is maintained from the tenth to the 14th day, the second bifurcation is observed on the 14th day. A similar regularity is found in other series of experiments. Such synchronicity of processes may indicate that there is a natural frequency of oscillatory processes of a particular ecosystem. In turn, knowing that the period of oscillatory processes depends only on the properties of the system, we can say that in each mesocosm the same

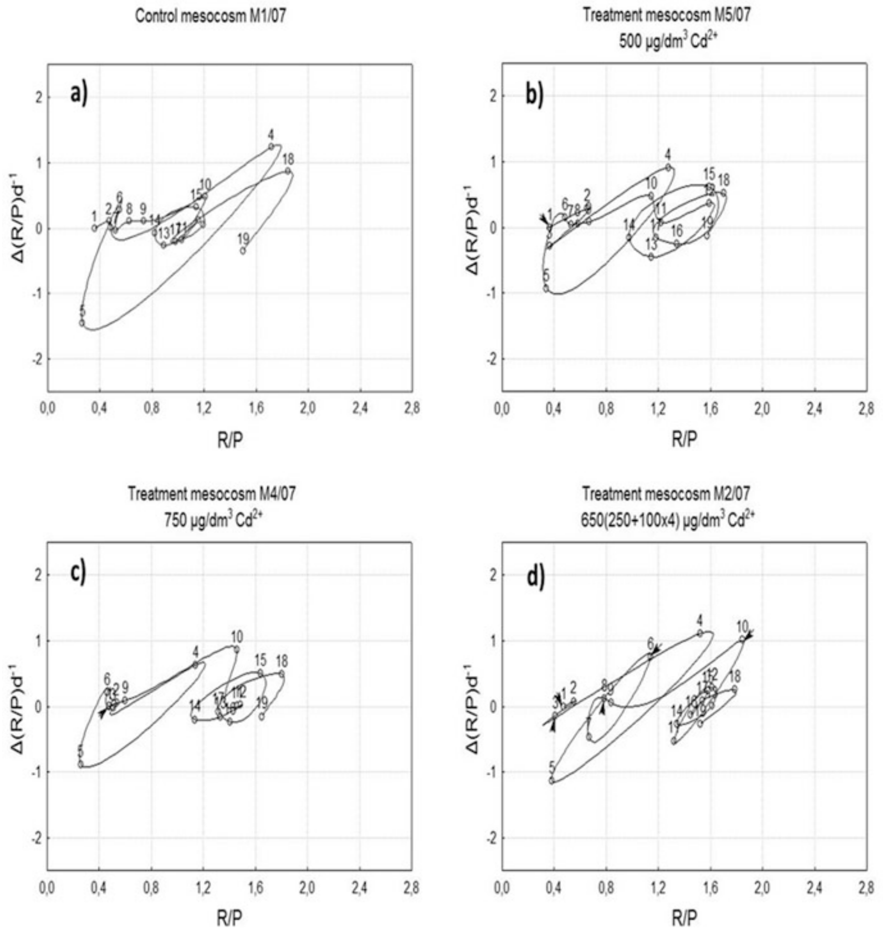

Fig. 4.3 The dynamics of the ecosystem characteristics (experiment series of 2007) (**a**) control mesocosm M1/07; (**b**) treatment mesocosm M5/07, 500 μg/dm^3 Cd^{2+}; (**c**) treatment mesocosm M4/07, 750 μg/dm^3 Cd^{2+}; (**d**) treatment mesocosm M2/07, 650 (250+100*4) μg/dm^3 Cd^{2+}

ecosystem was preserved, and, consequently, full-scale experiments in mesocosms provide ecological similarity of model ecosystems. Thus, the period of fluctuations of production and destruction processes can serve as a criterion of similarity of ecosystems.

Impact on the ecosystem the toxic load 500 μg/dm^3 Cd^{2+} (series 2007) leads to the fact that after the bifurcation, on the seventh day (Fig. 4.3b) the attractor shift in the direction of increasing the value of R/P, where a stable limit cycle is formed with an average value of R/P equal to 1,3. With an increase in the toxic load to 750 μg/dm^3 Cd^{2+} (in the same series of experiments), the phase space is compacted, especially in the second cycle, and the cycle is further shifted to the R/P value of

1.5 (Fig. 4.3c). Prolonged toxic effects (250 + 100 + 100 + 100 + 100 μg/dm^3 Cd^{2+}) (Fig.4.3d) despite the lower total concentration – 650 μg/dm^3 Cd^{2+}, caused a greater compression of the phase space of the model ecosystem than a single shock effect of 750 μg/dm^3 Cd^{2+} (Fig. 4.3c).

A similar regularity was observed in another case, when the model ecosystem was exposed to daily toxic effects of cadmium in concentrations exceeding MPC by five times (25 μg Cd^{2+}/dm^3) and the total was 375 μg Cd^{2+}/dm^3 (Fig. 4.2g). Up to the twelfth day, the dynamics of the destruction-production parameters of the mesocosm was similar to the dynamics of processes occurring in mesocosms with a single toxic effect at concentrations of 25 and 50 μg/dm^3 Cd^{2+} (Fig. 4.2b, d). The differences in the mode of toxicant effect on ecosystems were not manifested at first in the change of the phase space density or in the position of the attractors on the phase plane. However, starting from the twelfth day, there was a sharp increase in the value of R/P. on the 14th – 15th day at values of R/P equal to 1.6–1.7 bifurcation followed. The ecosystem, adapting to new toxic conditions, as if tried to stay in this area of phase space. But, apparently, the concentration of the toxicant exceeded the tolerance limits of this biotic structure and its further adaptive restructuring followed, manifested by another abrupt surge in the value of *R*/*P* to the value of 3.0. After the termination of the impact, the phase trajectory of the ecosystem returned to the attractor area. In this variant, the total toxic load was 375 μg/dm^3 Cd^{2+}. The same amount of toxicant, but in one step, was introduced into the mesocosm M7/09 (Fig. 4.2e). At the same time, the reaction of the ecosystem exposed to prolonged exposure to the toxicant was more pronounced. Thus, long-term pollution has a more negative impact on ecosystems than the same single pollution.

No matter how far the ecosystem has shifted in the phase space under the influence of toxicants, in most cases the return of ecosystems to the initial region of the phase space was observed. This trend was also observed in experiments with other metals (Fig.4.4) and SLS (Fig.4.5a, b). The exception was a series of

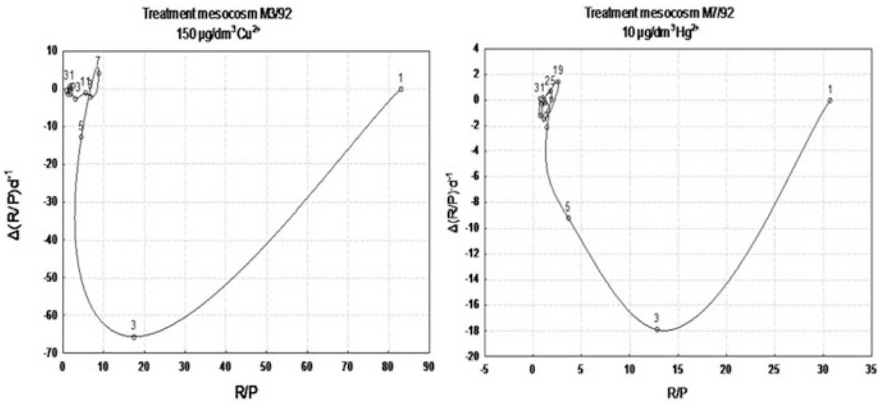

Fig. 4.4 The dynamics of the ecosystem characteristics (experiment series of 1992)

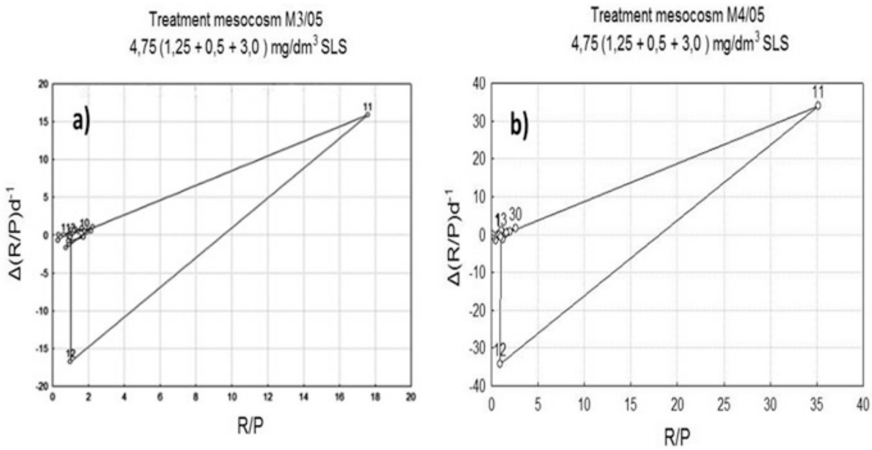

Fig. 4.5 The dynamics of the ecosystem characteristics (experiment series of 2005). (**a**) treatment mesocosm M3/05, 4,75 (1,25+0,5+3,0) mg/dm^3 SLS; (**b**) treatment mesocosm M4/05, 4,75 (1,25+0,5+3,0) mg/dm^3 SLS. Points 11, 12, 13 are denoted conventionally, because *R*/*P* values contain zero magnitudes *R* and *P* conventionally taken as 0.1. SLS was added to mesocosm in equal doses, but on different days

experiments, when the return of the ecosystem to its original state was not observed, perhaps, due to the short-term experiment (Fig.4.3b, d). In the study of the impact of SLS on model ecosystems in the first days after the toxic effects, only the compression of the limit cycle was observed. Then, after a two-turn cycle, the ecosystem directed to “infinity”, which corresponded to the almost death of the photosynthetic system while maintaining the destructive component. However, after the passing of this “infinite” trajectory, the ecosystem parameters returned to almost the initial state (Fig. 4.5a, b). Thus, the experimental results show that stable steady states of ecosystems are not probable in any region of *R*/*P* values, but only at certain values optimal for the given ecosystem, which lie within rather narrow limits. In other words, the biota of the ecosystem adapts to external conditions so that the balance of destruction and production remains optimal, regardless of the structure of the biotic community.

The presence of such a “constant” in the dynamics of ecosystems suggests the possibility of predicting their state at some times. The prediction of the state is also possible at the time when the dynamics of ecosystems is represented by the limiting cycle-deterministic mode.

Thus, the analysis of dynamic phase portraits clearly reveals the main regularities in the evolution of ecosystem states. The ecosystem moves to a new state not smoothly, but abruptly, at the point of bifurcation, forming a kind of “inversion” loops in the phase space. During these periods, there is a structural restructuring of the ecosystem. The area of attractors in impact ecosystems is reduced and, in case of exceeding the load intensity above the critical value, the limiting cycles-attractor are formed in another region of the phase space.

The transition of the ecosystem to a new state in all cases occurred at a zero or near-zero rate of change in the value of R/P and abrupt change in the direction of the phase trajectory. In general, as noted above, such regularities are characteristic for the limit states of dissipative systems and correspond to the transition between stability and instability when the excess entropy production vanishes (Glensdorf and Prigogine 1973).

The analysis of data obtained during several series of experiments carried out in different years revealed a number of important features of ecosystem behavior under the influence of external, including toxic, factors. It was found that against the background of these phenomena, response scenarios may be different, and are determined by the state of the ecosystem at the time of impact. In the case where the initial state of the ecosystem is represented by a stable point (Fig. 4.6b, d), the toxic effect immediately leads to a change in the type of attractor – the point is transformed into a limit cycle. The position of the attractor in the phase space is changed – the cycle is formed in the region of higher values of the ratio R to P. Then, after bifurcation, the ecosystem returns to the initial region of the phase space, where a new limit cycle is formed. I. e., the evolution of the states of model ecosystems in this case follows the scheme: stationary point ($R/P = 0.6$) → limit cycle ($R/P = 1.2$) → limit cycle ($R/P = 0.8$) (Fig.4.6f).

If the initial mode of functioning of the model ecosystem was the limit cycle (Fig. 4.6a, c), the first ecosystem response to toxic effects (from 500 μg/dm^3 Cd^{2+} to 750 μg/dm^3 Cd^{2+} in different mesocosms) was to compression the phase space limited by the initial limit cycle. Only six days the ecosystem parameters are shifted, after bifurcation, to higher values of the ratio R to P, where a new limit cycle is formed (Fig. 4.6e). In this case, the type of attractor is preserved, but its position in the phase space changes, which indicates a change in the state of ecosystems. The evolution of the state of model ecosystems follows the scheme: limit cycle ($R/P = 1.0$) → limit cycle ($R/P = 1.4$). It should be emphasized that in the second case, the level of toxic effects in a number of mesocosms was much higher than in the first, and it was possible to assume an instant reaction to toxic effects (change in the type of attractor and its position in the phase space) in mesocosms with a high level of pollution. The differences in the types of ecosystem responses appear to be related to their mode of functioning at the time of impact. It is known that the behavior of the system corresponding to the limit cycle is characterized by certain specificity, namely, small excitations do not destroy its stationary regime (Nicolis and Prigogine 2008). In this regime, the ecosystem is relatively stable and for some time retains its previous state, reacting to a significant toxic effect only by reducing the intensity of changes in production and destruction processes, which is manifested by the compression of the phase space limited by the limit cycle. After the exhaustion of the "reserve of stability" the bifurcation occurs, and the ecosystem shifted to another region of phase space.

The physical meaning of such differences in the behavior of ecosystems becomes clear if we consider the dimensions of the coordinates of the phase space. The abscissa axis R/P is the ratio of ecosystem destruction to its gross production, where R – destruction is defined as the energy spent by the ecosystem to maintain its own

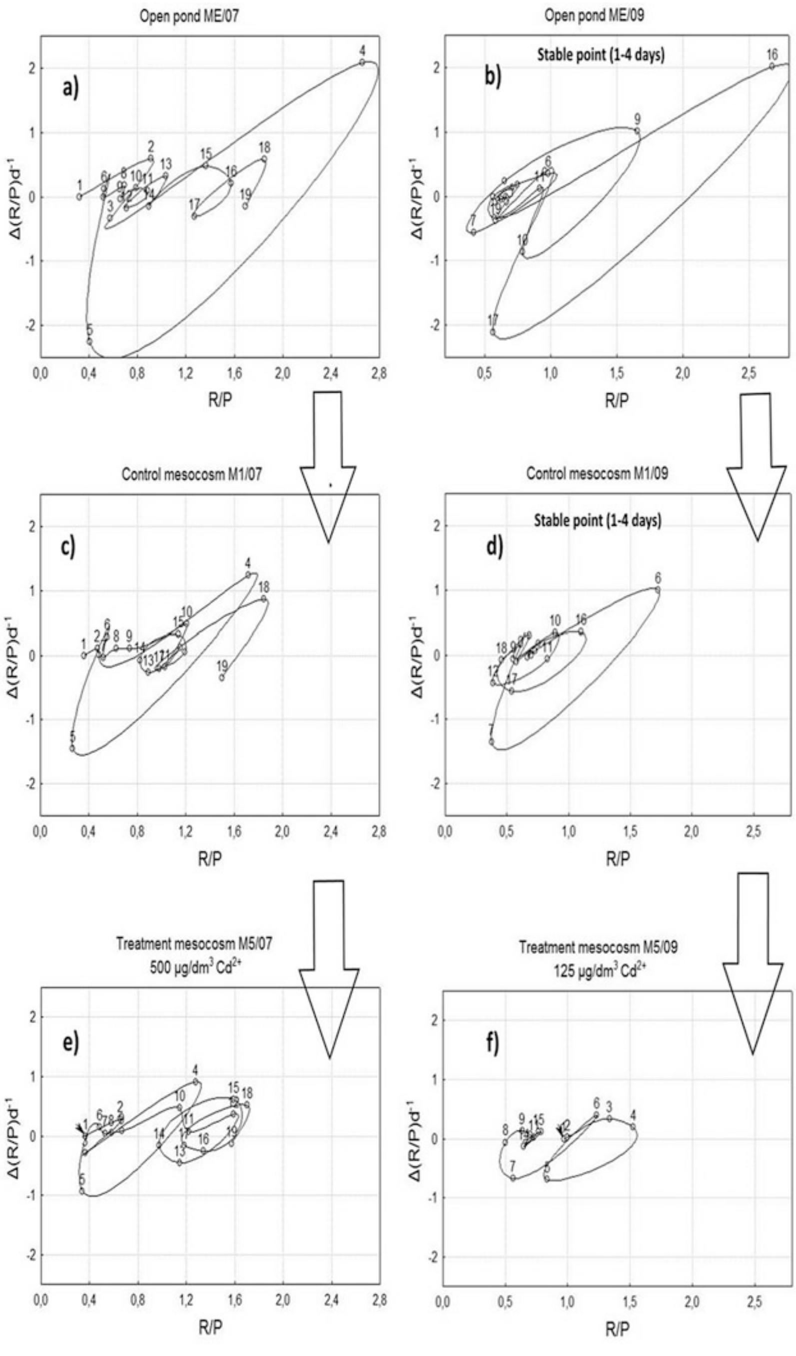

Fig. 4.6 The dependence of the ecosystem response on the regime of functioning at the time of impact: (**a**, **c**, **e**) – initial state is presented by the limit cycle; (**b**, **d**, **f**) – initial state is presented by stable point. The explanations are in the text

life for a certain period of time (in our case, per day) and has a dimension of Js^{-1}. P is the production of biomass photosynthesized at the same time, which can be expressed in both energy and mass units.

If these parameters are expressed in the same dimensions – energy units, then R/P is a dimensionless coefficient, convenient for comparative analysis, the physical meaning of which can be defined as the share of assimilated energy spent on the maintenance of life. If the products are expressed in units of mass, then we get the dimension R/P – $Js^{-1}/kgs^{-1} = Jkg^{-1}$, that is, the value, the physical meaning of which is the work done by the ecosystem to maintain the unit of biomass. The ordinate axis shows the change in R/P over time, that is, the rate of change of R/P. Accordingly, the dimension of the axis ordinate – Js^{-1} kg^{-1}, that is, work per unit time per unit of biomass, or ecosystem power per unit of biomass. The total value of $\Delta(R/P)\Delta t^{-1}$ can be considered as the specific power of the ecosystem, i.e. the work done per unit time to create and maintain a unit of biomass. Since we are talking about a living system and the main part of the destruction is the total respiration of hydrobionts, there is reason to call this parameter the specific metabolic power of the ecosystem. Note that the value of $\Delta(R/P)\Delta t^{-1}$ is thus identical to the dissipative function of the ecosystem.

The proposed interpretation of the results of modeling of aquatic ecosystems allows us to understand and explain why the reactions to the toxic effects of aquatic ecosystems characterized by different initial regimes are different. The initial modes differ quantitatively from each other in the size of the attractor, which, in turn, is determined by the value $\Delta(R/R)$ Δt^{-1}. At point (Fig. 4.6b) the ecosystem represented by this structure has a critically low, near-zero power. In other words, the initial structure of the model ecosystem does not have the necessary energy potential to resist external influence. Therefore, immediately after the impact occurs restructuring of the ecosystem, adapting it to new conditions. The restructured ecosystem is able to provide the necessary rate of energy inflow, i.e. power, for the further functioning of the ecosystem and its evolution to a state close to the initial level of the balance of destruction and production. In the limit cycle regime (Fig. 4.6a) the ecosystem, relatively speaking, has a sufficient reserve of power to maintain the existing structure for some time and to be kept in the same area of phase space, with the same balance ratio. Only after the exhaustion of this reserve ecosystem is rebuilt into a new structure corresponding to the new conditions of existence. Since structural adjustment requires additional energy expense, the parameters of the ecosystem in the first and in the second case are shifted to another area of the phase space.

Therefore, the dependence of the ecosystem response on the regime of functioning can be related to the potential of the ecosystem to mobilize the necessary level of power to preserve the balance of energy and matter existing at the time of impact. If the power level is lower than necessary, structural adjustments occur. Thus, it can be stated that the stability of ecosystems in relation to external, including toxic, effects is determined by the regime of functioning (state) of the ecosystem at the time of exposure, which, in turn, is quantitatively determined by the value of the specific metabolic power of the ecosystem. Thus, the specified parameter can serve as one of the indicators of the measure of stability of ecosystems to negative, including anthropogenic impacts.

It is extremely important in the applied aspect to identify the bifurcation points in the dynamics of ecosystems. It is known that in the vicinity of the bifurcation point dissipative systems are extremely sensitive to changes in control parameters and even a small fluctuation can lead to the destruction of the system and unpredictable changes in its evolution (Rozenberg et al. 2000). From this it can be concluded that even minor negative impacts on aquatic ecosystems during this period can lead to catastrophic consequences. "If the nature, as an essential characteristic, inherent instability, the person simply obliged to be more careful and sensitive to the world around him – at least because of the inability to clearly predict what will happen in the future."(Nicolis and Prigogine 2008).

The analysis of experimental data with the construction of two-dimensional dynamic phase space, allows to identify the steady state of the ecosystem, to characterize them as stable or unstable and to determine the critical points (bifurcation points) in the state of ecosystems. At the same time, the presence of self-intersections of phase trajectories, recorded in a number of graphs, shows that the two-dimensional dynamic phase space is not enough to fully describe the state of the ecosystem. In this regard, in some cases, the return of ecosystems to their initial state, may look as such in the two-dimensional projection of the n-dimensional process. In fact, between the initial and final states, most likely, there is a shift in the phase space along the missing axis. In fact, the analyzed time series seem to have a dimension greater than two. And, therefore, for a more accurate description of the state, it is necessary to use a phase space of greater dimension. Based on the topological characteristics of the phase trajectories, it can be assumed that it should be at least three-dimensional.

The two-dimensional dynamic phase space does not fully reflect the essential details of the state of ecosystems, in particular, it does not show of the dynamics of the absolute values of production and destruction. It is obvious that the same values of R/P can be obtained for different absolute values of R and P and thus belong to different states. To detail the description of the state of ecosystems and to establish differences in states with equal values of R/P, it is necessary to analyze them in the parametric phase space built on the axes P and R (Fig. 4.7a–d). The dynamics of the ecosystem state in this space is also depicted as phase trajectories. The time factor is reflected in these diagrams as a sequence of points.

In diagrams of the phase $R - P$ space, stationary states can be represented by cyclic closed trajectories (Fig. 4.7a–c) or relatively compact sections of trajectories in which both P and R parameters are meandered within a relatively stable region (Fig. 4.7d). The position of each area in the "destruction – production" space can be determined by a vector drawn from the origin to the geometric center of the area – a point having the average coordinates of the points of formation of the area. This $R - P$ vector can be proposed as one of the quantitative characteristics of the ecosystem state. One of the characteristics of the vector is the slope angle tangent, tgα, defined as the ratio R to P (R/P). The second indicator of the vector V_i – module

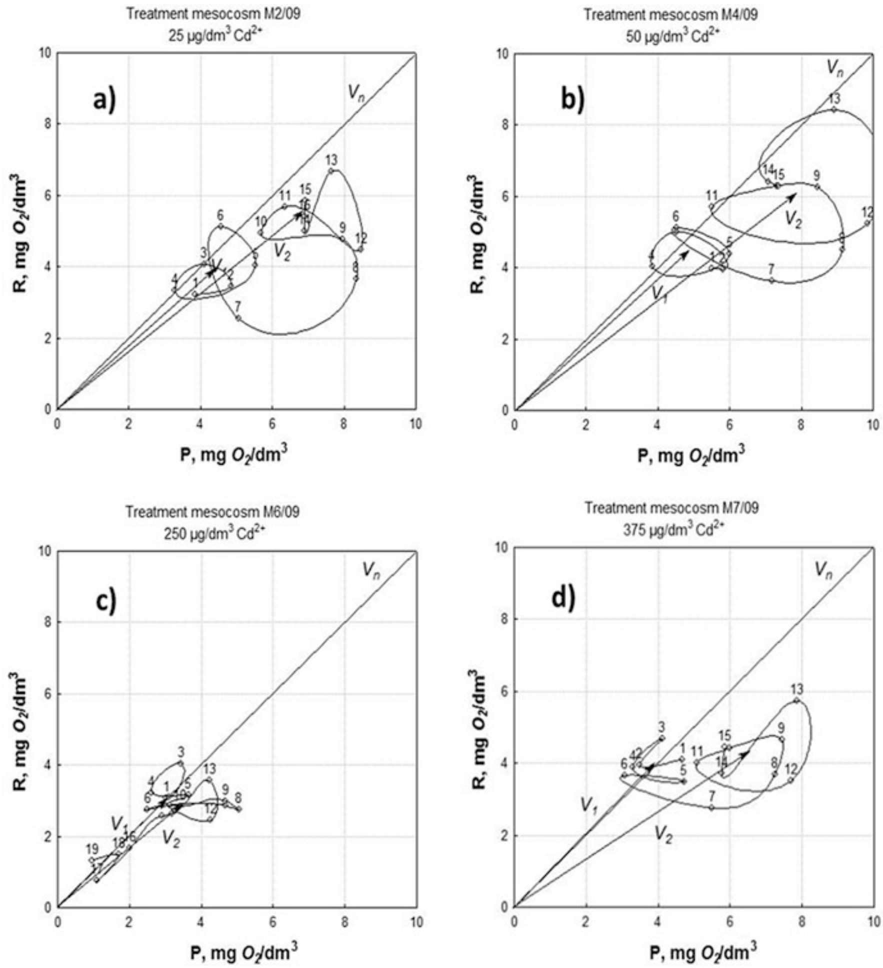

Fig. 4.7 Parametric phase portraits of the model ecosystems. (**a**) treatment mesocosm M2/09, 25 μg/dm^3 Cd^{2+}; (**b**) treatment mesocosm M4/09, 50 μg/dm^3 Cd^{2+}; (**c**) treatment mesocosm M6/09, 250 μg/dm^3 Cd^{2+}; (**d**) treatment mesocosm M7/09, 375 μg/dm^3 $Cd^{2+}$$V_1$, V_2 – vectors defining a location of the corresponding stationary area in phase $R - P$ space, V_n – vector of a "norm" ($R = P$). Digits at the trajectories indicate the days of R and P measurements

$|V_i|$ depends on the intensity of the processes of production and destruction. The vector module can be considered as one of the characteristics of the self-purification ability and stability of the ecosystem. The higher the value of the module, the more intense, all other things being equal (the structure of biological communities, the chemical composition of water, granulometric characteristics of suspended solids and sediments, hydrodynamic parameters), the processes of self-purification. Self-purification ability, which is considered in the aspect of participation of biota, has a significant impact on the overall stability of the ecosystem. A general analysis of all factors affecting sustainability indicates that sustainability, as the ability to maintain a state in response to external influences, including toxic ones, is higher the more at the moment of exposure to the ecosystem biomass and the rate of its production. In this case, a smaller proportion of the toxicant is accounted for by each individual of the populations forming the ecosystem, as well as a higher rate of binding and excretion of the toxicants included in one way or another in the biotic turnover.

Thus, through the use of the parametric phase plane, we obtain the third coordinate of the phase space-the vector module $|V_i|$, to describe the state of the ecosystem in three-dimensional phase space. Without mathematical calculations of the dimension of the phase trajectory of the processes under study, based on the obtained phase portraits (Figs. 4.8, and 4.9), it can be said that the three-dimensionality of the phase space is sufficient for the correct description of the evolution of the state of ecosystems. Parametric phase portraits are an essential complement of dynamic portraits and detail the condition of ecosystems. Thus, the dynamic phase portrait of an ecosystem with toxic load of 25 μg/dm^3 Cd^{2+} (Fig. 4.2b) is almost no different from the phase portrait of the mesocosm, which is made 50 μg/dm^3 Cd^{2+} (Fig. 4.2d). The similarity of dynamic phase portraits is

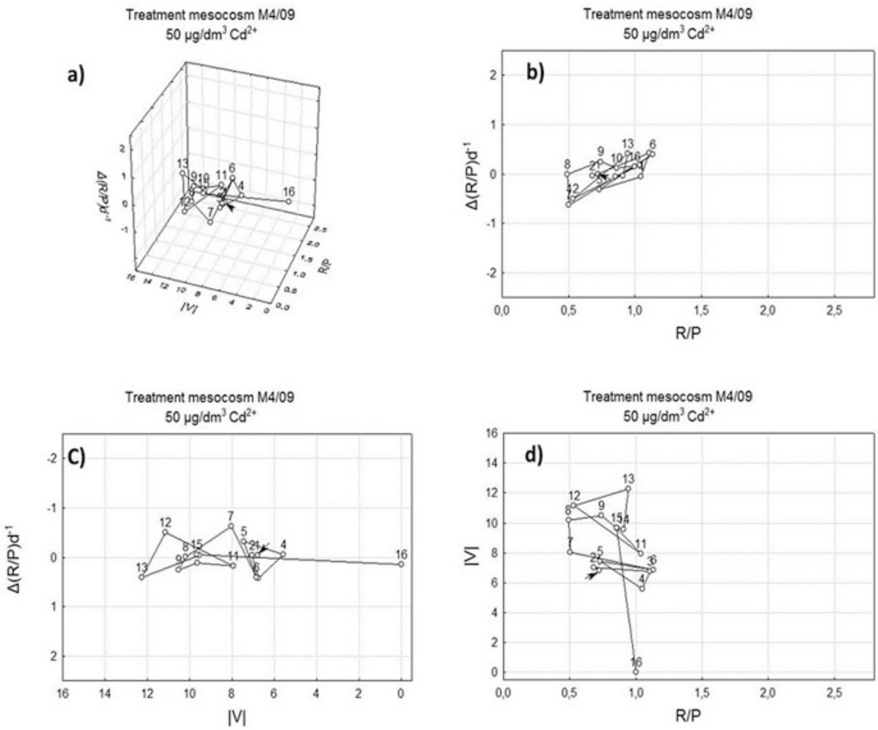

Fig. 4.8 The dynamics of M4/09 model ecosystem in three-dimensional phase space (**a**) and its projections (**b**-**d**) on the corresponding planes

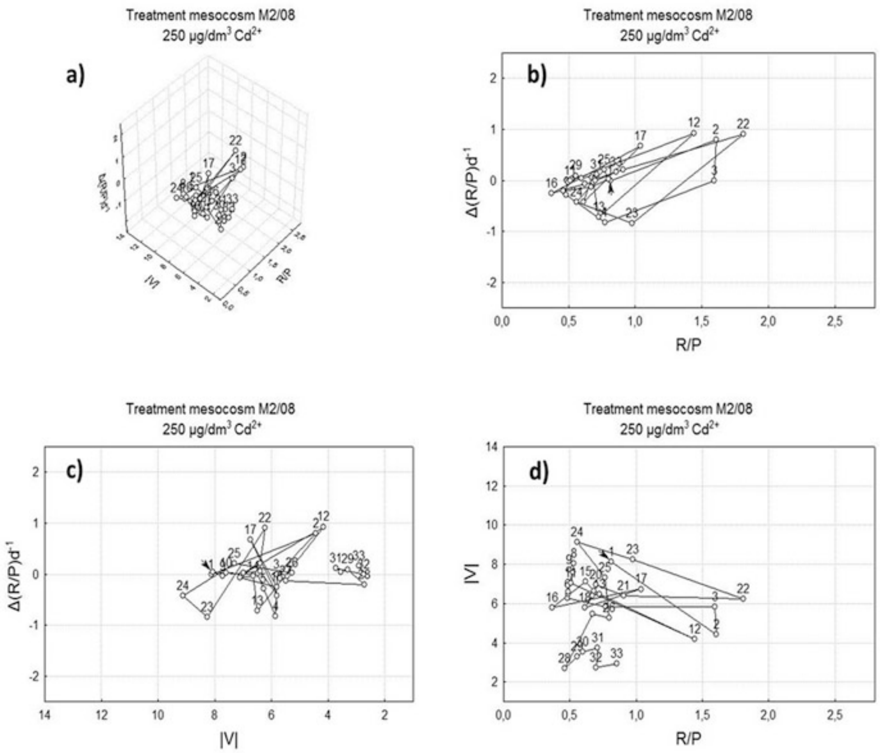

Fig. 4.9 The dynamics of M2/08 model ecosystem in three-dimensional phase space (**a**) and its projections (**b**-**d**) on the corresponding phase planes

also observed for mesocosms under the toxic effect of 250 μg/dm^3 and 375 μg / dm^3 Cd^{2+} (Fig. 4.2f, e). Parametric phase portraits of these mesocosms, as seen in the figures (Fig. 4.7a–d) have significant differences. The vector modules $|V_i|$ allow us to identify differences in states in cases where the values of R/P characterizing these states are equal or slightly different. Thus, after the impact on ecosystems of mesocosms by different concentrations of Cd^{2+} – 25 μg/dm^3, 50 μg/dm^3, 250 μg/dm^3, the state parameters were stabilized at the value of R/P equal to 0.8 (Fig. 4.2b, d, f). The modules of the vectors of $|V_2|$ and differed 8.8; 10; 4.5 the relevant options (Fig. 4.7a–c).

The analysis of phase trajectories in three–dimensional phase space significantly specifies the features of the dynamics of production and destruction processes in mesocosms. In Figs. 4.8 and 4.9, phase portraits of model ecosystems in three-dimensional phase space and their projections on the corresponding phase planes are presented. It is clearly seen that the return of ecosystems to their initial state appears to be such only in one projection – $\{\Delta(R/P)\Delta t^{-1} - R/P\}$. In the three-dimensional phase space there is a peculiar ecological hysteresis – shift of stationary areas along the $|V|$ axis. The trajectory shift along the $|V|$ axis is observed almost always during the transition of the ecosystem from one state to another.

Stationary states of ecosystems in three-dimensional phase space are represented by compact volume figures. The position of such a stationary region in the phase space can be determined by the state vector $\overline{\mathbf{H}}$, drawn from the origin to the geometric center of a three-dimensional figure. The coordinates of this center are equal to the average coordinates of the points forming a stationary figure. This vector can be used for formalized assessment of the state of ecosystems. But it is necessary to take into account that information reduction can lead to its loss. If the characteristics of the projections of phase portraits of water ecosystems on separate planes are amenable to unambiguous interpretation, the semantic content of the quantitative characteristics of the generalized vector $\overline{\mathbf{H}}$ requires further research.

Thus, based on the analysis of the behavior of ecosystems in three-dimensional phase space, it can be concluded that ecosystems after external influence tend to maintain the initial balance of production and destruction processes at different levels of intensity of these processes and, apparently, at different structural characteristics. In other words, changes in the biotic structure of the ecosystem and the intensity of production and destruction processes in response to changes in environmental conditions are aimed at maintaining the optimal balance of these processes in the new conditions.

4.4 Conclusion

Application of (8) for the evolution of the state of aquatic ecosystems in the analysis in three-dimensional space $\{\Delta(R/P)\text{day}^{-1} - R/P - |V|\}$ allows to identify the characteristic regimes of ecosystem functioning including stationary and non-stationary states, bifurcations, to fix the moment of transition of an ecosystem from one state to another, and to determine the parameters of the attractors and the limits of stability of water ecosystems.

The analysis of the behavior of ecosystems based on the dynamics of production and destruction processes in the proposed three-dimensional space allows us to draw the following conclusions:

- water ecosystems are inherent in the functioning with regular regime change not only under the influence of negative external factors, but also due to the processes of self-organization: stable regimes represented in the phase space by the appropriate attractor and characterized by minimum values of the rate of change of the ratio of destruction to production are interspersed with non-stationary regimes with an abrupt increase in the value of $\Delta(R/P)\Delta t^{-1}$;
- the transition of ecosystems from one state to another does not occur smoothly, but abruptly at bifurcation points with abrupt change in the direction of the phase trajectory, which allows to reliably separate one state from another, to fix the moment of transition and to determine the boundaries of stability;

- under the influence of external factors, the attractors are compressed in the case of preservation of the structure of ecosystems that existed at the time of exposure, the density of the attractor is higher, the greater the magnitude of the impact; in case of exceeding the level of exposure above a critical value and forming a new structure – attractors are formed in another region of the phase space, the size of the attractor may increase;
- the sustainability of aquatic ecosystems to external impacts depends not only on the strength and frequency of impacts, but also on the state (regime of functioning) of ecosystems at the time of impacts;
- the analysis of the differences in the reactions of aquatic ecosystems to different impact scenarios allowed to establish the range of values obtained from (8) not only as a criterion for the evolution of the state of aquatic ecosystems, but also presented as the specific metabolic power can be considered as a measure of the stability of aquatic ecosystems to negative impacts.

Thus, the proposed approach can serve as a methodological basis for assessing the level of permissible impacts on water ecosystems and regulating the operation of water bodies.

References

Anishchenko VS (1990) Slozhnyye kolebaniya v prostykh sistemakh: mekhanizmy vozniknoveniya. struktura i svoystva dinamicheskogo khaosa v radiofizicheskikh sistemakh (Complex oscillations in simple systems: mechanisms of occurrence, structure and properties of dynamic chaos in radiophysical systems). Nauka, Moskva

Beckman IN (2009) Informatika Kurs lektsiy. Moskva – Rim. Lektsiya 22. Informatsiya i khaos (Computer science lecture Course. Moscow – Rome. Lecture 22 Information and chaos) http://profbecman.narod.ru/InformLekc.htm

Buck P (2013) Kak rabotayet priroda: Teoriya samorganizovannoy kritichnosti (How nature works: the science of self-organized criticality). URSS, Moskva

Fedorov VD (1977) Problema otsenki normy i patologii sostoyaniya ekosistem v Nauchnyye osnovy kontrolya kachestva poverkhnostnykh vod po gidrobiologicheskim pokazatelyam. Trudy Sovetsko – Angliyskogo seminara. (Problem of evaluation of norm and pathology state of the ecosystems. Scientific basis of quality control of surface waters according to hydrobiological indicators). Gidrometeoizdat, Leningrad

Fonseca JC, Marques JC, Paiva AA, Freitas AM, Madeira VMC, Jørgensen SE (2000) Nuclear DNA in the determination of weighing factors to estimate exergy from organisms biomass. Ecol Model 126:179–189

Fursova PV, Levich AP, Alekseev VL (2003) Ekstremalnyye printsipy v matematicheskoy biologii Uspekhi sovremennoy biologii (Extreme principles in mathematical biology). Succes Mod Biol 123(2):115–137

Gaponov-Grekhov AV, Rabinovich MI (1981) Khaoticheskaya dinamika prostykh sistem (Chaotic dynamics of simple systems). Priroda 2:54–65

Glensdorf P, Prigogine I (1973) Termodinamicheskaya teoriya struktury, ustoychivosti i fluktuatsiy (Thermodynamic theory of structure, stability and fluctuations). Mir, Moskva

Grimm V, Wissel C (1997) Babel, or the ecological stability discussion: an inventory and analysis of terminology and a guide for avoiding confusion. Oecologia 109:323–334

Jørgensen SE (1999) State-of-the-art of ecological modelling with emphasis on development of structural dynamic models. Ecol Model 120:75–96
Jørgensen SE, Mejer HF (1979) A holistic approach to environmental modeling. Ecol Model 7:169–189
Jørgensen SE, Svirezhev YM (2004) Towards a thermodynamic theory for ecological systems. Elsevier, Oxford
Jørgensen SE, Nielsen SN, Mejer H (1995) Emergy, environ, exergy and ecological modelling. Ecol Model 77:99–109
Jørgensen SE, Mejer H, Nielsen SN (1998) Ecosystem as self-organizing critical systems. Ecol Model 111:261–268
Jørgensen SE, Ladegaard N, Debeljak M, Marques JC (2005) Calculations of exergy for organisms. Ecol Model 185:165–175
Jørgensen SE, Ludovisi A, Nielsen SN (2010) The free energy and information embodied in the amino acid chains of organisms. Ecol Model 221:2388–2392
Khaiter PA, Erechtchoukova MG (2009) The concept of sustainability in mathematics, biology, ecology and environmental sustainability. In: 18th world Congress IMACS/MODSIM, Cairns, Australia http://mssanz.org.au/modsim09
Klimontovich YL (1996) Vvedeniye v fiziku otkrytykh system (Introduction to the physics of open systems). Sorosovskiy obrazovatelnyy zhurnal 8:109–116
Knyazeva EN, Kurdyumov SP (1994) Zakony evolyutsii i samoorganizatsii slozhnykh sistem (Laws of evolution and self-organization of complex systems). Nauka, Moskva
Kondratyev KY, Losev KC, Ananicheva MD, Chesnokhova IV (2003) Estestvennonauchnyye osnovy ustoychivosti zhizni (Natural science foundations of life stability). TS AGO, Moskva
Loskutov AY, Mikhailov AS (1990) Vvedeniye v sinergetiku (Introduction to synergetics). Nauka, Moskva
Ludovisi A (2009) Exergy *vs* information in ecological successions: interpreting community changes by a classical thermodynamic approach. Ecol Model 220:1566–1577
Ludovisi A (2014) Effectiveness of entropy-based functions in the analysis of ecosystem state and development. Ecol Indic 36:617–623
Ludovisi A, Jørgensen SE (2009) Comparison of exergy found by a classical thermodynamic approach and by the use of the information stored in the genome. Ecol Model 220:1897–1903
Malinetskiy GG, Potapov AB (2009) Nelineynaya dinamika i khaos: Osnovnyye ponyatiya (Nonlinear dynamics and chaos: basic concepts). Komkniga, Moskva
Margaleff R (1992) Oblik biosfery (the appearance of the biosphere). Nauka, Moskva
Marques JC, Pardal MA, Nielsen SN, Jørgensen SE (1997) Analysis of the properties of exergy and biodiversity along the estuary gradient of eutrophication. Ecol Model 102:155–167
Marquez JC, Nielsen SN, Portal MA, Jørgensen SE (2003) Impact of eutrophication and river management in the framework of ecosystem theories. Ecol Model 166:147–168
Moiseyev NN (1987) Algoritmy razvitiya (Development algorithms). Nauka, Moskva
Nicolis G, Prigogine I (2008) Poznaniye slozhnogo (Exploring complexity). LKI, Moskva
Odum HT (1988) Self-organization, transformation, and information. Science 242:1132–1139
Odum HT, Pinkerton RC (1955) Time's speed regulator: the optimum efficiency for maximum power output in physical and biological systems. Am Sci 43:331–343
Opritov VA (1999) Entropiya biosystem (Entropy of biological systems). Sorosovskyi obrazovatyelnyi zhurnal 6:33–38
Patten BC (1995) Network integration of ecological extremal principles: exergy, emergy, power, ascendency and indirect effects. Ecol Model 79:75–84
Pechurkin NS (1982) Energeticheskiye aspekty razvitiya nadorganizmennykh sistem (Energetic aspects of development at the systems). Nauka, Novosibirsk
Pechurkin NS (1988) Energiya i zhizn (Energy and life). Nauka, Novosibirsk
Prigogine I, Stengers I (1986) Poryadok iz khaosa. Novyy dialog cheloveka s prirodoy (Order from chaos. A new dialogue between man and nature). Progress, Moscow
Ray S (2006) Extreme principles with special emphasis on exergy and ascendency – the modern approach in theoretical ecology. J Biol Syst 14(2):255–273

Riznichenko GY (2003) Lektsii po matematicheskim modelyam v biologii (Lectures on mathematical models in biology). NITs Regulyarnaya i khaoticheskaya dinamika, Izhevsk
Riznichenko GY, Rubin AB (2004) Biofizicheskaya dinamika produktsionyh protsesov (Biophysical dynamics of production processes). Institute of computer research, Moskva-Izhevsk
Rosen R (1976) Printsip optimalnosti v biologii (The principle of optimality in biology). Nauka, Moskva
Rozenberg GS, Mozgovoy DP, Gelashvili DB (2000) Ekologiya. Elementy teoreticheskikh konstruktsiy sovremennoy ekologii (Ecology. The elements of the theoretical structures of modern ecology). Samarskiy nauchnyy tsentr RAN, Samara
Rukovodstvo po gidrobiologicheskomu monitoringu presnovodnykh ekosistem (1992) (Guidebook on hydrobiological monitoring of freshwater ecosystems). Gidrometeoizdat, Sankt-Peterburg
Rybin IA (1990) Lektsii po biofizike (Lectures in biophysics). Publishing House of the Ural University Sverdlovsk
Silow EA, Mokry AV (2010) Exergy as a tool for ecosystem health assessment. Entropy 12:902–925. https://doi.org/10.3390/e12040902
Svirezhev YM, Logofet DO (1978) Ustoychivost biologicheskikh soobshchestv (Stability of biological communities). Nauka, Moskva
Trofimchuk MM, Sukhorukov BL, Bakayeva EN (2010) Fazovyye portrety vodnykh obyektov pri naturnom modelirovanii ekosistemnykh protsessov (Phase portraits of water objects in full-scale modeling of ecosystem processes). Vestnik Yuzhnogo Nauchnogo Tsentra RAN 2:28–37
Trubetskov DI (2010) Vvedenie d sinepgetiku: Khaos i struktury (Introduction to sinergetic: Chaos and structures). Editorial URSS, Moskva
Ulanowicz RE (1986) Growth and development: ecosystems phenomenology. Springer, New York
Ulanowicz RE, Jørgensen SE, Fath BD (2006) Exergy, information and aggradation: an ecosystems reconciliation. Ecol Model 198:520–524
Washida T (1995) Ecosystem configurations consequent on the maximum respiration hypothesis. Ecol Model 78:173–193
Yugay GA (1985) Obshchaya teoriya zhizni (General theory of life). Mysl, Moskva
Zhang J, Jørgensen SE, Tan CO, Beklioglu M (2003) Structural-dynamic modeling – Lake Mogan, Turkey as case study. Environ Model 164:103–120
Zhang J, Gurkan Z, Jørgensen SE (2010) Application of eco-exergy for assessment of ecosystem health and development of structurally dynamic models. Ecol Model 221:693–702
Zotin AI (1980) Termodinamika i kinetika biologicheskikh protsessov (Thermodynamics and kinetics of biological processes). Nauka, Moskva
Zotin AI (1982) Termodinamika stareniya. Biologiya stareniya. (Rukovodstvo po fiziologii) (Thermodynamics of aging in biology of aging (Handbook of physiology). Nauka, Leningrad
Zotin AI, Zotin AA (1999) Napravleniye, skorost i mekhanizmy progressivnoy evolyutsii (Direction, rate and mechanisms of progressive evolution). Nauka, Moskva
Zotin AI, Zotina RS (1987) Termodinamicheskiye kriterii ustoychivosti i nadezhnosti biologicheskikh sistem i protsessov razvitiya v Nadezhnost i gomeostaz biologicheskikh sistem (Thermodynamic criteria of the stability and reliability of biological systems and processes development in Reliability and homeostasis of biological systems). Naukova dumka, Kiyev

Part II
Promoting Sustainability Through Policies

Chapter 5
Balancing Sustainable Coastal Management with Development in New Zealand

Ashton Eaves, Paul Kench, Garry McDonald, and Mark Dickson

Abstract Historically in New Zealand, coastal environments were viewed as amenities for subdivision to be incorporated into town structure plans with little regard for hazards and scientific investigation. This subdivision of coastal land has led to the proliferation of developments that are increasingly vulnerable to the slow landward creep of sea level rise and increasing extreme storm events. Planning and management of vulnerable coastal communities and infrastructure could benefit from an emphasis on sustainable and resilient adaptation through managed retreat away from coastal hazards. However, it is not at all clear exactly how managed retreat can be accomplished. This chapter explores methods for analysing the interactions and manifestations of complex intersecting environmental and economic systems that are implicit in a managed retreat from coastal hazards. These complex systems can be quantifiably analysed using the principles of evolutionary economics, which enables identification of knowledge structures and information flows that can inform institutional decision-making and planning. The chapter aims to explore how policy planning, implemented through the lens of evolutionary economics, can inform sustainable land-use management and development through managed retreat in the coastal environment. It discusses Systems Thinking

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approaches to aid the decision-making process in order to reveal effective policy outcomes and financial mechanisms that enable resilient coastal management. Specific consideration is given to System Dynamics modelling, economic impact analysis and Robust Decision Making.

Keywords Managed retreat · Evolutionary economics · Coastal hazards · System Dynamics · Climate change

5.1 Introduction

New Zealand is a developed island nation where sea level rise and increasing storm events will affect its inhabitants more severely than larger and more affluent countries given its geographical location and extent. There is also a significant proportion of vulnerable assets at the coast when compared to total national capital (NIWA 2015). This makes it a good case study for other nation states to learn practical steps to enable managed retreat given the increasing risk from coastal hazards.

Coastal hazard planning in New Zealand has historically been decentralised, ad hoc and risk mitigation is largely achieved through the use of physical structures or modifications of building standards to protect vulnerable assets (Kirk et al. 1999). Relocating assets away from hazards has been employed only as a last resort after repeated failure of technical fixes (Waikato Regional Council 2006). To date, there have only been a few small-scale attempts at coastal relocation in New Zealand. For instance, between 1962 and 1965 at Mokau Spit, Waikato, eleven sections were revested with the crown following coastal erosion with compensation to property owners (Waikato Regional Council 2006). Similarly, between 1965 and 1975 at Ohiwa Spit in the Bay of Plenty, houses were lost to the sea, titles were revested with the Crown and compensation paid for residents to relocate (Waikato Regional Council 2006). In contrast to 'forced' relocation after disaster, there is increasing recognition internationally that managed retreat from coastal hazards will be necessary to minimise risk for communities and provide a resilient future for society (Dyckman et al. 2014; Freudenberg et al. 2016; Hino et al. 2017; Reisinger et al. 2015).

Managed retreat at the coast is a proactive, strategic and long-term management approach to eliminate exposure to the human-use system by migrating exposed assets, or vulnerable communities, inland due to threats posed by rising sea levels, coastal erosion and flooding (Reisinger et al. 2015). Managed retreat is an evolving process that demands a set of adaptive strategies over time as a single solution alone will not suffice (Owen et al. 2018). However, managed retreat is not without its issues: (1) it is currently constrained by a lack of knowledge of what it exactly is, otherwise known as a 'black box', (2) there is uncertainty around its implementation by government and communities, which exacerbates opposition to it, and (3) funding mechanisms for the large capital and labour costs of managed retreat do not currently exist in New Zealand (Boston 2017; Owen et al. 2018). Financial compensation is often not available and managed retreat can also be stifled by urban boundaries that concentrate development into allowable zones (Freudenberg et al. 2016). Currently retreat from areas prone to natural hazards occurs as a reactive approach to restore order to society after a disaster (Ryan 2018).

Insights from New Zealand have shown that the implementation of managed retreat will require scientifically informed decision-making on changes to the environmental system (New Zealand Government 2017), defining the extent of coastal vulnerability (New Zealand Government 2017), discovering the long-term stakeholder and community desires and expectations through co-creation (Kench et al. 2018), long-term land-use planning and financial incentives for relocation (Tombs and France-Hudson 2018). Modelling the economic impact of managed retreat through examining probable futures and policy implementations can enable scenarios for a smooth transition to resilience for populations exposed to coastal hazards. Modelled economic drivers can then provide insights into how a successful implementation of managed retreat to support hazard management would evolve. Economic drivers may include changes in business operability, value added, capital value or investment, land supply or household wealth. Whereas compensation arrangements, insurability or property taxes can also drive behavioural change (Storey et al. 2017; Tombs and France-Hudson 2018).

An analytical framework is required to assess plans through economic impact modelling of future scenarios and policy outcomes with regard to these economic drivers. This analytical framework consists of a theoretical framework derived through evolutionary economics, and a conceptual framework using System Dynamics. Evolutionary economics is analogous to that of evolutionary biology, it considers economic systems as dynamic, that they reflect historical process, and that they exhibit instinctual and habit-based behaviour (Schumpeter 1912; Veblen 1899). System Dynamics is an ontology of Systems Thinking that interprets how physical and social systems behave through modelling multi-loop nonlinear feedbacks in complex systems (Forrester 1971). Evolutionary economics considers the economic system as knowledge-based with stocks of knowledge and flows of information (Foster and Hölzl 2004). Similarly, System Dynamics facilitates knowledge creation on the drivers of change by adjusting the quantity of stocks in the system through flows between influential variables over time (Ruth and Hannon 2012). System Dynamics analysis leads to an understanding of behavioural drivers of complex systems at an aggregated level which is fundamental to evolutionary economics. System Dynamics can inform stakeholders about the possible impacts of the transition dynamics that they will pass through when implementing managed retreat. Combining this with models based on evolutionary economic theory enables us to better understand the economic consequences of coastal management and development decisions, recognising that economic considerations are a key component of decision-making.

This chapter reviews a process to enable managed retreat from coastal hazards through evolutionary economics and System Dynamics within a context of coastal management in New Zealand. Section 5.2 outlines how legislation has shaped the coastal environment. Section 5.3 addresses the evolving risk and exposure from a changing climate. Section 5.4 explores the contribution that evolutionary economics can bring to the planning regime. Finally, Sects. 5.5 and 5.6 discuss possible approaches to enable managed retreat through financing and planning implementations.

5.2 Legislating New Zealand's Coast

Coastal land-use planning in New Zealand is primarily governed by the statutory documents of the Resource Management Act 1991 (RMA 1991) and the New Zealand Coastal Policy Statement 2010 (NZCPS 2010). Previously, it was under the influence of the Town and Country Planning Act (TACPA). Other legislation that influences the coastal zone includes the Local Government Act 2002 (LGA 2002), the Public Works Act 1981 (PWA 1981) and the Civil Defense and Emergency Management Act 2002 (CDEMA 2002). However, these statutory legislative acts are not well integrated and operate under differing time frames (Boston and Lawrence 2017). Table 5.1 summarises coastal legislation over the past half-century.

Many vulnerable coastal developments in New Zealand were authorised under the TACPA 1953. They were established for their proximity to coastal amenities and leisure, often with a lack of robust environmental assessment. Part 1 of the TACPA 1953 required the preparation of regional planning schemes with an accompanying survey of natural resources and their potential uses and values for conservation and economic development. The approach employed a static use of planning instruments through structure plans and focused on lands as economic 'resources' that contributed to the expansion of residential development into the coastal environment. There was little regard for hazard identification or scientific investigation in zoning, which led to the incorporation of coastal environments into structure plans. For instance, at Omaha Beach (Rodney District) the sand spit was developed for housing with a marginal seawall in 1971 (Omaha Beach Community Inc 2017). A large storm in 1978 destroyed this seawall. Groynes were subsequently constructed and beach nourishment undertaken by developers to gain further land-use consent at the end of the spit and protect homes from storms (Omaha Beach Community Inc 2017; Peart 2009). The TACPA 1977 amended this issue by introducing regulatory zoning and allowed for the identification of areas vulnerable to natural hazards (de Lange 2006). These historical planning regimes were less focussed on coastal hazards and sea level rise and more so on the subdivision of farmland, maintaining amenity values and preserving access to the coast (Peart 2009).

Currently, the RMA 1991 is the foundation legislation in New Zealand for land-use and development. It provides authorities with an assessment of environmental effects from the applicant before resource consent is given. Land-use consents are granted based on the premise that any adverse effects are mitigated, and that appropriate scientific inquiry is undertaken to reveal less than minor hazard

Table 5.1 Historical and contemporary coastal legislation in New Zealand

Act	Timeframe	Purpose	Comments
Town And Country Planning Act (TACPA)	1953–1977	State-centred spatial resource planning.	The utility of natural resources dominates. Extensive subdivision and structural development at the coast. Many devolved councils and boards with minimal interaction.
Town And Country Planning Act (TACPA)	1977–1991	Amended original act.	Introduced regulatory zoning for hazards. A new emphasis on scientific investigation.
Resource Management Act (RMA)	1991-	Effects-based resource planning and management. Preservation of environments from inappropriate development while maintaining public access and ecosystems. Implicitly applies the precautionary principle. Legislatively enables the NZCPS.	Assessment of environmental effects dominates. Good policy, poor implementation due to stakeholder contestation.
New Zealand Coastal Policy Statement (NZCPS)	1994 & 2010-	Identify coastal hazards for 100 years. Assess the risks of climate change on new and existing development. Allow for the amenity and natural character of the coast.	Historically ambiguous to local government.
Local Government Act (LGA)	2002-	Provide infrastructure. Land-use plans at the annual and decadal interval with public consultation. Building control. Meet the needs of future generations through the provision of services, roads and access.	
Public Works Act (PWA)	1981-	Provision of infrastructure. Allowance for the compulsory acquisition of land for public areas and infrastructure. Long-term planning; usually through cost-benefit analysis.	Could be useful for the provision of ecosystems and amenity values. Provides for the maintenance and protection of roads at the coast.
Civil Defence and Emergency Management Act (CDEMA)	2002-	Provision for emergency powers during a disaster. Enables the centralisation of power. Provides for the allocation of emergency funding and resources.	A reactive approach to hazard management. Provides effective short-term responses in emergencies by overriding normal legislative barriers. Lack of long-term planning.

exposure. However, development can proliferate on hazardous land under the proviso that any adverse effect is remedied, even if adverse effects are complex in time and space, or beyond quantification (Komar 2009). Developers may provide evidence only on straight-forward technical solutions, and presiding commissioners may accept these simplistic worldviews over alternative complex, high uncertainty worldviews (Komar 2009) as in the case at Omaha Beach. These single consent decisions may also be flawed in the sense that they consider one proposal with a fixed set of outcomes rather than robustly examining cascading drivers and the temporal variability of hazards.

The decision-making process around land-use planning by governments often results from balancing the environmental, social and economic costs of resource allocations within an adversarial legal setting of competing stakeholders until a consensus is reached (Gibbs 2015) or a ruling made. When local government seeks to implement planning rules to manage sea level rise, it can be challenged by development interests, and the Environment Court then evaluates between competing interests (Campbell 2017). This approach to land-use planning through ad hoc mediated outcomes by the weighting of incomplete information to enable zoning changes for managed retreat becomes cumbersome and litigious. For example, in *Foreworld Developments v Napier City Council* [1998] 5 ELRNZ69 zoning changes consistent with adaptation to coastal hazards were imposed by Napier City Council on a resource consent applied for by Foreworld Developments which were counteracted with mitigation measures. Napier City Council imposed the principle of managed retreat through s106 of the RMA 1991 on new coastal development: a requirement for mitigating adverse effects through the vesting of vulnerable land with the council because of their liability given future coastal hazards. Donating land was not palatable for Foreworld, and therefore inundation mitigation measures to protect the development were put forward by Foreworld to maintain the spatial extent which was subsequently accepted by the Environment Court based on information supplied by the applicant (Foreworld Developments Ltd v Napier City Council 1998).

5.3 Evolving Risk and Hazard Exposure Due to a Changing Climate

Governments in New Zealand are often focussed on relatively short-term issues (Boston 2017). By contrast, the dynamics of climate change require that we focus on coastal hazards over decades as a result of the slow creep of sea level rise and changing intensity and frequency of extreme storms (IPCC 2014b; Komar et al. 2013; Williams and Micallef 2009). This dichotomy is exacerbated by temporal unpredictability in societal uses and values in the coastal environment that influence trade-offs between conservation and development (Kwakkel et al. 2015). Consequently, there is an urgent need to develop methods that allow government planning and decision making to occur over timeframes reflective of the diverse impacts that will be experienced at the coast (New Zealand Government 2017) and their flow-on effects to the wider economic system.

At the national scale, an assessment of vulnerability in New Zealand identified 9000 properties within 0.5 m of mean high water springs that can be directly impacted by coastal inundation (Parliamentary Commissioner for the Environment 2015). The estimated total building replacement cost of at-risk structures is NZD$19.3B (2011) for the 0–1.5 m elevation zone (NIWA 2015).[1] Insured losses for extreme weather events were NZD$240 M in 2017 from 25,000 claims of homes and businesses (Insurance Council of New Zealand 2018).[2] In the last decade, annual costs of repairing weather-related damages to land transport networks have increased from NZD$20 to NZD$90 M (Boston and Lawrence, 2017). Static, cost-based methods such as these are useful, but likely underestimate vulnerability as they do not consider how disruptions to markets influence the socio-economic systems, account for spillover trade effects or account for price changes due to changes in supply and demand that may impact an economy (Sugiyama et al. 2008). At the close of 2018, New Zealand has experienced 2 years in a row of the three most expensive years on record for insurance claims in history indicating the increasing frequency and intensity of storms (Radio New Zealand 2018). The impact of repeated disruption to the economy from flooding needs further exploration as they are one of the catalysts for social change (Okada et al. 2014). Therefore, these direct impacts from coastal hazards are exacerbated by the influence of indirect flow-on impacts (here referred to as 'higher-order impacts'). Integrating these higher-order impacts into the economic analysis of coastal vulnerability provides a more robust understanding of system tolerance, thresholds and feedbacks to hazards. Higher-order impacts are not considered deeply in the current approach to coastal vulnerability assessment in New Zealand which recommends estimating the loss in value-added and the loss of income (Reese and Ramsay 2010). To date, higher-order impacts have been derived statistically from the Annual Enterprise Survey for industries and sectors published by Statistics New Zealand (Reese and Ramsay 2010).

Both direct and higher-order economic impacts can be modelled through Systems Dynamics (McDonald et al. 2018; Smith et al. 2016). Hughes et al. (2017) describe how positive system feedbacks associated with higher-order impacts can precipitate a threshold response that can lead to a flow-on cyclical effect, hysteresis, or produce a catastrophic system collapse. Alternatively, they note that multiple weak feedbacks that act simultaneously may induce a regime shift. Figure 5.1, a causal loop diagram, provides an example of system drivers in the coastal environment and the associated reinforcing (positive) and balancing (negative) feedbacks. Many critical relationships exist between the environmental and economic systems. The relationships of concern are the reinforcing feedback loops that de-stabilise the complex system

[1]NZD$1 = US$0.83 as at 31 March 2011 (Reserve Bank of New Zealand, 2018).
[2]NZD$1 = US$0.69 as at 31 March 2017 (Reserve Bank of New Zealand, 2018).

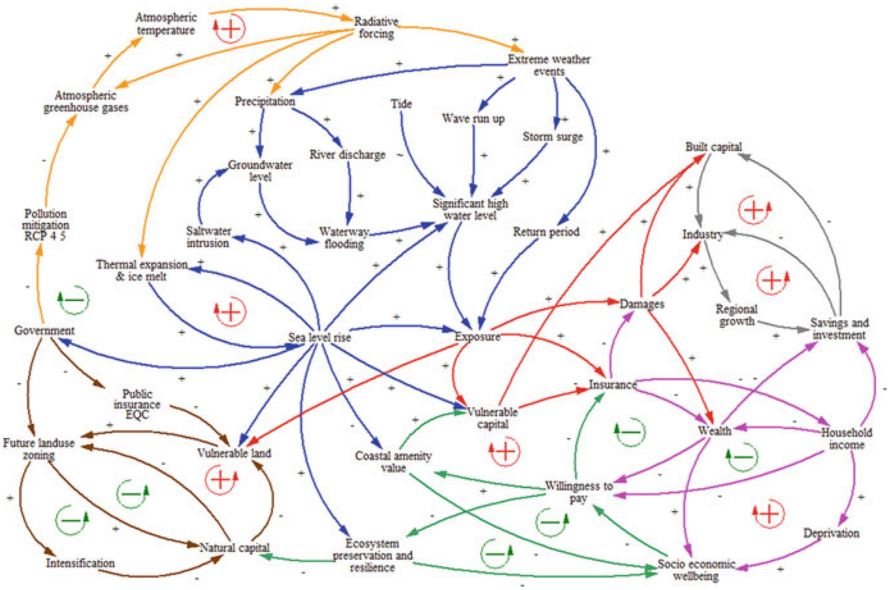

Fig. 5.1 The causal loop diagram illustrating the influencing variables within the environmental and economic systems and where there are reinforcing (positive) or balancing (negative) feedbacks. Climate change exacerbates reinforcing system feedbacks within the environmental system that can spill over into the socio-economic system. Resilience aims to moderate reinforcing system feedbacks by enabling sustainable balancing feedback loops

(Ford 2010). For example in Fig. 5.1, exposure to sea level rise creates vulnerable capital which in turn increases the insurance premium on that capital. Household income is then diminished, which reduces society's willingness to pay for coastal amenity values. A lower willingness to pay leads to a further reduction in the value of vulnerable capital through reduced demand. This example demonstrates how evolutionary economic analyses, supported with Systems Dynamics modelling, can help identify and potentially reduce, through effective policy intervention, system drivers of threshold-crossing reinforcing feedbacks and promote drivers that stimulate social change toward sustainability (Hughes et al. 2017).

The following sections will now address how society can move forward by developing and implementing long-term resilient policies and plans that enable dynamic adaptation in the form of managed retreat through evolutionary economic analysis.

5.4 Economic Planning in Systems Adapting to Knowledge and Information

Globally, adaptation to climate change is one of the least explored areas of climate economics when compared with the economics of mitigation, risk analysis or impact assessments (Burke et al. 2016). There are currently few techniques available describing how to incorporate inundation damage functions into adaptation (Burke et al. 2016). Most analyses of adaptation options have followed traditional approaches that emphasise market solutions, efficiency and cost-benefit analysis (CBA) (IPCC 2014b). It is now prudent to consider risks, inequalities, behavioural biases, non-market and non-monetary measures, limits and barriers, and ancillary costs and benefits (IPCC 2014b) over the long-term. The current approach in New Zealand to socio-economic decision-making typically utilises a mixture of econometric, CBA, multi-criteria analysis, real options analysis and economic impact modelling (e.g. Input-Output Analysis, Computable General Equilibrium) (Infometrics Consulting Limited 2017; Maven Consulting Ltd 2017; Tonkin and Taylor 2017), whereas fiscal impact analysis is popular in the USA (Freudenberg et al. 2016). These techniques are generally focused on the short-term or capture dynamics poorly through time. Economic assessments that are based on CBA do not typically assess wider environmental and social issues (Losada and Diaz-Simal 2014) and have no accepted institutional mechanism for assessing who pays for adaptation (Tonkin and Taylor 2017).

Traditionally in many developed countries, environmental policy theory has been based on applying neo-classical welfare theory to adaptation options, which strives to maximise welfare through a competitive equilibrium (van den Bergh 2004). This neo-classical economic theory of the utility maximisation of stakeholders is borne out of the microeconomic analysis of preferential consumption (Mas-Colell et al. 1995). Therefore, the neo-classical general equilibrium approach applies demand-supply relationships to estimate price changes through market redistribution based on rational responses (Sugiyama et al. 2008). It seeks to derive where the equilibrium is located rather than where it is tending toward or deviating to (Nelson and Winter 2002). This approach fails to accommodate the behavioural response (Sugiyama et al. 2008), or a dynamic equilibrium (Nelson and Winter 2002). Both of which are useful for long-term planning for managed retreat. Evolutionary economics can fulfil this role given its aggregated population approach to accommodate behaviour and its evolutionary tendencies which are driven by the systemic change brought on by continual economic development (Foster and Hölzl 2004). It can also assess the economic effects on society of various funding options for managed retreat. Box 5.1 provides an overview of evolutionary economics as an analytical tool for adaptive coastal management.

Box 5.1. Evolutionary Economic Analysis
Evolutionary economics provides a useful analytical framework for adaptive coastal management. Foster and Hölzl (2004) recognise three fundamental principles of evolutionary economics: (1) economic systems are knowledge-based systems in which knowledge and information are represented as stocks and flows; (2) it adopts an aggregated population approach based on behavioural variation instead of a typological approach based on representative agents; and (3) inertia, selection and development are the primary drivers of systemic change which enables a dynamic equilibrium.

Evolutionary economics has been compared to ecological economics and environmental economics (Christensen 1989; Rosser 2011; van den Bergh 2004). It is similar in spirit to ecological economics, as both are concerned with sustainable economic development (Van Den Bergh (2004), but it differs from environmental economics, which focuses on natural resource management and managing environmental externalities (Munda 1997).

Evolutionary economists view the economy as a domain characterised by dynamic equilibrium processes rather than a system transforming from shocks toward a stable equilibrium state (Foster and Hölzl 2004). They attempt to represent economics as a system of processes of consolidation and development, rather than resource or utility optimisation (Foster and Hölzl 2004). Evolutionary economics utilises a more behavioural and temporal approach for analysing the tendencies of populations displayed in complex systems (Foster and Hölzl 2004). The aggregated behavioural approach is in contrast to the incentive-based utilitarianism of representative agents commonly used as a guiding ethical principle in the economic decision-making process (Gorddard et al. 2012; Pyka and Hanusch 2006). The long-time horizons and the continuous selection and mutation processes inherent in evolutionary economic analysis are also complementary with the attributes of sustainable development and the slow-creep of climate change (van den Bergh 2004).

Evolutionary economics analyses stochastic fluctuations that are inherent in all complex systems. Fluctuations are imposed on the system through extreme flooding, or where water levels breach a threshold through slow-creeping sea level rise. System fluctuations are then accommodated through perturbation, saltation or bifurcation before finally coming to rest at a new dynamic equilibrium. Saltation (abrupt evolutionary change or mutation) creates the catalyst for societal change and bifurcation (path separation into divergent branches) drives the acceptance of the 'new normal' conditions (Foster and Hölzl 2004). Saltation and bifurcation can then manifest as trigger and tipping points for when society needs to make plans or take action.

Path dependency is a characteristic of evolutionary economics that can prove problematic for analysing multiple dynamic adaptation responses with

(continued)

reversibility (van den Bergh 2004). Unfortunately, Rosser (2011) describes very low reversibility of industrial, residential and transportation processes due to the long duration for a response. It is therefore crucial when analysing future options to discover if there are any potential for significant pathway dependencies such as substantial up-front costs, technological commitments, or environmental degradation that will reduce long-term well-being (Boston 2017). However, managed retreat is irreversible and path dependant if the original site no longer exists due to sea level rise.

Finally, evolutionary economics relies on the bounded rationality of individuals (van den Bergh 2004). The decision-making processes at the individual and policy levels are constrained by this imperfect knowledge, cognitive limitation and the time constraints of bounded rationality (van den Bergh 2004). Knowledge dissemination of the long-term benefits of managed retreat that result from evolutionary economic analysis helps to broaden this bounded rationality of limited information on which to base decisions.

Unfortunately, neo-classical economics or evolutionary economic solutions for planning alone do not guarantee socially optimum outcomes (van den Bergh 2004). Policy integration, stakeholder participation, funding initiatives and land-use zoning are also critical (van den Bergh 2004). Evolutionary economics does give society a new perspective to view a pertinent problem, by allowing decision-makers to be more informed of economic interdependencies and causalities. It incorporates knowledge over time for multiple stakeholders, and it allows for the changing demand and supply of land, capital, and populations. Evolutionary economic analysis can then test plans and policies ahead of implementation. It accounts for the rational behaviour of informed communities, the unpredictable manifestations of the environment and the counter-intuitive behaviour of institutions and markets. Thereby deriving a pragmatic balance between sustainable market prices, speculative investment, market uncertainty and aggregated behavioural variation.

In this chapter, we argue that evolutionary economics can be used in a coastal context to enhance long-term societal welfare by analysing coastal vulnerability, socio-economic dynamics and future policy options to enable managed retreat. A framework is suggested in which policy goals are set that align with the long-term needs of society. Modelling tools such as System Dynamics and Geographic Information Systems (GIS) can analyse dynamic economic impacts and spatial vulnerabilities based on the robust science of coastal hazards. These tools provide for the analysis of environmental-economic system interdependencies, thresholds and feedbacks (Dearing et al. 2010). Multiple plausible futures and their economic impacts can be explored and stress-tested through Robust Decision Making (RDM) to provide authorities with opportunities for managed retreat based on policy interventions with enhanced outcomes (Lempert et al. 2013). RDM is a method of probabilistic statistical analysis which seeks to minimise regret and uncertainty

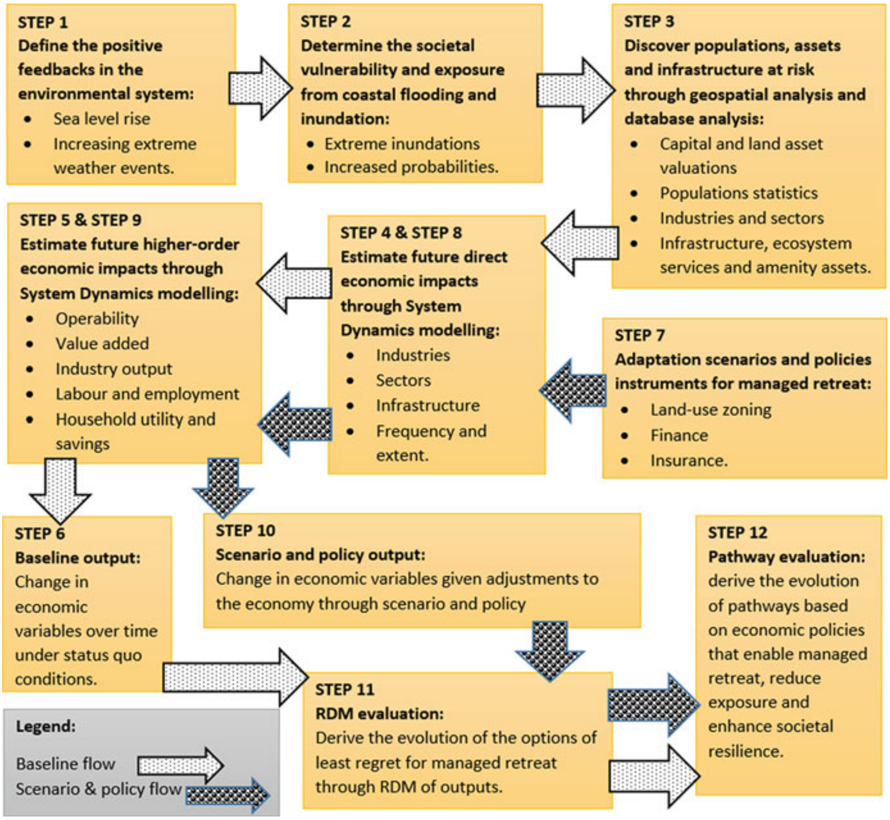

Fig. 5.2 The conceptual flow of the analysis of knowledge and information to enable long-term planning for managed retreat away from coastal hazards. Evolutionary economics and System Dynamics enable economic impact analysis over time that is then statistically tested through Robust Decision Making to define pathways toward managed retreat and societal resilience

when assessing local planning options before implementation (Lempert et al. 2013). Evolutionary economics then allows for the inclusion of a gradual and reflective dynamism of complex systems over the long term to allow knowledge and information-based preferential adaptation to occur (Foster and Hölzl 2004). Vulnerable areas can then implement strategic, individually-styled long-term plans for managed retreat that achieve greater integration for managing coastal risks in land-use management (Manning et al. 2015) when exposure becomes critical. Figure 5.2 illustrates this conceptual framework to enable long-term planning for managed retreat away from coastal hazards.

5.5 A Managed Hazard Response: Dynamic Adaptation and Financing Large-Scale Manage Retreat

The notion of 'managed' retreat implies a process of dynamic adaptation in which vulnerable communities and exposed assets can be relocated as new information on coastal hazards becomes available (Haasnoot et al. 2012a). Planning for dynamic adaptation requires the assessment of multiple plausible future scenarios (Haasnoot et al. 2012b; Kwakkel et al. 2015). It requires long-term planning across multiple pathways to guide future decisions (Barnett et al. 2014) because it is highly unlikely that one single action will eliminate all risk. Managed retreat can be viewed as a combination of dynamic adaptation plans and policies, such as integrated risk-reduction plans, land-use development restrictions, financial incentives, rezoning land-use, and accommodating affected parties (Abel et al. 2011). Its implementation is influenced by the cost of asset relocation, the ongoing costs of maintaining the existing situation, the cost of alternative actions, the effectiveness of current practice, and societal acceptance (Abel et al. 2011; Hino et al. 2017).

Currently, in New Zealand, unfavourable risk assessments for households and firms negatively affect welfare through declining valuations of exposed assets (Christchurch City Council 2015) inhibiting managed retreat. This is because the cumulative costs of relocation outweigh the perceived benefits of remaining in situ which maintains behavioural entrenchment. Globally, declining capital values are detrimental to the vulnerable, but a more risk-informed capital market is driven by, and beneficial to, society as it provides a more objective market valuation inclusive of any expected flood damage (McNamara and Keeler 2013). In order to reduce this loss of equity through declining capital values, central government administered financial compensation to the vulnerable at a fair market price would incentivise managed retreat (Freudenberg et al. 2016) sooner rather than later. Government compensation is unavoidable where state decisions impose restrictions, or eliminate, existing property rights (Tombs and France-Hudson 2018).

Enabling compensation requires new types and combinations of funding instruments in New Zealand to overcome the increasing exposure to coastal hazards (Local Government New Zealand 2015). Alongside new funding instruments are discussions around who inevitably pays for implemented strategies. Funding adaptation will be the critical enabler and needs to be addressed across scales of government (Lawrence et al. 2013). Current policy in New Zealand is devoid of practical guidelines on how managed retreat should be financed (Boston and Lawrence 2018). There is also the issue of investment decisions having non-simultaneous exchanges of immediate costs with distant benefits (Boston 2017). The greater the temporal gap between costs and the realisation of benefits, there tends to be a greater reluctance from governments to invest (Boston 2017). This uncertainty makes for a difficult task for governments who may have communities requiring expensive relocation strategies when they are socio-economically disadvantaged or facing a dramatic loss in equity (Hayward 2008).

System Dynamics modelling enables the assessment of alternative funding options ahead of implementation. It allows the economy to evolve and accommodate this new financial information as it becomes available with each iteration. Box 5.2 illustrates how differing levels of investment in managed retreat away from hazardous land can be modelled using Vensim® by Ventana Systems. Relocation costs and investment funding can be analysed to determine the appropriate level and timing of funding given the supply of new information with every model iteration. Box 5.2 shows four hypothetical simulations to discover the effectiveness of these different amounts of capital investment funding to cover relocation costs over time. The 'investment effectiveness' illustrates the long-term balance of increasing relocation costs offset by future investments in managed retreat. Discovering the dynamic equilibrium of investment effectiveness through System Dynamics allows economists to determine how much investment capital is required while simultaneously minimising the financial cost of borrowing.

Box 5.2 System Dynamics to Assess Evolving Funding Options for Managed Retreat

This Vensim® System Dynamics model based on evolutionary economics principles illustrates how differing levels of investment might be used to relocate communities from 200 ha of hazardous land to new land. Graph A illustrates the temporal investments of four simulations (Sim1, 2, 3, 4) for initial investments of USD$1, 2, 3 and 4 M respectively. Graph B illustrates the relocation from hazardous land to new land. Graph C shows the increasing cost of relocation over time for Sim 3 only as all simulations returned the same relocation cost. Graph D shows the 'Investment effectiveness', or the investment in managed retreat less the relocation cost. This illustrates the viability of the investment over time. An initial delay of 10 years, a 6% p.a. growth rate and a 3% discount rate were used. This example demonstrates that a dynamic equilibrium in investment effectiveness occurs under Sim3 around 2055, in which an investment of USD$3 M is enough to offset the relocation cost for managed retreat over this period. Dynamic equilibrium is achieved under Sim 3 where the investment covers relocation costs and the costs of borrowing are minimised.

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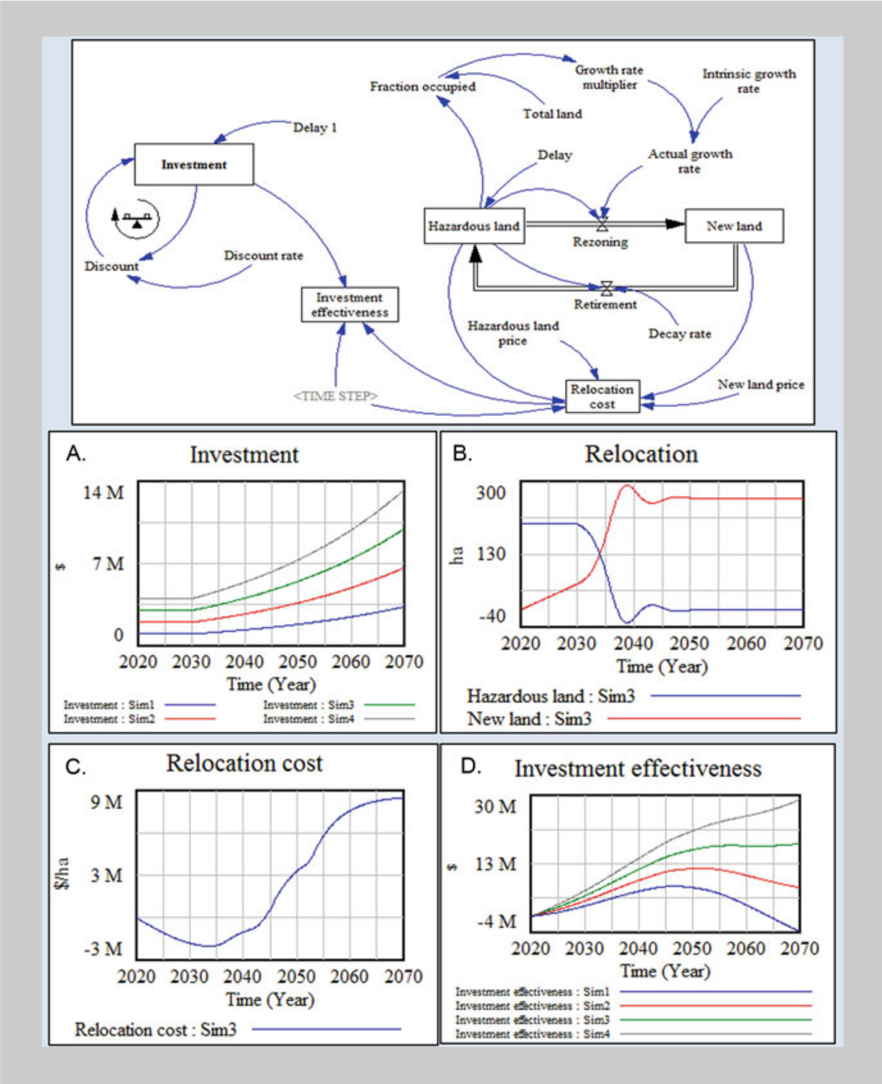

To date there have not been any direct climate change funding instruments for coastal hazards in New Zealand (Boston and Lawrence 2018). Although, the New Zealand Government recently announced the New Zealand Green Investment Finance Fund as it wishes to become a global leader in response to climate change (Herd 2018). This fund aims to manage the financial risk to the economy from climate change and unlock economic opportunities for emission mitigation (Herd 2018).

The range of possible funding instruments that can enable managed retreat include: public-private partnership (PPP) finance, loans, taxes, charges and subsidies, general or targeted rates, central government grants and funding, resilience bonds, improved resource pricing, risk transfer mechanisms, and insurance (Boston and Lawrence 2017; Cunniff and Meyers 2017; IPCC 2014b; Kartez and Merrill 2016; van den Bergh 2004). The insurance industry by default becomes the key driver in reducing potential human exposure and the financial costs of disaster (Murray et al. 2015). It can indirectly drive an ‘unmanaged retreat’ where policies are cancelled when the coastal risk becomes unacceptable, or when the fortuitous nature of insurance is no longer apparent (Storey et al. 2017). Insurance companies are requiring the use of these risk-based premiums and for preventative measures as a precondition for cover in hazardous zones to incentivise awareness, prepare for and adapt to future risk (Murray et al. 2015). Unfavourable insurance excesses and premiums can also discourage development in high-risk areas (Storey et al. 2017). Conversely, extreme excesses and premiums can become unpalatable for consumers which can lead to voluntary withdrawal from the insurance market. New insurance mechanisms are required to manage the evolving risk over the long term and provide for asset relocation rather than replacement.

Public insurance is also available to New Zealand households and firms through a compulsory levy on property payable to the government entity, The Earthquake Commission (EQC). EQC provides contingency funding and long-term financial resilience against natural disaster. It covers lands affected by flood disasters through the Natural Disaster Fund (Boston and Lawrence 2017). New Zealand is fortunate to have a Crown entity solely mandated to provide relief to parties affected by natural disaster. Public insurance through EQC has facilitated greater insurance penetration in New Zealand than other countries in order to avoid a socially unacceptable level of distress and loss caused by natural disaster (New Zealand Treasury 2015).

5.6 Mechanisms for Change

New approaches to technological economic impact analysis, regulatory policies on land-use, investment in new locations, and the formation of new governance structures need an avenue for proactive analysis and subsequent implementation into the hazard management practice (IPCC 2014b). These new approaches to hazard management can enable sustainable development (IPCC 2014b) through coastal managed retreat. For success, implementation needs to reflect a cohesive national vision and a drive for long-term sustainability (IPCC 2014b). However, sustainable development through managed retreat is not always economically favourable for society given expensive labour and capital requirements for relocation (IPCC 2014a).

Managed retreat may not be a rational adaptation measure under a neo-classical framework due to the key determinant of present cost but must go beyond this by incorporating a long-term behavioural aspect to solve this problem (Sugiyama et al. 2008). Compounding the issue is that the cost of land to relocate to is more expensive than the hazardous land, which can often leave some residents needing to re-mortgage their homes (Fleming 2017). The investigation into options for the compulsory acquisition of hazardous land where behavioural entrenchment is apparent also needs to take place, as well as discussion around how suitable land for urban development can be obtained affordably. Similarly, acquisition of land is required for coastal dynamics, ecosystem services and habitats, public access and amenity values as outlined in the NZCPS 2010. Local government is therefore required to amend plans to rezone rural, residential and industrial boundaries to mitigate run-away property prices brought on by land supply scarcity.

Governments can utilise strategic spatial planning instruments that are responsive to dynamic climate changes, social values (Manning et al. 2015) and population and trade dynamics through regular allowances for the rezoning and intensification of land-use. Structure plans that outline land-use zoning and areas for development can then give markets confidence in new developments and accommodate future development fairly, reduce uncertainty for future resource management and minimise exposure to risk. Accurate and updated national asset geodatabases are also essential to quantify vulnerable capital on a regular basis for physical changes in stock, value and extent, and accommodate new hazard information as it comes to light. These geodatabases enable spatial planning, modelling and statistical analysis. Ideally, planning instruments should be accompanied by integrated impact assessments, long-term monitoring of the physical environment, public participation (New Zealand Government 2017), risk management plans and economic impact modelling of adaptation and worst-case scenarios (Jevrejeva et al. 2014).

Finally, Van den Bergh (2004) claims that in the future, sustainable development will be built on an evolutionary perspective based on the relationship between economic evolution and environmental resources. Sustainable development will involve the integration of disparate knowledge on technology and innovations, coevolution and environmental history (van den Bergh 2004). Integration will give rise to a hybrid of social, biological, technological and economic processes that are dependent on specific problems and time horizons (van den Bergh 2004). The socio-economic and the biophysical systems can be analysed as one complex system to enable sustainable development through managed retreat. The overall patterns that lead to sustainable development can be tested over time and space to discover causal drivers and interdependencies of variables under multiple plausible futures. The very nature of evolutionary economic modelling is to find a dynamic equilibrium amongst multiple non-linear interactions. This dynamic equilibrium may fluctuate between a steady state (stable equilibrium), a dynamic state brought on by a sudden system shock, or positive reinforcement bought about by a chaotic perturbation (unstable equilibrium), or a disturbed state where shocks and perturbations lead to a new quasi-stable state (neutral equilibrium) (Ford 2010). Often bifurcation can arise in the unstable equilibrium (Rosser 2011) leading to dendritic divergent future pathways with or without human intervention. Even if the climate system were in a steady state, its interaction with the economy could drive chaotic dynamics (Rosser 2011). By modelling multiple futures and policies, resilient economic states can be discovered within the complex system. This modelling would enable robust institutional decision-making toward effective policy outcomes through minimising loss, disruption or chaotic perturbation. Scenarios and policies can then be implemented with the likelihood of the success of managed retreat vastly enhanced. Adaptation trigger points for planning and action emerge once system thresholds are breached (saltation), or new systems arise (bifurcation) allowing organisations to reconsider their operations through rational action (Stam 2006). Analysis of dynamic complex systems can then give an informed understanding of the interactions between all these influential elements (Tobin 1999) on which to base decisions and policy outcomes.

5.7 Conclusion

Changes to planning and policy are required to introduce new land-use practices and funding models that enable dynamic adaptation to coastal hazards through managed retreat. Policies and plans need to be modelled ahead of implementation to test their effectiveness to provide sustainable development within the complex and evolving environment-economic system. Modelled scenarios can then inform society of where change is needed to achieve policy outcomes. Risks and exposure of assets and infrastructure are evolving due to the slow creep of sea level rise and changes in extreme weather events which exacerbates the direct impacts of coastal flooding or inundation. Higher-order impacts such as economic disruption from flooding or inundation events also need analytical consideration. Evolutionary economics and System Dynamics have emerged as key tools to support decision-making in the presence of new knowledge and information. System Dynamics modelling provides a powerful framework for applying evolutionary economics through economic impact modelling, quantitative spatial risk assessment, and RDM for analysing multiple scenarios in a thorough statistical manner. Collectively these approaches allow exploration of future scenarios and policies for land-use and finance that can support effective coastal managed retreat. Analysing complex systems in this way facilitates knowledge creation of system relationships, discovers information flows that can modify behavioural drivers and provide insights that can enable institutional change. Successful policy outcomes can then be integrated into planning documents and development practices. Sustainable coastal management through managed retreat can then lead to more resilient coastal societies in an uncertain and changing world.

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References

Abel N, Gorddard R, Harman B, Leitch A, Langridge J, Ryan A, Heyenga S (2011) Sea level rise, coastal development and planned retreat: analytical framework, governance principles and an Australian case study. Environ Sci Pol 14:279–288

Barnett J, Graham S, Mortreux C, Fincher R, Waters E, Hurlimann A (2014) A local coastal adaptation pathway. Nat Clim Chang 4:1103–1108

Boston J (2017) Safeguarding the future: governing in an uncertain world. Bridget Williams Books Limited, Wellington

Boston J, Lawrence J (2017) The case for new climate change adaptation funding instruments. New Zealand Climate Change Research Institute, Wellington

Boston J, Lawrence J (2018) Funding Climate Change Adaptation: the case for a new policy framework. Policy Q 14:40–49

Burke M et al (2016) Climate economics: opportunities for advances in climate change economics. Science (New York, NY) 352:292

Campbell J (2017) Environment commissioner tells Govt to act faster, act now. Radio New Zealand

Christchurch City Council (2015) Coastal hazard LIM notations to be changed. https://ccc.govt.nz/news-and-events/newsline/show/957

Christensen P (1989) Historical roots for ecological economics — Biophysical versus allocative approaches. Ecol Econ 1:17–36

Cunniff S, Meyers E (2017) Encouraging investments in coastal conservation & resilience. Sage, Resilient shorelines, thriving communities

de Lange W (2006) Coastal erosion. The Encyclopedia of New Zealand

Dearing J, Braimoh A, Reenberg A, Turner B, van der Leeuw S (2010) Complex land systems: the need for Long time perspectives to assess Their future Ecology and Society 15

Dyckman C, John CS, London J (2014) Realizing managed retreat and innovation in state-level coastal management planning. Ocean Coast Manag 102:212–223

Fleming Z (2017) 'This is going to set a precedent' – council applying to evict homeowners. Radio New Zealand. http://www.radionz.co.nz/national/programmes/checkpoint/audio/201851000/this-is-going-to-set-a-precedent-council-applying-to-evict-homeowners

Ford A (2010) Modeling the environment, 2nd edn. Island Press, Washington, DC

Foreworld Developments Ltd v Napier City Council (1998). Environment Court

Forrester J (1971) Counterintuitive behaviour of social systems. Theor Decis-Making 2:109–140

Foster J, Hölzl W (2004) Applied evolutionary economics and complex systems. Edward Elgar Pub, Cheltenham/Northhampton

Freudenberg R, Ellis C, Tolkoff L, Brawley D (2016) Buy-in for buyouts: the case for managed retreat from flood zones. Lincoln Institute of Land Policy, Cambridge MA

Gibbs M (2015) Coastal climate risk and adaptation studies: the importance of understanding different classes of problem. Ocean Coast Manag 103:9–13

Gorddard R et al. (2012) Striking the balance: coastal development and ecosystem values. CSIRO, Australia

Haasnoot M, Kwakkel J, Walker W, Ter Maat J (2012a) Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world. Glob Environ Chang 23:485–498. https://doi.org/10.1016/j.gloenvcha.2012.12.006

Haasnoot M, Middelkoop H, Offermans A, Beek E, Deursen W (2012b) Exploring pathways for sustainable water management in river deltas in a changing environment. Clim Chang 115:795–819

Hayward B (2008) 'Nowhere far from the sea': political challenges of coastal adaptation to climate change in New Zealand. Pol Sci 60:47–59

Herd E (2018) Investors welcome the New Zealand Green Investment Finance fund. Investor Group on Climate Change

Hino M, Field C, Mach K (2017) Managed retreat as a response to natural hazard risk. Nat Clim Chang 7:364–370

Hughes T et al (2017) Coral reefs in the Anthropocene. Nature 546:82–90
Infometrics Consulting Limited (2017) Real options analysis of strategies to manage coastal hazard risks. Wellington
Insurance Council of New Zealand (2018) Adapting to climate change needs to be a top priority. ICNZ. https://www.icnz.org.nz/media-resources/media-releases/single/item/adapting-to-climate-change-needs-to-be-a-top-priority/
IPCC (2014a) Adaptation planning and implementation. In: AR IWGICt (ed) Climate change 2014: impacts, adaptation, and vulnerability. Cambridge University Press, Cambridge
IPCC (2014b) Technical summary. In: Field CB et al (eds) Climate Change 2014: impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge/New York, pp 35–94
Jevrejeva S, Grinsted A, Moore JC (2014) Upper limit for sea level projections by 2100. Environ Res Lett 9:104008(9pp)
Kartez J, Merrill S (2016) Climate adaptation finance mechanisms: new frontiers for familiar tools. J Ocean Coast Econ 3(2):Article 4. https://doi.org/10.15351/2373-8456.1066
Kench P et al (2018) Co-creating resilience solutions to coastal hazards through an interdisciplinary research project in New Zealand. J Coast Res 85:1496–1500. https://doi.org/10.2112/SI85-300.1
Kirk R, Morgan R, Single M, Fahey B (1999) Applied physical geography in New Zealand. Prog Phys Geogr: Earth Environ 23:525–540. https://doi.org/10.1177/030913339902300404
Komar P (2009) The oregon coast experience: good management but ‘bad apples’. In: Williams A, Micallef A (eds) Beach management: principles and practice. Earthscan, London
Komar P, Allen, Ruggerio, Harris (2013) Earth’s changing climate and coastal hazards: The U.S. Pacific North West and Hawke’s Bay, New Zealand. In: New Zeland Coastal Society Annual Conference, Hokitika, New Zealand, 2013. New Zealand Coastal Society
Kwakkel J, Haasnoot M, Walker W (2015) Developing dynamic adaptive policy pathways: a computer-assisted approach for developing adaptive strategies for a deeply uncertain world. Clim Chang 132:373–386
Lawrence J, Sullivan F, Lash A, Ide G, Cameron C, McGlinchey L (2013) Adapting to changing climate risk by local government in New Zealand: institutional practice barriers and enablers. Local Environ 20:298–320
Lempert R et al. (2013) Ensuring robust flood risk management in Ho Chi Minh City. https://doi.org/10.1596/1813-9450-6465
Local Government New Zealand (2015) Local government funding review: a discussion paper. Local Government New Zealand, Wellington
Losada I, Diaz-Simal P (2014) Adaptation in coastal areas. In: Markandya A, Galarraga I, Sainz de Marieta E (eds) Routledge handbook of the economics of climate change adaptation. Routledge, London
Manning M, Lawrence J, King D, Chapman R (2015) Dealing with changing risks: a New Zealand perspective on climate change adaptation. Reg Environ Chang 15:581–594
Mas-Colell A, Whinston M, Green J (1995) Microeconomic theory. Oxford University Press, New York
Maven Consulting Ltd (2017) Cape coast area coastal hazards social impact analysis and valuation. Wellington
McDonald G, Smith N, Kim J, Brown C, Buxton R, Seville E (2018) Economic systems modelling of infrastructure interdependencies for an Alpine Fault earthquake in New Zealand Civil Engineering and Environmental Systems:1–24. https://doi.org/10.1080/10286608.2018.1544627
McNamara D, Keeler A (2013) A coupled physical and economic model of the response of coastal real estate to climate risk. Nat Clim Chang 3:559–562. https://doi.org/10.1038/nclimate1826. www.nature.com/articles/nclimate1826#supplementary-information
Munda G (1997) Environmental economics, ecolgical economics, and the concept of sustainable development. Environ Values 6:213–233

Murray C, McDonald G, Cronin S (2015) Interpreting Auckland's volcanic governance through an institutional lens. Nat Hazards 75:441–464. https://doi.org/10.1007/s11069-014-1340-z

Nelson RR, Winter SG (2002) Evolutionary theorizing in economics. J Econ Perspect 16:23–46. https://doi.org/10.1257/0895330027247

New Zealand Government (1953) Town and Country Planning Act. Wellington

New Zealand Government (1991) Resource Management Act. Wellington

New Zealand Government (2002) Local Government Act. Wellington

New Zealand Government (2017) Coastal hazards and climate change: guidance for local government. Ministry for the Environment, Wellington

New Zealand Treasury (2015) New Zealand's future natural disaster insurance scheme: proposed changes to the Earthquake Commission Act 1993. New Zealand Government, Wellington

NIWA (2015) National and regional risk exposure in low-lying coastal areas: Areal extent, population, buildings and infrastructure: Prepared for the Parliamentary Commissioner for the Environment. Hamilton

Okada T, Haynes K, Bird D, van den Honert R, King D (2014) Recovery and resettlement following the 2011 flash flooding in the Lockyer Valley. Int J Disaster Risk Reduct 8:20–31. https://doi.org/10.1016/j.ijdrr.2014.01.001

Omaha Beach Community Inc (2017) Information about Omaha Beach, New Zealand. https://omahabeach.co.nz/about/

Owen S et al. (2018) Anticipating staged managed retreat at the coastal margins Planning Quarterly:8–11

Parliamentary Commissioner for the Environment (2015) Preparing New Zealand for rising seas: certainty and uncertainty. New Zealand Government, Wellington

Peart R (2009) Castles in the Sand: what's happening to the New Zealand coast? Craig Potton, Nelson

Pyka A, Hanusch H (2006) Applied evolutionary economics and the knowledge economy. Edward Elgar, Cheltenham

Radio New Zealand (2018) Insurance payouts for extreme weather events hit $226m for 2018. https://www.radionz.co.nz/news/national/378165/insurance-payouts-for-extreme-weather-events-hit-226m-for-2018

Reese S, Ramsay D (2010) Riskscape: flood fragility methodology. NIWA, Wellington

Reisinger A, Lawrence J, Hart G, Chapman D (2015) From coping to resilience: the role of managed retreat in highly developed coastal regions of New Zealand. In: Glavovic B, Kelly M, Kay R, Travers A (eds) Climate change and the coast: building resilient communities. CRC Press, Florida, pp 285–310

Rosser J (2011) Complex evolutionary dynamics in urban-regional and ecologic-economic systems from catastrophe to chaos and beyond. Springer, New York

Ruth M, Hannon B (2012) Modeling dynamic economic systems, 2nd edn. Springer, New York

Ryan E (2018) Managed retreat; unpacking the 'black box'. https://resiliencechallenge.nz/edge-programme/3296/

Schumpeter J (1912) Theorie der wirtschaftlichen Entwicklung, "The Theory of Economic Evolution". Dunker & Humblot, Leipzig

Smith N, McDonald G, Harvey E (2016) Dynamic economic model: a technical report prepared under the economics of resilient infrastructure programme. Market Economics Ltd, Auckland

Stam E (2006) A process model of location change in entrepreneurial firms: an evolutionary perspective. In: Pyka A, Hanusch H (eds) Applied evolutionary economics and the knowledge economy. Edward Elgar, Cheltenham, pp 143–165

Storey B, Noy IT, Townsend W, Kerr S, Salmon R, Middleton D, Filippova O, James V (2017) Insurance, housing and climate adaptation: current knowledge and future research, vol 27. Motu Economic and Public Policy Research, Wellington

Sugiyama M, Nicholls R, Athanasios V (2008) Estimating the economic cost of sea level rise. Massachusetts Institute of Tech nology, Cambridge, MA

Tobin G (1999) Sustainability and community resilience: the holy grail of hazards planning? Global Environ Change B Environ Hazard 1:13–25

Tombs B, France-Hudson B (2018) Climate change compensation: an unavoidable discussion. Policy Q 14:50–58

Tonkin & Taylor (2017) Franz Josef natural hazards options assessment and cost-benefit analysis. Auckland

van den Bergh J (2004) Evolutionary thinking in environmental economics: retrospect and prospect. In: Foster J, Hölzl W (eds) Applied evolutionary economics and complex systems. Edward Elgar, Cheltenham, pp 239–275

Veblen T (1899) The theory of the Leisure class: an economic study of institutions. The Modern Library, New York

Waikato Regional Council (2006) Managed retreat from coastal hazards: Options for implementation. Hamilton

Williams A, Micallef A (2009) Beach management: principles and practice. Earthscan, London/Sterling

Chapter 6
Remediation Measures for Accumulated Environmental Damages Using Principles of Sustainable Development: A Case Study of Russian Regions

Sergey G. Tyaglov, Marina A. Ponomareva, and Victoria B. Cheremina

Abstract Remediation of environmental damages accumulated from the past requires support in form of regional and federal policies. To ensure that such policies are formulated and established, the analysis of existing practices is conducted. The analysis reveals the main components of the restoration process including environmental objects, stakeholders, tools, and institutions responsible for policy implementation and enforcement mechanisms. A special attention is paid to increasing the efficiency of remediation measures from the environmental-economic perspectives. It supports further generalization of remediation measures for accumulated environmental damages and lead to recommendation for local authorities to implement them in practice and to return damaged territories into economic activities through the restoration process.

Keywords Sustainable development · Intergenerational environmental externalities · Accumulated environmental damage · Regions of Russia · Ecological-and-economic policy

6.1 Introduction

The concept of sustainable development emerged in the second half of the twentieth century is still one of the leading ideas which implementation is a priority task for the majority of powerhouses in the modern world. The interconnection of economic, ecological and social problems and their transition to the intergenerational direction requires the managerial structures to rank priorities providing greater opportunities for future generations to meet their needs.

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The formation of objects of accumulated environmental damage is one of the most illustrative examples characterizing the problems of human separate areas development when disobeying the principles of sustainable development. Without taking into account the ecological consequences, the progress in production took place in most of the developed countries in the twentieth centuries has led to forming so-called object of accumulated environmental damage. Over decades, these objects continue to have a prolonged negative influence on the health of the population and the environment. In addition, they prevent further economic development of present and future generations and the territories of their dwelling.

In the Russian Federation and its regions, accumulated damage is becoming more and more alarming economic and ecological-social problem.

On the one hand, many Russian regions observe the lack of new industrial sites with the access to different kinds of infrastructure services including transport ones. Furthermore, there is a high cost of building the new infrastructure and insufficient development of public-private collaboration mechanisms that may encourage its building. Thus, the cost of implementing the new investment projects may grow in case of building additional communications. Moreover, it significantly increases the terms of implementing investment projects, and, consequently, it discourages the efficient development and investment in the regions.

On the other hand, in such established industrial regions, huge territories are affected by the objects of accumulated environmental damage formed in the age of central economic system when all the enterprises were owned by the state. It leads to the existing problem of allocating the responsibility between the participants of investment-production relations for remediating the consequences of accumulated damage. As a result, the use of such territories to develop new production turns out to be impossible although more often there appears the appropriate infrastructure provision. Thus, the solution of the accumulated damage problem may become a cheaper way of eliminating the restrictions of investment development both for public and commercial organizations in Russian regions compared to the search for new industrial sites.

Territories of accumulated environmental damage as an object of ecosystems are the source of constant environmental hazard affecting all the components of the environment (air, water, soil, land) The prevention of adverse environmental impacts requires regional and municipal authorities to continuously monitor the environmental situation on the respective territories, as well as to implement the necessary measures in cases of specific environmentally adverse situations. In addition, it requires a significant budget of different levels. Furthermore, the degree of harm to the health of the population, duration and amount of the costs of preventing environmental effects are difficult to foresee, both in the nearest and distant future. The solution to the problem of accumulated damage today, thus, can save significant amounts of resources in the future; the latter ones could be used for other pressing development needs.

It requires more detailed analysis of practices on remediating the consequences of accumulated damage in Russian regions in order to make suggestions on improving federal and regional policies implemented in this problematic area.

6.2 Theoretical, Informational, Empirical and Methodological Background of the Research

Theoretical and methodical background to the research is the concept of sustainable development as a founding doctrine connecting economic, ecological and social priorities of the social development taking into account the needs of future generations. Furthermore, the study relies on the ecosystem approach, reflecting the need for integrating the impact of objects accumulated environmental damage on all components of the environment (air, soil, land, water). To study practices of remediating accumulated damage, Russian regions use generally accepted methods of scientific knowledge such as comparative, logic, retrospective analysis, tabular and graphical data visualization, software-target method, etc.

The information-empiric base of the research is data of official statistics bulletins and the website of the Federal statistics service, Ministry of natural resources and ecology of the Russian Federation, program-targeted documents implemented within the issues of accumulated environmental damage, official reports on their implementation, etc.

6.3 Results

The analysis of scientific literature has shown that there are different approaches to studying the issue of accumulated (past) environmental damage within the context of sustainable development. As the experience of the developed countries, such as Germany and the USA, shows there is the need for allocating the responsibility for remediating accumulated damage, defining the mechanisms of legal regulation and sources of funding. Schoukens (2017) notes in his article that recent developments in the area of legal regulations of the European Union are mostly connected with preventing environmental damage while restoration of the territories is becoming the last resort that can serve as an incentive for unsustainable development, thus suggesting that any damage caused to the nature can be rectified.

Nevertheless, most developed and developing countries formed the areas of accumulated damage in earlier periods of the past century. The modern generation has to eliminate this damage due to the fact that it negatively affects both the use of territories and human health. The lack of attention to these issues and postponing the elimination of consequences of accumulated damage may dent the grounds of sustainable development on the local level and lead to more serious social and economic losses in the future.

Large cities face this issue to a far greater degree, particularly the accumulation of harmful chemical agents in the atmosphere and the soil of urbanized territories. Different methods are suggested to study and eliminate them. Studying the impact of accumulated damage on human health and flora and fauna is one of the important directions. For instance, Sujetoviene and Sliumpaite (2013) looked into the changes in physiological parameters and the trace metals (Cd, Cu, Pb) uptake by the lichens transplanted to an urban environment. The study showed that city pollutants damaged the cell membranes of the lichens. Chinese scholars (Wang et al. 2018) revealed the interrelation between the development of pancreatic cancer and the pollution of the environment.

As a result, the research corps devoted to the ecosystem restoration, particularly urban ones, is being gradually developed. In addition, it should be noted that there are different programs to design the scoring system of monitoring the condition of restored ecosystems (Baldera et al. 2018) and to create balanced urban environment based on the ecological concept together with the sustainable development of urban landscape (Dong et al. 2018).

The programs in the area of forming the efficient economic incentives for different participants take an important place among the studies dedicated to the elimination of accumulated damage and territory restoration. British scholars (Hewett et al. 2018) suggest CAVERTI tool aimed at encouraging farmers, private landowners and other stakeholders to reduce soil erosion through providing multiple benefits from protecting local infrastructure and reducing water pollution.

Since the mining industry is the main source of the accumulated environmental damage, special attention is paid to this problem in countries such as the USA, Germany, Great Britain, Canada, Korea, China and Russia.

A great number of works is devoted to the issues of restoring former coal-mining territories and assessing the impact of coal mining operations on the ecosystems to work out decisions ensuring the conservation of environmental sustainability while enabling economic development. Indonesian scholars (Kodir et al. 2017) held the research on the opportunity to design a spatial plan of coal lands with integrated protected areas, conservation areas and cultivated areas containing different types of land use to ensure sustainable development. Chinese scholars (Zhang et al. 2018) analyzed the ecological impact of coal exploitation, utilization and transportation taking into account the coal status in China. In their works, international scientists (Alexandrov et al. 2011; Khaiter and Erechtchoukova 2010, 2009) pay a great attention to designing mathematical model of the environment and ecosystems to assess their conditions with IT technologies (Khaiter and Erechtchoukova 2018) and methods of AI, in particular machine learning algorithms (Erechtchoukova and Khaiter 2017; Erechtchoukova et al. 2016).

Chinese (Zhu et al. 2016) and Korean (Zhang et al. 2016) scholars study the subsidence and possibility of extracting coal under buildings, railways and water objects its reuse in order to raise the economic sustainability under the terms of resource deterioration.

In Russian science, the issue of accumulated damage as a factor ensuring sustainable development is presented in the works considering accumulated industrial waste as secondary technogenic resources whose recycling allows to reduce the amount of extracted raw materials as well as to decrease the environmental damage connected with their accumulation. Moreover, Russian scholars offer economically efficient methods that are of great importance as well as regional mechanisms of remediating accumulated damage that require additional justification and taking into account regional specifics while developing managerial decisions, mechanisms and toolkit of raising the interest of business entities in their implementation (Potravniy et al. 2017; Zhukova et al. 2017).

Nowadays, in foreign practice, accumulated environmental damage is defined as "the residual impact/damage on human health and the environment, caused by past or ongoing economic activity, including compensation for remediation of the damage (harm)" (Assessment 2006).

Furthermore, such notion as "responsibility for past damage" is considered as "residual costs which should ultimately be incurred in connection with the remediation, reduction and/or localization of damage for the environment, health or property, arising from past or ongoing business activities" (Interpretation 2006).

In the Russian legal field, the term "accumulated environmental damage" was introduced only relatively recently, nevertheless, it contradictive representation and the absence of appropriate legally-approved mechanisms on remediating its consequences did not allow the regions to implement the target activities in this direction.

In recent years, a number of changes have taken place in the Russian legislation aimed at a more effective solution to the problem of accumulated damage. In 2016, the Federal Law of the Russian Federation №7-FZ "About the protection of the environment" was passed providing more clear definitions of the following concepts:

- "accumulated environmental damage is a damage to the environment emerged due to the past economic or other activities, in which the obligations on its remediating were not performed or were not performed to the full extent" (Federal Law 2016);
- "objects of accumulated environmental damage are territories and water areas detected accumulated environmental damage, objects of capital construction and objects of waste disposal being the source of accumulated environmental damage" (Federal Law 2016).

In addition, the document specifies mechanisms for identifying, assessing, recording and categorizing objects of accumulated damage to the environment, as well as the basis for organizing work to remediate the accumulated damage to the environment.

The need to remediate the objects of accumulated damage in the Russian regions is long overdue.

"In the course of a large-scale inventory, 340 objects of accumulated damage to the environment were identified. By polluting air and water, they increase the risk of health deterioration for 17.6 million people. Such objects are located in all regions of the Russian Federation and occupy 173 thousand hectares. In total, more than 370 million tons of contaminated components of the natural environment have been accumulated over an area of more than 77,000 hectares. This is equal to the population of cities such as Ruza or Kashin. The annual economic damage from the consequences of the previously destroyed nature can be estimated at 50 billion rubles. Features of localization of objects of the accumulated damage to the environment in the Russian Federation are connected with the territorial distribution of the country's industrial complex taking into account geographical and natural resource aspects. Intensive economic and defense activities have caused serious damage to the environment of the Arctic zone of the Russian Federation. The intensification of works on developing natural resources of the Arctic zone, including on the continental shelf, creates new environmental threats, taking into account the extremely low capacity of disturbed Arctic ecosystems to restore (Report 2015).

The bulk of the objects of accumulated damage in the Russian Federation was formed mainly as a result of contamination by oil products and waste from the chemical industry. In regions with a developed coal mining and mining industry, significant areas that are prone to accumulated damage have also been formed, represented by tailing pits, sludge collectors and waste pits.

"Overburden and enclosing rocks with a fine fraction, are subject to wind erosion and have a significant negative impact on the biocenoses of the enclosed territories, the ecological situation and the health of the population. In addition to this, systemic pollution of water bodies occurs. The territory of petrochemical enterprises and warehouses of oil products, being objects of accumulated environmental damage, create a threat of soil contamination and ingress of oil products into groundwater, which can lead to emergencies, related to oil spills. A separate problem is the waste of the oil refining industry, which are oil-containing sludge of the 2nd and 3rd hazard classes. More than 40,000 tons of pesticides have been accumulated in the Russian Federation, which are banned for use in agriculture by the Stockholm Convention. A special danger to the environment is the waste of galvanic production, as well as waste containing mercury and organochlorine. One of the objects of the accumulated environmental damage are the places of the former deployment of military units, as well as places for testing and destroying military equipment and weapons (Report of the National Council 2016).

At the end of 2015, the total amount of accumulated and accounted production and consumption waste in the country as a whole was approximately 31.5 billion tons, and by the end of 2016 - about 40.7 billion tons (National report 2017).

Despite the fact that the given values of the indicators are estimated in connection with the objective difficulties in the waste recalculation, formed many decades ago, it is evident from their dynamics that the process of accumulation of production and consumption wastes continues and it may result in forming new objects of accumulated damage in the future. It means that the issue of accumulated damage under Russian conditions should include two main directions: remediation of the consequences of existing objects of accumulated damage and prevention of the formation of new similar objects.

The accumulated and recorded production and consumption wastes were distributed across the federal districts of the Russian Federation unevenly (Fig. 6.1).

However, if we take into account the unevenness of the total area of the federal districts, as well as the territorial distribution of the "dirtiest" industries in them, the contribution of each of the districts to the general result becomes natural.

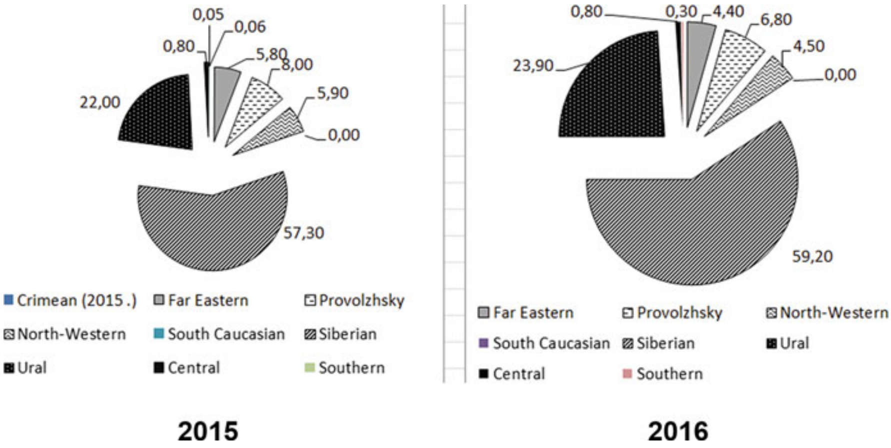

Fig. 6.1 Distribution of accumulated and accounted industrial waste across Federal districts of the Russian Federation, 2015–2016, %. (Source: National report 2017)

Since 2011, the Russian Federation has implemented a number of measures aimed at remediating the accumulated damage in the regions. By 2014, the Ministry of Natural Resources and Ecology of Russia together with the subjects of the Russian Federation has completed the work on inventorying and accounting for objects of accumulated environmental damage. A set of measures was developed to remediate environmental damage accumulated as a result of past economic activities, mechanisms and amounts of financing for these measures were identified, including pilot projects for working out technologies for liquidating the accumulated damage.

The list of objects of the accumulated environmental damage was published in the public domain on the website of the Ministry of Natural Resources and Ecology of Russia. By regions of the Russian Federation, the objects of accumulated damage are distributed as shown (Fig. 6.2).

Taking into account that about 340 objects of accumulated damage were identified during the preliminary inspection, and only 90 objects entered into the official list, according to which the real work began, it can be said that at present, the most priority objects covering the largest territories and having a negative impact on the largest number of people were chosen.

Since 2011, a number of pilot projects were implemented in the regions characterized by the greatest negative impact coming from the objects of accumulated damage, in particular, on the territory of the Arctic zone of the Russian Federation, in the Baikal natural area and in the Nizhny Novgorod area.

The financing of these projects includes federal budget funds, consolidated budgets of the constituent entities of the Russian Federation, as well as extra-budgetary sources (Table 6.1).

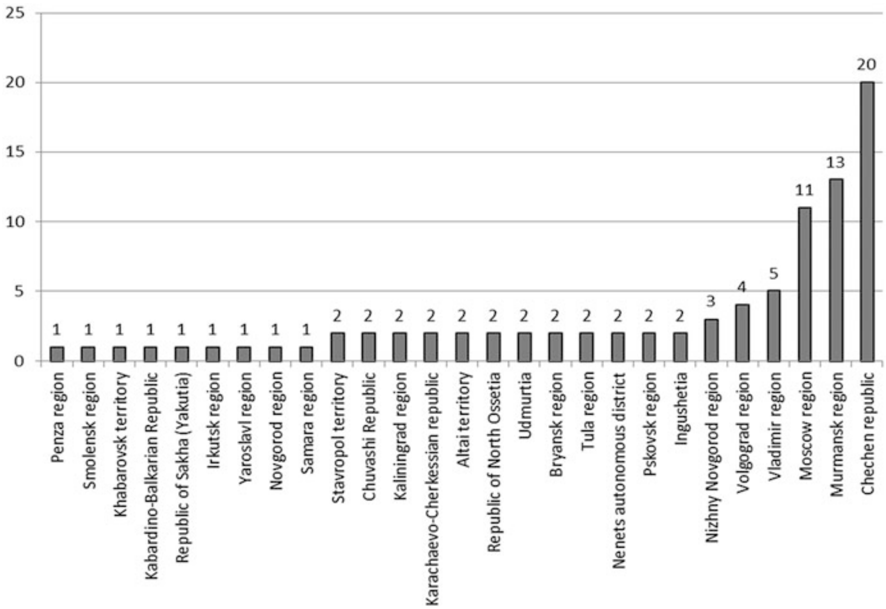

Fig. 6.2 Distribution of objects of accumulated damage in the subjects of the Russian Federation. (Designed by authors according to: http://www.mnr.gov.ru/activity/directions/likvidatsiya_nakoplennogo_ekologicheskogo_ushcherba/)

Within the framework of the Action Plan of the Ministry of Natural Resources and Ecology of the Russian Federation for 2016–2021, a separate direction "Remediation of accumulated environmental damage" was provided which suggests an increase in the share of re-cultivated and ecologically rehabilitated lands involved in economic turnaround in the total area subject to negative impact of accumulated environmental damage from 0.1% in 2016 to 0.5% in 2020. This means carrying out works not only to rehabilitate territories that are prone to accumulated damage but also to increase their involvement in secondary economic turnover, which will allow compensating for current expenditures at the expense of the development of new industrial sites on the involved territories. Table 6.2 reflects the actual values of target indexes according to the annual reports of the Ministry of Natural Resources and Ecology of the Russian Federation.

As can be seen from the data in Table 6.2, the planned values of the indicator under consideration in the new work plan of the Ministry of Natural Resources and Ecology of the Russian Federation are several times lower than in the previous work plan for 2013–2018, which is explained by unfavorable macroeconomic conditions in the country. In addition, the planned indicators in 2015 and 2016 were underfulfilled due to insufficient funding from the federal budget. At the same time, in 2017, there is a significant almost ten-fold over-fulfillment of the target values. The

Table 6.1 Major pilot projects to remediate accumulated environmental damage in the regions of the Russian Federation[a]

Implementation period	Region, characteristics of the project	Volume of financing from the federal budget, million rubles
2011–2013	Polluted islands of the Franz Josef Land Archipelago	1397,0
2013	Polluted territories in the area of Cape Zhelaniya, Island Northern, Archipelago Novaya Zemlya	124,9
2011–2013	Chukotka Autonomous District, territory of the state natural reserve "Wrangel Island"	185,6
	Nenets Autonomous District, the territory of the municipality "Poselok Amderma"	
	Elimination of pollution sources in the territories of Russian presence in the Svalbard archipelago	
2012–2020	Republic of Buryatia, liquidation of the consequences of the activities of the Dzhidinsky tungsten-molybdenum plant, subsoil accumulation of oil products polluting the waters of the Selenga River near village Steklozavod of Ulan-Ude	4380,4
	Irkutsk region, liquidation of the negative impact of waste accumulated as a result of the activities of the open joint-stock company "Baikal Pulp and Paper Mill"	3010,2
	Nizhny Novgorod region, liquidation of the depth burial ground in the bowels of industrial sewage and the unorganized industrial waste dump "Black hole" of the former production of the open joint-stock company "Plexiglass", the sludge collector "White Sea"	4279,1

[a]Source: http://government.ru/orders/selection/405/10190/

actual value of that year was more than twice as higher as even the initially higher target value of 2015.

Nevertheless, the share of territories introduced into economic turnaround after their rehabilitation remains extremely small. This means that the costs incurred by them are not justified economically.

Table 6.2 Reaching the actual values of the indicator «The share of re-cultivated and ecologically rehabilitated lands involved in economic turnover in the total area of lands subject to negative impact of accumulated environmental damage, %, 2015–2017 гг[a]

Index value	2015	2016	2017
Planned	0,9	0,1	0,2
Factual	0,8	0,076	2,07

[a]Source: Report (2015, 2016, 2017)

Despite the rather complicated macroeconomic situation, work to remediate the accumulated damage will continue. At the same time, more active work is beginning not only to eliminate the accumulated damage, but also to prevent the emergence of new objects. So in 2017, projects on construction of modern enterprises for heat treatment of wastes have been started. The construction of four new plants in the Moscow region and one in Kazan began. During the construction of these plants, green tariffs for connection to power grids are provided. It is planned that these projects should not only improve the quality of life, but also create an almost new industry that will be oriented to producing modern recycling equipment (State Council 2017).

6.4 Conclusions and Recommendations

The carried out analysis of the practice of remediating the consequences of the accumulated environmental damage in the regions of the Russian Federation shows that at the present time at the federal level there are organizational, economic and regulatory prerequisites for solving this problem. At the same time, it is obvious that not all regions have so far actively joined this process, although it would be a competitive advantage for them to get federal support for the implementing relevant projects and programs. Thus, out of more than 80 regions-subjects of the Russian Federation, only about 30 have been able to contribute the existing territories of accumulated damage to the list of objects formed at the federal level. This is due to both the limited federal budget resources and the need to implement the principle of priority, as well as the untimely preparation of relevant documents by the regions themselves. In the latter case, the right to federal support must be confirmed by the relevant studies of the old-developed territories, the evaluation of the accumulated damage, which requires time and political will on the regional level of the government.

It is advisable at the same time to engage the private sector more actively when solving the problem of involving the territories of accumulated damage in the secondary economic turnover. Low values of the corresponding indicator reflect, in our opinion, either an incorrect priority in the selection of priority objects for the remediating the damage or, more likely, a lack of thoughtfulness of the mechanism for their involvement in the secondary turnover, inconsistent data works with the real needs of producers and investors. In this regard, at the regional level, in addition to assessing the extent of the accumulated damage, it would obviously be effective to plan the sequence of rehabilitation of the relevant territories and their production use by new investors well in advance. At the federal level, in order to activate these processes, it is necessary to continue work on developing the practice of applying public-private partnership, its regulatory and legal support, protecting the rights of investors and local society when implementing similar projects.

In addition, we should pay attention at the need of an integrated approach to solving the problem of accumulated damage in terms of its environmental significance. Currently, the approach used to eliminate the objects of accumulated damage is more aimed at solving the problem by reclamation of land. For example, such cases as the presence of mine cavities and changes in the structure of subsoil, the penetration of pollutants into groundwater, etc. should be neutralized by other technologies. In our opinion, it is important to combine measures on improving the composition of water in natural water bodies with remediation measures, while these two sections are even referred to different tasks in terms of the work of the Ministry of Natural Resources and Ecology of the Russian Federation.

Finally, it is clear that the remediation of already accumulated damage will be useless unless the volume of industrial waste is reduced at the current stage and the formation of new objects of accumulated damage is prevented in the future. In addition to general improvement of environmental legislation in the Russian Federation providing economic incentives to entities to reduce negative effects on the environment, introducing the best available technologies, modernization and raising economic energy efficiency of Russian regions, it is necessary to consolidate the responsibility of new owners for the consequences of their activities in the field of possible future accumulated damage, with the transfer of such responsibility from current owners to subsequent stakeholders. The development of these directions allows raising the efficiency of the implemented policy at the federal and regional levels in the area of remediating accumulated damage.

References

Alexandrov GA, Ames D, Bellocchi G, Bruen M, Crout N, Erechtchoukova M, Hildebrandt A, Hoffman F, Jackisch C, Khaiter P, Mannina G, Matsunaga T, Purucker ST, Rivington M, Samaniego L (2011) Technical assessment and evaluation of environmental models and software. Environ Model Softw 26(3):328–336

Assessment of accumulated environmental damage in Kemerovo region. Under the research of World Bank on assessing past environmental damage in the Russian Federation (Assessment) (2006). http://consulting.ineca.ru/?dr=projects/pel/

Baldera A, Hanson DA, Kraft B (2018) Selecting indicators to monitor outcomes across projects and multiple restoration programs in the Gulf of Mexico. Ecol Indic 89:559–571

Dong J, Zho, T, Xin L, Tan Y, Wang Z (2018) The sustainable expression of ecological concept in the urban landscape environment design. In: IOP conference series: Earth and environmental science, vol 113 (1), p. 22

Environmental management. Assessment of past accumulated damage in the areas of orgaisation's location. http://files.stroyinf.ru/Data 2/1/4293809/4293809544.htm
Erechtchoukova MG, Khaiter PA (2017) The effect of data granularity on prediction of extreme hydrological events in highly urbanized watersheds: a supervised classification approach. Environ Model Softw 96:232–238
Erechtchoukova MG, Khaiter PA, Saffarpour S (2016) Short-term predictions of hydrological events on an urbanized watershed using supervised classification. Water Resour Manag 30(12):4329–4343
Federal Law of the Russian Federation "On introducing amendments in separate legal acts of the Russian Federation" (Federal Law) (2016) Passed on July 3, 2016, FZ-254
Hewett CJM, Simpson C, Wainwright J, Hudson S (2018) Communicating risks to infrastructure due to soil erosion: A bottom-up approach. Land Degrad Dev 29:1282–1294. https://doi.org/10.1002/ldr.2900
Interpretation of international experience concerning the responsibilities for past environmental damage in Russia. The document for the consideration at the Seminar on issues of responsibilities for past (accumulated) damage (Interpretation) (2006). http://consulting.ineca.ru/?dr=projects/pel&pg=material
Khaiter PA, Erechtchoukova MG (2018) Conceptualizing an Environmental Software Modeling Framework for Sustainable Management Using UML. J Environ Inf. https://doi.org/10.3808/jei.201800400
Khaiter PA, Erechtchoukova MG (2010) Simulating the Hydrological Service of Forest for Sustainable Watershed Management. The International Journal of Environmental, Cultural, Economic and Social Sustainability 6(3):227–240
Khaiter PA, Erechtchoukova MG (2009) Model Aggregation and Simplification in Sustainable Environmental Management. The International Journal of Environmental, Cultural, Economic and Social Sustainability 6(1):227–242
Kodir A, Hartono DM, Haeruman H, Mansur I (2017) Integrated post mining landscape for sustainable land use: A case study in South Sumatera, Indonesia. Sustainable Environment Research 27(4):203–213
National report "About the conditions and preservation of the environment in the Russian Federation in 2016" (National report) (2017). http://www.mnr.gov.ru/activity/directions/likvidatsiya_nakoplennogo_ekologicheskogo_ushcherba/
Potravny IM, Kolotyrin KP, Gengut IB (2017) Encouraging investment projects on liquidating accumulated environmental damage base on ecological insurance. Economic sciences in modern Russia 2(77):78–90
Report "About inventorying and accounting for objects of accumulated environmental damage and developing a set of measures for its remediation" (Report) (2014). http://government.ru/orders/selection/405/10190/
Report of the National Council of the Russian Federation "About environmental development of the Russian Federation on behalf of future generations" (Report of the National Council) (2016) Kremlin, Moscow
Report on implementing the activities plan of the Ministry of Natural Resources and Ecology of the Russian Federation for 2016-2020 (Report) (2016)
Report on implementing the activities plan of the Ministry of Natural Resources and Ecology of the Russian Federation for 2016-2020 (Report) (2017)
Report on implementing the activities plan of the Ministry of Natural Resources and Ecology of the Russian Federation for 2013-2018 (Report) (2015)
Schoukens H (2017) Habitat restoration measures as facilitators for economic development within the context of the EU habitats directive: balancing no net loss with the preventive approach? (2017). Environmental Law 29(1):47–73
State Council presidium meeting on strategic development and priority projects (State Council) (2017). http://government.ru/projects/selection/658/29405/
Sujetoviene G, Sliumpaite I (2013) Response of Evernia prunastri transplanted to an urban area in central Lithuania. Atmos Pollut Res 4(2):222–228

Wang Y, Li M, Wan X, Sun Y, Cheng K, Zhao X, Zheng Y (2018) Spatiotemporal analysis of $PM_{2.5}$ and pancreatic cancer mortality in China. Environ Res 164:132–139

Zhukova IA, Shekhovtsov RV, Ponomareva MA, Tyaglov SG (2017) The Mechanism to Eliminate the Accumulated Damage to the System of Socio-Economic Development of the Region. European Research Studies Journal XX(3B):67–75. http://www.ersj.eu/index.php?option=com_content&task=view&id=690&ltmid=1

Zhang B, Luo H, Lv L, Wang J, Zhang B (2018) Analysis of ecological environment impact of coal exploitation and utilization. IOP Conference Series: Earth and Environmental Science 121(3):16

Zhang YJ, Feng GR, Zhang M, Ren HR, Bai JW, Guo YX, Jiang HN, Kang LX (2016) Residual coal exploitation and its impact on sustainable development of the coal industry in China. Energy Policy 96:534–541

Zhu XJ, Guo GL, Zha JF, Chen T, Fang Q, Yang XY (2016) Surface dynamic subsidence prediction model of solid backfill mining. Environ Earth Sci 75(12):1007–1015. https://doi.org/10.1007/s12665-016-5817-9

Chapter 7
Defining Sustainability as Measurable Improvement in the Environment: Lessons from a Supply Chain Program for Agriculture in the United States

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Abstract Around the world the private sector is increasingly committing to supporting sustainable agriculture through supply chain engagement. These sustainability efforts focus on one or more dimensions of economic, environmental or social concerns for agricultural producers and target goals to ensure adequate production, conserve natural resources and address global environmental challenges. Programs to establish industry standards of sustainability have been designed to address the most pressing local challenges for the producers, transparently document production practices, and provide requirements for adoption of alternative practices. Increasingly the question turns to whether these programs are resulting in environmental improvement. Programs that are designed specifically to achieve

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and verify measurable environmental impact are gaining acceptance but require re-thinking the design of sustainability programs to achieve that objective. Here we describe, and present lessons learned from, an example of this approach for commodity crop agriculture in the United States. Development of the approach is documented, with a focus on the scientific, technological and computational challenges of establishing accessible and meaningful metrics for assessing environmental change. This design can be adapted for other regions and agricultural systems where the key to improvement in environmental outcomes is productive co-development with all stakeholders.

Keywords Sustainable agriculture · Sustainability metrics · Environmental modeling · Supply chain

7.1 Introduction

Definitions for sustainable agriculture standards often vary based on region and crop system of focus, socioeconomic status and level of mechanization of producers, as well as ease of access to agronomic data. Three pillars of sustainability are typically considered - social, economic and environmental - in the context of the risks and needs associated with the crops and regions that the standards are designed for. In many cases, standards will focus on issues that are considered the highest risk for local communities or sourcing companies. A multi-sector global standards body, the ISEAL Alliance, states that credible sustainability standards must clearly define and communicate their objectives and approach (ISEAL 2013). Voluntary sustainable agriculture standards typically achieve this through defining a minimum threshold that shows a producer meets their definition of "sustainable" through adoption of prescribed practices and protocols.

Food industry standards have approached environmental sustainability of crop production by requiring changes in agronomic practices that are expected to result in improvements to the environment, without directly measuring or requiring change in environmental indictors. This simplicity works well for producers asked to comply with the requirements – it is relatively easy to understand and prove compliance with a change in agronomic practice. However, general acceptance of a practice as "good for the environment" does not always mean that adoption will have the same positive impact on every farm or for every farmer. Evaluating the impact is more complex than an accounting of practices adopted, and standards bodies often work with third parties, such as the Committee on Sustainability Assessment (COSA), to help them understand whether their programs on the ground are achieving environmental goals.

Another challenge for practice-based programs is farmer resistance to requirements imposed by outside entities who are not experienced in managing a farm, particularly if the requirements are technically challenging to adopt or increase the cost of production. Farmers may be skeptical of the value or accuracy of prescribing a practice as uniformly "better" without considering trade-offs. For example, many studies have found a positive impact on environmental outcomes from the use of winter cover crops, and they are often promoted as sustainable. However, when cover crops are grown in semiarid regions without irrigation, crop yields can decline due to the soil moisture and nitrogen used by the cover crop that is then not available to the cash crop (Reese et al. 2014). This does not mean that the practice cannot be beneficial, but rather that local social and environmental context needs to be used to guide adoption and providing technical assistance is critical to prevent negative experiences by participating farmers from reducing engagement in the standard. Scientific and technical guidance that accounts for the farmer's economic and cultural situation is necessary to achieve successful adoption of practices and ensure they achieve the desired environmental improvement.

For this reason, science-based approaches have emerged that include farmer participation at the design phase. Sustainability science has recognized the importance of co-development of knowledge as key to implementing successful solutions, particularly when it comes to land use (Verburg et al. 2013). Sustainable agriculture solutions to environmental challenges must account for the local economic context, land tenure, market situation, and community values. Understanding and incorporating this perspective into science-based metrics and programs requires investing time in consensus-building. This investment will improve chances of success by transforming the impacted community (farmers and rural communities) into advocates for the solutions. Developing a sustainability standard through a multi-stakeholder engagement process follows this co-development approach.

Recognizing the need for clear science-based guidelines, in 2016 the American Society of Agricultural and Biological Engineers (ASABE) published a sustainable agriculture standard (S629) based on the experience of Field to Market: The Alliance for Sustainable Agriculture. S629 documents a multi-stakeholder approach based on achieving, measuring and verifying continuous improvement in environmental outcomes (ASABE 2016). This standard defines legitimate sustainable indicators as science based, outcomes driven, and transparent. Continuous improvement in key environmental indicators identified by the stakeholders is to be measured by field-level metrics with progress evaluated over time. It is improvement over time, therefore, not a specific practice adoption or target, that becomes the driving force when following this standard. The process of setting aspirational and strategic goals for environmental improvements is a collaborative discussion between producers and their supply chains, conservation organizations, and other stakeholders.

This ability to measure, improve, and communicate improvement opens numerous possibilities to drive significant environmental change. Practice-based standards, by their design, recognize advanced, progressive producers who can meet the prescribed thresholds but leave behind producers who must overcome greater challenges to change their practices. This has the unintended effect of excluding producers who have the highest potential to improve on sustainability outcomes, precisely because they are the farthest away from achieving the standard. For real environmental impact to be achieved, a sustainability program must provide a point of entry for all producers to begin working towards improvements and eventual standards participation. However, from a supply chain risk mitigation perspective, the minimum performance thresholds approach is effective for reducing business risks and additional motivation is required to take on additional complexity to focus on environmental outcomes.

Another challenge with the practice-based approach is that as corporate sustainability goals become increasingly common, the full demand for sustainably sourced products cannot be met by just those producers who currently meet standards. Seventy-five percent of food, energy and finance companies in the Global Fortune 500 have set and are tracking publicly communicated high-impact sustainability goals (O'Nell and McElroy 2017). To meet these goals requires more than simply shifting to source from producers who already meet standards but rather working with all producers to provide the assistance necessary to improve their performance. In cocoa supply chains, for example, the World Bank has estimated that less than 40% of the world's cocoa supply is certified sustainable; however, substantial double counting exists as high performing producers gain multiple certifications (Kroeger et al. 2017). Thus, a new standard could emerge and be adopted, yet have little to no net impact on environmental outcomes if it only reaches the same producers who are already participating in sustainability standards.

This complexity has led many companies to look for alternatives that focus on achieving impact as the standard for sustainable agriculture. The ASABE S629 continuous improvement standard has been adopted by several multi-stakeholder agricultural groups in the United States and Canada (Thomson et al. 2017) who are co-developing programs to address unique sustainability concerns for commodity crops, specialty crops, dairy and meat production, with the farmers and producers as key stakeholders engaged in the development at every step. Such approaches require concerted effort to meet farmers where they are and provide mechanisms to move them along a continuum of improvement. Calculating environmental impact requires a science and technology focused approach to developing appropriate metrics and deploying appropriate models capable of robust assessments of outcomes.

While farmers seek solutions that can best recognize the complexity of farm decisions that they make, downstream companies and partner organizations are increasingly looking to standards to achieve and demonstrate progress toward meeting sustainability goals. Brands must also consider consumer desire for simple ways to make sustainable choices. Consumers are bombarded with information about food choices and have more products to choose from than ever before, so they seek simplification - products with short ingredient lists, certifications, callouts, or claims of greater product purity on the package (Hartman Group 2018). Supply chains therefore need complex scientific information to show that they are meeting their goals, while also needing to communicate their sustainability story in lay terms for consumers (Friedberg, 2018).

Field to Market: The Alliance for Sustainable Agriculture began as a multi-stakeholder roundtable with 12 participants in 2006 and has grown to include more than 140 member organizations representing the full spectrum of the commodity crop supply chain in the United States. Over a decade of development, metrics, technical approaches, engagement strategies and sustainability claims have been explored. Here we discuss insights and lessons learned on the scientific, technological and program development requirements for implementing this program. We focus first on program development, and then discuss the scientific requirements and technology considerations. We conclude by discussing how companies are engaging with the program to meet their sustainability commitments and communicate progress to stakeholders and consumers.

7.2 Multi-Stakeholder Program Development

The process of co-development for sustainability begins with convening all relevant stakeholders and establishing ground rules and guiding principles for discussion. Field to Market began in 2006 with a series of discussions that led to establishment of program guidelines and governance structure, including rights and obligations for participating organizations. Equal representation is elected from each of five identified sectors – Growers, Agribusiness, Brand & Retail, Civil Society, and Government/University. Program development is the result of member participation in structured work groups, standing committees and on the board of directors that maintain proportional representation for each sector. In addition, each member organization has a vote in a general assembly, where major program elements are considered for adoption. To ensure no sector is marginalized by inequality in the number of members, a majority of members in each sector must vote in approval at the general assembly for a motion to pass. This provides a sector-level veto power.

Early in the process, all participants agreed to adopt a continuous improvement approach. This decision was the product of exploration of common experiences with other approaches and was strongly influenced by the work of RESOLVE (RESOLVE 2012). The common objectives for the group included reducing impact on the environment from agricultural production, securing basic prosperity for producers, and ensuring continued productivity of the land. Certain key principles that were agreed on in early meetings were to establish a program that was focused on measured, scientifically-based environmental outcomes and did not prescribe specific production practices. The primary principles established to guide the initial Field to Market discussions are still followed today:

- Engage the full supply chain in program development and implementation
- Focus on commodity crops with unique traceability concerns
- Commit to data privacy for individual growers
- Driven by environmental outcomes
- Grounded in science
- Remain technology neutral
- Commit to transparency

By committing to these common principles, designated work groups can develop program elements and communicate them in common language to build internal and external stakeholder support and agreement.

Within Field to Market the needs of all participants define the program. For example, many sustainability programs have a requirement of an on-farm site audit to verify farmer provided data is correct, and to certify performance. The grower organization members of Field to Market felt that an audit requirement would lead to very low adoption of the program by US farmers, due to cost and cultural considerations. The commodity crops in Field to Market typically have very small profit margins and supply chains that cannot absorb additional production costs or pay a premium for program participation. To balance the need for quality assurance with the on-farm audit concerns, the alliance developed a verification program that focuses on external audits of the data collection system rather than individual farm operations. The trade-off is that individual farmers are not certified or verified as sustainable and cannot market themselves as such; however, they can enroll in a supply chain project with a group of farmers who share a common market. The organization or brand sourcing from the project farmers can then make sustainability claims on the represented commodity supply. Willingness to work through this on-farm audit concern has enabled greater trust and acceptance of the entire program by farmers.

At the time Field to Market was formed, several food and beverage companies were considering developing their own unique sustainability programs and reporting requirements for commodity crops sourced from US farms. The grower organizations became more enthusiastic about Field to Market as a common standard as more of these end customers became engaged in the collaborative program. Having multiple companies accept the same standard proved to be important to farmers, who often produce multiple commodity crops and sell into multiple supply chains. A common framework reduces the number of systems of reporting and verification that they must respond to, substantially decreasing the paperwork burden of multiple overlapping surveys.

Over the course of alliance building, work groups and standing committees developed program elements and guidelines around key topics including:

- Sustainability metrics development
- Claims and verification of company participation and progress
- Technology implementation
- Establishing program level goals and objectives
- Educational development for growers and agronomic advisors
- Recognition and awards program for leading farmers and organizations

Ad-hoc short-term work groups have also been used to develop in depth reports or recommendations on issues of importance to membership, including soil health and pest management. The program is integrated through a technology platform that serves as a calculation engine for metrics to assess farmer performance over time, and to analyze data for groups of farmers engaged in partnership projects. Thus, one important consideration throughout the history of the organization has been developing and maintaining science-based metrics that can measure environmental outcomes and be used to incentivize and track continuous improvement.

Early explorations of potential metrics were made through a national indicators report (Field to Market 2009) which examined the history of environmental change for major commodities in the US. The report also provided an opportunity for engagement of the scientific community through a peer-review process. That first report, which has been repeated twice to include additional data, crops and environmental indicators (Field to Market 2012, 2016) then led to development of field-scale metrics and a technology platform to collect data, calculate metrics and report on outcomes to both individual farmers and supply chain customers.

7.3 Sustainability Metrics Development and Implementation

Implementing the continuous improvement in environmental outcomes approach requires more than data collection from producers. Indicators and metrics for sustainability must be selected to support specific strategic goals (ASABE 2016). Farmers do not routinely measure or instrument their fields to collect data on such environmental outcomes as soil erosion or greenhouse gas emissions and doing so at a large scale is prohibitively complex and expensive. Thus, information provided by a farmer must be first run through an environmental model – or metric - to generate the environmental outcome indicator. Metric calculation approaches range from simple equations to complex biophysical models. The choice of a metric calculation method must balance the stakeholder needs to capture relevant field level information while considering data privacy concerns and providing results that are sensitive to changes in land management. Finally, the metrics must be scientifically sound and transparent for ease of communication with diverse stakeholders.

This adds a layer of scientific and technological complexity to program development and operation. Not only does the multi-stakeholder process need to come to agreement on what the indicator should reflect, but also the appropriate metric to model it (Fig. 7.1). Finally, appropriate technology is necessary to collect and store data and calculate the metric results in a reliable and time efficient manner.

In the United States, the USDA's Natural Resources Conservation Service has developed several conservation assessment tools for use in providing financing and technical assistance to farmers. Because of this, certain environmental outcomes identified by Field to Market can be measured using available tools. However, even when existing models are available, they must be adapted to the specific purpose defined by the alliance. Substantial collaboration with scientific communities and model developers is required to implement approaches that are acceptable to all stakeholders. Field to Market has used a range of approaches, from adoption of existing tools (e.g. Wagner 2013), to development of new tools through scientific collaborations (e.g. Linquist et al. 2018), to use of simple efficiency calculations in order to balance the needs for usability, transparency and scientific robustness.

7.3.1 Metric Approaches

Each metric that serves as an environmental outcome indicator in the Field to Market program is calculated using user input data, available public databases of environmental conditions (e.g. soils, weather), and a set of algorithms. We

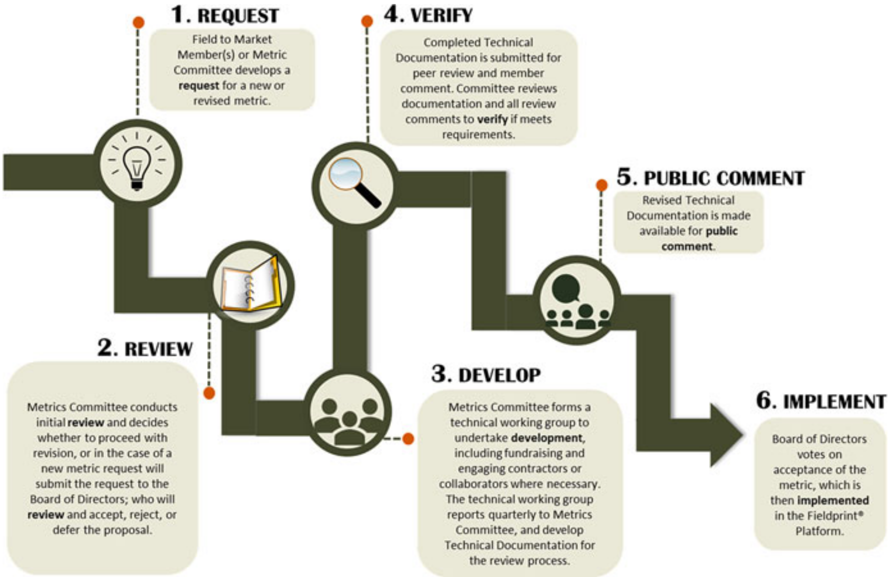

Fig. 7.1 Field to Market metric development and revision process roles and responsibilities

have defined four types of algorithms that can be applied – simple and complex quantitative approaches, biophysical models, and index models.

1. **Simple algorithm quantitative metrics**: A simple algorithm can be a useful approach to some environmental indicators. These have the advantage of transparency and simplicity in interpretation. An example is a simple indicator of land use efficiency that calculates the amount of land required to produce a unit of a crop. This approach provides a measure of efficiency, is quantitative, and is meaningful to both the farmer (yield) and to the supply chain (understanding of land requirements for sourcing).
2. **Complex algorithm quantitative metrics**: A complex algorithm may be required in the cases where single equations cannot capture all facets of an environmental outcome of interest. These also have the advantage of transparency but require additional guidance for interpretation by a user. An example is an energy use efficiency metric, which calculates energy requirements for different components of a farming operation (e.g. field operations such as planting, harvesting, irrigation, applications of fertilizer or manure, grain drying energy) and then aggregates these together for a comprehensive metric of the total energy required per unit of crop yield produced. This approach can provide useful quantitative feedback to farmers on their environmental performance and is also meaningful to the supply chain by providing quantitative details on the environmental impact of their sourcing.
3. **Index models:** Complex algorithms that result in indices of performance can also be applied. These tools give a qualitative score of risk or probability (e.g.

probability that a field is losing soil carbon), rather than a physical quantity (e.g. amount of carbon gained or lost). They have the advantage of generally being user friendly – requiring minimal amounts of data and providing results that are easy to interpret. However, they also rely more on subjective ratings or rankings, making them less transparent that the simple or complex algorithm approaches. An example is the Soil Conditioning Index of USDA which provides a measure of the likelihood that a field is gaining or losing soil carbon (Soil Quality Institute, 2003). It can be used with minimal inputs and provides useful feedback to a farmer based on just one year of information. Where an index model falls short, however, is in meeting supply chains' interest in understanding quantitative soil carbon amount and the potential for quantifying changes in carbon levels.

4. **Complex biophysical models:** The research community has developed many complex biophysical models that simulate crop growth, soil dynamics, hydrology and land-atmosphere gas fluxes. Such models generally require a certain level of scientific expertise to use. Computational advances mean that the barrier to using such models is not the hardware or software of the models; rather, the challenge is scientific. Such models must first be calibrated and validated against measurements to ensure the simulation is accurate for the intended production system and region. The calibration and validation processes ensure a known level of accuracy or uncertainty for the simulations, which is critical to the interpretation of results for the farmer and supply chain partners. The advantage is that complex models serve as aggregations of scientific knowledge on a topic and can provide a mechanistic description not just of what the outcome is, but why. The disadvantage is that such models, even when well documented in the literature, are less transparent to a non-scientific audience due to the complexity of the biophysical dynamics involved.

An additional challenge with using complex biophysical models is that they require substantial time and expertise to update with new findings from field research. For example, cover crops are rapidly being adopted across the US; however, relatively few years of data are available on many of the different combinations of cover crops and production systems, and thus their representation in crop growth models is still incomplete. The models lag the scientific findings from field research, which often lag the practices being implemented by innovative farmers. This delay can provide a frustration to users when the practices they have adopted for purposes of improving sustainability cannot be represented in the metric.

An example of a complex model used as a metric is the Integrated Erosion Tool (IET), composed of water (WEPP) and wind erosion (WEPS) components that simulate crop growth and hydrologic dynamics. This modeling system has been developed over several decades by USDA and specifically adapted for use as a tool to directly model erosion on individual fields, and provide actionable guidance to farmers. In this instance, the needs of Field to Market align closely enough with those of USDA - reducing soil erosion - that their scientific tools can be directly applied in the supply chain program. Simplified simulation models can be very good at comparing the impacts of practices on outcomes for a site or field over time; they are less useful for comparing impacts across different sites or fields because of the complexity of even the most well understood processes. This requires substantial technical coordination between organizations to implement effectively, which is addressed below in section 7.3.3.

7.3.2 Providing context to metrics

Participating farmers use their metric scores to identify areas for improvement; an essential component of a continuous improvement program is some measure to provide context to the metric scores to help the farmer understand if theirs are "high" or "low" compared to a known reference point. Ideally, a participant will measure multiple fields over time and begin to develop their own context, however a standard set of benchmarks helps to orient metric scores to a known point in time and space. Benchmarks provide important feedback to help users put numerical results on environmental outcomes in context. By visualizing whether their results are higher or lower than those of their peers (defined as the statistical sample survey by USDA, or by a community of farmers in a specific region), the results become more meaningful and provide immediate indications of where metric performance could potentially improve.

Field to Market enables two forms of benchmarks for users. State and national benchmarks for each crop can be derived for certain metrics using publicly available data. The Fieldprint Platform data analysis therefore includes the option to view the relevant state or national benchmark (Fig. 7.2). These benchmarks are possible due to data collected by USDA through statistically robust grower surveys of practices (e.g. USDA 2015; USDA ERS 2016; USDA NASS 2016a,b; USDA NASS 2014). An alternative approach is the calculation of a "Project" benchmark. A project is defined as a group of farmers collaborating with supply chain partners to measure, document and improve on environmental performance. Projects can range from fewer than five to more than five hundred farmer participants; they typically reflect a specific crop and a discrete geographic area. A project can establish benchmarks for all metrics for the crop of interest and view that as an additional point of reference for interpreting their results. One caveat is that benchmarks are not provided for the metrics represented by index models; as described above, such tools cannot be used to compare across different fields, and thus an average score across a group of fields would not provide a meaningful comparison point for project participants.

Providing individual metric scores and appropriate benchmarks is not enough to ensure change or improvement. Rather, these technical elements provide the starting point for developing programs of education, technical assistance and partnerships that can make use of the metrics to guide changes in farmer practices that will lead to environmental improvement. Thus, while measurement is critical to managing for improvement, it is not sufficient to achieve change without economic or social motivation.

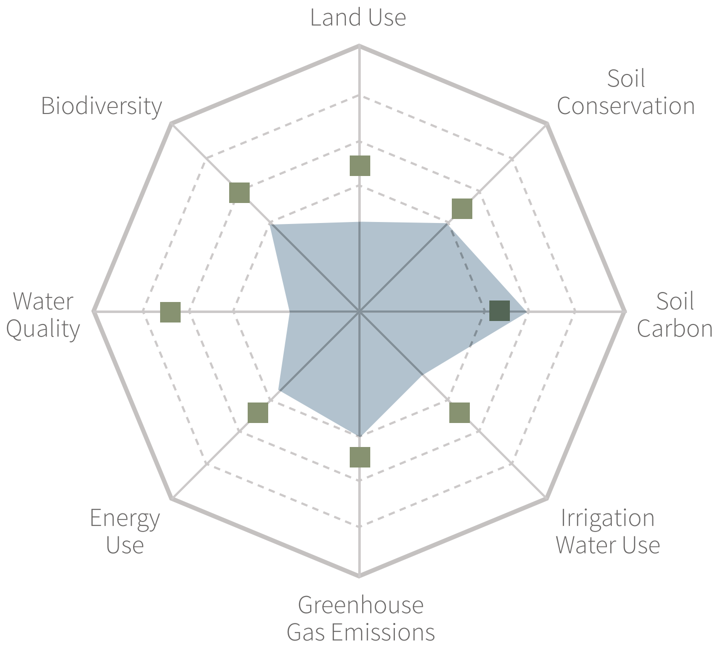

Fig. 7.2 Example of a field level score from the Fieldprint Platform with the state average benchmark included for context

7.3.3 Technological considerations for metric calculation approaches

Of the metric approaches described above, the simple and complex algorithms and index models can generally be implemented in a web-served computer program with relatively few concerns about computational power requirements or performance. Complex biophysical models, on the other hand, involve many moving parts and require considerably more planning and coordination for keeping versions aligned, accommodating peak user loads, provisioning input data, and diagnosing and solving problems. Despite more internal complexity, biophysical models provide a more realistic sense of crop management and its impact on resource conditions of the farm field. Here we describe the technological considerations for deployment of a complex model in a supply chain tool to illustrate the challenges and highlight opportunities for future growth.

Field to Market collaborates with member organizations USDA-NRCS and Colorado State University to operate two biophysical models supporting the soil conservation metric. Initially, the Revised Universal Soil Loss Equation (RUSLE2) was used to calculate water erosion and Wind Erosion Prediction System (WEPS) to calculate wind erosion. Both models provide a measure of soil lost based on dynamic simulation of the cropping system, the dominant soil properties, and climate conditions.

Field to Market chose these two models in large part because USDA-NRCS used them to support the development of conservation plans with farmers and ranchers, providing the basis for cost-sharing agreements to apply conservation practices to control erosion and improve soil health. To ensure farmers participating in both programs receive consistent messages regarding their soil sustainability, the versions of the models used in the Fieldprint Platform are aligned with the versions of those used by USDA-NRCS. This alignment requires on-going coordination to keep synchronized and abreast of scientific developments and technology changes. For example, the Water Erosion Prediction Project (WEPP) model recently replaced RUSLE2 in the Fieldprint Platform.

WEPP and WEPS are process-based models developed by the USDA Agricultural Research Service. WEPP simulates water erosion from a representative slope in a farm field while WEPS simulates wind erosion on a representative region in a farm field. USDA research scientists began development of WEPP and WEPS in the mid-1980s, and although they both used common algorithms and data for crop growth, hydrology, management, soils, weather, and other components, they initially deployed as self-contained stand-alone desktop applications, each with their own supporting code repositories and databases (Flanagan et al. 2007). The advent of high-speed broadband networks in the 2000s enabled deployment of these models as web services using a cloud platform in a data center for centralized and remote deployment to multiple users simultaneously (David et al. 2014). With multiple services and databases supporting the Field to Market soil conservation metric, version management is necessary to ensure orderly operation, maintenance and scientific credibility.

Field to Market also provides a Fieldprint Platform Application Programming Interface (API) to member organizations who wish to incorporate the sustainability metrics into their own technology platforms already used by farmers. This capability benefits users by reducing the level of effort and data entry required to calculate the metrics as many of the Platform data requirements are already collected automatically through the technology platforms. These applications also access the USDA erosion model and data services to calculate the soil conservation metric. Increasing demand for these services has led to container-based deployments to separate model version control from IT operations and support rapid scaling of computing resources (David et al. 2016; Traff et al. 2018). With the advent of software containers, model developers can isolate an application and its software dependencies from physical servers. Orchestration tools have made it possible to dynamically deploy these containers seamlessly across a cluster of machines.

As an example of model demand, over an 11 month period, the Fieldprint Platform executed 1.16 million service calls (343 thousand RUSLE2 simulations, 302 thousand WEPS simulations, and 515 thousand soil data payloads). The Fieldprint Platform request load typically ranged from 2–5 thousand simulations per week per model, whereas two API partners requested batch simulations exceeding 2000 requests per model on 36 days during the 11 months, as high as 18,500 requests per model. Container-based deployment enabled quick adjustment to accommodate the variation between base load and periodic large batch requests.

Although the demand for these services is low compared to systems in the retail or financial sectors, the erosion model services have much longer run times. For example, the WEPS model service will simulate a crop for 50 years at a daily timestep, which can take up to 1 min to execute. Therefore, computing resources are configured to accommodate several simulations running concurrently when demand is high. Also, systems are established to request model simulations in asynchronous mode, enabling users to work on other metrics while the erosion models are running.

As the Fieldprint Platform user community has grown, service availability has become increasingly important. Infrastructure-caused outages can be minimized by deploying model services through a commercial hosting service with hardened and redundant facilities, but the costs must be weighed against the level of availability. Erosion simulations involve the orchestration of the two models with eight supporting data services, and four databases. Enough system monitoring and response support and reducing recovery complexity through an automated streamlined DevOps process (David et al. 2016) minimize software and data-caused outages. Longer term solutions have also been identified including moving to next generation surrogate models that leverage machine learning methods (Serafin et al. 2018). Surrogate models can be developed from millions of simulations by their parent process models, having fewer inputs, lightweight, fast, with many fewer moving parts; the process-based models can then be reserved for detailed analysis.

In addition, technology systems must be configured to comply with data privacy considerations. Agricultural producers and other sustainability stakeholders do not want personal and farm field location-specific data in the public domain. Technical steps taken to ensure data privacy include:

1. excluding all personal data in service request and response payloads,
2. short (seconds) time to live service requests and responses at the backend, and
3. encrypting service requests and responses in the backend.

The erosion model services need to know the nearest climate and wind stations, as well as the representative soil for the farm field to be assessed, inputs which do not directly associate to farm field boundary or centroid geometry. Where and how long the output for each simulation is stored is defined in data privacy policies and agreements between participating farmers, Field to Market, and project partners.

The erosion model services rely on soil data from Soil Data Access (USDA-NRCS 2018); climate data from Cligen (USDA-ARS 2018), Windgen (Wagner 2013), and PRISM (PRISM Climate Group 2018); and cropping system data from the Land Management Operations Database (Carlson et al. 2018). NRCS periodically updates and continues to host these data stores and tools through on-going stewardship support. The long-term viability of sustainability programs using the erosion models and even the simpler tools and methods depend on the stability of these resource data sources.

The soil erosion models, while the most complex used within the Fieldprint Platform metrics, are less complex than biophysical models that produce dynamic quantitative simulations of soil carbon dynamics or nutrient loss in field runoff (e.g. DayCent, APEX, etc.). The developments and experience described here increase the technological capacity of the program to consider adoption of more complex models over time. In addition, other recent technology developments, such as the use of remote sensing to generate farm management data products that can be used to populate environmental models (Begue et al. 2018), may change what is feasible for metric calculations in a supply chain program.

7.3.4 Complex models as tools for sustainability assessment

While the outcomes-based continuous improvement approach is relatively new to the sustainability community, the use of models and tools for assessing environmental outcomes of agricultural practices has been an active research and development field for decades (Jones et al. 2017). Models have been applied for research at the field, regional and global scale, and have also been applied to specific decision support and information assessments. For example, complex models are applied annually to produce estimates of greenhouse gas emissions from US agriculture to inform government reporting into a UN treaty (USEPA 2018).

Sustainable agriculture metrics development can be informed by looking at such approaches that have shared considerations of scientific robustness, practical limitations and the need for transparency. Examples include tiers of complexity of measurements to allow for each user to calculate the best measure they can with available data and resources (IPCC 2006) or may focus in on feedback requested by the user (COMET-FARM). The metrics selected should always be specific to the purpose, and typically some modification of the modeling approach will be necessary when applied in a new program to ensure usability by non-experts and transparency requirements.

One example can be found in the approach of the Intergovernmental Panel on Climate Change (IPCC), which issues guidelines to countries for their required reporting of greenhouse gas emissions into a United Nations treaty (United Nations Framework Convention on Climate Change) (IPCC 2006). Emissions of nitrous oxide from soils are a critically important component of greenhouse gas emissions from agriculture and a high priority to reduce. Guidelines were produced to standardize country reporting and provide an example of the hierarchy of complexity for environmental outcome measures. A Tier 1 calculation is designed to estimate emissions with minimal information - a simple multiplier is used with nitrogen application rate. This allows all countries to report some information, however the indicator is limited in both accuracy and in providing opportunities for improvement. The second Tier provides guidelines for establishing individual factors based on environmental factors such as climate and soil that are known to influence soil emissions; these approaches are more complex but offer a more accurate accounting. The third Tier provides guidelines for using complex environmental models to calculate nitrous oxide from all agricultural lands according to both biophysical processes and land management practices. While this provides the most accurate and robust measure, it is also the technologically most difficult to implement and requires advanced modeling capabilities as well as access to high quality data on land management.

These Tiers were designed as an inventory methodology to be applied by experts. In the case of sustainability indicators that are intended to be used by a broad group of land managers, farmers and their advisors, there is an additional barrier to using complex biophysical models. While these can provide detailed mechanistic simulations of impacts, they require sufficient observed data and experience in calibration of model parameters to such observed data. For decision support purposes, therefore, such complex models are pre-calibrated and simplified at the level of the interface. One example is the COMET-Farm model, a user-friendly interface that runs a more complex biophysical model underneath. Under development at the Natural Resources Ecology Lab (NREL) since 2004, COMET-Farm is now a stand-alone web-based scenario tool for evaluating greenhouse gas emissions and soil carbon storage on farms. (Paustian et al. 2018). It has been used by NRCS field offices for assessments on an estimated one million acres annually since 2015.

Appropriate tools may have been developed for other purposes. For example, in the US, the USDA has invested decades of research and model development into farmer-facing tools for assessing conservation practice adoption opportunities. Several of these can be adapted to serve as sustainability indicators, as they are designed to be valuable to farmers and to be scientifically rigorous yet easy to use. However, they must be carefully assessed in the multi-stakeholder framework to ensure they can be used to represent the environmental outcome of interest. Another consideration is that such tools may be geographically specific or limited; in this case, the tools are readily available and tested only for the United States, while many brands and retailers are global and collect and analyze data across continents. These examples do, however, still provide important insights for development of environmental outcome metrics in sustainable agriculture.

The more complex the environmental outcome, the more challenging it has been to develop models that can be applied in a decision support or assessment context like a sustainability program. For example, increasingly over the past two decades, concerns regarding water quality - the loss of nitrogen and phosphorous in surface and subsurface runoff from farm field – have become a critical sustainability outcome of concern for communities and organizations operating in the United States. While several research models have been developed and applied over broad geographies they have not been focused on field-scale dynamics. It is the individual field scale where feedback to a farmer on their environmental footprint is most impactful. Models like WEPS and WEPP for soil erosion are relatively mature after several decades of development. By comparison water quality metric development is still in early phases with no clear consensus on a suitable edge of field model and insufficient data available for model calibration at the field scale across wide geographies. Models like RUSLE2 were critical to the development and assessment of soil conservation success across the United States - without such metrics the soil conservation movement would not have achieved the reductions in erosion that have been observed over the past several decades. There is a critical need for development of the next generation of water quality models with the same rigor and levels of investment that were put into soil erosion metrics. This will require significant investment in field research and monitoring to gather appropriate water quality calibration data.

Sustainability metrics and models also need to be viewed as valuable and easy to use by farmers. During the development of metrics, it is critical to have farmer input to ensure they can and will use the metrics once developed. Farmers have virtually no way to measure their operations against their neighbors so are very interested in anything that provides the ability to “grade” the success of their operation. The ability to compare your operation to your neighbors, anonymously, is one key way to ensure interest. Field to Market is also evaluating the use of scenario tools that allow farmers to run “what if” scenarios. This is a no-cost way to test out various production systems to see if they result in better sustainability scores and overall production efficiency.

The scientific and technical challenges to developing an effective continuous improvement program can be addressed in several ways, using available tools and expert guidance specific to the program scope of region and crop systems. However, to serve as an effective program for consumer facing companies means that the metrics, results and improvements must be communicated to a general audience. This challenge - developing effective communications of what continuous improvement means, why it is important and how it connects with environmental sustainability goals – requires a shift in perspective of what sustainability is. Consumers have become familiar with standards that promise that certain actions were or were not taken within a supply chain, but not with the nuances of change that are the cornerstone of continuous improvement. Developing a methodology for calculating change, verifying data and communicating performance through the supply chain is as critical to successful adoption as developing science based metrics.

7.4 Communicating Continuous Improvement

Achieving and documenting continuous improvement is a long-term process requiring strong partnerships and commitment to a shared vision and objectives. While Field to Market develops the metrics, individual member companies are responsible for implementation of the program by establishing a project, collecting data, interpreting benchmarks, establishing baselines and incentivizing change results in knowledge transfer and shared learnings across the diverse viewpoints of a commodity supply chain (Fig. 7.3). Despite the challenges involved, agricultural supply chain organizations across North America have begun implementing the continuous improvement approach, including the US Roundtable for Sustainable Beef, the US Poultry and Egg Federation, the National Pork Board, the Stewardship

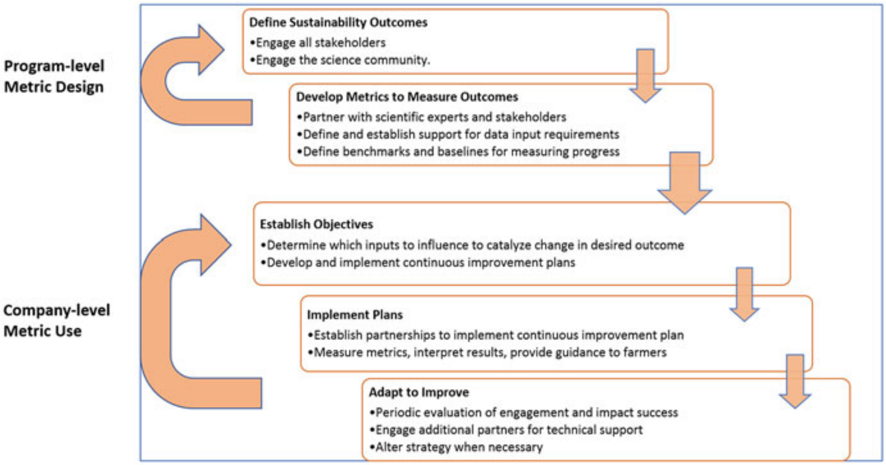

Fig. 7.3 Flow of metric development and program implementation

Index for Specialty Crops, the Canadian Fieldprint Initiative, and the United Soybean Federation.

Industries that have become familiar with practice-based certification models must overcome pre-conceptions to make the shift to outcomes-based sustainability. Practice-based standards require a certification system to assure that companies employing them are complying with performance thresholds, criteria and other requirements. Many schemes such as the Marine Stewardship Council[1] and Fair-trade[2] use the credibility and rigor that is built into their assurance systems to support consumer-facing labels and claims. Growers receive third-party audits to ensure compliance with standards, and, if they are found to comply, are certified against the corresponding standard. Companies that wish to buy and label certified product from these growers also receive chain of custody audits so that these companies can prove that products they label and sell as certified came from a certified entity. Procuring and labeling certified products provides corporate buyers with a mechanism to outsource supply chain risk while also communicating sustainability to consumers right on the packaging.

A key consideration in making a shift to a continuous improvement model is the time that is required to show measurable improvement on the ground. Companies want to communicate to their consumers that they, and the entities that they source from, are sustainable today, or will be within a specific time frame. These are straightforward and easy to understand statements whereas communicating the nuance of continuous improvement means accepting the risk of not being able to communicate a current threshold of sustainability. This creates a communications

[1] https://www.msc.org/for-business/use-the-blue-msc-label

[2] https://www.fairtrade.net/about-fairtrade/the-fairtrade-marks.html

challenge and need for clearly defined statements and claims that are transparent and verifiable.

The first question that arises when considering how to demonstrate and communicate continuous improvement is how to define the state that is being improved upon. While valuable reference points, benchmarks (described above) typically will represent a broader population than the group interested in documenting their specific improvement. Since the objective of continuous improvement is to achieve change over time, an appropriate baseline, or reference point for change, will represent the historical outcomes that are targeted for improvement, and the actors responsible for driving change.

Field to Market works on the assumption that the individual land manager (farmer) is the unit of change (Floress et al. 2017); that is, a change in farmer perception or behavior as a result of knowledge, skills or assistance gained from participating in a sustainability program is what will drive changes in practices and, eventually, changes in environmental outcomes. Farmers are adaptive learners and as they test and adopt new practices that perform well in a crop system, they are likely to adopt these practices over time across the lands they farm.

Baselines therefore should be defined specifically for the target farmer and crop combinations within sourcing regions, or projects. The technical calculations to develop baselines for a group should be the same as for a project benchmark; however, the population of farmers, fields and years of analysis must be specific to the metric being analyzed for a continuous improvement statement, or claim. In addition, baselines must account for multiple years of historical performance to account for the fact that some of the most important determining factors – weather and climate variables – for the metric calculations vary considerably from year to year.

In Field to Market's program, supply chain companies sponsoring projects with groups of farmers can only make claims of improvements in environmental impact after a third-party has verified that a data set of five or more years shows such improvement. In order to enable communication in the earlier years of engagement, companies can also make measurement claims - static, one-year claims of snapshots of activity at the project level, including size of project by number of growers and acreage involved. The multi-stakeholder group continues to discuss additional claims that might be made as program development and adoption continues.

7.5 Conclusions

Measurable improvement in environmental outcomes on the ground requires validated science-based metrics, technology support, long-term producer engagement, planning, investment, and a credible process for describing the journey of continuous improvement. While it is understood that measurable, sustained change in any environmental outcome takes time, many participants may underestimate the complexity of designing and sustaining long-term projects. Producers must first be recruited to participate which requires building relationships and providing incentives. Following recruitment, producers and related stakeholders must be retained in the project over multiple years. To incentivize this sustained engagement, projects require credible ways to report on progress being made towards improvement goals before those goals have been reached.

Despite the complexity and challenges across the multiple dimensions of environmental science, technology and stakeholder engagement, the concepts of continuous improvement and measureable environmental outcomes are increasingly viewed as the objective of sustainable agriculture programs in the private sector. Consumer and public awareness of environmental challenges means enhanced scrutiny of personal responsibility and purchasing choices to ensure reductions in environmental impact and agricultural lands that can support continued production into the future.

The lessons learned from the experience of the Field to Market alliance can be used to help inform development of sustainable agriculture programs.

- Inclusion and meaningful involvement of all stakeholders and affected sectors of the supply chain is necessary to establish the trust necessary for collaboration.
- Establishing core principles and revisiting them periodically will help to ensure all members stay engaged and on board with the same objectives.
- Establishing strong relationships with relevant scientific communities engaged in research relevant for sustainability metrics improves the credibility and transparency of the metrics and results.
- Identifying the right approach for measuring a specific outcome must balance the needs of all the users with the complexity of available tools and state of scientific knowledge and tool development about the outcome.
- Ensuring the available technology resources can be engaged to support the scientific tools.
- Ensuring farmer and company commitment to participate for the length of time required to achieve continuous improvement is essential to long-term success.
- Establishing an ongoing participatory process to consider improvements and track developments in science and modeling helps maintain member engagement and ensure transparency and communicate scientific information to diverse audiences among the stakeholders. An emphasis on consensus building is critical.
- Engagement with the scientific community to inform program development as well as identify gaps and needs of the sustainable agriculture and farmer communities can lead to research investment by funding organizations and increased collaboration with researchers.

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References

ASABE (2016) ANSI/ASABE S629 Framework to Evaluate the Sustainability of Agricultural Production. Developed by the ASABE technical committee ASE-16 Engineering for Sustainability. Approved by ASABE and ANSI June 2016. 11p

Begue A, Arvor D, Bellon B et al (2018) Remote sensing and cropping practices: A review. Remote Sens 10(1):99. https://doi.org/10.3390/rs10010099

Carlson J, Yaege L, Poore J et al (2018) Standardizing cropping system data for integrated agricultural resource assessment. In Mazdak Arabi, Olaf David, Jack Carlson, Daniel P. Ames (Eds.) 9th International Congress on Environmental Modelling and Software, Fort Collins, Colorado, USA. https://scholarsarchive.byu.edu/iemssconference/2018/.

David O, Lloyd W, Rojas K et al (2014) Model-as-a-Service (MaaS) using the Cloud Services Innovation Platform (CSIP). In Daniel P. Ames, Nigel W.T. Quinn, and Andrea E. Rizzoli (Eds.) International Environmental Modelling and Software Society (iEMSs) 7th International Congress on Env. Modelling and Software, San Diego, CA, USA. https://scholarsarchive.byu.edu/iemssconference/2014/.

David O, Arabi M, Carlson J et al. (2016) Supporting collaborative model and data service development and deployment with DevOps, American Geophysical Union (AGU) Fall Meeting, December 12–16, 2016, http://abstractsearch.agu.org/meetings/2016/FM/H41B-1327.html.

Field to Market: The Keystone Alliance for Sustainable Agriculture (2009) Environmental Resource Indicators for Measuring Outcomes of On-Farm Agricultural Production in the United States. January 2009, Keystone, CO. Available from: www.Fieldtomarket.org.

Field to Market (2012) Environmental and Socioeconomic Indicators for Measuring Outcomes of On-Farm Agricultural Production in the United States (Version 2) December, 2012. Keystone, CO. Available from: www.Fieldtomarket.org.

Field to Market: The Alliance for Sustainable Agriculture (2016) Environmental and Socioeconomic Indicators for Measuring Outcomes of On Farm Agricultural Production in the United States (3rd Edn). ISBN: 978–0–692-81902-9. December 2016. Washington, DC. Available from: www.fieldtomarket.org/national-indicators-report-2016/

Flanagan DC, Gilley JE, Franti TG (2007) Water Erosion Prediction Project (WEPP): development history, model capabilities and future enhancements. Trans ASABE 50(5):1603–1612

Floress K, Garcia de Jalon S, Church SP et al (2017) Toward a theory of farmer conservation attitudes: dual interests and willingness to take action to protect water quality. J Environ Psychol 53:73–80

Friedberg S (2018) Assembled but unrehearsed: corporate food power and the ‘dance’ of supply chain sustainability. J Peasant Stud. https://doi.org/10.1080/03066150.2018.1534835

Hartman Group (2018) Organic and natural 2018 study overview. www.hartman-group.com

IPCC (2006) In: Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K (eds) IPCC guidelines for national greenhouse gas inventories, prepared by the national greenhouse gas inventories programme. IGES, Japan. http://www.ipccnggip.iges.or.jp/public/2006gl/vol4.html

ISEAL (2013) Principles for credible and effective sustainability standards systems, ISEAL Credibility Principles, ISEAL Alliance, 2013

Jones J, Antle J, Basso B et al (2017) Brief history of agricultural systems modeling. Agric Syst 155:240–254. https://doi.org/10.1016/j.agsy.2016.05.014

Kroeger A, Bakharty H, Haupt F et al (2017) Eliminating deforestation from the Cocoa supply chain. World Bank Report. March 2017. Washington DC http://documents.worldbank.org/curated/en/876071495118818649/pdf/115144-REVISED-20170530-Cocoa-final-updated.pdf

Linquist BA, Marcos M, Adviento-Borbe A et al (2018) Greenhouse gas emissions and management practices that impact emissions in US rice production systems. J Environ Qual. https://doi.org/10.2134/jeq2017.11.0445

O’Neill R, McElroy S (2017) Targeting value, setting, tracking & integrating high-impact sustainability goals. http://s10458.pcdn.co/wp-content/uploads/2017/12/sa-es-targeting-value.pdf

Paustian K, Brown K, Easter M (2018) Farm-scale full GHG accounting with the COMET-Farm tool. In Mazdak Arabi, Olaf David, Jack Carlson, Daniel P. Ames (Eds.) 9th International Congress on Environmental Modelling and Software, Fort Collins, Colorado, USA. https://scholarsarchive.byu.edu/iemssconference/2018/.

PRISM Climate Group (2018) PRISM climate data, Northwest Alliance for computational science and engineering, http://www.prism.oregonstate.edu

Reese CL, Clay DE, Clay SA et al (2014) Winter cover crops impact on corn production in semiarid regions. Agron J 106(4):1479–1488. https://doi.org/10.2134/agronj13.0540

RESOLVE Steering Committee of the State-of-Knowledge Assessment of Standards and Certification (2012) Toward sustainability: the roles and limitations of certification. RESOLVE, Inc, Washington, DC

Serafin F, David O, Dozier A et al (2018) Framework-enabled meta-modeling. In Mazdak Arabi, Olaf David, Jack Carlson, Daniel P. Ames (Eds.) 9th International Congress on Environmental Modelling and Software, Fort Collins, Colorado, USA. https://scholarsarchive.byu.edu/iemssconference/2018/.

Soil Quality Institute (2003) Interpreting the soil conditioning index: a tool for measuring soil organic matter trends. Soil Quality – Agronomy Technical Note No. 16. USDA NRCS. April 2003

Thomson AM, Ramsey S, Barnes E et al (2017) Science in the supply chain: Collaboration opportunities for advancing sustainable agriculture in the United States. Agric Environ Lett 2:170015. https://doi.org/10.2134/ael2017.05.0015

Traff K, Wible T, Yaege L, et al (2018) Building containerized environmental models using continuous integration with Jenkins and Kubernetes. In Mazdak Arabi, Olaf David, Jack Carlson, Daniel P. Ames (Eds.) 9th International Congress on Environmental Modelling and Software, Fort Collins, Colorado, USA. https://scholarsarchive.byu.edu/iemssconference/2018/.

USEPA (2018) Inventory of U.S. greenhouse gas emissions and sinks: 1990–2016. US Environmental Protection Agency, Washington, DC. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks

USDA (2015) Summary report: 2012 national resources inventory. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. 210 pages. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd396218.pdf

USDA ERS (2016) ARMS farm financial and crop production practices database. All data accessed June–August 2016. http://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/tailored-reports-crop-production-practices.aspx

USDA NASS (2016a) National agricultural statistics service quick Stats 2.0 Database. All data accessed June–August 2016. https://quickstats.nass.usda.gov/

USDA NASS (2016b) Agricultural chemical usage report. Online data for all crops after 2009. All data accessed June–August 2016. https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/

USDA NASS (2014) 2013 Farm & Ranch Irrigation Survey. In 2012 Census of Agriculture. Available from https://www.agcensus.usda.gov/Publications/2012/Online_Resources/Farm_and_Ranch_Irrigation_Survey/

USDA-NRCS (2018) Soil data access – query services for custom access to soil data, https://sdmdataaccess.nrcs.usda.gov.

USDA-ARS (2018) Cligen stochastic weather generator, https://www.ars.usda.gov/midwest-area/west-lafayette-in/national-soil-erosion-research/docs/wepp/cligen/.

Verburg P, Mertz O, Erb K-H et al (2013) Land system change and food security: towards multi-scale land systems solutions. Curr Opin Environ Sustain 5:494–502. https://doi.org/10.1016/j.cosust.2013.07.003

Wagner (2013) A history of wind erosion prediction models in the United States department of agriculture: the wind erosion prediction system (WEPS). Aeolian Res 10(2013):9–24. https://doi.org/10.1016/j.aeolia.2012.10.001

Chapter 8
Local Aspects of Water Quality Assessment as the Basis for Regional Sustainable Development

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Abstract The natural ecosystem state including aquatic one is crucial for sustainable regional social and economic development. The key elements of effective water resource administration are evaluation and forecast of surface water quality. This article provides an overview of international and Russian experience in surface water quality assessment. Many countries such as the EU countries, EECCA countries, the USA, Canada, the UK, etc. carry out water quality assessment on the basis of local standards depending on the content of pollutants in water bodies. As for Russia, generally accepted water quality indices are still based on the maximum permissible concentrations of pollutants that do not take into consideration specific regional conditions of the formation of chemical compositions and water quality of aquatic ecosystems. Therefore, there is a need to develop regional standards for the Russian Federation which focus on the chemical content of water bodies and take into account natural hydrochemical background. Local natural features of water bodies can be used in many ways: as a basis for assessing the 'chemical status' of the river ecosystem; for harmonization of water quality requirements with other countries and for the elaboration of ecologically justifiable water protection measures as the necessary foundations for environmentally sustainable development.

Keywords Water quality · Pollutants · Hydrochemical background · River ecosystem · Chemical status

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8.1 Introduction

Nowadays, relevant assessment of water resources status remains a live issue and one of the priority problems in the field of environmental protection and the Concept of Sustainable Development. Ecological water resources monitoring should identify water quality variability and the ecological status of aquatic ecosystems considering their functional aspects. It is important to predict some possible consequences of adverse external impacts. The state of natural ecosystems is crucial for sustainable regional social and economic development.

The Concept of Sustainable Development is easy to understand, but difficult to implement. It assumes strengthening of environmental priorities in the state policy and ecologically balanced approach to economy restructuring (Khovansky et al. 2000; Brodhag and Taliere 2006). Rational use of water resources has a great value for the Concept of Sustainable Development. The deficiency of good quality fresh water and gradual decreasing of its stocks become the result of anthropogenic pollution and remain vital global problems.

Hence, the assessment and forecast of the surface water quality changes are the basic elements of effective water resource administration. To prevent the aquatic ecosystems degradation, stabilize the ecological situation, and improve the water resources quality, it is necessary to base water policy on relevant information regarding the regional surface water quality taking into account the natural background concentrations (NBCs) of their dissolved chemicals.

Water quality assessment based on background regional standards of the pollutants content in water bodies has already been conducted in the EU countries, the UK, the USA and Canada and part of EECCA. Generally accepted water quality indices based on the pollutants maximum allowable concentration (MAC) are still used in the Russian Federation (RF). These indices are the same for the huge country's territory. This paper provides a brief overview of international and Russian experience in assessing the surface waters quality. It is shown that nowadays the RF needs to elaborate regional standards for the pollutants content in water bodies taking into account the NBC. The authors suggest an original methodology for their calculation based on the ideas of the ecosystem functioning stability from the point of nonlinear dynamics view.

The authors also describe results from the analysis of water quality assessment using the unified standards (MACs) for RF territory and compare them with the individual ones for the river basin NBC. It was found out that complex water quality assessments conventionally applied in the RF were hardly suitable for the direct use of NBC. The improvement of complex assessments is needed not to reach the requirements' coherence to the surface waters quality between Russia and other countries, but to develop agreed standards for surface water quality in accordance with the principles set out in the Water Framework Directive (EC 2000) is required.

8.2 The Reasons for Regional Differences in the Chemical Composition of Surface Waters

Usually, concentrations of chemicals in water bodies located in different climatic conditions are variable and typical for the certain area. This heterogeneity occurs due to both natural factors and the type of the anthropogenic impact, which is different in various regions (Alekin 1970). Distribution of chemical elements in natural waters depends on the environment type (geochemical environment) and the properties of the elements themselves. In general, the process obeys the basic geochemical regularities. There is a certain territorial pattern in the content of elements and the chemical composition of river waters (i.e. hydrochemical zonality) clearly noticeable on the Russian territory due to its latitudinal spread. For example, there is an overall trend of increasing water mineralization and main ions content in most of the European parts of Russia from north to south and from west to east. This is a natural consequence of the aggregate physical and geographical conditions affecting the formation of the chemical composition of river waters. Northern territories are characterized by higher geosphere humidity and the predominance of less mineralizing soil waters (such as tundra, swamp, forest) and large areas of permafrost. In contrast, the precipitation decreases southwards, the climate dryness increases, podzolic soils are replaced by chernozems or chestnut soils, and in the southwest – by solonchak soils, highly mineralizing waters (Alekin 1970).

In some cases, large rivers cross different natural zones and modify hydrochemical zonality. These rivers are complex systems that combine many small rivers watersheds often with different hydrological regimes underlying strata compositions and climatic conditions. As a rule, large rivers have a great length and cross different natural zones. Although the chemical composition of large rivers integrates water properties of individual tributaries, often it does not correspond to the conditions for their hydrochemical formation in a given area.

The detection of chemicals NBC in natural waters with the allocation of zones of high and low content is especially important from the point of view of assessing the environmental pollution, especially in the areas of intensive economic development. Background concentrations are a kind of “benchmark” that allows reliably estimate the rate of anthropogenic impact (Levich et al. 2011).

At present, there is no unified methodology for calculating NBC of chemicals in the river water. The main challenge in assessing NBC of chemicals is the selection of water body sites not affected by anthropogenic impact as well as the availability of long-term observations of the chemical concentrations. In fact, there hardly ever can be found any river sections unaffected by the anthropogenic impact and a sufficient number of observations for valid estimation. The selection of background sites for the NBC calculation can be made on data:

1. obtained at water bodies (or their parts) located on the nature reserve territories, or areas remote from large industrial centers which have not been the subject of intensive anthropogenic impact;

2. characterized by ecosystem stability of their hydrobiocenosis conditions.

Some methodological approaches and techniques for identifying NBC in water bodies are considered below.

8.3 A Review of International and Russian Experience in Assessing the Surface Water Quality

Surface waters are multicomponent natural objects. Nowadays, more than 1300 chemical compounds are controlled in the aquatic environments and their number is gradually going to increase. The analysis of such a great number of pollutants is certainly impossible because it is laborious, expensive and time-consuming (Gagarina 2012).

The challenges of surface water quality evaluation are directly related to the problem of ecological standardization of anthropogenic loads on ecosystems aimed at maintaining their natural diversity and preserving the structure and sustainable functioning of the corresponding ecosystems. Modern assessment of water quality and water conditions includes a set of criteria for structural and functional analysis of aquatic life, its epigenetics and of the component composition variability of the aquatic environment. There are two main approaches commonly used for water quality assessment: physicochemical and biological ones. Each of them has its own advantages and disadvantages (Nikanorov 2005). The physicochemical approach allows carrying out so-called ‘point’ evaluation of water quality, determining contamination form and its nature as well as some ‘side’ effects. The main advantage of this approach is that its results are accurate and quantitative data can be used for evaluating the compliance of water quality with existing standards. The biological approach makes it possible to estimate the generalized contamination impact on the aquatic ecosystem, determine the disturbance rate and allows calculating an integral criterion of water quality.

Some of the most distinct methodological approaches are considered below. They are applied to estimate water quality and ways to identify background characteristics for water bodies in Russia and abroad.

Water quality assessment in **Western European countries** implements three main functions. The first of them is the exclusion of deliberately unacceptable environmental damage. Ecological deprivation is frequently calculated into the monetary equivalent. Failure to comply with the specified standards entails economic sanctions. The second function is to regulate anthropogenic burden and costs for nature conservation in order to provide a background for self-restoration of disturbed ecosystems. However, environmental measures should not impede economic growth. The third function is to stimulate anthropogenic impact reduction on the environment (Vorobeychik et al. 1994).

The first attempts to assess the surface water quality were taken in 1912 in England by the Royal Commission on wastewaters (Drachev 1964). Chemical parameters were mainly used then. Water bodies were divided into six groups ranging from very pure to bad ones according to the external signs of aquatic contamination. The 5 day biochemical oxygen demand (BOD_5), oxidation, ammonium and nitrate nitrogen, suspended substances, chlorine ion and dissolved oxygen were applied as indicators. In addition, the smell, water turbidity, the presence or absence of fish, the nature of aquatic vegetation were also taken into account. The value of BOD_5 had the greatest importance (Gagarina 2012).

At present, the UK National Water Council scheme is used to assess and classify water quality in Great Britain (in England, Wales, and Northern Ireland). The system is based on the definition of quality criteria needed for specific types of water use and consists of four main grades determined by values of dissolved oxygen, BOD_5, and ammonium nitrogen concentrations. The quality grades correspond to waters suitable for (1) drinking water supply; (2) industrial fishery of valuable fish species or recreational zones; (3) drinking water supply after pre-treatment and for industrial fisheries of low-value fish species; (4) technical needs (Nikanorov 2005).

Due to the geographic specific and types of river use in Scotland, it was considered unacceptable to apply a common UK scheme of chemical classification of river waters to them. Therefore, the Scottish Environment Protection Agency in collaboration with the Agency for the Clyde, Solway and Tweed rivers purification have developed classification schemes for water quality estimation. One such scheme, the water quality index, includes the following water data analysis: dissolved oxygen, BOD_5, ammonia and ammonium ions, pH, total nitrogen, phosphates, suspended substances, temperature, electrical conductivity, fecal coliform bacteria (*E. coli*) (Nikanorov 2005).

In assessing water quality in Benelux countries (Belgium, the Netherlands and Luxembourg), two most important sets of indicators are considered: oxygen balance of water (OBW) and heavy metal content. Three key balance parameters are examined to estimate the OBW: the percentage of dissolved oxygen saturation, BOD_5, and ammonium nitrogen content. Then points are determined for each parameter on a 5-point expert scale and summed to calculate the total value of OBW. So water quality is rated from very good (OBW = 3–4) to very bad (OBW = 14–15). Heavy-metal contamination is calculated according to the 5-point expert scale and corresponds to the values of ≤ 20, ≤ 40, ≤ 60, ≤ 80 and $> 80\%$ of long-time average annual cadmium concentration (Nikanorov 2005).

In Denmark, the quality of waters (especially rivers that receive water from waste treatment facilities) is estimated by the degree of contamination according to organoleptic, physicochemical and biological indicators (Nikanorov 2005).

The water quality assessment method in Germany (Bavarian Water Use Service) is based on the chemical index (CI). Eight parameters are needed to calculate CI: dissolved oxygen, BOD_5, water temperature, ammonium salts, nitrates, phosphates, pH and electrical conductivity, their sub-indexes (the value between 0 and 100, which is a function of the desirability of the value of each parameter) and the relative weight of each parameter (the number between 0 and 1), showing their importance. Water with a CI close to 100 can be classified as safe, and with a value close to 0 as unfavourable (Kimstach 1993).

The Water Framework Directive (WFD) was adopted by the European Union members in the early 2000s (EC 2000, 2003). This document is based on the general principles of cooperation between all EU members and neighboring countries, which are united by the need for management of transboundary water resources to achieve sustainable development goals in the field of water policy. In addition, a number of supporting documents have also been developed, including guidelines for convergence with the EU water policies for partner countries on the European Neighborhood Policy (ENP Partners) and Russia (EC 2008, 2011, 2013; REC 2015; OECD 2007, 2011). The key principle of the WFD common for all the countries is prevention of the natural water quality degradation, but various approaches are possible in the assessment of these quality standards. For example, according to the principles of the WFD, water objects are classified into five categories according to their ecological status: 'high', 'good', 'moderate', 'poor', and 'bad'. The category of the water body is assigned according to the analysis of: (1) the ecological status as per the quality of the biological community, temperature, pH, nutrient concentrations, etc. and (2) chemical status (i.e., compliance with EU standards for priority and secondary polluting chemicals).

In **the Netherlands,** estimation of elevated NBC is focused on the 'added risk' approach. According to this approach, it is assumed that adverse (toxic) effects can occur if concentration rises to a certain level *on top* of the NBC. This level of concentration is not absolute, but such concentration adds to the background level where negative effects can happen (Struijs et al. 1997).

The first attempt to create a composite water quality index (the Horton Index) was undertaken in **the USA** in 1965. Later, the National Sanitation Organization (USA) developed the water quality index that includes nine parameters: dissolved oxygen, coli-index, pH, BOD_5, nitrates, phosphates, temperature, turbidity and suspended substances. Its distinctive feature is the use of continuous harm curves designed expertly for the calculation of sub-index values (Gagarina, 2012).

Eutrophication (i.e., surface waters enrichment by biogenic substances) is a serious problem in the United States of America because it leads to significant disruption of aquatic ecosystems. So, the detection of NBC of nutrients is very important. Nowadays, American scientists from the Environmental Protection Agency suggested preliminary criteria and standards for the contents of total nitrogen and total phosphorus for US rivers in order to reduce the risk of eutrophication (US EPA 2000; Smith et al. 2003; Dodds, Welch, 2000; Dodds et al. 2002). When calculating NBC they recommend using the 75th percentile of chemical concentrations in rivers located in natural ecoregions (i.e., landscapes with a relatively homogeneous geomorphology and biotic community). If such rivers cannot be identified, then reference concentrations are estimated as the 25th percentiles of data set for all streams within an ecoregion. The fifth percentile is used to determine NBC in the region with heavily degraded streams.

Water quality evaluation **in Canada** is based on the Environmental Quality Guidelines (CCME 2003). The procedure is developed to calculate 'water quality indicators for specific points', threats to aquatic organisms from dissolved contaminants and the NBC. They determine the permissible deviations from acceptable conditions of water quality in the examined area. To reveal natural chemical substances concentration in water, there can be used: (1) average value plus two standard deviations (Dunn 1989); (2) 90th percentile (Breidt et al., 1991); (3) the median sample value (Sinotte et al. 1996); or (4) some other alternative statistical estimates (Warn 1982; Van Hassel Gaulke 1986).

Thus, in the EU countries, the USA and Canada, environmental guidance documents do not insist upon specific techniques for calculating NBC enabling experts to apply the most reasonable ones. To ensure greater sensitivity of evaluation methods, water quality indices most often range from 0 to 100.

As for the water quality assessment in countries of the Commonwealth of Independent States (CIS) and Eastern Europe, the Caucasus and Central Asia (EECCA), they do not use NBC. The water quality estimation in Central Asian countries (Kazakhstan, Uzbekistan, Turkmenistan, Tajikistan and others) is based on officially established maximum allowable concentration (MAC) and water pollution index (WPI). A number of improvements in the field of water quality assessment have been made in that region over the last decade. For example, an additional classification of water bodies according to hydrobiological indicators was put into practice in Kazakhstan. The classification depends on the integral saprobity index. There are six distinguished classes of water quality ranging from “very clean” to “very pollute” (UN 2012).

However, it is obvious that simultaneous application of several classifiers based on different principles complicates water quality regulation procedures and the development of inter-state cooperation in managing trans-boundary water resources.

That is why to harmonize the surface water quality assessing techniques some measures have been undertaken recently: (1) the development of unified classifications establishing water quality requirements for various categories of water use; (2) optimization of controlled pollutant list; (3) requirements clarification for procedures, methods and means of measuring water quality indicators.

It is proposed to use the principles of European Union Water Framework Directive (EC 2000) as a basis for these activities. The Republics of Belarus and Moldova have already unified their approaches to water quality assessment with the EU legislation. This standardization was completed within the Environmental Protection of International River Basins (EPIRB) project and included the monitoring and assessment of the chemical and ecological status of water bodies (Buijs 2015; Kampa et al. 2007). The main criterion for assessing the chemical status in these countries is in compliance with environmental quality standards (EQS) defined in Directive 2013/39/EU (EC 2013). For heavy metals (i.e., cadmium, lead, mercury and nickel), water EQSs concern their dissolved forms (Buijs 2015). The Directive 2013/39/EU permits participating countries to register the NBC of metals and their compounds if such concentrations obstruct the relevant EQS because of the natural metals content in rivers (EC 2013). Water hardness, pH, dissolved organic carbon and other parameters that affect the bioaccumulation of metals should also be taken into account.

Since the 1930s, in the **Russian Federation** (the RF), the surface waters quality has been estimated on the basis of the multiplicity and frequency of exceeding

Table 8.1 Comparison of some MACs with mandatory EU indicators for fishery reservoirs[a]

Index	Units	MACs in RF	MACs in EU	
			Salmonid waters	Cyprinid waters
Temperature	°C	3,0 (summer)	1,5	3,0
Dissolved oxygen	mg/d^3	4–6	50% >9	50% >7
BOD_5	mg/d^3	≤2,0	≤3,0	≤6,0
pH	–	6,5–8,5	6–9	6–9
Ammonium nitrogen	mg/d^3	≤0,39	≤1,0	≤1,0
Nitrite nitrogen	mg/d^3	≤0,02	≤0,01	≤0,03
Petroleum hydrocarbons	mg/d^3	≤0,05	Do not form a visible film on the water surface;	
			Do not impart a detectable 'hydrocarbon' taste to fish;	
			Do not produce harmful effects in fish	
Phenolic compounds	mg/d^3	0,001	Taste and smell in fish are absent	
Zinc (dissolved or total)	mg/d^3	≤0,01 (d/s)	≤0,3 (total)	≤1,0 (total)
Copper (dissolved)	mg/d^3	≤0,001	0,04	0,04

[a]Source: EC (2006); MARF (2016)

the measured concentrations of dissolved chemicals over their maximum allowable concentration (MAC) (Timofeeva and Frumin 2015). Until the early 2000s, one of the most common complex indicators of water quality was the hydrochemical index of water pollution (IWP) established by the USSR State Committee for the Hydrometeorology in 1986. However, in 2002 with the introduction of the Guidance document (GD) 52.24.643-2002 (Roshydromet 2006), an algorithm for calculating the combinatory water pollution index (CWIP) and the specific combinatory water pollution index (SCWIP) was proposed for generalizing information on the chemical composition of waters. Thus, the IWP era as the main indicator for assessing the surface waters quality ended in Russia (Gagarina 2012).

So, in the RF the water quality standards of water bodies are based on different MAC levels: drinking, household water use, utility and the strangest fishery. The values of these MACs are included in the calculation of standards for the permissible impact on water bodies. It is done in order to achieve sustainable functioning of natural or established ecosystems, preserve biodiversity and prevent negative impacts from economic or other activities. The comparative analysis of water quality requirements shows that some requirements to indicators are stricter in the RF than in the EU countries (Table 8.1).

The use of MACs in the normalization of anthropogenic load allows limiting the introduction of certain compounds into natural waters however this standard is still fairly criticized. Among the main claims to MAC is ignoring natural factors of water formation. Many Russian scientists are rightfully pointing out those uniform requirements to the water bodies' quality might be either exorbitant or diminished and not followed due to natural reasons. It is highly unlikely that water bodies' biological communities or even various parts of large rivers formed under the influence of different geochemical, climatic and anthropogenic factors in diverse territories have the same adaptability to water quality.

The approach to water resources quality should be an ecosystem to achieve the goals of water body sustainable functioning. The term 'water quality' should be interpreted as physicochemical properties that meet the requirements for the existence and reproduction of species adapted in the evolutionary development process to exist in the conditions of a specific water body (Moiseenko 2002). Such an approach to assessing water resources quality shouldn't be focused upon the laboratory-measured MACs but rather on the natural content of chemicals.

However, the challenge of calculating the NBC is still disputable. None of the simple point-based statistical measures is properly reasoned. For example, the arithmetic average requires a normal statistical law of benchmark data samples, but in reality, the lognormal distribution is much more common. The quartiles, including the median, are affected by the frequency of sample selections during the year (if the sampling frequency is not monthly). The ratio of samples taken in high and low flow is especially important.

It seems more reasonable to use the proportional average value of the variation data series collected at least over 10–12 years in all the hydrological seasons (Savichev 2010), or the use of the weighted estimates, for example, weighted arithmetic average, taking into account the flow phase at averaging time periods (Dubrovskaya and Dmitrieva 2015) provided that the relation between river discharge and concentration is significant.

8.4 Comparative Water Quality Assessment Using MACs and NBCs

One of the possible options for harmonizing the water quality assessments used in the Russian Federation with European approaches is the use of NBC for calculating integrated assessments. The authors have attempted to calculate the specific combinatory index of water pollution (SCIWP) traditional for Russia and define the water quality class. The authors applied the NBC instead of MAC as the reference concentration. The Western Siberian river ecosystems were chosen for research because they have a different level of contamination (Table 8.2). The Kola Peninsula water bodies were the control samples as environmentally friendly. The results of comparing the obtained estimates are shown in Table 8.3 and described below.

Table 8.2 Characteristics of the research objects

No	The river, point of observation (above the settlement)	Geographical position	Area
Western Siberia			
1	Ob at Fominskoye	52° N, 84° E	Forest steppe
2	Ob at Kamen-na-Obi	53° N, 81° E	Forest steppe
3	Ob at Aleksandrovskoe	60° N, 77° E	Middle boreal forest (taiga)
4	Ob at Oktyabrskoye	62° N, 66° E	Middle boreal forest (taiga)
5	Chulym at Baturino	57° N, 85° E	Southern boreal forest (taiga)
6	Katun at Srostki	52° N, 85° E	Forest steppe
7	Ket at Volkovo	58° N, 83° E	Southern boreal forest (taiga)
8	Vasyugan at Sredniy Vasyugan	59° N, 78° E	Middle boreal forest (taiga)
9	Vakh at Laryak	61° N, 80° E	Middle boreal forest (taiga)
10	Northern Sosva at Sosva	63° N, 61° E	High boreal forest (taiga)
11	Ishim at Ust-Ishim	57° N, 71° E	Southern boreal forest (taiga)
12	Tobol at Tobolsk	58° N, 68° E	Southern boreal forest (taiga)
13	Taz at Krasnoselkup	65° N, 82° E	High boreal forest (taiga)
14	Taz at Tazovsky	67° N, 78° E	Tundra and forest tundra
15	Pur at Urengoy	66° N, 78° E	High boreal forest (taiga)
Kola Peninsula			
16	Vite, estuary	67° N, 32° E	High boreal forest (taiga)
17	Kovdora at Kovdor	67° N, 30° E	High boreal forest (taiga)
18	Virma at Lovozero	68° N, 35° E	High boreal forest (taiga)
19	Patso-yoki, Borisogleb. GES	69° N, 30° E	High boreal forest (taiga)

The general concept of combinatorial indices used in the former USSR is based on a comparison of measured concentrations with MAC. The closer the chemicals content to the MAC, the higher the class of natural water. As a rule, such indices are the result of some mathematical operations with a group of initial indicators. In most cases, this operation is a trivial summation based on the hypothesis about the additivity of individual contributions to the complex index, but it doesn't correspond to the truth in the whole. It is known that both synergistic and antagonistic effects can occur at a complex pollution (Chebotarev et al. 2012). In some cases, the intention to combine various quantitative indicators plays an adverse role.

In turn, the use of integrated assessments was predetermined by the presence of different pollutants in surface waters. As a result, there was a requirement to estimate pollution and classify water simultaneously on a wide range of ingredients for a uniquely scalar value. The most informative complex estimates are the SCIWP and the water quality class (Roshydromet 2006). SCIPW varies from 1 to 16; the highest index value corresponds to the worst water quality. It is calculated considering 15 most common pollutants in surface waters: (1) dissolved oxygen (dO2); (2) 5 day biochemical oxygen demand (BOD5); (3) chemical oxygen demand (COD); (4) phenols (Phe); (5) petroleum hydrocarbons (PHCs); (6) nitrite nitrogen ($N(NO_2-)$); (7) nitrate nitrogen ($N(NO_3-)$); (8) ammonium nitrogen

Table 8.3 The MAC and NBC of dissolved chemicals in the Western Siberia rivers and on the Kola Peninsula

		Dissolved chemicals														
		mg/dm^3											mkg/dm^3			
		dO_2,	BOD_5	COD	Phe	PHCs	$N(NO_2^-)$	$N(NO_3^-)$	$N(NH_4^+)$	Cl^-	SO_4^{2-}	Fe	Cu	Zn	Ni	Mn
MACs		>6,0	2,00	15,00	0,001	0,05	0,020	9000	0,39	300,00	100,00	0,10	1,00	10,00	10,0	10,00
NBCs	1[a]	10,32	1,24	9,14	0,002	0,07	0,007	0,220	0,12	2,21	11,40	0,13	1,73	–	1,50	2,02
	2	10,54	0,87	7,07	0,002	0,31	0,006	0,236	0,15	4,36	5,08	0,03	1,85	1,00	1,50	2,93
	3	10,03	2,68	15,05	0,002	0,21	0,004	0,143	0,33	3,02	20,00	0,28	1,49	4,31	1,50	–
	4	9,22	2,28	30,53	0,002	0,04	0,006	0,055	0,15	5,21	8,89	0,88	6,48	7,14	1,50	29,04
	5	8,38	1,65	17,49	0,002	0,29	0,006	0,040	0,25	2,38	12,15	0,25	2,45	–	1,50	2,01
	6	10,40	1,24	7,52	0,002	0,08	0,004	0,216	0,10	2,00	10,32	0,13	1,00	1,00	1,50	0,60
	7	8,33	1,30	25,12	0,002	0,31	0,004	0,050	0,50	2,06	4,52	0,80	2,88	–	1,50	2,90
	8	7,88	1,41	44,50	0,002	0,31	0,003	0,061	0,74	3,63	5,65	0,63	2,02	–	3,59	7,68
	9	9,61	1,39	33,60	0,002	0,03	0,003	0,024	0,26	2,75	7,43	0,90	3,79	9,25	–	–
	1	9,44	2,38	30,84	0,002	0,03	0,004	0,028	0,21	3,13	5,23	0,79	7,61	40,00	3,05	26,50
	11	8,00	–[b]	47,22	0,002	0,03	0,005	0,063	0,35	87,63	64,66	0,04	1,87	5,44	3,06	33,50
	12	34	1,21	41,67	0,002	0,03	0,006	0,133	0,77	19,89	37,48	0,86	3,67	8,27	3,65	25,62
	13	10,35	2,66	25,95	0,002	0,13	0,005	0,011	0,56	3,38	3,72	0,95	1,56	14,67	1,50	18,30
	14	8,84	3,31	21,73	0,003	0,09	0,006	0,008	0,51	4,20	9,18	0,99	1,60	31,58	1,50	21,19
	15	8,46	–	22,79	0,003	0,20	0,005	0,009	0,89	4,77	4,36	1,29	1,42	11,25	1,50	25,95
	16	11,46	0,55	6,63	<LOD[c]	<LOD	<LOD	<LOD	<LOD	1,56	4,82	0,03	3,97	5,51	2,59	3,33
	17	12,14	0,50	11,15	<LOD	<LOD	<LOD	<LOD	<LOD	2,01	4,91	0,04	2,59	9,02	2,43	4,50
	18	11,28	0,68	20,99	<LOD	<LOD	<LOD	<LOD	0,01	3,84	3,79	0,48	3,22	5,20	2,30	10,35
	19	10,86	0,60	8,77	<LOD	<LOD	<LOD	<LOD	0,01	2,40	3,93	0,04	3,27	5,35	5,82	5,42

[a]the observation point number according to Table 8.2
[b]dash means 'no measurements' (the chemical is not included in water quality assessment);
[c]low of detection

Table 8.4 Comparison of water quality class and CIPs in the Western Siberia rivers in 2017 using MAC or NBC as a reference

No[a]	WQC–MAC[b]	CIP–MAC[c]	WQC–NBC[d]	CIP–NBC[e]
1	3a	–	4c	dO_2, $N(NO_3{}^-)$
2	3a	–	4b	–
3	4a	$N(NO_2{}^-)$	4c	dO_2, $N(NO_3{}^-)$
4	4a	dO_2, Fe, Zn	4c	dO_2, $N(NO_3{}^-)$, Zn
5	3b	–	4a	–
6	3a	–	4b	$N(NO_3{}^-)$
7	3b	Fe	4b	$SO_4{}^{2-}$
8	4a	Fe, Petroleum	5	$N(NO_2{}^-)$, $N(NO_3{}^-)$, dO_2, $SO_4{}^{2-}$
9	4a	Fe	4c	dO_2, $N(NO_2{}^-)$, $N(NO_3{}^-)$
10	3b	Fe	4b	dO_2, $N(NO_3{}^-)$, Fe
11	3a	–	4a	
12	4a	–	4b	dO_2, COD
13	3b	Zn	4a	$SO_4{}^{2-}$
14	3b	Fe	4b	dO_2,
15	4a	Fe	4b	$SO_4{}^{2-}$

[a]the observation point number according to Table 8.2;
[b]water quality class using MAC as a reference;
[c]CIP using MAC as a reference;
[d]water quality class using NBC as a reference;
[e]CIP using NBC as a reference

($N(NH_4+)$); (9) iron compounds (Fe); (10) copper compounds (Cu); (11) zinc compounds (Zn); (12) nickel compounds (Ni); (13) manganese compounds (Mn); (14) chloride-ions (Cl^-); (15) sulfate-ions ($SO_4{}^{2-}$).

Only dissolved forms of the metals are used for calculations. The combination of the frequency of exceeding the MAC (or NBC) by any components from the above list and the level of this excess allows to obtain the numerical value of the SCIWP and match it with water quality classes (WQC): class 1 – conditionally pure; class 2 – slightly contaminated; class 3a – polluted, 3 b – very polluted; class 4 a and b – dirty; class 4 c and d – very dirty; and class 5 – extremely dirty.

Such an approach allows identifying critical indicators of water pollution (CIPs) when calculating SCIWP. CIPs are the ingredients that cause the water transfer to the ‘very dirty’ class according to the contamination degree.

We tested the replacement of MAC to NBC for rivers with different water quality classes. The values of both indexes are presented in Table 8.3, and the results of a complex water quality assessment are shown in Table 8.4.

According to the results, using NBC instead of MAC would worsen the complex estimates (i.e., SCIPW and water quality class). But this method sets new priorities in the list of CIPs allowing to detect real regional problems with water quality. It emphasizes the unreasonableness of unified standards for Russia water bodies not accounting for their natural features.

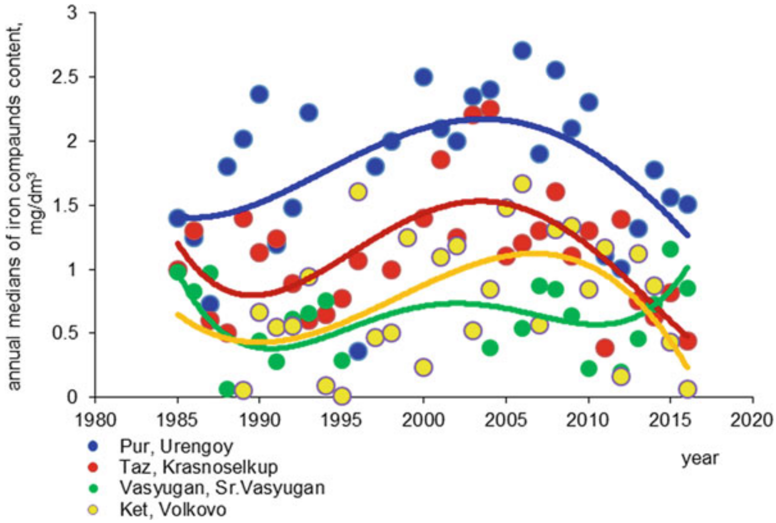

Fig. 8.1 The long-term dynamics of iron compounds in the Western Siberia rivers (where iron compounds are CIPs while using MACs)

Two tendencies are particularly noticeable: iron and zinc compounds have been excluded from the list of CIPs and, conversely, it has included nitrites and nitrates as well as sulfate-ions and oxygen dissolved in northern low-mineralized waters with a long ice-covered period.

The natural concentrations of iron and zinc compounds obey the law of latitudinal zonality. The background content of iron and zinc compounds increases in the north. This is mainly due to natural factors, namely the increased iron concentration in bog waters as complexes with humid acids salts and acidic groundwaters. Iron is a typomorphic element of the Western Siberia north landscapes. The gley reducing conditions are widespread there and iron becomes an active element. In these cases, the iron is able to form chemical compounds and acquire a mobile state (Moskovchenko 2012). As a result, measurable iron concentrations are getting higher. However, this 'increased' concentration is typical for those long-lasted ecosystems and they are adapted to it.

In the rivers where iron compounds considered a CIP the 30 year content dynamic does not reveal any distinct feature trends. It indirectly confirms the weak influence of anthropogenic factors (Fig. 8.1). Nevertheless, applying unified federal MACs leads to the regular inclusion of iron and zinc compounds into the list of CIPs. Thus, an incorrect goal-setting in the protection of water quality is formed. The struggle against natural specific features of surface waters replaces combating anthropogenic contaminations.

The revealing of sulfate-ions in the list of CIPs is an expected effect of the same error in the arrangement of environmental priorities. An incorrect policy of

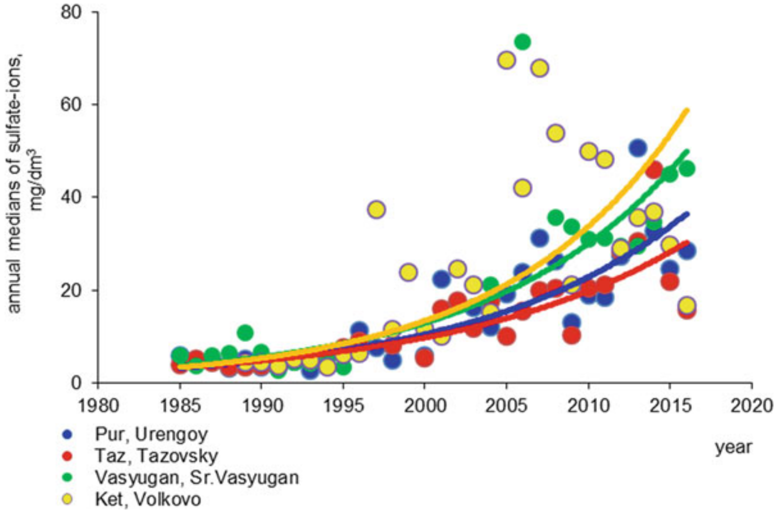

Fig. 8.2 The long-term dynamics of sulfate-ions in the Western Siberia rivers (where sulfate-ions are CIPs while using MACs)

regulating their shedding into surface waters has led to pronounced long-term trends in the Western Siberia northern rivers (Fig. 8.2).

The MAC of sulfate-ions is 100 mg/dm^3, while the sites of the rivers where the NBC of this chemical substance exceeds at least 0.5 MAC are encountered in Western Siberia in the latitude from 58° to 54°N. The sulfate-ions NBC in surface water is found in concentrations below 0.5 MPC to the North and South of these latitudes and even below 0.1 MAC in the tundra and forest tundra. At the same time, water users are not legally prohibited to pollute wastewater with sulfate-ions much more then NBC if their concentrations do not exceed the MAC.

Thus, the long-lasting trend of increasing the iron and sulfate-ions concentrations in the Western Siberia rivers is a clear example of the wrong water management policies consequences that are not focused not on the sustainable ecosystems functioning but on the water consumers needs.

The MACs of nitrates as well as sulfates are quite large in the Western Siberia surface waters in comparison with their NBC. In most cases, nitrates NBC do not exceed 0.1 mg/dm^3 in rivers flowing at latitudes north of 58°N, while federal MPCs are 9.0 mg/dm^3. To this regard, nitrate nitrogen has become a CIP in the part of water bodies. The intra-basin processes associated with the consumption of this biogen by aquatic vegetation during the growing season, play the role of negative feedback. That's why the nitrates dynamics has not been established in the long-term aspect. The emerging of nitrogen mineral forms in the CIPs list also reflects regional water quality problems, as they reveal the eutrophication danger.

The oxygen dissolved deficiency is an often occurring phenomenon as compared with the natural background level due to the long ice-covered period under the

Table 8.5 Comparison of the water quality class and CIPs in the Kola Peninsula rivers in 2017 using MAC or NBC as a reference

No[a]	WQC–MAC[b]	CIP–MAC[c]	WQC–NBC[d]	CIP–NBC[e]
16	2	–	4a	
17	3a	–	4d	dO_2, $N\left(NO_3^-\right)$, $N\left(NH_4^+\right)^6$
18	1	–	4a	$N\left(NO_3^-\right)$
19	1	–	4b	dO_2, $N\left(NO_3^-\right)$

[a]the observation point number according to Table 8.2;
[b]water quality class using MAC as a reference;
[c]CIP using MAC as a reference;
[d]water quality class using NBC as a reference;
[e]CIP using NBC as a reference

rigorous Siberian climate conditions. The Siberian climate induces a comparatively short photosynthetic activity period of aquatic vegetation and feeding some of the rivers with swamp oxygen-depleted waters.

Thus, using NBC in the complex assessments has significantly reduced the water quality class, but it does not mean its real deterioration. It has just demonstrated the weaknesses of the integral approach in assessing water quality on the basis of many chemical indices simultaneously. This is particularly evident in an attempt to develop an integral contamination assessment of the environmentally prosperous water bodies. The Kola Peninsula rivers (listed in Table 8.2) were considered for this purpose. They are characterized as ecosystems with excellent I–II water quality class (conditionally pure and slightly contaminated) according to the state of phyto-, zooplankton and zoobenthos (Roshydromet 2016). Obviously, in these water bodies, which serve as an ecological wellbeing etalon, water quality class of the aquatic environment is the highest. However, a formal assessment leads to the opposite result because of such indicators as mineral nitrogen forms and dissolved oxygen (Table 8.5).

The NBC of nitrogen mineral forms in the most of the Kola Peninsula rivers is not just below the MAC, but it is even less than limit of detection (LOD). However, the SCIWP calculation method is constructed in such a way that it detects each case of exceeding the predetermined threshold (NBC in this case). That is, almost all samples taken off the vegetation period will cumulatively reduce the water quality class. Note that we have in mind water bodies located in the high boreal regions, where the vegetation period is very short.

The same problem occurs while using NBC of dissolved oxygen. The oxygen dissolves very well in the pure and cold Kola Peninsula rivers. Oxygen is weakly consumed in the process of organic matter oxidation because of the low concentration of oxidizable substrates. It increases the NBC rate but does not mean that NBC decrease negatively affects the hydrobiocoenosis.

8.5 Conclusions

It is common knowledge that sustainable development presupposes human needs satisfaction while preserving the environment, so that these needs could be met not only for the present but also for future generations. The hydrosphere safety mostly depends on the ecologically competent work of the states, including their joint measures for environmental activity to reduce the anthropogenic burden on water bodies. The maximum effect from such efforts can be achieved only if the water economy policy gives priority to the water body needs but not to those of water users. To achieve this effect, a regional approach to the water quality estimation is required. Such an approach takes into account the complex of natural factors forming the chemical composition of water and, as a consequence, uses NBC as standards. Since NBC are reference conditions, their achievement already means a good chemical status.

The transition from MAC water quality criterion to NBC means a huge amount of work on the assessments unification for countries using complex indices. In particular, one cannot use NBC as a standard similar to the regional MAC as it has already been shown above in these indices. Therefore, in addition to a scientifically based approach to the NBC calculation, it is necessary to set its justified upper limit, safe for ecosystems. For example, in the Netherlands, such 'added risk' approach is common and it is presumed that negative effects can start when the natural levels of concentrations of chemical substances are exceeded.

There are two-level standards in the practice of water resources management in the EU member countries. So Directive 2008/105/EC establishes two environmental quality standards (EQS): AA-EQS (annual average) and obligatory MAC-EQS (maximum allowable concentration) (EC 2008). Essentially, the NBC is equal to the AA-EQS, and 'NBC + added risk' is MAC-EQS for substances of dual genesis.

The NBC can also be directly used in the development of environmental quality standards for substances of dual genesis. Nowadays, EU Water Framework Directive laws and regulations have established such standards for some heavy metals only. According to the relevant Directive lists, the other remaining substances have a synthetic origin and, as a consequence, cannot have a NBC. To harmonize relations with the EU countries in water policy issues, it is necessary to develop general standards and classification of surface water quality by hydrochemical indicators based on NBC, which provide justification of and scientific background for the threshold values for each quality class, for each measurable indicator. The results accumulated by the monitoring system for surface water quality in the Russian Federation allow to develop the similar principles for chemical status assessment, using not only 'good', 'not very good', but also the same granularity as applied in the ecological status assignment.

Five-class unified classification of the river waters quality takes into account the background indicators of the hydrochemical condition, in its turn, will allow to directly identify problem zones and get an assessment of the river waters quality. That gives an opportunity to evaluate the efficiency of the activities aimed at achieving excellent or good river waters quality according to the WFD recommendations and the principles of sustainable development.

References

Alekin OA (1970) Osnovy gidrohimii (the bases of hydrochemistry). Gidrometeoizdat, Leningrad

Breidt FJ, Boes DC, Wagner JI, Flora MD (1991) Antidegradation water quality criteria for the Delaware River: a distribution-free statistical approach. Water Resour Bull 27(5):849–858

Brodhag C, Taliere S (2006) Sustainable development strategies: tools for policy coherence. A U N Sustain Dev J 30(2):136–145

Buijs P (2015) Guidelines for monitoring the chemical status of surface water bodies. EPIRB project activity 1.3 development of WFD-compliant monitoring programmes. http://blacksea-riverbasins.net. Accessed 15 Aug 2018

CCME (2003) Canadian water quality guidelines for the protection of aquatic life: guidance on the site-specific application of water quality guidelines in Canada: procedures for deriving numerical water quality objectives. https://www.ccme.ca. Accessed 15 Aug 2018

Chebotarev GN, Moiseenko TI, Borodach MV, Gladun TA, Kremleva TA (2012) Obosnovanie regional'nykh normativov kachestva vod i pravovykh mekhanizmov ikh ustanovleniya na urovne sub"ektov Rossijskoj Federatsii (Justification of regional standards for water quality and legal mechanisms for their establishment at the level of constituent entities of the Russian Federation). Bulletin of Tumen State University 12:227–237

Dodds WK, Smith VH, Lohman K (2002) Nitrogen and phosphorus relationships to benthic algal biomass in temperate streams. Can J Fish Aquat Sci 59:65–74

Dodds WK, Welch EB (2000) Establishing nutrient criteria in streams. J North Am Benthol Soc 19:186–196

Drachev SM (1964) Bor'ba s zagryazneniem rek, ozer, vodokhranilishh promyshlennymi i bytovymi stokami (fighting pollution of rivers, lakes, reservoirs with industrial and domestic sewage). Nauka, Leningrad

Dubrovskaya LI, Dmitrieva NS (2015) Sravnitel'nyj analiz metodov rascheta fonovykh kontsentratsij glavnykh ionov v vodakh levoberezhnykh pritokov Srednej Obi (comparative analysis of methods for calculating the background concentrations of the main ions in the waters of the left-bank tributaries of the Middle Ob). Bull Tomsk State Univ 396:225–231

Dunn GW (1989) An approach used to establish site-specific water quality indicators on interprovincial streams. In: Proceedings of the CCME workshop on the development of water quality objectives. Canadian Council of Ministers of the Environment, Ottawa

EC (2000) Directive 2000/60/EC of the European parliament and of the council (water frame directive). https://eur-lex.europa.eu. Accessed 15 Aug 2018

EC (2003) Common implementation strategy for the water framework directive (2000/06/EC). Guidance Document No. 10. River and lakes – Typology, reference conditions and classification systems. https://circabc.europa.eu. Accessed 15 Aug 2018

EC (2006) Directive 2006/44/EC of the European parliament and of the council. https://eur-lex.europa.eu. Accessed 15 Aug 2018

EC (2008) Directive 2008/105/EC of the European parliament and of the council. https://eur-lex.europa.eu. Accessed 15 Aug 2018

EC (2011) Common implementation strategy for the WFD (2000/60/EC). Guidance Document No. 27. Technical guidance for deriving environmental quality standards. https://circabc.europa.eu. Accessed 15 Aug 2018

EC (2013) Directive 2013/39/EU of the European Parliament and of the Council. https://eur-lex.europa.eu. Accessed 15 Aug 2018

Gagarina OV (2012) Otsenka i normirovanie kachestva prirodnykh vod: kriterii, metody, sushhestvuyushhie problemy (assessment and regulation of the natural waters quality: criteria, methods, existing problems). Publishing house «Udmurt University», Izhevsk

Kampa E, Ward JG, Leipprand A (2007) Convergence with EU water policies. Short guide for ENP partners and Russia. http://ec.europa.eu. Accessed 15 Aug 2018

Khovanskiy AD, Khlobystov VV, Parashchenko MV, Panova SV (2000) Planirovanie ustojchivogo razvitiya na mestnom urovne (sustainable development planning at the local level). Publishing house of the Rostov State University, Rostov-on-Don

Kimstach VA (1993) Klassifikatsiya kachestva poverkhnostnykh vod v stranakh Evropejskogo ehkonomicheskogo soobshhestva (classification of surface water quality in European economic community countries). Gidrometeoizdat, Saint Petersburg

Levich AP, Bulgakov NG, Maksimov NV, Risnik DV (2011) «In situ»-tekhnologiya ustanovleniya lokal'nykh ehkologicheskikh norm (Technology «in situ» for establishing local environmental standards). In: Plenum materials of the Scientific Council of the Russian Academy of Sciences in Hydrobiology and Ichthyology, the Hydrobiological Society of the Russian Academy of Sciences and the Interdepartmental Ichthyological Commission, Moscow, 30 March 2011

Ministry of Agriculture of the Russian Federation (MARF) (2016) Order No. 552 of December 13, 2016 Ob utverzhdenii normativov kachestva vody vodnykh ob"ektov rybokhozyajstvennogo znacheniya, v tom chisle normativov predel'no dopustimykh kontsentratsij vrednykh veshhestv v vodakh vodnykh ob"ektov rybokhozyajstvennogo znacheniya (On the approval of the of water quality standards for water objects of fishery importance, including standards for maximum permissible concentrations of harmful substances in the waters of water objects of fishery importance). http://www.consultant.ru

Moiseenko TI (2002) Vodnye resursy Evro-Arkticheskogo regiona i klyuchevye problemy izmeneniya ikh kachestva (water resources of Euro-Arctic region and key problems of their quality transformation). In: «Kola Scientific Center of RAS – 70 years old». KSC of RAS publishing house, Apatity

Moskovchenko DV (2012) Gidrogeokhimicheskie osobennosti landshaftov bassejna r. Kyzym (Hydrogeochemical features of the Kyzym river basin landscapes). Bulletin Ecol For Landscape Stud 12:124–129

Nikanorov AM (2005) Nauchnye osnovy monitoringa kachestva vod (scientific basis of water quality monitoring). Gidrometeoizdat, Saint Petersburg

OECD (2007) Proposed system of surface water quality standards for Moldova (Technical Report). http://www.oecd.org/env/outreach/38120922.pdf

OECD (2011) Establishing a dynamic system of surface water quality regulation: guidance for countries of Eastern Europe, Caucasus and Central Asia. http://www.oecd.org/environment/outreach/48994623.pdf

REC (2015) Handbook for Implementation of EU Environmental Legislation. http://ec.europa.eu

Roshydromet (2006) GD 52.24.643-2002. Metod kompleksnoj otsenki stepeni zagryaznennosti poverkhnostnykh vod po gidrokhimicheskim pokazatelyam (method of comprehensive assessment of the surface waters contamination degree by hydrochemical indicators). In: Normativno-metodicheskoe obespechenie monitoringa poverkhnostnykh vod sushi, chast' 2 (normative and methodological support of surface water monitoring, part 2). Meteoagentstvo Rosgidrometa, Moscow

Roshydromet (2016) Ezhegodnik kachestva poverhnostnyh vod po gidrobiologicheskim pokazatelyam na territorii deyatel'nosti Murmanskogo UGMS (annals of surface water quality by hydrobiological indicators in the Murmansk GMD territory). Murmansk, Murmansk

Savichev OG (2010) Problemy opredeleniya fonovykh kontsentratsij veshhestv v poverkhnostnykh vodakh i dopustimykh sbrosov zagryaznyayushhikh veshhestv v vodnye ob"ekty Sibiri (Problems in determining background concentrations of substances in surface waters and permissible discharges of pollutants into water bodies of Siberia). In: «Fundamental problems of water and water resources», Barnaul 24–28 Aug 2010

Sinotte M, Bilodeau P, Croteau G, Guay I, Jauron L, Richard F, Rousseau N, Talbot L, Theberge S (1996) Method for calculating environment-based effluent objectives for aquatic pollutants. Quebec City, Quebec

Smith RA, Alexander RB, Schwarz GE (2003) Natural background concentrations of nutrients in streams and Rivers of the conterminous United States. Environ Sci Technol 37(14):3039–3047

Struijs J, van de Meent D, Peijnenburg WJ, van den Hoop MA, Crommentuijn T (1997) Added risk approach to derive maximum permissible concentrations for heavy metals: how to take natural background levels into account. Ecotoxicol Environ Saf 37(2):112–118

Timofeeva LA, Frumin GT (2015) Problemy normirovaniya kachestva poverkhnostnykh vod (problems of rationing surface water quality). Scientific notes of the Russian State Hydrometeorological University. Ecology 38:215–229

UN (2012) Towards development of regional cooperation to ensure water quality in Central Asia: diagnostic report and cooperation development plan. http://wedocs.unep.org

US EPA (2000) Nutrient criteria technical guidance manual. Rivers and streams. https://nepis.epa.gov

Van Hassel JH, Gaulke AE (1986) Site-specific water quality criteria from in-stream monitoring data. Environ Toxicol Chem 5:417–426

Vorobeychik EL, Sadykov OF, Farafontov MG (1994) Ekologicheskoe normirovanie tekhnogennykh zagryaznenij nazemnykh ehkosistem (lokal'nyj uroven') (Ecological regulation of local ecosystems technogenic pollution). Nauka, Yekaterinburg

Warn AE (1982) Calculating consent conditions to achieve river quality objectives. Effluent and Water Treatment Journal 22(4):152–156

Chapter 9
Indicators for Sustainable Management of Water Supply: A Case Study from Australia

Rob Braaten, Ulrike Bende-Michl, and Sunil Dutta

Abstract This chapter presents a case study of the use of indicators to inform water supply planning and management, using data from Australia's National Water Account. The study draws on the rich tradition on indicators, ratios and metrics in the financial field, to select a suite of 17 indicators to best represent a broad picture of context, sustainability and security relating to water availability and supply. The selected indicators fit into four broad themes relating to water availability, water use, sustainability and water security. The indicators were found to be useful for providing insight into key questions likely to be raised by decision makers in water policy and sustainable water resource management such as: How much water is available for use? How much water is being used and how is it being used? Is water use sustainable? Can future demand be met? They were also useful for standardising water information across water systems that differ in size, climate and type of use, allowing rapid comparison of key issues between regions.

Keywords Indicators · Water supply · Water account · Water management · Sustainability

9.1 Introduction

Water scarcity has become a major constraint to socio-economic development in many parts of the world (Liu et al. 2017). While water consumption increased fourfold over the period 1901–2010, the population under water scarcity increased from 14% in the 1990s to 58% in 2000 (Kummu et al. 2016). Sustainable water supply management is critical to meeting long-term needs for population growth, agriculture and the environment. This is reflected in the United Nations' Sustainable

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Development Goal 6, "Sustainable Water and Sanitation", which includes a target of implementing integrated water resources management at all levels by 2030 (UNDP 2018).

Sustainable water management requires high quality data and information to guide decision makers. Indicators are a tool that can be used to present complex water information in an accessible format that can be used by decision makers in the water industry, government policy makers and the public. Indicators can be used to track progress and trends, identify emerging issues, compare between regions, set priorities, target investigation and investment, and evaluate progress.

In this chapter, we present a series of indicators to inform water supply planning and management in Australia using data derived from Australia's National Water Account (NWA). The NWA is an annual 'stocktake' of Australia's water supply system prepared by Australia's Bureau of Meteorology, drawing on methods used in the financial accounting discipline. Indicators are a well-established tool to provide insight into corporate health and have become more prominent in hydrological disciplines (e.g. Vanham et al. 2018; Xu and Wu 2017). This chapter draws on and synthesises these two approaches to extract new insights from the National Water Account dataset, with the aims of (i) reporting on the status and trend of water systems, (ii) identifying regional water supply stress, flexibility, security and resilience between regions and (iii) highlighting emerging issues in water sustainability across the major water use areas across Australia.

Australia provides a good case study for the development of water indicators because of the importance of effective water management to its economy and society, and the availability of high quality water data. Australia is the driest inhabited continent and its variability in rainfall and streamflow is amongst the highest in the world (Australian Government 2019). In response to climate variability and increasing pressure on water resources, over the past two decades, industry and government have made substantial investments in water data collection, water planning, development of a secure water entitlement system, and tradeable water markets (Slattery et al. 2012). As a result, there is both a good base of data to develop water indicators and a clear demand for value-added water information to support water management.

The first section of the chapter provides a brief background of the Australian climatic setting, the development of water accounting in Australia, and the National Water Account. The next section describes the process of indicator selection and their methods of calculation. The results for these indicators across 10 nationally significant regions are then presented in relation to key questions likely to be posed by water managers, followed by a final section that discusses the results and presents conclusions.

9.2 Background

9.2.1 Australian Climatic Setting

Due to its physiography and climate conditions, Australia faces many challenges to water resource availability and management. Australia covers a wide range of climate zones, and the regional distribution of rainfall and runoff is highly uneven across Australia (Fig. 9.1). High rainfall and evapotranspiration occur in the northern tropical regions, along the east coast, where the Great Dividing Range runs parallel to the coast, and in western Tasmania. In contrast, about 40% of the country, mostly in the centre, has 300 mm or less of rainfall each year. Australia's rainfall also varies greatly from one year to the next and from one decade to the next, as it is strongly influenced by large-scale phenomena such as El Niño and La Niña, and the Indian Ocean Dipole (Keywood et al. 2016).

Despite this large natural variability, underlying longer-term trends are evident in some regions, and these are likely to be climate change related. Shifts in climate are leading to regional increases or decreases in rainfall, changes in seasonality and increases in extreme events (Bureau of Meteorology and CSIRO 2018). All these changes can affect streamflow and groundwater fluxes.

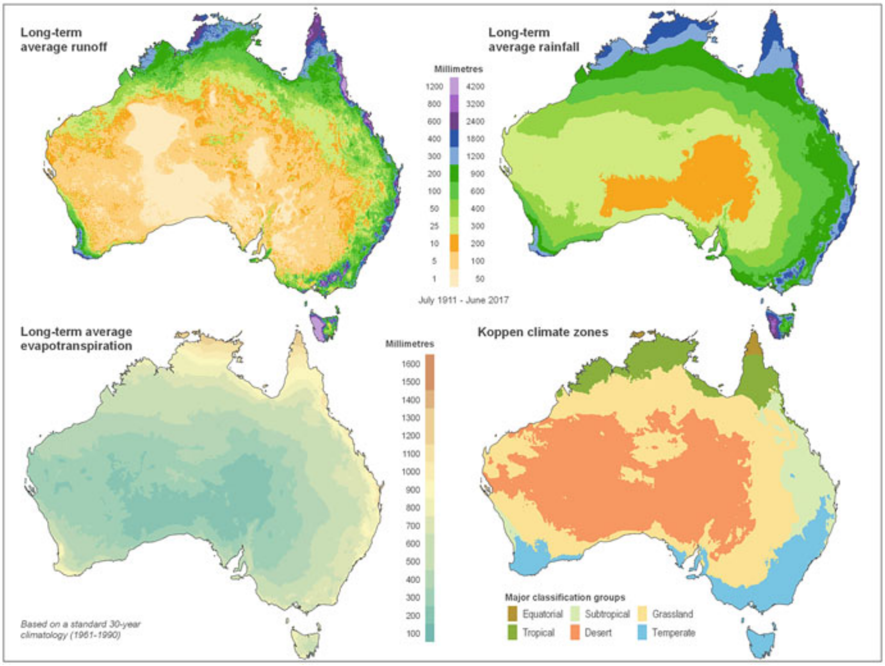

Fig. 9.1 Key climate characteristics for Australia

9.2.2 National Water Account

Between 2004 and 2006, in response to climate variability and increasing pressure on water resources, and coinciding with a record-breaking drought in southeastern Australia (the 'Millennium Drought'), the Australian federal, state and territory governments agreed to the National Water Initiative (NWI). The NWI committed governments to wide-ranging water reforms including the implementation of secure and tradeable water entitlements, integrated management of groundwater and surface water resources, and water resource accounting. As part of this process, the Water Accounting Standards Board was created to develop standards for general purpose water accounting, culminating in the creation of the Australian Water Accounting Standard (AWAS) (WASB 2012; Godfrey 2011; Chalmers et al. 2012).

Under the Australian Water Act 2007, the Bureau of Meteorology was given a mandate to provide standardised water information across the country, including a National Water Account (NWA). The Bureau's National Water Account (NWA) was first published in 2010, and provides water resource management information in an independent, accountable form for a series of nationally significant regions across Australia representing about 80% of Australia's water use and all its large urban centres (Fig. 9.2). The accounts are built through close partnership with reporting partners from a wide range of organisations in each state and territory, to gather the best available water related physical and regulatory data (BOM 2018).

The preparation and presentation of the NWA are guided by AWAS and draw on methods from the financial accounting field. The NWA is a collection of water accounting reports presenting quantitative and qualitative information on the water resources of each region for a reporting year from July to June. The NWA reports volumetric information about water resources in three water accounting statements:

- The Statement of Water Assets and Liabilities is analogous to a financial balance sheet and presents the volume of water assets and water liabilities at the start and end of a reporting year. Water assets include both physical water (e.g. water in reservoirs) and rights or claims to water. Water liabilities include commitments to deliver water to users.
- The Statement of Water Flows is analogous to a financial cashflow statement and shows the actual water inflows into and outflows from the water stores of a region that occurred during the reporting year. Inflows include items such as surface water runoff and groundwater recharge, while outflows include items such as water abstraction and river discharge to the ocean.
- The Statement of Changes in Water Assets and Water Liabilities is analogous to a financial income statement and presents changes in water assets and liabilities that occurred during the reporting year, including accrual transactions, such as water allocations, as well as actual water flows.

The volumes in the statements are derived from a range of data sources including metered data, model outputs, climate data and water licensing information, devel-

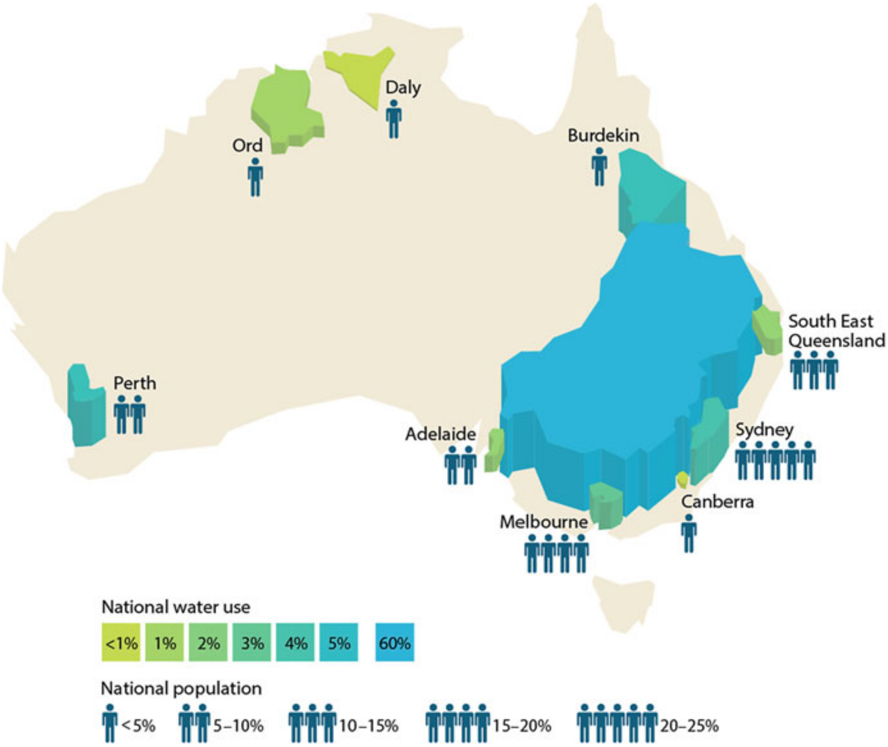

Fig. 9.2 National water account regions

oped in a partnership between the Bureau of Meteorology and its reporting partners. Further details of the NWA, its methods, statements and terminology are available from BOM (2013 and 2018).

The indicators presented in this chapter were derived from the NWA statements for ten key regions (Fig. 9.2). Indicators were calculated for all five reporting years from 2012–2013 to 2016–2017 for all regions except Adelaide and Burdekin (all four years from 2013–2014 to 2016–2017) and Daly (all three years from 2014–2015 to 2016–2017).

9.3 Indicator Selection

There is a need for water managers, decision makers, users and investors to be able to rapidly compare regions, identify emerging trends, areas of concern and priorities for investment and intervention, and target further deeper analysis of more detailed data. The financial industry has analogous needs and, in response, has developed a rich collection of indicators, ratios and metrics to provide insight into corporate health for shareholders and investors (e.g. Penman 2007; Delen et al. 2013). Financial metrics focus on attributes such as profitability, liquidity, solvency and expected investment returns, and play an important role in investment decisions and business valuation.

Drawing on the experiences of the financial field, we have tested and reviewed a wide range of indicators using the water accounting statements from the NWA dataset. We have selected a suite of 17 indicators to best represent a broad picture of context and sustainability relating to water supply. These generally fit into four broad themes:

- measures of sources and availability of water;
- indicators to characterise the use and supply of water;
- indicators of sustainability and impacts of water use;
- measures of water security.

The first two categories of indicators provide contextual information for water management while the latter two provide information on status, stress, trends and sustainability which can be used to inform water policy and decision making.

The selected indicators, their methods of calculation, and key questions addressed by each indicator are shown grouped by water theme in Table 9.1.

The table also shows analogous financial themes with examples of associated financial indicators. Financial concepts such as revenue and expenditure could be considered analogous to water availability and use. Likewise, financial themes such as business sustainability, solvency and liquidity can be compared to water supply sustainability and security, and financial indicators within these themes have useful analogues in water systems. However, we found that the financial analogy is not a perfect one. In business, profitability and growth are indicators of good management whereas in water systems, surplus and growth are limited by the physical environment and must be balanced against environmental impacts. For example, growth in physical water assets is limited by reservoir and aquifer storage; likewise, growth in water abstraction can be associated with environmental stress. Consequently, some financial indicators, such as profit margin or return on equity, lack useful analogues in hydrology.

Another difference from financial accounting in that water fluxes are often harder to quantify than financial transactions and can have significant uncertainty bounds or data gaps. Under AWAS, items are recognised in the statements only if they can be quantified with “representational faithfulness”. The uncertainty and gaps are reflected in the NWA in the ‘unaccounted-for difference’, which is used to reconcile the change in water storage with the difference between inflows and outflows (WASB 2012). The highest uncertainty bounds in the NWA generally occur in inflows that are estimated using modelling, such as runoff and groundwater recharge. Consequently, the indicators that are derived from water use, assets and liabilities may have higher accuracy than those based on water inflows.

Table 9.1 Water indicators used and calculation methods

Water theme	Analogous financial theme and example indicators	Water indicator	Numerator	Denominator	Question addressed by indicator
Water availability	Revenue and assets (operating cash flow; working capital; asset turnover ratio)	Water availability per area[a]	Total water inflows[b]	Region area (km^2)	How wet is the region?
		Water availability per capita[a]	Total water inflows[b]	Region population	Is there sufficient water available for human needs?
		Water variability	Highest inflows in period of record	Lowest inflows in period of record	How variable is the water supply?
		Water velocity[a]	Total water inflows[b]	Total water assets	How quickly does water storage replenish?
Water supply and use	Expenditure (accounts payable turnover; operating expense ratio)	Water allocation intensity[a]	Total water allocation	Total water inflows	How much of the available water is allocated to people?
		Surface water/groundwater index[a]	Surface water use	Surface water use + groundwater use	What is the mix between groundwater and surface water use?
		Inter-region dependency[a]	Inter-region deliveries	Total water use	How much is the region dependent on importing water from outside?
		Urban water use[a]	Urban water use	Total water use	How much of the region's use is for urban supply

(continued)

Table 9.1 (continued)

Water theme	Analogous financial theme and example indicators	Water indicator	Numerator	Denominator	Question addressed by indicator
Water supply sustainability	Financial sustainability or health (operating margin; dividend payout ratio; return on assets)	Water use intensity	Total water use	Total water inflows[b]	How much of the total water availability is used by people?
					How stressed is the water system?
		Groundwater use intensity	Total groundwater use	Total groundwater inflows	As above but for groundwater only
		Surface water use intensity	Total surface water use	Total surface water inflows	As above but for surface water only
		Water payout ratio	Total water use	Total water inflows[b] – Total water outflows (excluding usage) + unaccounted-for difference	What proportion of the water captured in the region is used?
					How much buffer is there in water supply?
		Water assets change	Change in net water assets	Total water assets	How much does stored water in the region change in a year?
					Is the region banking reserves or drawing them down and by how much?
		Water banking	Change in net water assets	Total water inflows[b]	How much of the total water availability is banked, or drawn from reserves in a year?

Water security	Financial liquidity (current ratio; quick ratio; debt ratio; cash flow adequacy)	Banked water liquidity	Total water assets	Total water liabilities	Can the region meet its current commitments with its stored water? If so how much buffer does it have?
		Total water liquidity	Total water assets + projected inflows next year	Total water liabilities + projected usage net year	Will the region likely meet its current and future commitments? If so, how much buffer is available?
		Climate independent water liquidity[a]	Desalinated water use + recycled water use	Total water use	How much of the region's water supply is robust to climate variability and change?

Water units are in ML and/or ML/annum
[a]Denotes indicators that are presented in this chapter as averages of the annual values from the reporting years used in the analysis. These were the five years from 2012–2013 to 2016–2017 for most regions except Adelaide and Burdekin (four years from 2013–2014 to 2016–2017) and Daly (three years from 2014–2015 to 2016–2017)
[b]Total water inflows include both groundwater and surface water inflows where included in the accounting statements

9.4 Results

9.4.1 How Much Water Is Available for Use in Australia?

Indicators of water availability are mapped in Figs. 9.3, 9.4, 9.5 and 9.6. The water availability per area indicator (Fig. 9.3) reflects the distribution of rainfall in Australia, with most of the coastal regions and all of the urban regions having higher water availability, and inland regions relatively less well endowed with water resources.

The water availability per capita indicator (Fig. 9.4) is also commonly known as the Falkenmark indicator (Falkenmark 1997). Kummu et al. (2016) defined thresholds of 1.7 and 1.1 ML/person/annum for the indicator, below which regions were considered to be under water stress and water scarcity, respectively. On this basis, most of Australia's urban regions would be considered to be water stressed, and Adelaide and Melbourne would be considered to have water scarcity. However the indicator values are highly dependent on where the region boundaries are drawn relative to population centres and significant water resources. The results suggest that Adelaide and Melbourne may be areas where alternative water sources such as desalination or other water sources outside the region boundary would need to be sought. The rural regions all have Falkenmark indicator values high above the stress threshold reflecting their sparse populations.

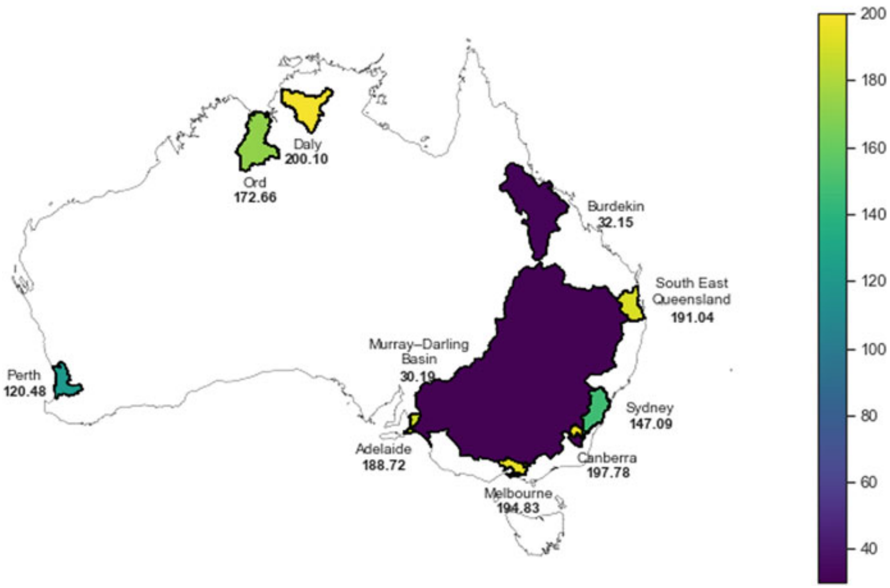

Fig. 9.3 Water availability per area (ML/km^2/year)

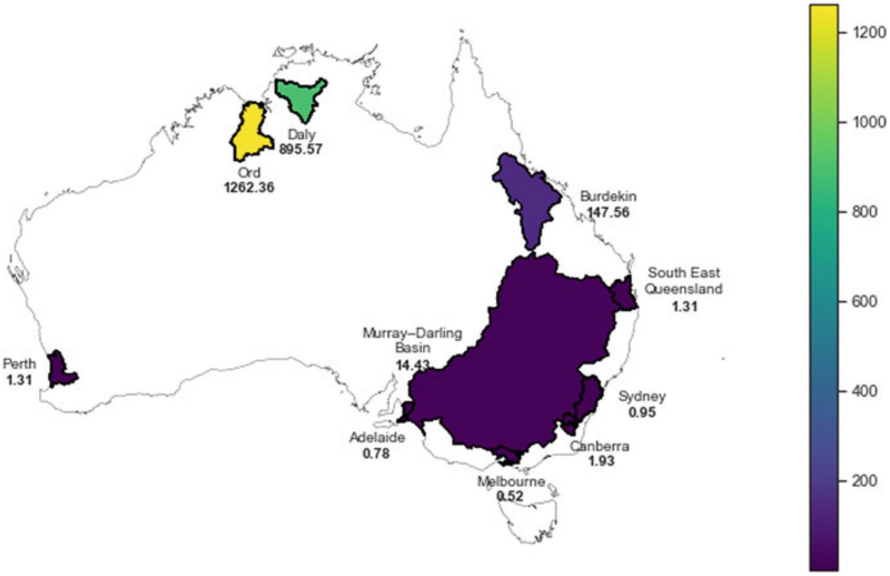

Fig. 9.4 Water availability per capita (Falkenmark indicator) (ML/person/year)

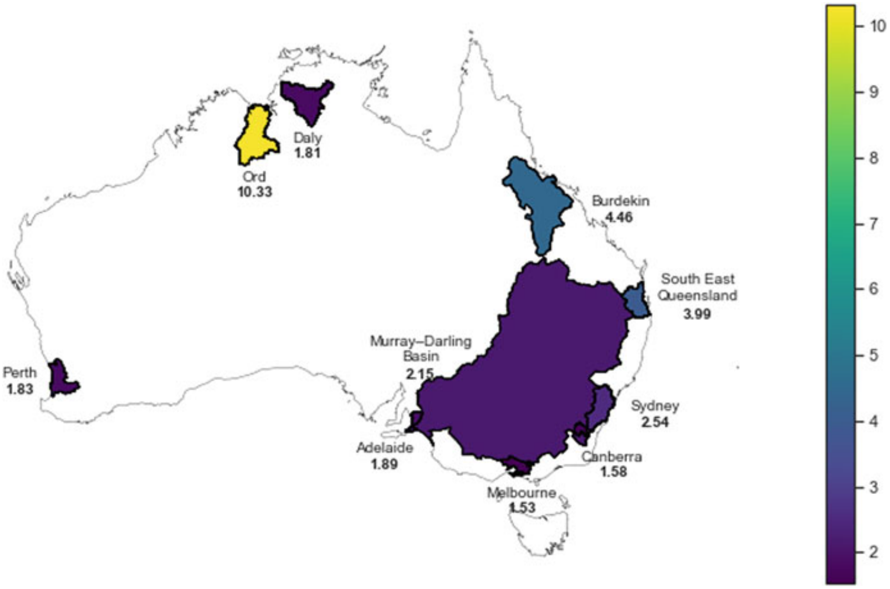

Fig. 9.5 Water variability (dimensionless ratio)

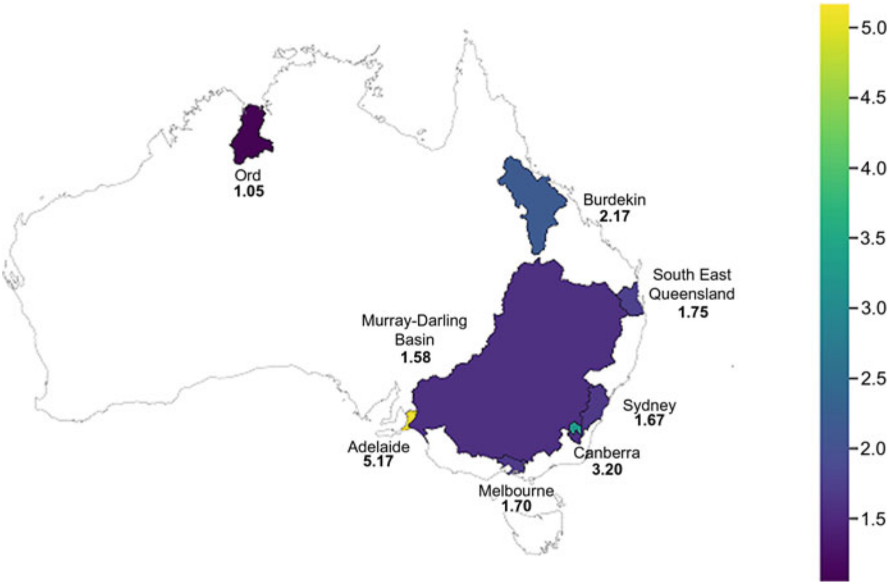

Fig. 9.6 Water velocity (dimensionless ratio)

Critical to managing water resources in Australia is the variability in water supply (Fig. 9.5). Areas with higher variability may require greater storage, contingency water sources, and more conservative allocation strategies. The Ord region in Australia's north stands out as having the highest variability of all the regions, with its wettest year in the five year National Water Account dataset being 10 times wetter than its driest. The two Queensland regions also have higher variability than the other regions. Most urban regions have an indicator value of around two suggesting water availability has fluctuated approximately two-fold from year to year during the five-year period of data.

The water velocity indicator (Fig. 9.6) provides information on the rate of turnover of water assets (mainly water stored in reservoirs and aquifers) in a region. In areas with higher water velocity, climate fluctuations will propagate through the region's storages more rapidly, whereas in regions with low velocity the effects of a dry spell on the region's water reserves may be more prolonged as storage takes longer to replenish. Data are not shown for the groundwater dependent regions of Perth and Daly as groundwater storage could not be quantified for the NWA due to data limitations. The results for the remaining regions show that in Adelaide and Canberra, water storage may turn over several times per year, while in other regions the water velocity is lower with around one to two turnovers per year. The high turnover in Adelaide is likely due to regular inter-region water transfers from the Murray River to the region's reservoirs for urban water supply.

Further insight can be obtained by comparing two or more indicators in a matrix. Figure 9.7 shows an example of water velocity versus variability. Areas with low

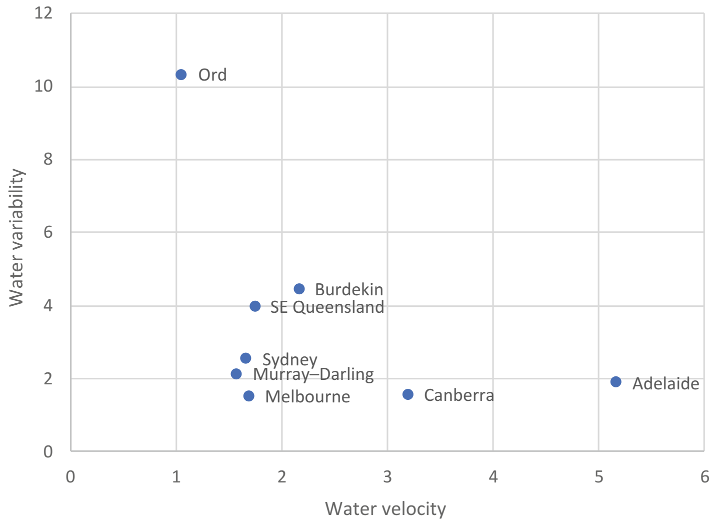

Fig. 9.7 Water velocity vs water variability (dimensionless ratios)

velocity and high variability are likely to have more variable water availability and require more conservative allocation strategies such as the retention of several years of buffer supply in storage reservoirs. The Ord region stands out as being in this category and this may be reflected in its much higher storage to usage ratio than the other regions. In areas with high velocity and low variability, storage is likely to be more robust, and less conservative allocation strategies may be warranted. Adelaide stands out in this category with the highest water velocity and with lower water variability. A less conservative allocation strategy in this region may be evidenced by the fact that most of the water in storage is used each year.

9.4.2 How Is Water Supplied and Used in Australia?

The indicators describing how water is supplied and used in a region are mapped in Fig. 9.8, 9.9, 9.10 and 9.11. The water allocation intensity indicator (Fig. 9.8) illustrates the proportion of the region's inflows that have been allocated for usage. Higher indicator values indicate systems with more potential for competition between users and environmental water needs, which require more intensive management. The Murray-Darling Basin is a complex, hydrologically interconnected river system covering one million square kilometres in southeast Australia, containing 55% of Australia's water use and 70% of Australia's irrigated land area (BOM 2018). It has one of the highest values for this indicator and this is reflected in it being the most intensively managed water region in the country. The Ord and

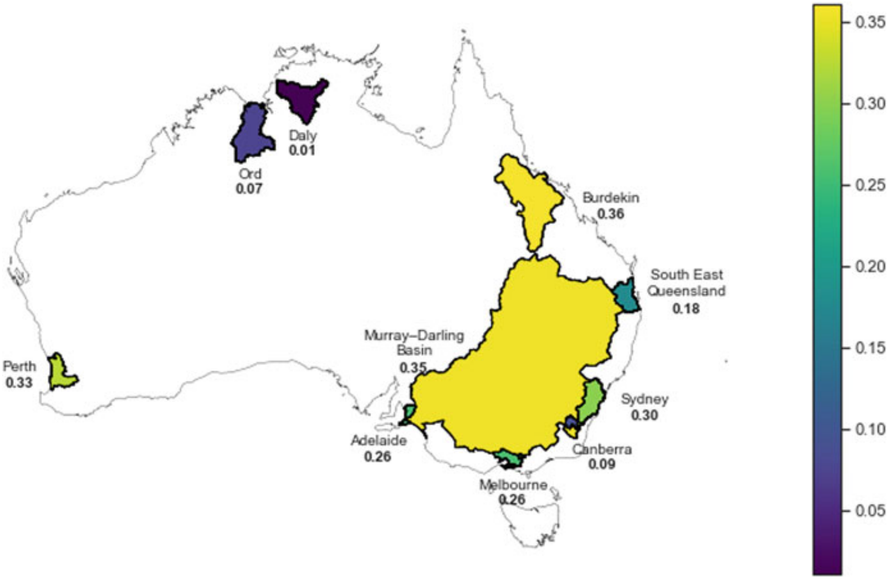

Fig. 9.8 Water allocation intensity (dimensionless ratio)

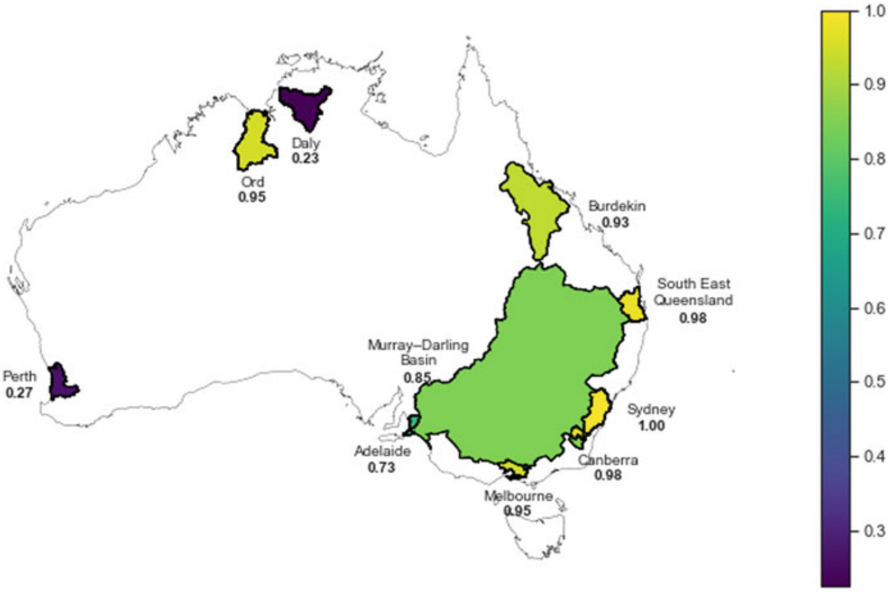

Fig. 9.9 Surface water / groundwater index

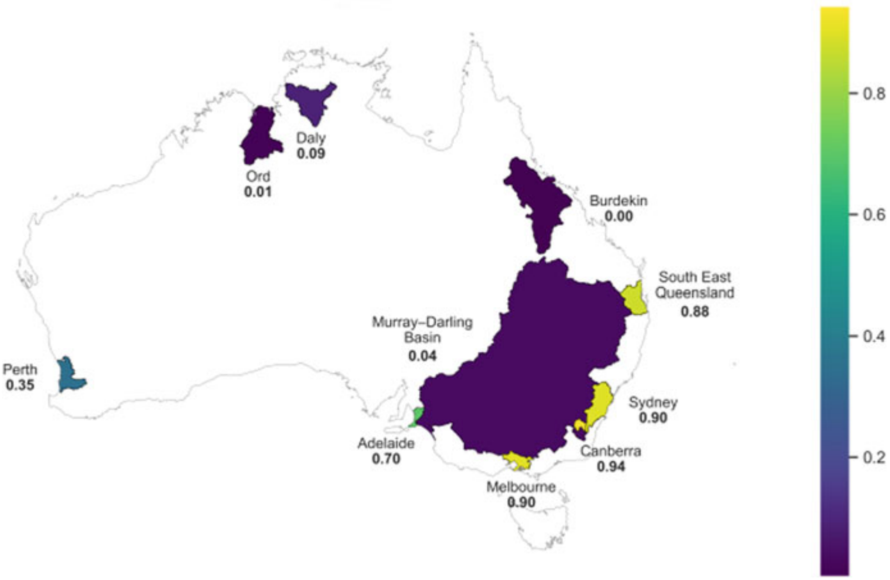

Fig. 9.10 Urban water ratio

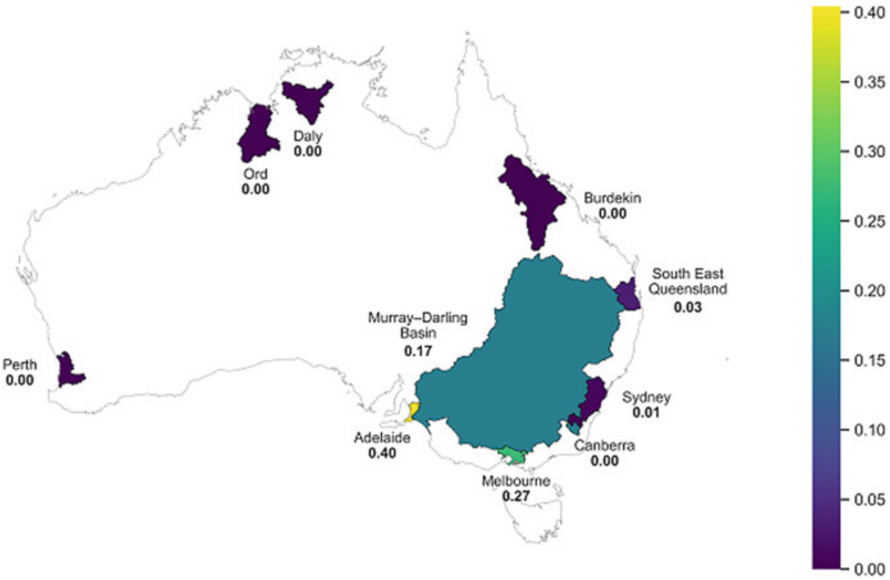

Fig. 9.11 Inter-region dependency (dimensionless ratio)

Daly in the north, by contrast, have a low allocation intensity and may have potential for future development (e.g. Petheram et al. 2014).

The surface water / groundwater index and urban ratio describe the source and destination of water supplies in a region, which can help frame the management responses required. Perth, Daly and, to a lesser extent, Adelaide, are groundwater dependent regions, while the rest of the regions are mainly surface water dependent (Fig. 9.9).

Most of the urban regions have very high urban ratios indicating that the majority of water supply is for urban purposes (Fig. 9.10). These high indicator values suggest that supply security is likely to be a key driver for management in these regions, and management may focus on ensuring a buffer of supply in urban water storages to minimise the need for water restrictions. In the other regions with lower urban ratios, where water supply is primarily for agricultural purposes, drivers of water management could be more mixed, with maximisation of economic benefits from agricultural production also an important driver. This is reflected in a less conservative allocation strategy in most of these regions, in which higher draw down of storages in wet years is balanced by reduced allocations in dry years.

The inter-region dependency indicator (Fig. 9.11) illustrates how dependent a region is on the imports of water from outside the region to secure its water supply. A key driver for inter-region transfers is highlighted by comparing this indicator with the water availability per capita indicator (Fig. 9.12). The two regions that are considered to be water scarce based on the water availability per capita indicator, Adelaide and Melbourne, are those most dependent on inter-region transfers. Both regions have sought water supplies more than 100 km from their urban centres.

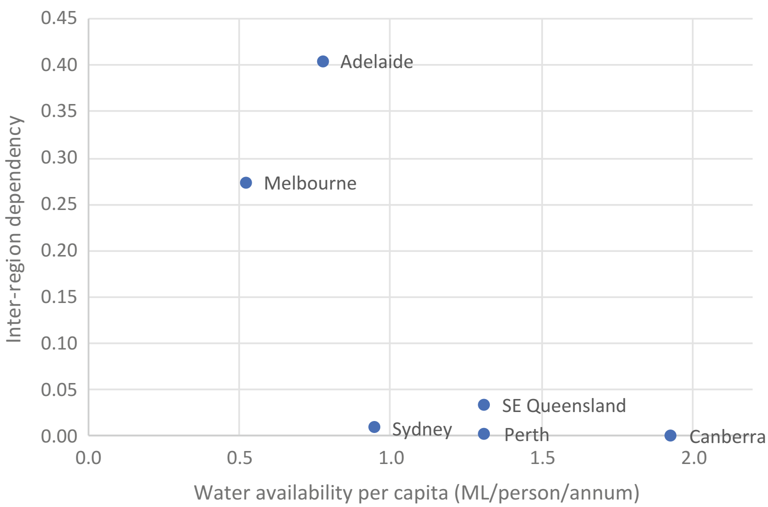

Fig. 9.12 Inter-region dependency versus Water availability per capita – urban regions

9.4.3 How Sustainable Is Water Supply in Australia?

The indicators of water supply sustainability are best viewed in time series to identify trends and provide insight into inter-annual variability. These are shown in Fig. 9.13, 9.14, 9.15, 9.16, 9.17 and 9.18.

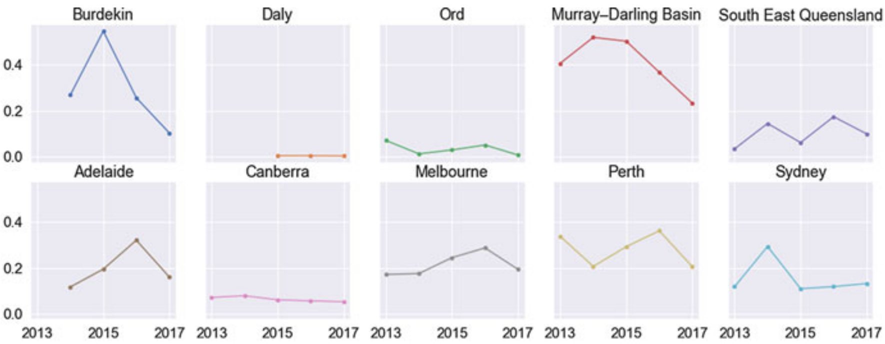

Fig. 9.13 Water use intensity (dimensionless ratio)

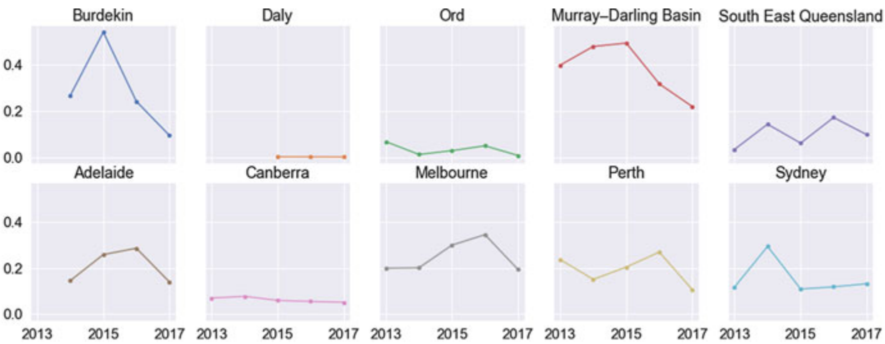

Fig. 9.14 Water use intensity – surface water (dimensionless ratio)

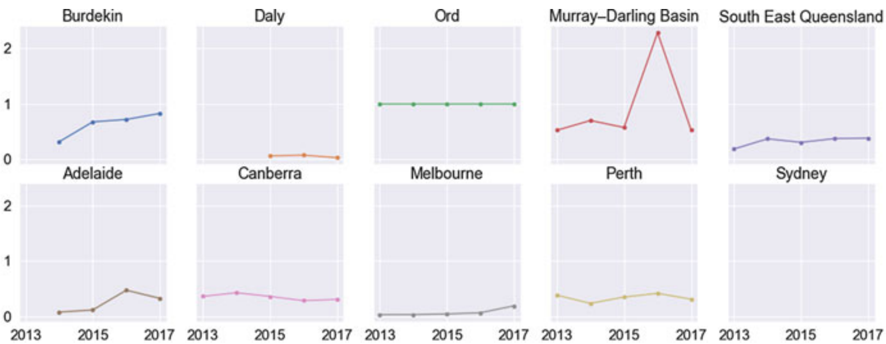

Fig. 9.15 Water use intensity – groundwater (dimensionless ratio)

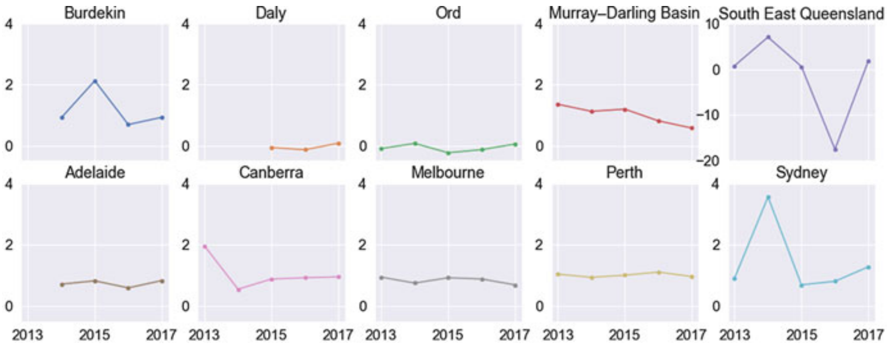

Fig. 9.16 Water payout ratio (dimensionless ratio)

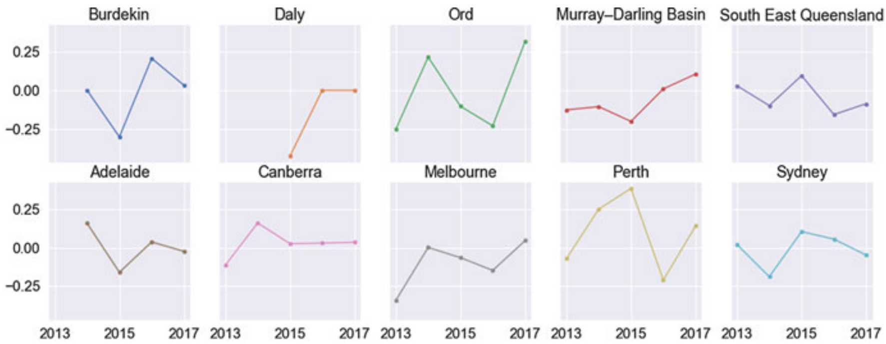

Fig. 9.17 Water assets change (dimensionless ratio)

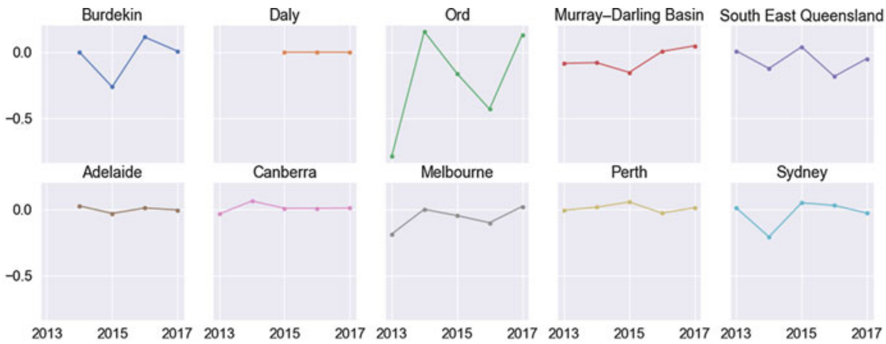

Fig. 9.18 Water banking indicator (dimensionless ratio)

Various permutations of water use intensity indicators have been used in previous studies, referred to by names such as water exploitation index (WaterinCore 2010) or water stress index (California DWR 2014). These refer to water usage as a proportion of water availability. A higher value could lead to lower security for users and higher environmental impacts and consequently more stress on the water resource. Water use index thresholds of 0.2 and 0.4 have previously been used to denote the potential for "water stressed" and "severely water stressed" regions (European Environment Agency 2004, WaterinCore 2010).

The results for Australia (Fig. 9.13) indicate that the Murray-Darling Basin has fallen into the "severely water stressed" category in three out of the five years of analysis, from 2013–2015. In recognition of this situation, the Australian Government has invested substantially in water management in the region through development of the 'Basin Plan' and a buyback of water entitlements for the environment (MDBA 2018). The recent decline in this indicator in the Murray-Darling Basin may be indication of the effect of these policies, as well as a shift to wetter conditions. The Perth and Melbourne regions both lie consistently within or near the "stressed" category and have both shown rising trends in their water use intensity indicators over several consecutive years albeit with recent declines in 2017. These trends have led the two regions to invest in climate independent water sources (primarily desalination) in recent years.

Global catchment-scale information for a similar indicator, termed 'baseline water stress' is also published in the Aqueduct Water Risk Atlas (Gassert et al. 2014) and has been recommended for use in water sustainability reporting (GSSB 2018). Comparison of the Aqueduct atlas with the water use intensity results in Fig. 9.13 shows generally similar trends. The major Australian urban regions and Murray-Darling Basin appear in higher stress categories and the far northern regions fall into lower stress categories in both products. However, there are some prominent differences. For example, the Burdekin region falls into the stressed category based on the NWA data but in the low stress category in the Aqueduct atlas. This is likely related to the lower accuracy catchment-scale water use data in Aqueduct, which are derived from automated disaggregation of national scale data, compared to the more accurate usage data based mainly on local allocations and meter readings in the NWA. The comparison suggests that the NWA indicators – in areas where NWA data are available – could be more useful inputs to sustainability reporting than the global scale indices,

The water use intensity indicator can also be separated into its surface water and groundwater components to provide insights into the status of each component of the water resources in the region (Fig. 9.14 and Fig. 9.15). These results highlight that in many regions the groundwater systems are in a higher stress category than surface water. This likely reflects generally higher storage capacity in aquifers compared to surface water reservoirs, which buffers climate variability and allows a higher proportion of the inflows to be intercepted by users. This buffering effect is illustrated by the groundwater use intensity of greater than one in 2016 in the Murray-Darling Basin, which reflects groundwater being drawn from storage during a dry year. The relatively high groundwater use intensity in many regions could indicate the potential for stress to groundwater dependent ecosystems in these areas.

The water payout ratio indicator (Fig. 9.16) illustrates the proportion of the *net* water availability (i.e. inflows minus non-usage outflows) that has been used. A water payout ratio of less than one indicates that not all water that has been captured in the region has been used in that year and some has instead been banked in the region's surface water reservoirs or aquifer storage, while a value greater than one indicates that more water has been used than captured and therefore reserves are being drawn down.

While the payout ratio would be expected to fluctuate around a long-term average of one, a consistent value above one or below zero would indicate that the region's reserves are being depleted. Most regions show fluctuations around one indicating storage that is drawn down in dry years is replenished in wet years. The fluctuations are generally highest in the Burdekin and South East Queensland regions, reflecting their higher water variability (Fig. 9.5).

The Ord, Daly and South East Queensland regions also have some years with negative payout ratios. A negative payout ratio reflects negative net water availability, meaning more water was discharged from a region than flowed into it in that year. These indicator values reflect years in which all usage came from water stored in previous years as opposed to new inflows. This can occur in dry years such as in the South East Queensland region in 2016, when evaporation and leakage from the region's reservoirs exceeded the volume of water captured in them. It can also occur following a wet year when storages are at capacity and are unable to capture new inflows, such as in the Ord region in 2015. These negative payout ratios are another indication of regions with high variability in inflows in which storage in surface water reservoirs or aquifers is very important to buffer the variability.

The water assets change and water banking indicators both provide an indication of the improvement or depletion of a region's water assets in a given year. These indicators are broader than the payout ratio because they include not just changes in physical water storage, but also accrual (paper) transactions, which include water licence claims and inter-region claims. The water assets change indicator (Fig. 9.17) shows the year's change in water assets relative to the total, while the water banking indicator (Fig. 9.18) shows the proportion of that year's inflows that were 'banked' as an asset. Values above zero for both indicators represent 'banking' while values below zero represent asset depletion. Fluctuations around a long-term average of zero should indicate a sustainable abstraction regime, while a persistent negative trend would indicate a problem with resource depletion.

In general, most regions do show a fluctuation around zero. An example of a management response that could be informed by this indicator occurred in the Melbourne region in 2017. Following two years of negative and declining values of both indicators in Melbourne, the state government of Victoria ordered water from its desalination plant for the first time to secure Melbourne's supply (Office of the Premier (Victoria) 2017).

9.4.4 How Secure Is Water Supply in Australia?

While the water sustainability indicators look backward in time at water system performance to identify issues and trends, the water security indicators are forward looking, providing an indication of future performance. They are analogous to

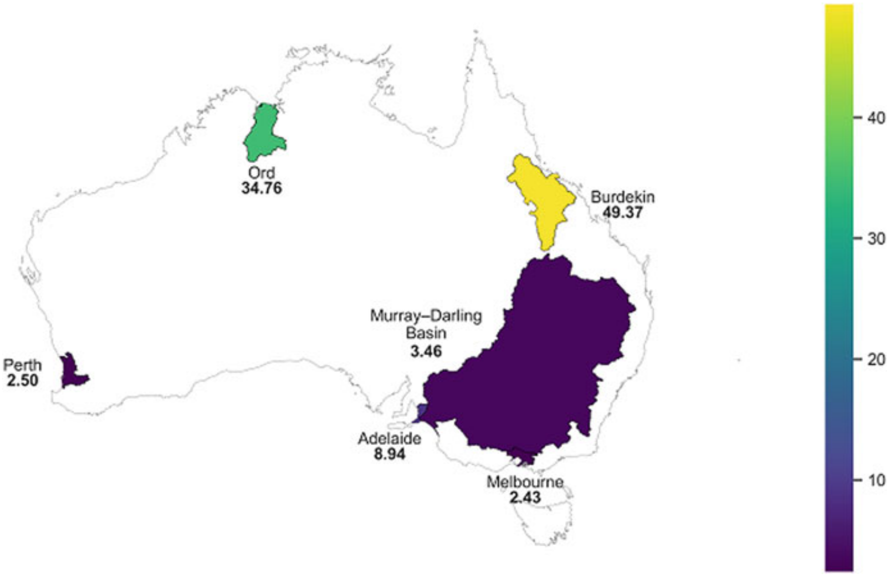

Fig. 9.19 Banked water liquidity at 30 June 2017 (dimensionless ratio)

liquidity indicators in the financial industry. Banked water liquidity (Fig. 9.19) provides an indication of a region's ability to meet its current water liabilities (licensed allocations, inter-region commitments, etc.) with its current water assets (water in storage, inter-region claims, etc.). A value of greater than one means the region currently has enough assets to meet its liabilities. A value of less than one indicates a risk that if sufficient inflows do not eventuate the region may not be able to meet its commitments.

As of 30 June 2017, all regions where this indicator was calculated had banked water liquidity indicator values of greater than one. The indicator was not calculated for several regions because they had no liabilities at 30 June 2017. Of the remaining regions, Melbourne had the lowest value, and this was reflected in its state government's decision to access desalinated water for the first time in 2017 as a result of a steady decline in storage over the previous two years (Office of the Premier 2017). The Perth region's value was also one of the lowest because it relies heavily on groundwater storage, for which a water asset value has not been quantified in the NWA due to data limitations. The Ord and Burdekin regions had the highest values reflecting wetter conditions in recent years.

Total water liquidity (Fig. 9.20) considers projected future inflows and projected usage over the coming year as well as current water assets and liabilities. A value of greater than one indicates that the region is predicted to be able to meet its commitments in the coming year. The extent to which the value exceeds one provides an indication of how much buffer or contingency supply capacity is available. A value close to or less than one indicates a risk of non-delivery of

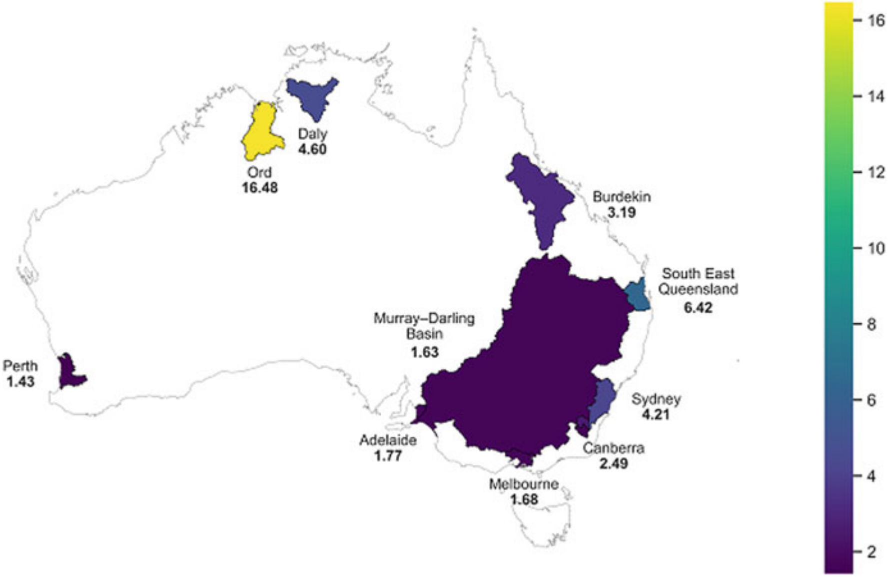

Fig. 9.20 Total liquidity at 30 June 2017 (dimensionless ratio)

supply commitments and could trigger management response such as activation of contingency plans like imposing water restrictions or developing alternative water sources. The northern regions, Daly, Ord and Burdekin, had some of the highest total liquidity values reflecting more conservative allocation strategies in light of high variability. The southern urban capitals of Perth, Adelaide and Melbourne had some of the lowest values and this is reflected in recent management responses in all three regions to source resources that are not affected by climate variability ('climate-independent water resources'), including desalinated water and recycled water.

The climate independent liquidity indicator (Fig. 9.21) illustrates the proportion of the region's water demands that is met by climate independent water sources. This provides an indication of the proportion of the region's demands that is not at risk from climate variability. The Perth region has the highest value, reflecting recent investment by the state government in desalination and reinjection of wastewater to the region's aquifers, in response to a persistent drying trend in the region over the past several decades (Western Australian Department of Water and Environmental Regulation 2018).

A useful snapshot of management priority is illustrated by plotting the water use intensity indicator against total liquidity (Fig. 9.22). Regions that plot toward the bottom right are those with a high usage intensity ('stress') and low security, that are likely to be the highest priority for intensive management or intervention. Out of the NWA regions, the Murray-Darling Basin plots furthest to the bottom right, reflecting the most intensively managed area in Australia. The top left quadrant

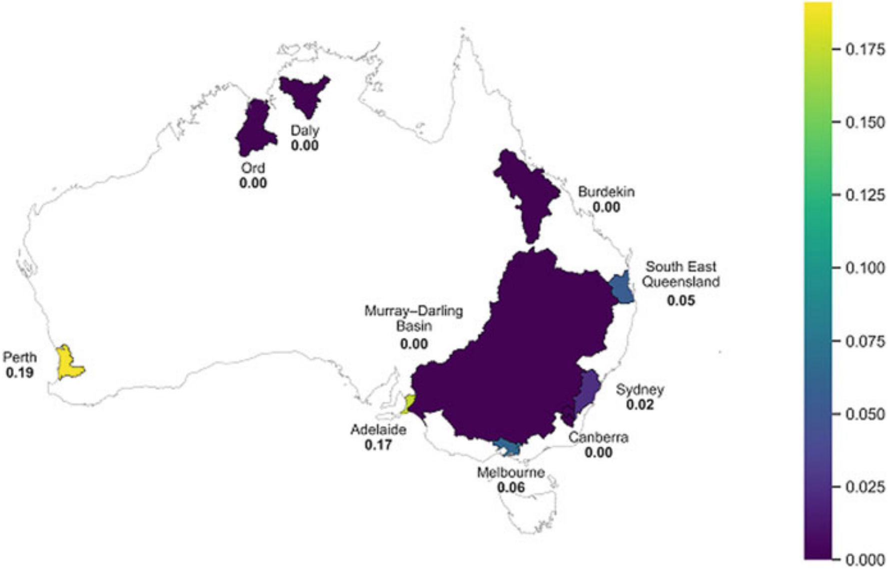

Fig. 9.21 Climate independent liquidity (dimensionless ratio)

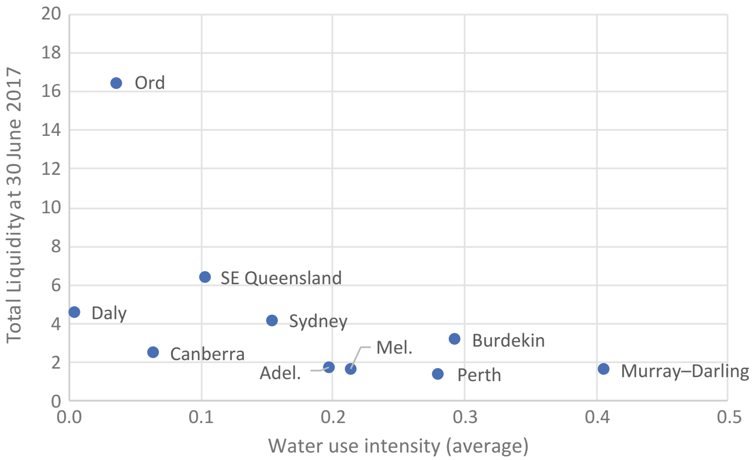

Fig. 9.22 Water use intensity versus total liquidity (dimensionless ratios)

of the chart is the opposite and indicates regions that are likely to require a lower level of management. The Ord region plots the furthest in this direction. Of the urban regions, Perth plots the furthest toward the intensive management quadrant, validating the response of high investment in climate independent water sources by the State government.

9.5 Discussion and Conclusion

Our analysis has shown that indicators can be useful in answering key questions likely to be raised by decision makers in water policy and sustainable water resource management such as: How much water is available for use? How much water is being used and how is it being used? Is water use sustainable? Can future demand be met?

The four water availability indicators described how much water is available by area or per person, as well as how variable the water supply is, how quickly it replenishes and therefore how robust to variability it is. These key questions are of key importance in the Australian context due to the high variability in water resource availability and the fact that the majority of population is centralised in the capital cities. For example, this suite of indicators clearly highlights the contrast between coastal regions such as Melbourne and Sydney with higher water inflow density but lower water availability per capita due to high urban populations, and more arid interior regions with sparse population and higher water availability per capita. Similarly, the indicators differentiated between regions with long replenishment times and high variability, which are likely to have more variable water supplies, such as the Ord region, and more robust water regions with rapid storage turnover and lower availability such as Adelaide.

The four water supply and use indicators provided an overview of how water is secured, sourced and distributed in a region. The indicators described whether a region depends mainly on surface water or groundwater, whether it uses water mainly for urban or non-urban purposes and whether it depends on importing water. The water allocation intensity indicator also told us how much of the available water has been committed for human use.

Together these groups of water availability and water use indicators can help inform the intensity and type of water management required. For example, regions with high allocation levels, high variability, high urban demand, and low turnover of water storage are likely to require the most intensive management to ensure a robust and reliable supply. Predominantly agricultural water-use regions, with high availability and low allocation levels may be suited to a less conservative management approach, with the objective of optimising economic benefit from water resources taking precedence over maximising water security.

The water supply sustainability and security groups of indicators borrow from the financial field's concepts of solvency and liquidity, which illustrate a company's health, profitability, and ability to continue as a going concern. They can be useful for answering water questions such as: how stressed is the water system and how secure is the water supply?

The water supply sustainability group of indicators can highlight which regions, and which type of water resources in these regions, are more at risk of being stressed. The trends in these indicators can also show which regions are drawing down their reserves and which are banking water to improve security. For example, these indicators highlighted high water use intensity in the Murray-Darling Basin, an indication of stress, and help to validate the Australian Government's major investment in water management in the region through the development of a basin-scale allocation framework (the 'Basin Plan'), creation of the Murray-Darling Basin Authority specifically tasked to manage water in the region, and a major investment is buying back water entitlements for the environment (MDBA 2018).

The water security group of indicators are analogous to financial liquidity and solvency indicators and can help to highlight areas of risk where further investigation, analysis and water management may be required. For example, the liquidity indicators highlighted declining water security in Melbourne in 2017. This helps to validate a decision by the Victorian Government's to activate a desalination plant for the first time in that year. The desalination plant had been constructed for just this purpose to ensure supply security in times of low natural water availability (Office of the Premier 2017).

By helping to answer the key water system questions of how much, how it is used, how sustainable and how secure, we believe the indicators can be useful tools for stakeholders in the water industry, including water managers, policy makers, water users such as irrigators or water utilities, and potentially the general public (Tello et al. 2016). The indicators can be useful in several ways:

- Standardising water information across water systems that differ in size, climate and type of use, allowing rapid comparison of key issues between regions.
- Setting the context for the type of management required, for example distinguishing between areas with high availability and low variability, and those with high competition for scarce and variable resources.
- Helping to evaluate past management or investment decisions, for example, recent investment in climate-independent sources in Perth.
- Informing water policy decisions for future investment into new water supplies or climate-independent resources.
- Highlighting trends of concern, such as the declining security in Melbourne in 2017 that led to the region's desalination plant being activated.
- Contributing to sustainability reporting requirements, such as under Global Reporting Initiative 303 (GSSB 2018).
- Targeting more detailed analysis and investment strategies.

The indicators presented here are based on the dataset from the National Water Account which is an annual product focusing on water quantity, aggregated across significant water resource management regions in Australia. They are most useful for comparison on a broad, national scale.

For more local decision making, further insight could be derived from drilling down into these data to calculate indicators at finer scales, both spatially (e.g. sub-catchments) or temporarily (e.g. monthly basis).

New indicators derived from water quality data could also be a valuable input to water management decision making showing, for example, suitability of water for various uses or areas where water quality is declining. Incorporation of economic information into water indicators, such as the value-add of water, operating costs for water delivery, or the capital costs of water infrastructure, could also assist decision making by highlighting trade-offs between costs and benefits. Finally, the indicators presented here are mainly backward looking, relying on measured data. The indicator suite could be enhanced in the future through development of new future-projection indicators based on forecasts of future climate scenarios, population growth and infrastructure capacity.

References

Australian Government (2019) Our natural environment. https://www.australia.gov.au/about-australia/our-country/our-natural-environment. Accessed 18 Feb 2019
Australian Government Bureau of Meteorology (2013) The national water account companion guide. http://www.bom.gov.au/water/nwa/document/companion-guide.pdf. Accessed 16 Feb 2019
Australian Government Bureau of Meteorology (2018) National water account. http://www.bom.gov.au/water/nwa. Accessed 24 Jan 2019
Australian Government Bureau of Meteorology and CSIRO (2018) State of the climate 2018. http://www.bom.gov.au/state-of-the-climate/State-of-the-Climate-2018.pdf. Accessed 24 Jan 2019
California Department of Water (2014) The California water sustainability indicators framework. https://water.ca.gov/LegacyFiles/waterplan/docs/cwpu2013/Final/vol4/sustainability/05Sustainability_Indicators_Framework.pdf. Accessed 24 Jan 2019
Chalmers K, Godfrey JM, Lynch B (2012) Regulatory theory insights in the past, present and future of general purpose water accounting standard setting. Account Audit Account J 25(6):1001–1024
Delen D, Kuzey C, Uyar A (2013) Measuring firm performance using financial ratios: a decision tree approach. Expert Syst Appl 40(10):3970–3983
European Environment Agency (2004) Water exploitation index. https://www.eea.europa.eu/data-and-maps/indicators/water-exploitation-index. Accessed 24 Jan 2019
Falkenmark M (1997) Meeting water requirements of an expanding world population. Philos Trans R Soc Lond Ser B Biol Sci 352:929–936
Gassert F, Landis M, Luck M, Reig P, Shiao T (2014) Aqueduct global maps 2.1. Working paper. World Resources Institute, Washington, DC. http://www.wri.org/publication/aqueduct-global-maps-21. Accessed 24 Jan 2019
Global Sustainability Standards Board (2018) GRI 303: water and effluents 2018. https://www.globalreporting.org/standards/gri-standards-download-center/gri-303-water-and-effluents-2018/. Accessed 24 Jan 2019
Godfrey JM (2011) Australia leads the water reporting initiative. Charter 82(1):24–26
Keywood MD, Emmerson KM, Hibberd MF (2016) Climate: rainfall. In: Australia state of the environment 2016. Australian Government Department of the Environment and Energy, Canberra. https://soe.environment.gov.au/theme/climate/topic/2016/rainfall. Accessed 16 Feb 2019. https://doi.org/10.4226/94/58b65c70bc372
Kummu M, Guillaume JHA, de MH, Eisener S, Flörke M, Porkka M, Siebert S, Veldkamp TIE, Ward PJ (2016) The world's road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability. Nat Sci Rep 6:38495
Liu J, Yang H, Gosling SN, Kummu M, Flörke M, Pfister S, Hanasaka N, Wada Y, Zhang X, Zheng C, Alcamo J, Oki T (2017) Water scarcity assessment in the past, present, and future. Earth's Future 5:545–559
Murray-Darlin Basin Authority (2018) A plan for the Murray-Darling Basin, https://www.mdba.gov.au/basin-plan/plan-murray-darling-basin. Accessed 24 Jan 2019

Office of the Premier (Victoria) (2017) Government provides water storage certainty. Press release. https://www.premier.vic.gov.au/government-provides-water-storage-certainty-2/. Accessed 11 Oct 2018

Penman S (2007) Financial statement analysis and security valuation. McGraw-Hill/Irwin

Petheram C, Gallant J, Wilson P, Stone P, Eades G, Rogers L, Read A, Tickell S, Commander P, Moon A, McFarlane D, Marvanek S (2014) Northern rivers and dams: a preliminary assessment of surface water storage potential for northern Australia. CSIRO Land and Water Flagship Technical Report, CSIRO, Australia, Queensland

Slattery M, Chalmers K, Godfrey JM (2012) Beyond the hydrographs' legacy: water accounting in Australia. In: Godfrey JM, Chalmers K (eds) Water accounting: international approaches to policy and decision making. Edward Edgar Publishing, Cheltenham

Tello E, Hazelton J, Cummings L (2016) Potential users' perceptions of general purpose water accounting reports. Account Audit Account J 29(1):80–110

United Nations Development Programme (2018) Sustainable development goals. www.undp.org/content/undp/en/home/sustainable-development-goals.html. Accessed 24 Jan 2019

Vanham D, Hoekstra AY, Wada Y, Bouraoui F, de Roo A, Mekonnen MM, vand Bund WJ, Batelaan O, Pavelic P, Bsatiaanssen WGM, Kummu M, Rockstrom J, Lui J, Bisselink B, Ronco P, Pistocchi A, Bidoglio G (2018) Physical water scarcity metrics for monitoring progress towards SDG target 6.4: an evaluation of indicator 6.4.2 "level of water stress". Sci Total Environ 613-614:218–232

Water Accounting Standards Board (2012) Australian water accounting standard 1: preparation and presentation of general purpose water accounting reports. Commonwealth of Australia (Bureau of Meteorology), Canberra

WaterinCore (2010) Sustainable water management through common responsibility enhancement in Mediterranean River Basins. Water management. Common list of indicators & database. http://www.waterincore.eu/deliverables/03_03_01_en.pdf. Accessed 24 Jan 2019

Western Australia Government Department of Water and Environmental Regulation (2018) Climate change and waterways. http://www.water.wa.gov.au/water-topics/waterways/threats-to-our-waterways/climate-change-and-waterways. Accessed 24 Jan 2019

Xu H, Wu M (2017) Water availability indices – A literature review. Argonne National Laboratory, Energy Systems Division, http://water.es.anl.gov/documents/Technical%20Report_% 20Literature%20Review%20of%20Water%20Availability% 20Indices_030317.ems_vs.pdf. Accessed 24 Jan 2019

Chapter 10
Evolving Perspectives of Sustainability in the Case of Community Forestry in Nepal

Mani Ram Banjade and Naya S. Paudel

Abstract Nepal's community forestry has evolved from afforestation, forest conservation, social inclusion and equity to harnessing economic potentials. It has shown immense potential for forest sustainability by integrating ecological, social and economic dimensions but historically these dimensions received shifting focus hence one or more dimensions received inadequate attention. The donor priorities, discourses spanning from national and international arenas and shifting government policies had an effect on inflated treatment to one or the other dimensions of sustainability. We argue that by granting clear, strong and perpetual tenure rights to local communities would help better integrate ecological, social and economic dimensions of sustainability of forest commons.

Keywords Community forestry · Sustainability · Community rights · Forest governance · Nepal

10.1 Introduction

This chapter provides a historical account of how forest governance in general and that of community forestry in Nepal has advanced overtime from sustainability perspective. Sustainability of community-based forest management modalities is defined in relation to their balanced performance on environment, economic and social fronts. More specifically, the sustainability of forestry should be understood as right balance between forest conservation as well as harnessing economic and social values that forests offer (Maini 1992). Nepal's community forestry is a

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compelling case of globally acclaimed approach to forest governance but there is hardly any attempt made in analyzing the much-hailed noble approach from the sustainability perspective. Incepted in the late 1970s, the community forestry has survived and thrived through various international pressures including donor priorities and discourses as well as internal pressures such as insurgency and shifting government priorities.

Soon after unification of principalities of Nepal began in 1740s, Nepal's forest met with an enduring interest of rulers in exploitation of the productive forests, particularly that of southern plains called Terai. The main motive of forest exploitation was guided by meeting the burgeoning state expenses for financing unification process. Major revenue sources were land and forest, of which forest products including timber, medicinal herbs and elephants were lucrative sources (Regmi 1999). Agricultural policies aimed at expanding tax base impacted severely on forests in the Middle Hills and drove large scale deforestation in the century or so prior to 1950. Similarly, urban expansion within Kathmandu valley syphoned large volume of timber from surrounding hill districts such as Sindhupalchok and Kabhrepalanchok (Mahat et al. 1987). To conquer new lands and convert them from passive forest to active agriculture landscapes, the government also offered forestland as *Birta* to its close allies and *Jagir* to its employees as part of their remuneration. The process continued during the Rana oligarchy that ruled between 1846–1951. As a result, large tracts of forest territories were privatized until the late 1950s, when the civil government of Nepal nationalized all forests in 1957. The nationalization of forests meant bringing all the forests under central government control. In order to operationalize the centralized forestry, the government instituted powerful forest bureaucracy and equipped them with strong legal backing and paramilitary forces. Major thrust of centralization was on conserving forest and taking strong legal action against 'transgressors'.

Sustainability of forestry was largely defined to protect the resource base for forthcoming generations; approaches of yield regulations for sustained timber supply was the key aspects of sustainable forest management principles until 1990s. In the case of community forestry, the regulatory frameworks and institutional arrangements were largely geared towards satisfying subsistence forest product needs of local people; any commercial use was largely discouraged.

Centralized forestry agencies led forest administration devoid of local people. Amidst the centralized forest sector governance, Nepal observed an extremely high rate of deforestation between 1950 and 1975, which accounted as 4.1% per annum (Thapa and Weber 1990), which is claimed to be among the highest in tropical countries. Rapid incidence of deforestation and corresponding acute shortfall of forest products in meeting forest products needs together with rapid soil loss led to the alarming situation in the Nepal Himalaya. Ecological crises of 1970s led to the focus only on reclaiming deforested landscapes (Eckholm 1976; World Bank 1979). The Himalayan environmental degradation narrative attracted global attention on revisiting the approaches to forest sector governance for sustainability of the highly vulnerable hill environment. In the 1970s participatory web of development was gaining momentum worldwide, and this also contributed in Nepal to experiment new approaches of forest management. This ultimately led to the evolution of community-based forestry. The initial purpose of CF was to encourage participation of local people on restoring severely degraded forests by a mix of artificial and natural regeneration. Thereafter, the entire focus of community forestry was on forest protection and employed tactics such as a ban on grazing, restrictions on forest product use, patrolling to prevent ‘illegal’ forest extraction, fencing, plantation and fire control. This conservation orientation of community forestry remained until 1990s. From the late 1990s, the focus has shifted from conservation and subsistence use to economic returns from forestry from sustainable utilization of forest products. Initially, emphasis was given to commercial exploitation of non-timber forest products but since 2010 timber extraction is also slowly included as a major forest product to sell in the market.

The chapter builds on the review of literature that capture the historical evolution of community forest management from the sustainability point of view defined as the integration of three dimensions namely environmental, social and economic. After recapping a brief history of forestry in general in the introduction we discuss about key drivers and evolutionary dynamics that jointly contributed in shifting forest governance regimes from centralization to decentralization and devolution. In Sect. 10.3 we discuss about ecological dimension in light of how ecological restoration as a major environmental conservation was enacted in Nepal with positive contribution in halting deforestation and restoring forests in denuded areas. We cover social dimension of forest sustainability in Sect. 10.4 and highlight the considerable success of community forestry program on inclusion and equity. Section 10.5 deals with economic dimension and cautions the ecological risks associated with undue exploitation of forest resources. Then, before conclusion Sect. 10.6 assesses the challenges of finding a balance between environmental/ecological, social and economic dimensions.

10.2 Evolution of Community Forestry in Nepal: Key Drivers and Dynamics

In the 1970s, the world faced a two-pronged energy crisis: (i) world oil crisis – cartel of OPEC countries for rising petroleum price by four times – had triggered a shift in energy focus from fossil fuel to renewal energy; and (ii) pressure on forest land for timber and fuelwood gave rise to think beyond woodlots in natural forest areas resulting into the emergence of the concept of social forestry. Rapid upsurge of social forestry in this period witnessed plantation projects in communal land to reduce the pressure on the existing, often deteriorated, natural forests (Arnold 2001). Similarly, there were certain local responses to declining natural resource conditions such as (i) enforcing for restrictive use of certain resources; (ii) setting out certain areas for not use particularly around water holes or in the religious locations; and/or (iii) planting in agricultural incursions or in communal land. Similarly, civil society and market forces began to seek their role in the governance process through demanding or facilitating for certain standards or ‘changing consumer preferences’ (Agrawal et al. 2008).

The centralized form of top-down governance characterized much of the nineteenth and twentieth centuries (Agrawal et al. 2008). Critics of the state-centric traditional way of natural resource governance and management (largely environmental governance) argue that it ignores or bypasses the historical human-environmental interactions (Bryant and Wilson 1998). In the face of this criticism, the alternative approaches to natural resource governance that share in common is the redistribution of power and responsibility from state officials to local people and other stakeholders (FAO 2011). Restructuring of the natural resource sector is evolving fast and at least 60 developing countries put in place formulated decentralization over some parts of NRM up to the end of the twentieth century (Agrawal 2001). At least six major drivers are identified below that contributed in the introduction and development of community-based forest management in Nepal, most of them are also equally considered as major drivers in other countries:

One of the major reasons for the states being ready to cede some of their power to the local people for managing and using the resources was the failure of the states to protecting the resources (Fisher 2000; FAO 2011; Poffenberger 2006). In fact, state departments could not exercise effective control over most parts of the countryside in spite of stringent legislative back-up (Gilmour and Fisher 1991; Feeny et al. 1990). Similarly, policy makers started to realize that top-down decision-making could trigger a spiral of conflict on the ground, putting natural resources at risk of destruction and degradation (Fabricius et al. 2004). When the existing centralized form of governance could neither conserve the resources nor fulfil the expectations of people, changing the governance of natural resource management was, in a way, ‘a move away from centrally administered, top-down regulatory policies’ (Agrawal et al. 2008). In Nepal, CF was introduced amidst the ecological degradation largely attributed to the centralized forestry (Hobley 1996; Gilmour and Fisher 1991). Deforestation and soil erosion led to an alarming situation of immense environmental degradation of the Himalayas (Eckholm 1976; Ives and Messerli 1989). While these mounting challenges forced donors and policy makers in changing forest policy for participatory forestry but at the same time triggered for conservation focused forest management often compromising social and economic aspects.

Second, the decades of 1970s and 1980s are also known for evolving bottom-up approach as concept of building up from the local concerns, knowledge and capacities (Chambers 1983), which was later further developed to the extent that ‘participation’ became the buzzword across all the development sectors. 1980s experienced two parallel developments. First, is that natural resource management agencies faced shortages of funding for conservation (Plummer and Fitzgibbon 2004; Fabricius et al. 2004) and wanted to reduce the financial burden of managing these resources (Agrawal et al. (2008) point out this in reference to forest governance). And, second, concept of ‘Integrated Conservation and Development’ was put forward by WWF within protected areas in mid 1980s. The Earth Summit of 1992 is a noteworthy international policy deliberation which set milestones through Rio Declaration, particularly that of ‘the Convention on Bio-Diversity’, which highlighted the rights of people over natural resources and set equitable benefit sharing and sustainable use of resources as the conditions for sustainable management of bio-genetic resources.

Third, the formalization of rights of local communities over natural resources has its root on the recognition of local knowledge and existing indigenous management systems. Local people have more legitimate interest and concern over surrounding natural resources than external agencies (Ostrom 1990). Existing indigenous management practices provided the fertile ground for community forestry in Nepal (Gilmour and Fisher 1991). While exogenous perception was critical, local support for community forestry was immense and was also driven by the local realization of forest conservation: forest land degraded, short supply of forest products, soil erosion (Springate-Baginski and Blaikie 2007).

Fourth, decentralization was often taken as a populist strategy by autocratic Panchayat political system to reach out to otherwise vast territories with dissent political ideologies than the rulers. One-party Panchayat system was facing a severe crisis because of rising demand for democracy from people, and rulers found decentralization as a populist program to soothe the growing dissention (Malla 2001). In addition, the international environmental aid also was in favor of community-based forestry (Guthmann 1997; Malla 2001). In other words, in light of external donor persuasion and opportunity for gaining support from local people, the then government of Nepal accepted community forestry as a new regime of forest management. Moreover, the government had nothing to lose by handing over denuded and degraded 'forest' territories in the middle hills.

Fifth, handover of forest areas to local communities for protection and use had also economic rationality. The state was struggling to undertake its duty of surveillance and forest conservation in the less valuable hill forests. As most of the hill forests were already heavily degraded, the state had little to lose by giving up its control over forest territories (Malla 2001). While Worldwide wave toward participatory and community-based forest management (Guthmann 1997; Hobely 1996) added impetus for developing community forestry in Nepal, the World Bank sponsored structural adjustment programs also contributed in developing user group forestry for reducing budgetary burden on forest development (Guthmann 1997; Malla 2001).

Finally, post 1990 democratic era remained a fertile ground for the emergence and strengthening of various kinds of social and political movements in Nepal. In Nepal, after the reinstatement of democracy in 1990, movements for greater citizen rights and their access to natural resources took height that also contributed significantly in expanding community rights over forests. Establishment of FECOFUN, a strong community forestry network having over 10,000 members from all over Nepal have emerged as a formidable force for securing community rights over forests. This is also a global phenomenon. *Chipko* movement of India (Jain 1984; Agrawal 2005; Guha 1989) is a notable environmental movement of local people who denied the existing timber oriented industrial forestry in India. In Latin America, coinciding with Rio declaration which challenged the existing modality of heavy reliance on commercial enterprises failing to address several socio-cultural issues, social movements of indigenous communities, specific forest product users such as rubber tappers and small-holder farmers for the rights over natural resources paved way to the emergence of community forestry (Pokorny and Johnson 2008) reported in reference to Bolivia, Brazil, Ecuador and Peru). Social movements also triggered in recognising customary and traditional forest rights of local people in many parts of Latin America and Asia (Larson et al. 2010).

10.3 Ecological Dimension

As mentioned above, one of the key drivers for decentralized forestry was the wider realization that centralized forestry couldn't arrest accelerating deforestation and environmental crises in Nepal. The theory of environmental degradation was the main discourse leading to development and implementation of the massive plantation projects. The vicious circle of increased demand, decreasing supply and over exploitation of fuelwood led to the development of massive plantation projects by the donors in mid-hills and Terai. One of the narratives of the time was aimed at addressing environmental crisis by resolving fuelwood crisis (Bajracharya 1983). Amidst these crises, the Government of Nepal introduced the community forestry program with the primary objectives of forest conservation and satisfying subsistence forest product needs of local people (Gilmour and Fisher 1991). As a desperate intent of restoring otherwise highly degraded 'forest' territories the government pushed for a massive handover of accessible forests to local communities. As a result a large number of forest patches were handed over to local communities between 1990 and early 2000 (see Fig. 10.1). So far over 20,000 CFUGs have been formed and about 1.9 million hectares of forests have been handed over to them. About 40% of Nepal's population is involved in this community forestry movement.

To serve the forest restoration and conservation purpose, forest protection was kept at the central stage in developing policies, regulations, institutions and programs. Major attention was deployment of forest watchers, grazing control, and limiting harvest (Pokharel 1997) promoted passive management (Yadav et al. 2009; Ojha et al. 2009; Nurse and Malla 2005). The protectionist approach started to showing its effect by reclaiming forests on previously denuded hills. Apparently, people could observe these changes easily such as the photograph of 1975 (before CF) and 2005 of Dandapakhar, the north-eastern hills of Nepal (see Fig. 10.2).

The latest Forest Resource Assessment shows an increase of forest area and quality in last two decades, and community forestry is considered as one of the key reasons of increase in forest cover and improved forest quality (DFRS 2015). By the late 1990s and early 2000s, while conservation role of community forestry program was recognized everywhere, its role in economic contribution and social inclusion and equity were often criticized. Situation was alarming as many reports showed that the existing conservative approaches have not been able to meet the local market needs, and Nepal is embarking on importing timber and other forest products in large quantities. For example, less than 4% of the total timber demand is met through the timber coming from the government managed forests (total annual

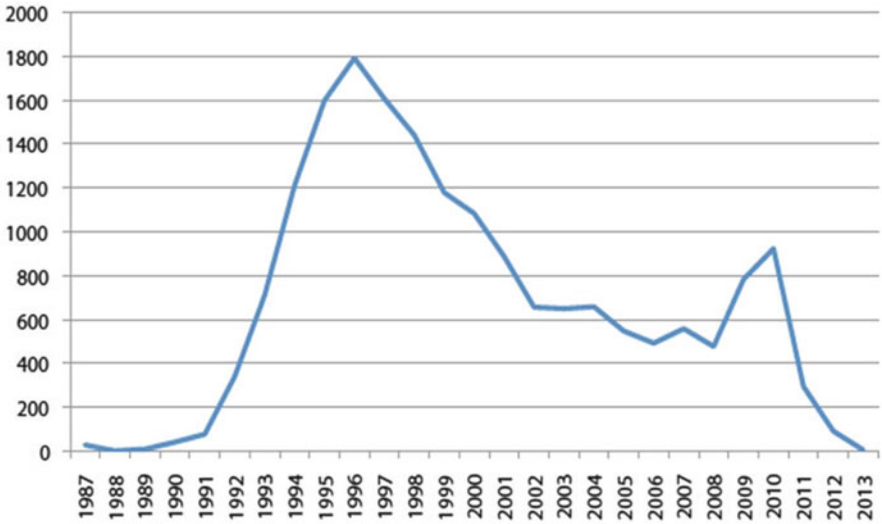

Fig. 10.1 Community forest handover trend in Nepal. (Source: Bhattarai 2016)

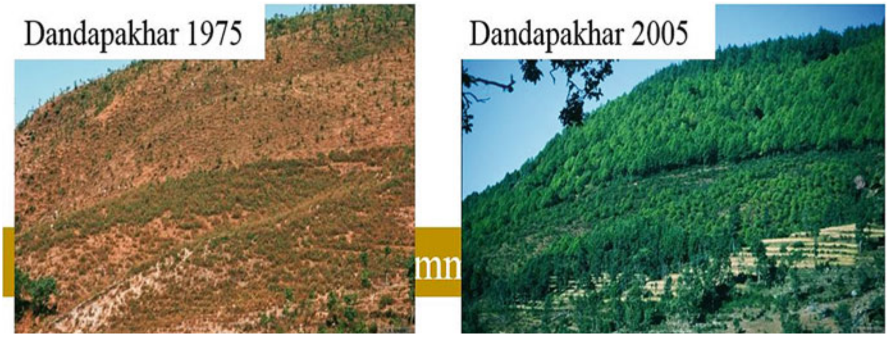

Fig. 10.2 Dandapakhar, Eastern hill region of Nepal before CF and after CF. (Source: NSCFP 2011)

demand of timber is estimated as 3.37 million cubic meter whereas supply is only about 113,000 cubic meter) (Subedi et al. 2014). This unmet demand has triggered illegal logging and corruption, undue increase in market prices, and encouraged the import of timber and timber products (MSFP 2016). FENFIT, a network of timber traders and entrepreneurs, claimed that over 80% of timber demand in the country was met from import, which worth about 88 billion rupees (THT 2016).

Since the entire sector focused on conservation, and discourses, funding and other supports were intended for conservation, outcomes in terms of ecological restoration in mid-hills was extraordinary. As discussed below, other dimensions of sustainability were largely overlooked.

10.4 Social Dimension

Social dimension of community forestry in Nepal is generally found gradually improving in terms of generating trust among various stakeholders and community groups, enhanced social capital, institutional robustness, and accommodation of cultural diversity. Improved social dimension also contributed in enhanced institutional resilience, which was evident during the ecological stress such as deadly earthquake of 2015 and a decade long insurgency (1996–2006).

Initial focus of the community forestry was handing over potential forest areas to local communities and external support was given to plantation activities and forest protection. The community forestry processes were highly driven by the external agents. The targets were set by the government in terms of number of community forestry hand over, without much attention on the due procedures for inclusive and democratic governance of the groups that would manage forests. Generally, in practice, existing local leaders were handpicked; a committee formed; a constitution and an operational plan prepared by the government forestry staff; and an agreement between District Forest Officer and executive committee of the respective community forest user group was signed.[1] In many cases, the local male leaders made decisions impacting the forest use conditions bypassing women's voices. As most of the household chores and forest product collection mainly fuelwood and fodder were undertaken by women, and committees dominated by men, restriction or ban on collection of fuelwood and fodder increased the workload of women.

Elite capture of local political space created around community forestry was also evident in many places (Garner 1997), which were largely ingrained in socio-economic and political structures nurtured in hierarchical social system (Agarwal 2001; Nightingale 2002). Since 2000s, there has been increasing pressure from local people and other stakeholders to move beyond forest conservation, and policies and programs have been geared towards embracing other sustainability principles in forest management. Introduction of the provisions of rigorous forest inventory, and mandatory provisions of inclusive governance, and allocation of community fund in forest management, community development and poverty reduction are some provisions added after 2000s to accommodate sustainability principles in community forestry (Pokharel et al. 2008). However, these provisions are inadequately implemented in practice, and technical provisions are often critiqued for strengthening techno-bureaucratic grip in forest governance rather than ensuring sustainability (Ojha 2006). Inventory and prescriptions of harvest are not followed in practice (Ojha et al. 2009; Rutt et al. 2015; Basnyat et al. 2018).

[1]When the concept of community forestry was first introduced in mid-1970s, initially patch of forests were handed over to the local government. Later user group concept was accepted but the approval has to be made by the regional forest directorates rather than district forest offices (DFOs). People had practically no access to these directorates as they were situated in distant places, and all the processes were facilitated by the DFOs.

Post 1990 also was flourishing period for development of vibrant civil society that advocated for inclusive governance, and hence forest sector also saw a wave of gender and ethnic inclusion and equity in forest governance (Ojha et al. 2014). Other drivers for promoting inclusive governance in community forestry include: research heavily pointed out elite capture (Agarwal 2001; Rai Paudyal 2008; Khadka 2009), and increasing donor support for inclusive development (Khadka 2009). Strong civil society movement for community forestry, and resulting multi-stakeholder contributions are reflected and lessons integrated in CF guidelines prepared in 1999, 2005, 2009 and 2014.

Now, the community forest user groups should have at least 50% women in their committees including at least one woman in vital positions such as chairperson and secretary. Growing recognition of women's role in community forestry and improved policy provisions for expanding their positions in political spaces have also contributed in overall increase in women's participation in forest management (Agarwal 2009). In addition, women leadership development and their increasing roles is attributed for improved transparency and accountability of community forestry in general (Pokhrel and Nurse 2004; Ojha et al. 2009; Kanel 2004; Pokhrel et al. 2009; MSFP 2013). There are several spillover effects of inclusive governance in other sectors such as school management, irrigation, drinking water, health center management, national politics and other collective action settings (Pokharel et al. 2008). In addition, the community forestry over time has also set the example of conflict resolution mechanism (Nightingale and Sharma 2014; LFP 2010; Negi et al. 2018) and deepening local democracy (Ojha et al. 2009; Pokharel et al. 2009). Community forestry has also given some attention in recent years for supporting poverty reduction, and has provisioned for pro-poor focus agenda such as wellbeing ranking, capacity building and integrating entire CF benefit sharing mechanisms with wellbeing ranking (Chadwick et al. 1995; Pokharel and Nurse 2004).

Similarly, Nepal's community-based forest management also evolved from community control and management with some direct influence of feudal authorities before 1957 to diversity of actors now claiming stake in forest governance demanding innovative approaches of responding to the expanding institutional landscape (see Fig. 10.3).

10.5 Economic Dimension

As mentioned above, once community forestry in Nepal achieved its goal of ecological restoration, demand from communities and civil society was growing for harnessing economic potential of the same. There was growing realization among researchers, donors and policy makers of the gap between actual realization from and full economic potential of community forests (Thoms 2008; Ojha et al. 2009). So, policies started to be revised, primarily for non-timber forest products in early stages. However, focus on economic dimension limited largely at discursive level and seldom materialized them in programs and practices. Nonetheless, increased

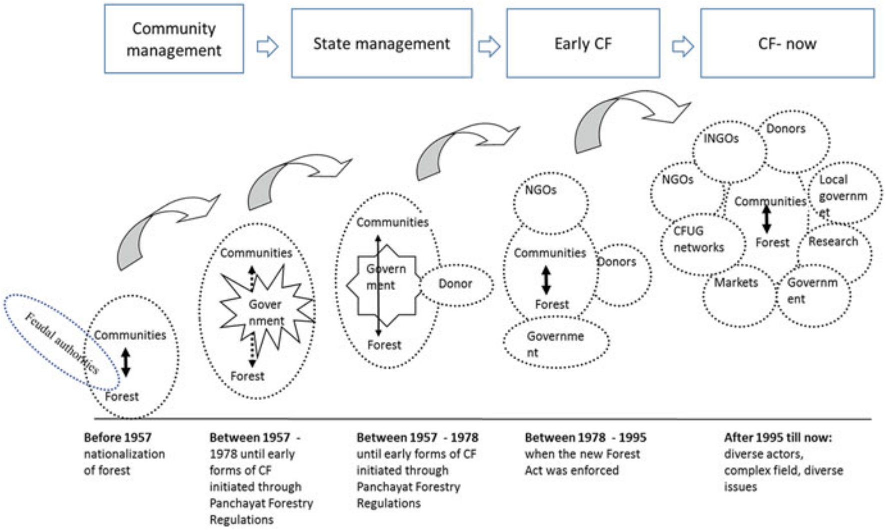

Fig. 10.3 Expanding institutional landscape in community forestry in Nepal adapted from (Ojha 2009)

demand of timber and expanding markets for various forest products (Paudel et al. 2019) have been driving community forestry towards increased economic returns through sustainable management of forests. In recent years, market for carbon and environmental services have expanded economic potential of forests for new products and services.

The government of Nepal since over last one decade has been promoting scientific forest management, which leads to considerable increase in harvest from the current conservative level that eventually increases the supply of forest products in the market. Similarly, communities, donors and government are promoting value addition in community forestry and have invested considerably in forest-based enterprises. By the end of FY 2015/16, the total number of small-scale forest enterprises was 14,708, providing employment to around 85,000 individuals (DCSI 2016). These enterprises had a total capital investment worth NPR 9.8 billion, with each producing average output valued at NPR 1.3 million. By multiplying the total number of registered enterprises by output per unit (i.e. 14,708 × NPR 1.3 million), the estimated total output of these enterprises is NPR 19.12 billion. There is no data on the contribution to large and medium scale enterprises; adding this too would mean significant contribution to the economy.

While the vision of forestry for prosperity and scientific forestry program can be considered as sharp paradigmatic shifts for giving due consideration of economic dimension of community forestry, stakeholders and researchers cautioned that there is a danger of a narrow timber focus and over exploitation, which eventually could pose considerable ecological risks.

10.6 Integration Challenges

Evolution of community forestry in Nepal for last four decades have demonstrated considerable amount of institutional maturity and has been adaptive to shifting focus and demand for accommodating emerging issues and priorities. As we have seen in above sections, the focus of community forestry has expanded from ecological restoration, social inclusion and equity to economic returns. While ecological, social and economic aspects of sustainability are embraced in principle, integration of these dimensions is often a formidable task. The integration challenges are espoused by shifting focus across these dimensions, seemingly progressive policy provisions have limited ownership at local level, limited local capacity for integration of technical and social elements, and mismatch between definition of local and global sustainability.

10.6.1 Shifting Focus on Single Dimension of Sustainability

The shifting focus from one dimension of sustainability to another, rather than seeking integrated solutions, is often resulted from the ongoing global and local discourses, corresponding shifting priorities of the donors, and policy crises perceived by the techno-bureaucrats and policy makers. Ojha et al. (2014) discuss the shifting, and occasionally overlapping, focus namely conservation (1970–present), afforestation (1970–1990), participatory (1980–present), inclusive (1990–present) and carbon forestry (2007–present). In addition, since the late 1990s policy deliberations were also on increasing economic return from community forestry. The herbs and non-timber forest product development policy 2004, and later focus on 'scientific forestry' are two significant shifts in harnessing economic potentials of community forests against the earlier conservative focus on forest protection and conservation.

Partial sustainability with undue focus on swing between ecological, social and economic dimensions is problematic, posing considerable challenges to the overall sustainability of community forestry. For example, the weak emphasis on social dimension has negative implications to environmental sustainability; poor governance led to the increased concern of over exploitation and unsustainable use of forest resources.

10.6.2 Limitations with Top-Down Approaches

Nepal's experience of top-down approach to forestry shows that regulatory instruments alone could not be successful. Strong administrative control and stringent regulatory and institutional measures could not stop deforestation in Nepal be the

1960s and 1980s until community based forestry was adopted as a major approach and program, and demonstrated its positive implication on forest restoration. The forest policies, regulations and institutions that were framed to address deforestation and massive environmental degradation since the 1960s were mostly ineffective. It was often argued that centralization of forestry detached forests from people, who previously acted as forest custodians (Malla 2001). Restrictive measures in resource use, criminalizing many of the needed interactions with forest and adopting strong punitive measures for 'illegal' actions did not help much.

Nepal's CF case shows clear limitations of top-down approaches in achieving sustainability. Consequently, a bottom up, community owned and locally led CF programme was introduced. Bottom-up approach helped in forest conservation but the government bureaucracy often tried to impose techno-bureaucratic hegemony and introduced technical and administrative measures which often was outside the capacity of local communities managing forests. Strategies for ensuring sustainability within CF were adopted in a slightly indirect and persuasive ways usually by imposing techno-bureaucratic approaches (Ojha 2006) such as forest inventory, and annual allowable cut combined with long and exhaustive administrative approval process. However, the harvest quantity is often resulted from the hard negotiation with government forestry authorities; in many cases the CF leaders had to offer an inducement to the officials to get harvesting permission. In forefront, these strategies were guided largely by ecological sustainability, and did not adequately considered social and economic dimensions of sustainability. As a result, while forests were regenerated, their contribution to local economy was considered extremely low against their potential. In other words, successful CF became less relevant to over three million people who are compelled to migrate to Middle East in search of law paid labour opportunity. Narrow focus on forest sustainability that could not adequately embrace the changing local economy, increased need of cash and potential of benefiting from increased interface with the market. Though recent policy documents increasingly emphasise on 'forest for prosperity', such discursive shift has yet to be translated in legal structure and institutional behavior of forest officials.

10.6.3 Limitations of Community-Based Approach

Despite impressive success in regenerating once denuded hills of Nepal, CF programme exhibits some inherent limitation of bottom up, community led approach in addressing wider drivers that shape sustainability at larger scale. First, they operate in micro scale and can hardly transact with external environment at landscape level. While CFUGs are well proven rural institutions in protecting small sized forests (average size of CF in Nepal is 85 ha), we have no working institutional model that can handle relatively larger forests/landscapes. Secondly, these too small sized management units have become barrier to run any forest based enterprise that need larger feed of raw materials. Third, while forest- based ecosystem services are increasingly valued for hydropower, drinking water or REDD+, these small CF units cannot provide needed scale and cannot negotiate for their fair price with the state and private companies. In terms of governance approach, the CFUGs operate through the practice of direct democracy. However, as the scale grows, direct participation and decisions increasingly becomes challenging and there needs representative democratic tools to govern resources and link with outside world. These practices have yet to be designed and practiced within CF scheme.

10.6.4 Local vs Global Sustainability

There is also inherent problem of community forestry in addressing larger environmental issues due largely to their limited institutional capacity to grasp the larger environmental goals, and also because of the perception among them that their contribution in this global cause is meagre. In addition, the groups are always struggling to satisfy local forest product and economic needs. In many places, community leaders are under constant pressure of increasing income from forest management, large part of which is determined through the total timber harvest they could ensure. Their capacity is often judged on their ability to get the permission from the government forest authorities for the quantity of timber they can harvest. Environmental issues such as carbon and biodiversity are key global agenda of ecological sustainability but local may not put the same level of thrust. Local development priorities may at times supersede the global sustainability issues. The key challenge is to seeking the balance between these two.

10.6.5 Key Institutional Innovations

Under the CF programme a number of institutional innovations have flourished, some of which have critically contributed to sustainability. Community forestry is often regarded as the successful case of collective action over forest commons, which is visible through crafting and compliance of rules. On ecological front, subsistence oriented management, restrictions on grazing, intensive management, fire control, land allocations to landless households, plantation of local species, and control of invasive species have become characteristics of CF. On the social front, empowerment of women and poor, well-being ranking and design benefit sharing arrangement as per specific wealth group, 50% representation of women and similar quotas for specific groups of people, arrangement of membership free of cost for the poor, support households during one of the positions out of chairperson and secretary for women, listing both husband and wife as household members in CF group, nested model of its federation organization – FECOFUN, periodic events and campaigns for institutional strengthening, solidarity with other NRM and human rights related federations and association within and outside the country, strong value based advocacy on rights and inclusion are some of the identified strategies practiced within CF institutions. Similarly, on economic front, systematic opening for collecting key forest products (timber, fuelwood), free collection of minor forest products such as fodder/grass and leaf litter, differentiated price of forest products in favour of poor, dedicated spending of 35% forest revenue to the poor, cheap interest lending of CF savings, investments in community infrastructure and social services, targeted support to identified poor in health and education, establishing forest based enterprises that provides employment to the poor are some of the innovative initiatives taken under CF.

While all these initiatives sound ideal, there has been only partial success in practice. Many of these attempts come locally, some of them are encouraged or even guided from the top. For example, there is a mandatory guidance to spend 35% revenue to the poor or to have at least one women in two most critical positions of the executive committee. It suggests that sustainability initiatives that combines policy and regulatory framework with locally initiated innovations are more likely to be implemented and long last with observed outcomes on the ground.

After four decades of conservation oriented CF, strong market oriented approaches have begun to shape the forest policy discourses. With the increasing interface with the market and as the forests have become mature, the private sector has become influential in shaping forest policies and practices. Few years back, the government introduced the moto of 'Forestry for Prosperity'. An associated policy emphasis was increased role of private sector in management and trade of forest products. In the meantime, the government started a new programme called, 'scientific forest management', that began with small scale piloting in few Terai districts and has now expanded across the country. In the aftermath of devastating earthquake of 2015, the reconstruction process demanded timber that induced massive timber import from Malaysia, Myanmar and many other countries. These all situation together have now created pressure in the forests management for active management, more harvest and import substitution.

However, the shifting focus on active management, optimum harvesting and increased role of private sector appears to have low appreciation of conservation. Instead of appropriate integration of conservation and active management, the policies, institutions and everyday practices have increasingly becoming dominant. This is especially true, in the context of weak governance where the government officials, CF leaders and contractors develop nexus, often called 'iron tringle' resulting in over-harvesting, illegal harvesting. There are concerns that increased harvesting and trading may have generated increased income to the CFUGs but these are wasted in the lack of well-planned equitable investment schemes. In many cases, such harvesting and trading practices have not generated corresponding benefits to the communities. In this context, FECOFUN has stood against scientific forest management programme. They oppose it arguing that it has increased techno-bureaucratic control, alienated CF members, focus on harvesting has undermined conservation, and increased revenue has gone back to consultants/technicians and any saving has been prone to corruption and conflicts (Joshi et al. 2018)

A similar shift is observed in the forest based enterprises. Earlier, CFUGs individually or collectively established and ran various enterprises such as saw mills, essential oil extraction units, which could not operate in the long run. One of the reasons suggested is that these enterprises became impractical due to strong social and ecological components in their operations. This has then followed a strong wave of privatization of these enterprises. While the privatization has somehow addressed the issues of management performance, the entrepreneurs benefitted often at the cost of worsening equity and sustainable harvesting. To get out of this dilemma, there have been efforts to explore and experiment with diverse community-private partnership arrangement. The new institutional arrangement brings ecological and community concerns in management decisions while the private sector brings management efficiency ensuring financial viability of the enterprise. Distribution of equity shares among CF members and private investors or renting out the enterprise to a private operator are the most common forms of such partnership.

10.7 Conclusion

Evolution and experience of community-based forestry in Nepal for over four decades demonstrates that it is a viable and potentially very sustainable approach to forest management. However, as discussed throughout this paper, the shift in focus between ecological, social and economic dimensions have demonstrated some integration challenges between these three dimensions of sustainability. The history shows a protection-oriented policies and practices, and hence hailed for its success on environmental sustainability front but on the way compromised the economic and social fronts of sustainability. The institutional innovations on social inclusion and, in part, various initiatives of poverty reduction, have made Nepal's community forestry in the forefront of global forest rights movement, and exhibited the potential of endorsing all three fronts on sustainability. However, recurring attempts of techno-bureaucratic control (Ojha et al. 2009) and government restrictions on exploring commercial potential (Paudel et al. 2019) has posed considerable challenges on economic aspect of sustainability. Expanding spaces for political deliberations and vibrancy of civil society are key avenues that can be strengthened for balancing environmental, economic and social sustainability of community-based forestry in Nepal.

It also demonstrates that shifting focus on productivity alone with increased pressure for more harvesting and trade especially along with increased role of private sector may not adequately consider the ecological and social dimensions. This would be the case especially if the forestry institutions are suffering from poor governance. In such cases, productive management and accelerated harvesting must be integrated with strong environmental and social safeguards. CFUGs with firmly established transparent and accountable governance culture have been better able to handle sustainability with appropriate integration of ecological, social and economic aspects of forest management.

References

Agarwal B (2001) Participatory exclusions, community forestry, and gender: an analysis for South Asia and a conceptual framework. World Dev 29:1623–1648
Agarwal B (2009) Gender and forest conservation: the impact of women's participation in community forest governance. Ecol Econ 68:2785–2799
Agrawal A (2001) Common property institutions and sustainable governance of resources. World Dev 29:1649–1672
Agrawal A (2005) Environmentality: technologies of government and the making of subjects. New ecologies for the twenty-first century. Duke University Press, Durham and London
Agrawal A, Chhatre A, Hardin H (2008) Changing governance of the world's forests. Science 320:1460–1462
Arnold JEM (2001) Forests and people: 25 years of community forestry. FAO, Rome
Bajracharya D (1983) Deforestation in the food/fuel context – historical and political perspectives from Nepal. Mt Res Dev 3(3):227–240
Basnyat B, Treue T, Pokharel RK, Lamsal LN, Rayamajhi S (2018) Legal-sounding bureaucratic re-centralisation of community forestry in Nepal. Forest Policy Econ 91:5–18
Bhattarai B (2016) Community forest and forest management in Nepal. Am J Environ Prot 4(3):79–91. http://pubs.sciepub.com/env/4/3/3
Bryant RL, Wilson GA (1998) Rethinking environmental management. Prog Hum Geogr 22:321–343
Chadwick MT, Seeley JA, Sherchan GR (1995) Preliminary comments on a wealth ranking exercise performed with forest user groups from three geographical areas of Nepal. Nepal-UK Forestry Research Project, Kathmandu
Chambers R (1983) Rural development: putting the last first. Longman, London/New York
DCSI (2016) Industrial promotion statistics 2015/16. Department of Cottage and Small Industries. Ministry of Industries Government of Nepal, Kathmandu
DFRS (2015) State of Nepal's forests. Forest Resource Assessment (FRA) Nepal, Department of Forest Research and Survey (DFRS), Kathmandu
Eckholm EP (1976) Losing ground: environmental stress and world food prospects. World Watch Institute, New York
Fabricius C, Koch E, Magome H, Turner S (eds) (2004) Rights, resources and rural development: community-based natural resource management in Southern Africa, First edn. Earthscan, London/Sterling, VA
FAO (2011) Reforming forest tenure: issues, principles and process, FAO forestry paper. Food and Agriculture Organisation of the United Nations, Rome
Feeny D, Berkes F, McCay BJ, Acheson JM (1990) The tragedy of the commons: twenty-two years later. Hum Ecol 18:1–19
Fisher RJ (2000) Decentralization and devolution in forest management: a conceptual overview. In: Enters T, Durst PB, Victor M (eds) Decentralization and devolution of forest management in Asia and Pacific. FAO and RECOFTC, Bangkok
Gilmour DA, Fisher RJ (1991) Villagers, forests and foresters: the philosophy, process and practice of community forestry in Nepal. Sahayogi Press, Kathmandu
Graner E (1997) The political ecology of community forestry in Nepal. Verlag fur Entwicklungspolitik, Saarbrucken
Guha R (1989) The unquiet woods: ecological change and peasant resistance in the Himalaya. Oxford University Press, Delhi
Guthmann J (1997) Representing crisis: the theory of Himalayan environmental degradation and the project of development in post-rana Nepal. Dev Chang 28:45–69
Hobley M (1996) Participatory forestry: the process of change in India and Nepal. Rural Development Forestry Network, Overseas Development Institute, London
Ives JD, Messerli B (1989) The Himalayan dilemma: reconciling development and conservation. Routledge, London

Jain S (1984) Women and people's ecological movements: a case study of women's role in the Chipko movement in Uttar Pradesh. Econ Polit Wkly 19:1788–1794

Joshi O, Parajuli R, Kharel G, Poudyal N, Taylor E (2018) Stakeholder opinions on scientific forest management policy implementation in Nepal. PLoS One 13(9):e0203106. https://doi.org/10.1371/journal.pone.0203106

Kanel KR (2004) Twenty-five years of community forestry: contribution to millennium development goals. In: Kanel K, Mathema P, Kandel BR, Niraula DR, Sharma A, Gautam M (eds) 25 years of community forestry: contributing to millennium development goals. Proceeding of the fourth National Workshop on community forestry. Department of Forests, Kathmandu, pp 4–18

Khadka M (2009) Why does exclusion continue? Aid, knowledge and power in Nepal's community forestry policy process. Shaker Publishing, Maastricht

Larson AM, Barry D, Dahal GR (2010) New rights for forest-based communities? Understanding processes of forest tenure reform. Int For Rev 12:78–96

LFP (2010) The resilience of community forestry user groups in conflict: lessons from Nepal, findings of a study on the impact on forest user groups of Nepals Maoist insurgency (1996–2006). Livelihoods and Forestry Project, Kathmandu

Mahat TBS, Griffin DM, Shepherd KR (1987) Human impact on some forests of the Middle Hills of Nepal. Part 4. A detailed study in southeast Sindhu Palchok and northeast Kabhre Palanchok. Mt Res Dev 7(2):111

Maini JS (1992) Sustainable development of forests. Unasylva 43(169). http://www.fao.org/docrep/u6010e/u6010e03.htm#sustainable%20development%20of%20forests

Malla YB (2001) Changing policies and the persistence of patron-client relations in Nepal: stakeholders' responses to changes in forest policies. Environ Hist 6(2):287–307

MSFP (2013) Persistence and change: thirty years of community forestry in Nepal. Multi-stakeholder forestry program. Government of Nepal, Kathmandu

MSFP (2016) Scientific forest management initiatives in Nepal: MSFC experiences and lessons learnt. Multi Stakeholder Forestry Programme, Kathmandu

Negi S, Pham TT, Karky B, Garcia C (2018) Role of community and user attributes in collective action: case study of community-based forest management in Nepal. Forests 9(3):136. https://doi.org/10.3390/f9030136

Nightingale A (2002) Participating or just sitting in? The dynamics of gender and caste in community forestry. J For Livelihood 2(1):17–24

Nightingale A, Sharma JR (2014) Conflict resilience among community forestry user groups: experiences in Nepal. Disasters 38(3):517–539

NSCFP (2011) Two decades of community forestry in Nepal: what have we learned? NSCFP, SDC, Kathmandu

Nurse M, Malla Y (2005) Advances of community forestry in Asia: workshop on capitalisation and sharing of experiences on the interaction between forest policies and land use patterns in Asia. Regional Community Forestry Training Center (RECOFTC), Kathmandu

Ojha HR (2006) Techno-bureaucratic Doxa and challenges for deliberative governance: the case of community forestry policy and practice in Nepal. Polic Soc 25(2):131–175. https://doi.org/10.1016/S1449-4035(06)70077-7

Ojha HR, Persha L, Chhatre A (2009) Community forestry in Nepal: a policy innovation for local livelihoods, IFPRI Discussion Paper. International Food Policy Research Institute, Washington, DC. 00913

Ojha HR (2009) Science, bureaucrary and politics. The dynamics of community forestry evolution in Nepal: a presentation made during the Community Forestry International workshop, 15–18 Sept. 2009, Pokhara

Ojha HR, Banjade MR, Sunam RK, Bhattarai B, Jana S, Goutam KR, Dhungana S (2014) Can authority change through deliberative politics?: lessons from the four decades of participatory forest policy reform in Nepal. Forest Policy Econ 46:1–9

Ostrom E (1990) Governing the commons: the evolution of institutions for collective action. Political economy of institutions and decisions. Cambridge University Press, New York

Paudel NS, Adhikary A, Mbairamadji J, Nguyen Quang T (2019) Small scale forest enterprise development in Nepal: overview, issues and challenges. FAO, Rome
Plummer R, Fitzgibbon J (2004) Co-Management of natural resources: a proposed framework Environ Manag 33:876–885 https://doi.org/10.1007/s00267-003-3038-y
Poffenberger M (2006) People in the forest: community forestry experiences from Southeast Asia. Int J Environ Sustain Dev 5:57–69
Pokharel BK (1997) Foresters and villagers in contention and compact: The case of community forestry in Nepal. Ph.D. Dissertation, Norwich, East Anglia, UK
Pokharel BK, Nurse M (2004) Forests and peoples livelihood: benefiting the poor from community forestry. For Livelihood 4(1):19–29
Pokharel BK, Branney P, Nurse M, Malla Y (2008) Community forestry: conserving forests, sustaining livelihoods and strengthening democracy. In: Ojha HR, Timsina NP, Kumar C, Banjade MR, Belcher B (eds) Communities, forests and governance: policies and institutional innovations from Nepal. Adroit Publications, New Delhi, pp 55–91
Pokharel B, Carter J, Parajuli RR, Byrane S, Gurung BD (2009) Community forestry in Nepal as a means of empowering people living in poverty: an assessment of its social, economic and environmental sustainability. Paper presented in Community Forestry International Workshop, Pokhara, Nepal
Pokorny B, Johnson J (2008) Community forestry in the Amazon: the unsolved challenge of forests and the poor. Nat Resour Perspect 112:1–4
Rai Paudyal B (2008) Agrarian structures and distributive outcomes: a study of community forestry in Nepal. Shaker Publishing, Maastricht
Regmi MC (1999) [1972] A study in Nepali economic history. Adroit Publications, New Delhi (2nd reprint), pp 1768–1846
Rutt RL, Khanal-Chhetri BB, Pokhrel R, Rayamajhi S, Tiwari K, Treue T (2015) The scientific framing of forestry decentralization in Nepal. Forest Policy Econ 60:50–61
Springate-Baginski O, Blaikie P (eds) (2007) Forests, people and power: the political ecology of reform in South Asia. EarthScan Forestry Library. Earthscan, London/Sterling, VA
Subedi BP, Ghimire PL, Koontz A, Khanal SC, Katuwal P, Sthapit KR, Mishra SK (2014) Private sector involvement and investment in Nepal's forestry: status, prospects and ways forward. Multi Stakeholder Forestry Programme – Service Support Unit, Kathmandu
Thapa GB, Weber KE (1990) Actors and factors of deforestation in tropical Asia. Environ Conserv 17(1):19–27. https://doi.org/10.1017/S0376892900017252
Thoms CA (2008) Community control of resources and the challenge of improving local livelihoods: a critical examination of community forestry in Nepal. Geoforum 39:1452–1465. https://doi.org/10.1016/j.geoforum.2008.01.006
THT (2016) Over 80 per cent of timber imported from foreign countries. https://thehimalayantimes.com/kathmandu/80-per-cent-timber-imported-foreign-countries/
World Bank (1979) Nepal: development performance and prospects: a World Bank country study. World Bank, Washington, DC
Yadav NP, Yadav KP, Yadav KK, Thapa N (2009) Facilitating the transition from passive to active community forest management: lessons from Rapti Zone, Nepal. J For Livelihood 8(2):51–66

Part III
Implementing Sustainability in Practice

Chapter 11
A Study of Seasonal Trends in Precipitation Patterns During a Period of Forty Years for Sustainable Agricultural Water Management in Buenos Aires Province, Argentina

Olga Eugenia Scarpati and Alberto Daniel Capriolo

Abstract An analysis of semestral precipitation for the sixteen drainage areas of Buenos Aires province (Argentina) was performed. Precipitation daily data, for the period 1971–2010, were provided by the National Meteorological Service and the National Agronomic Technology. The test Mann-Kendall was applied and an Excel template (Makesens) was used for detecting and estimate trends. There were found significant statistical results for cold semester in some sectors: Northwestern area of the Salado River basin, Central area of the Salado River basin, Salado River mouth, Southern area of the Salado River basin and northern area of Vallimanca River basin, Southern area of the Salado and Vallimanca Rivers basins and Arrecifes River basin, Western Channels area at south of the Salado River basin, Region without surface drainage and Lagoon area at the Southwest, Small rivers and streams with Atlantic drainage and Basins and Streams of South (to west) for different periods and mostly decreasing. The sectors Southern area of the Salado and Vallimanca Rivers basins and Lagoon area at the Southwest were the only two with significant statistical results for the warm semester.

Keywords Precipitation · Buenos Aires province · Makesens · Drainage areas · Crop yield

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11.1 Introduction

Buenos Aires province has an area of 307.571 km^2 and represents 11.06% of Argentina territory. It is located in the east central region, bordered to the north by the provinces of Entre Rios and Santa Fe, at west with the provinces of Córdoba, La Pampa and Río Negro, at south and east by the Atlantic Ocean and at northeast by the Río de La Plata. The total population in the province, according to the last Census (in 2001) was 13,827,203 inhabitants. Of that population, 502,962 (3.6%) live in rural areas. It has the highest population density in Argentina (more than 31%) and important cities (National Geography 2013). The Province is also surrounded by important rivers like Paraná River and its estuary (Río de La Plata), Colorado River, Negro River and, in its own region, the Salado River.

The predominant relief is plain, presenting a negative slope towards the east. The province is a large plain with elevations below 300 m with the exceptions of Tandilia and Ventania hills, in the southern area, whose heights are 520 m and 1240 m respectively.

Also, within the plain -with natural grasslands- there are present, almost indistinguishable, various subregions. In the northern sector, the relief becomes wavy with some "hills", leading to what is known as "rolling pampas". The lower Salado River basin presents lower altitude in relationship to the rest of the Pampas and is the "depressed pampa". To the west, the relief shows long sandy north-southwest undulations alternating with low surface drainage, named "sandy pampa". The region over the Atlantic coast is characterized by the presence of large dunes and coastal cliffs naturally moving or with large sandy beaches.

The drainage system consists of meandering rivers that are partially connected to permanent and seasonal lagoons. The low regional gradient leads to the detention of rainwater for long periods, in various forms of storage, mainly in the soil or on floodplains and in shallow lagoons. The province has several basins and sub-basins, which show different behaviour in terms of soil characteristics and rainfall patterns (National Water Resources 2002; Giraut et al. 2007).

The main soil types are argiuols, hapludols, natracuols and haplustols (National Agronomic Technology 2011).

The climate of the province is temperate and humid, with warm summers and cool winters. Mean annual temperatures oscillate between 13 °C and 16 °C. The warmest month (January) has mean monthly temperatures varying from 20 °C to 23 °C and the coldest month (July) between 7 °C and 9 °C. Annual precipitation ranges from 1000 mm in the north-east to 800 mm in the south-west of the region. Precipitation is usually generated by the meeting of the warm and humid air mass from the semi-permanent anticyclone over the Atlantic Ocean and the cold air mass from the south-west (Murphy and Hurtado 2013).

This province is part of the Pampa region, one of the world's major agricultural regions and is the production base for the important agriculture of the country and 71% of its surface has agriculture use.

Argentina is still one of the top 10 world wheat producers, which was historically its flagship crop and Buenos Aires is the main producer province raising 58% of the national production.

Argentina is the world's largest supplier of oil and flour soybean and the third one in corn.

Argentine oilseed production represents 18% of the total world market. Argentina ranks third as a world producer of soybean oil, behind China and the United States.

Precipitation interannual variability can affect, directly or indirectly, many hydrological, ecological, and biogeochemical processes that, in turn, influence climate. Although projections of precipitation change indicate increases in variability, most studies of impacts of climate change on ecosystems focused on effects of changes in amount of precipitation, overlooking precipitation variability effects, especially at the interannual scale and sometimes they are variable in regional scale (Huntington 2006).

Most agricultural activities of the province are carried out under rain fed conditions and therefore, crop production is dependent on rainfall during the growing season and it is strongly affected by climatic variability. Furthermore, against the background of the very unfavourable economic scenarios of the last decades, farmers have been struggling to maintain their income by continuously trying to increase yields, intensifying their production systems (use of improved seeds, agrochemicals, etc.), which have often become more vulnerable to climate variability and potential climate change (Barsky et al. (2008) and Capriolo and Scarpati (2012)).

It is quite common that low water availability in critical crop stages prevents reaching crop yield potential in Argentina's Pampas. Therefore, supplementary irrigation could be an interesting option for increasing crop production and decreasing yield variability.

Buenos Aires province has 374,246 ha with irrigation. There are approximately 170,000 ha with irrigation used for wheat, corn and soybean crops. The rest of the mentioned surface belongs to horticultural and fruit crops.

Forte Lay et al. (2007) said that the natural storage (depression and groundwater storage) and vertical movement of water (evapotranspiration and infiltration) dominate over horizontal movement (surface and subsurface runoff) and showed that the water table fluctuations and soil water balance (water surplus and water deficit) are strongly correlated in the region, so the edaphic and topographic characteristics influence floods.

El Niño Southern Oscillation (ENSO) has an impact on Pampean precipitation and El Niño phase has more or less a 30% influence over floods (Scarpati et al. (2002) and Celis et al. (2009)).

There are many studies considering extreme hydrological events and climate variability as Moncaut (2003), Rusticucci and Penalba (2000) and Scarpati and Capriolo (2013).

While the increase in rainfall observed in recent years (Minetti et al. (2003), Penalba and Vargas (2004), Magrin et al. (2005), Forte Lay et al. (2008) and Penalba and Robledo (2010)) favours summer crops (for greater input of water in the system), the imbalance between Precipitation and Potential Evapotranspiration gives evidence that this situation can not satisfy all their requirements. In addition, the greater variability observed during the warm semester until April, highlights the vulnerability in agricultural planning.

Water surplus conditions predominate eastward during the cold semester (April–September) and water deficit conditions predominate westward during the warm semester (October–March). The transition zone is characterized by high seasonality, with similar behaviour as eastern, during warm months and western during cold months, in terms of surplus variability. The variety of factors affecting water availability and their variability, determine the complexity of the soil – atmosphere system, in which precipitation is the most important contribution to the soil water content (Pántano et al. 2014).

Available precipitation records indicate that it has increased significantly during the second half of the past century, particularly since the middle 1970s. There was found a similar increase in summer rainfall records, with a wet spell that started in the mid-1970s and continues still this century.

Most studies relating weather and climate influence on food production have examined crop yields. However, climate influences all components of crop production, includes cropping area (area planted or harvested) and cropping intensity (number of crops grown within a year). Although yield increases have predominantly contributed to increased crop production over the recent decades, increased cropping area and in cropping intensity, have played a substantial role.

In this paper are considered the needs of summer (corn, sunflower and soybean) and winter crops (wheat), but not as first priority.

Semester precipitation is analyzed by the importance they have on both types of crops. For example, planting dates (spring); bloom-start fruiting (summer) and harvest (autumn) are important to summer crops and, end of autumn-winter start date coincides with the planting of winter wheat and other cereals. Indeed, in crops grain harvest is essential to have a good supply of resources for the generation of performance at the time that these grains are being generated in the plant.

The largest source of water balance variability is rainfall, so should especially consider the observed changes that significantly alter the water content in the soil.

There is a wide variability in predicted yields across years as a result of variation in rainfall. Yield in many cases is limited by resource availability. Without increased accumulation of nitrogen and increased acquisition of water by crops, there is little likelihood that genetic improvements can be successful.

Retention of crop residue on the soil surface as a result of no-tillage practices is an important sustainability practice to minimize soil evaporation and to decrease runoff of precipitation. The use of cover crops as winter barley, wheat, oat and rye is a sustainable and compatible alternative to current production systems. Clearly, management improvements are particularly important in exploiting these possibilities.

Table 11.1 presents the production of Buenos Aires province, using data from the National Agriculture (2015) and it can be seen the evolution of the main crops

Table 11.1 Evolution of corn, soybean and wheat crops in Buenos Aires province

Crop	Years	Cropping area (ha)	Harvested area (ha)	Production (t)	Yield (k/ha)
Corn	1971/72	1,156,800	997,200	4,448,000	4,460
	2009/10	1,133,400	928,470	8,128,850	7,752
Soybean	1971/72	1,580	1,580	2,020	1,278
	2009/10	5,676,132	5,609,544	17,054,947	3,040
Wheat	1971/72	2,940,450	2,741,350	3,500,000	1,277
	2009/10	2,168,120	1,986,860	5,792,553	2,915

from 1971 to 2010. All yields and production had increased and soybean became the most important one by the strong incentives for Argentina's soybean producers.

The goal of this paper is to analyze the distribution and evolution of the precipitation during the warm semester, which considers the precipitation of the period from October of the previous year to March, and during the cold semester which run from April to September.

11.2 Materials and Methods

The studied region is shown in Fig. 11.1 with the meteorological stations location which is listed in Table 11.2.

Daily precipitation data, for the 40 years period 1971–2010, were provided by the National Meteorological Service (29 stations) and by the National Agronomic Technology Institute (INTA 5 stations).

The maps showing the semestral precipitation were performed using the software Surfer 8.0. This mapping software allows the construction of isoline maps using its kriging option (the Point Kriging estimates the values of the points at the grid nodes). When the are shown precipitation maps over Pampa region, the meteorological stations are forty one, and, they are those used in Forte Lay et al. (2008).

The maps obtained allow the observation of the spatial distribution of this element.

The studied drainage areas or sectors of the province, according to National Water Resources (2002), can be seen at Fig. 11.2 and Table 11.3.

The non-parametric test Mann-Kendall was applied for all the data series, and then, an Excel template – Makesens – was used for detecting and estimating trends and their magnitudes in the time series of precipitation values (Salmi et al. 2002). The mentioned test has been widely used to detect trends in hydro-meteorological time series (Abdul Aziz and Burn (2006), Eris and Agiralioglu (2012) and Hannaford (2015)).

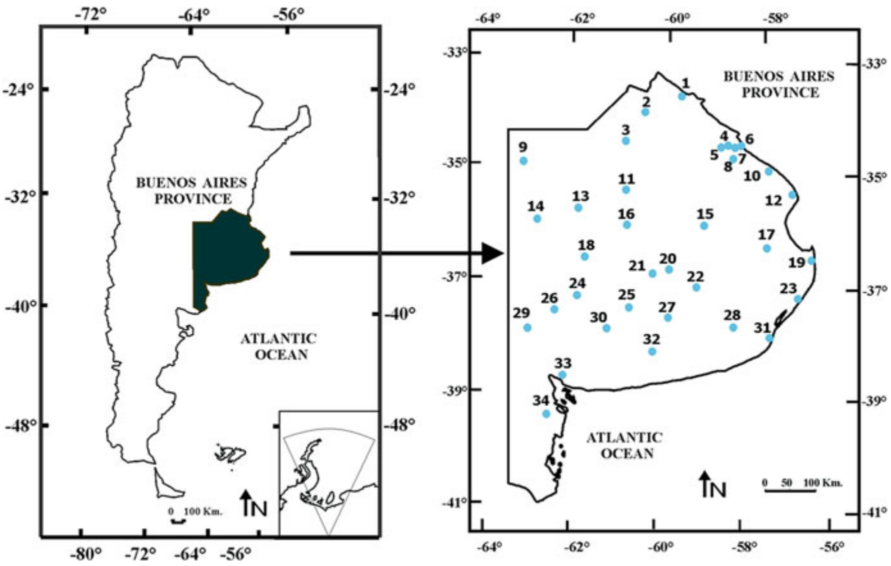

Fig. 11.1 Buenos Aires province and meteorological stations used

Table 11.2 Meteorological stations

Number	Station	Number	Station
1	San Pedro INTA	18	Daireaux
2	Pergamino INTA	19	Santa Teresita
3	Junín	20	Azul
4	San Miguel	21	Olavarría
5	Mariano Moreno	22	Tandil
6	Aeroparque J. Newbery	23	Villa Gesell
7	Buenos Aires	24	Coronel Suarez
8	Ezeiza	25	Laprida
9	General Villegas	26	Pigüé
10	La Plata	27	Benito Juárez
11	Nueve de Julio	28	Balcarce INTA
12	Punta Indio	29	Bordenave INTA
13	Pehuajó	30	Coronel Pringles
14	Trenque Lauquen	31	Mar del Plata
15	Las Flores	32	Tres Arroyos
16	Bolivar	33	Bahía Blanca
17	Dolores	34	Hilario Ascasubi INTA

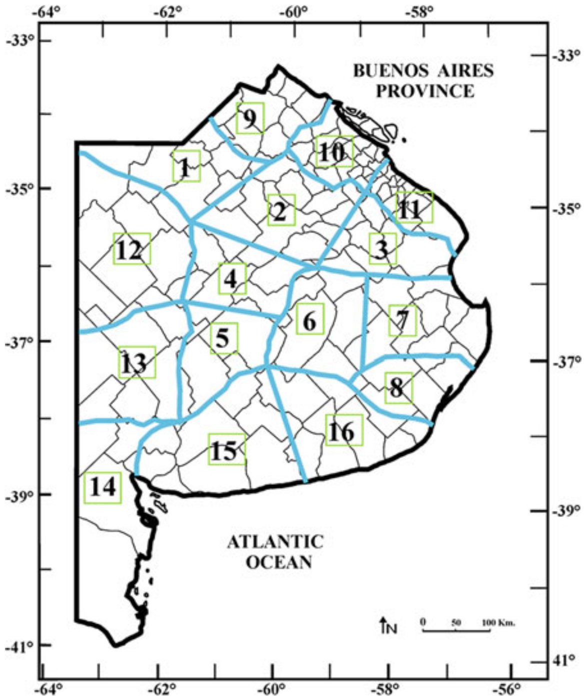

Fig. 11.2 Sectors or drainage areas studied

Table 11.3 Sectors or drainage areas studied

Sector	Name in Figures	Name
S1	1	Northwestern area of the Salado River basin
S2	2	Central area of the Salado River basin
S3	3	Salado River mouth
S4	4	Southern area of the Salado River basin and northern area of Vallimanca River basin
S5	5	Southern area of the Salado and Vallimanca Rivers basins
S6	6	Western Channels area at south of the Salado River basin
S7	7	Channels area at south of the Salado River
S8	8	Southeastern basin and streams
S9	9	Arrecifes River basin
S10	10	Northeastern streams basin
S11	11	Drainage basin of the La Plata River at the South of Samborombon River
S12	12	Region without surface drainage
S13	13	Lagoon area at the Southwest
S14	14	Small rivers and streams with Atlantic drainage
S15	15	Basins and Streams of South (to west)
S16	16	Basins and Streams at South (to east)

11.3 Results and Discussion

The Figs. 11.3 and 11.4 present the evolution of warm and cold semester's precipitation for all studied sectors for the period 1971–2010.

Figure 11.3 shows that the highest values of the warm semester and correspond to the years 1976/1977, 1983/1984, 1985/1986, 1986/1987, 1987/1988, 2000/2001, 2001/2002, 2006/2007 and 2009/2010. And in Fig. 11.4 the highest values for cold semester correspond to the years 1980, 1982, 1993, 1998, 2000 and 2001.

Furthermore, it can be observed that years 1980 and 1993 had high precipitation values in cold semester and low in warm semesters, years 1988, 1999 and 2008 were dry ones and in 2001 both semesters had high amount of precipitation.

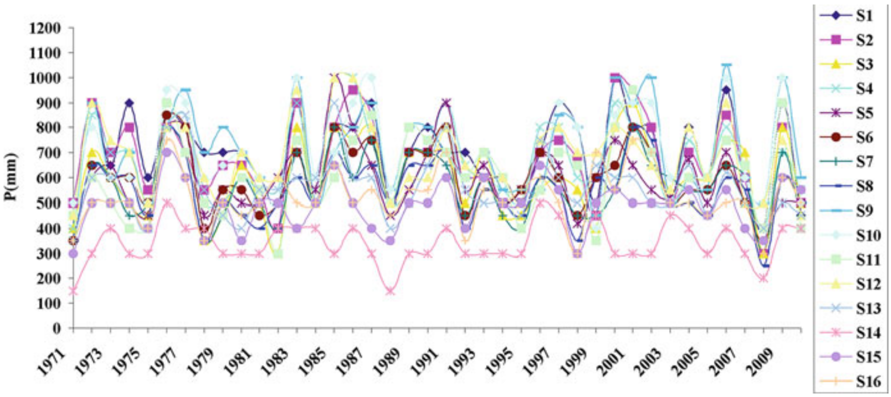

Fig. 11.3 Evolution of warm semester precipitation. (Source: Realized by the authors)

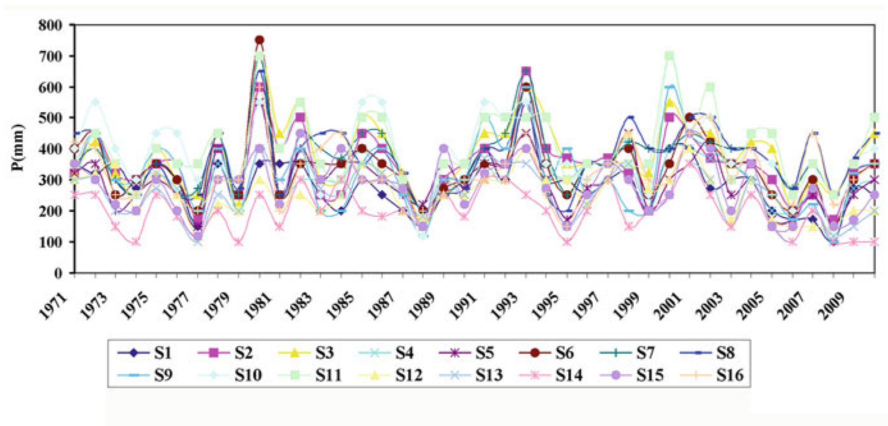

Fig. 11.4 Evolution of cold semester precipitation

Tables 11.4 and 11.5 present the average value and the standard deviations for the analyzed periods1971–1980, 1981–1990, 1991–2000, 2001–2010 and 1971–2010; for the warm and cold semesters respectively.

Table 11.4 Average (X) and standard deviations (σ) for the analyzed periods during warm semester

	1971–2010		1971–1980		1981–1990		1991–2000		2001–2010	
Sector	X	σ	X	σ	X	σ	X	σ	X	σ
S1	707.5	155.9	725.0	141.9	690.0	159.5	680.0	131.7	735.0	200.1
S2	675.5	163.6	695.0	132.2	680.0	190.3	617.0	103.8	710.0	214.5
S3	603.8	154.2	555.0	148.0	630.0	171.9	560.0	112.5	670.0	168.7
S4	668.8	158.8	640.0	163.0	690.0	205.2	670.0	127.4	675.0	151.4
S5	595.3	141.7	555.0	157.1	630.0	167.0	622.0	132.3	574.0	111.6
S6	595.0	127.0	585.0	156.4	615.0	127.0	595.0	114.1	585.0	124.8
S7	568.8	128.4	545.0	149.9	605.0	130.1	530.0	103.3	595.0	130.1
S8	550.0	124.6	555.0	146.2	555.0	98.5	535.0	110.7	555.0	153.6
S9	712.5	178.2	720.0	163.6	705.0	170.7	655.0	134.3	770.0	237.1
S10	703.8	173.7	690.0	161.2	735.0	182.7	640.0	156.0	750.0	197.2
S11	613.8	159.7	550.0	156.3	620.0	168.7	600.0	133.3	685.0	171.7
S12	683.8	147.8	660.0	152.4	725.0	199.0	670.0	97.8	680.0	139.8
S13	560.5	129.4	545.0	173.9	570.0	139.8	595.0	116.5	532.0	81.1
S14	336.3	83.2	325.0	103.4	325.0	79.1	360.0	81.0	335.0	74.7
S15	483.8	99.6	465.0	129.2	465.0	91.4	510.0	102.2	495.0	76.2
S16	518.8	111.3	485.0	122.6	525.0	63.5	530.0	129.5	535.0	127.0

Table 11.5 Average (X) and standard deviations (σ) for the analyzed periods during cold semester

	1971–2010		1971–1980		1981–1990		1991–2000		2001–2010	
Sector	X	σ	X	σ	X	σ	X	σ	X	σ
S1	283.5	85.3	299.0	71.7	260.0	65.8	332.0	97.3	243.0	85.4
S2	347.0	106.7	351.0	116.3	335.0	105.5	391.0	117.8	311.0	84.0
S3	379.0	113.3	363.0	141.2	364.0	121.5	427.0	98.1	362.0	88.8
S4	316.8	104.0	334.0	149.9	292.0	48.0	362.0	103.3	279.0	80.9
S5	295.3	88.1	302.0	113.2	304.0	57.4	314.0	91.8	261.0	85.3
S6	339.8	108.9	370.0	158.5	312.0	59.6	360.0	96.6	317.0	102.2
S7	370.0	104.0	357.0	138.8	342.0	94.1	407.0	101.3	374.0	76.8
S8	368.8	102.7	367.0	131.7	334.0	89.6	380.0	103.3	394.0	86.6
S9	320.8	113.7	335.0	85.1	282.0	90.8	375.0	151.4	291.0	106.9
S10	388.5	124.7	415.0	94.4	377.0	143.6	420.0	145.7	342.0	110.4
S11	398.8	120.6	385.0	135.5	375.0	118.4	440.0	122.0	395.0	114.1
S12	259.0	75.4	256.0	70.6	247.0	53.3	314.0	64.8	219.0	85.4
S13	252.5	81.7	240.0	82.9	287.0	61.5	281.0	75.3	202.0	85.9
S14	199.0	69.3	185.0	64.2	211.0	54.9	225.0	67.7	175.0	85.8
S15	277.0	89.9	269.0	82.8	301.0	93.5	284.0	75.5	254.0	111.4
S16	325.0	95.1	329.0	117.3	307.0	79.9	320.0	88.8	344.0	101.9

Table 11.4 (warm semester) shows that a) during 1971–1980 the standard deviations for all sectors varied between 103 and 173 mm, b) the next decade (1981–1990) had more variability among sectors and σ oscillated between 63 and 203 mm, c) during 1991–2000, σ varied between 81 and 155 mm, d) the last studied decade (2001–2010) presented the highest standard deviations because σ varied between 76 and 237 mm, e) Sector 14 (Small rivers and streams with Atlantic drainage) had the smallest variability for all the analyzed periods, f) during 1971–1980 the highest variability was in Sector 13 (Lagoon area at the Southwest), in 1981–1990 in Sector 4 (Southern area of the Salado River basin and northern area of Vallimanca River basin), in 1991–2000 in Sector 10 (Northeastern streams basin) and during 2001–2010 in Sector 9 (Arrecifes River basin).

In the cold semester (Table 11.5) it can be seen that a) during 1971–1980 the standard deviations for all sectors varied between 158 and 64 mm, b) in the decade 1981–1990 σ oscillated between 48 and 144 mm, c) in the next decade σ varied between 151 and 65 mm, d) the last decade (2001–2010) presented the smallest variability because σ varied between 114 and 77 mm, e) during 1971–1980 the highest variability was in Sector 6 (Western Channels area at south of the Salado River basin), in 1981–1990 in Sector 10 (Northeastern streams basin) and during the two last decades (1991–2000 and 2001 = 2010) in Sector 9 (Arrecifes River basin).

On the other hand, average values were considered for semesters and to the whole province. Thus, allow the classification of the drainage areas according to their different semestral amount of rainfall and to their frequency. They are, 600 mm for the warm semester and 320 mm for the cold semester.

Figure 11.5 presents the number of years with precipitation values lower than 600 mm and those with values equal or higher than this amount during the warm semester. A red line separates the areas with more quantity of years with high precipitation values. It can be seen that sectors S1 (Northwestern area of the Salado River basin), S2 (Central area of the Salado River basin), S4 (Southern area of the Salado River basin and northern area of Vallimanca River basin), S9 (Arrecifes River basin), S10 (Northeastern streams basin) and S12 (Region without surface drainage) are those with higher precipitation values and where the crops of corn and soybean are more successful, mainly because they have not water deficit in their key developing stages (November to January).

Figure 11.6 presents the number of years with precipitation values equal or higher than 320 mm and lower than it during the cold semester. The red line separates the areas with more quantity of years with high values of precipitation. It can be seen that sectors S1 (Northwestern area of the Salado River basin), S3 (Salado River mouth), S6 (Western Channels area at south of the Salado River basin), S7 (Channels area at south of the Salado River), S8 (Southeastern basin and streams) S10 (Northeastern streams basin), S11 (Drainage basin of the La Plata River at the South of Samborombon River) and S12 (Region without surface drainage), are those with more years of high values.

The sectors S9 (Arrecifes River basin), S10 (Northeastern streams basin), S11 (Drainage basin of the La Plata River at the South of Samborombon River), S1

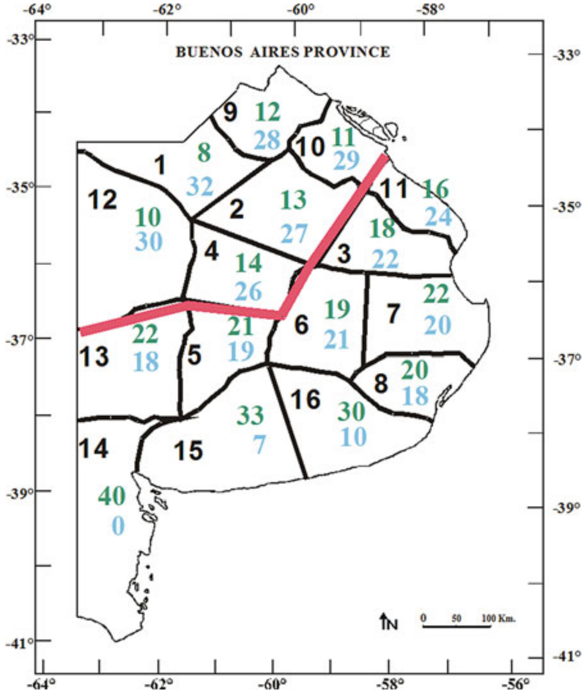

Fig. 11.5 Number of years with precipitation values equal and higher than 600 mm (blue) or lower than this value (green) during the warm semester

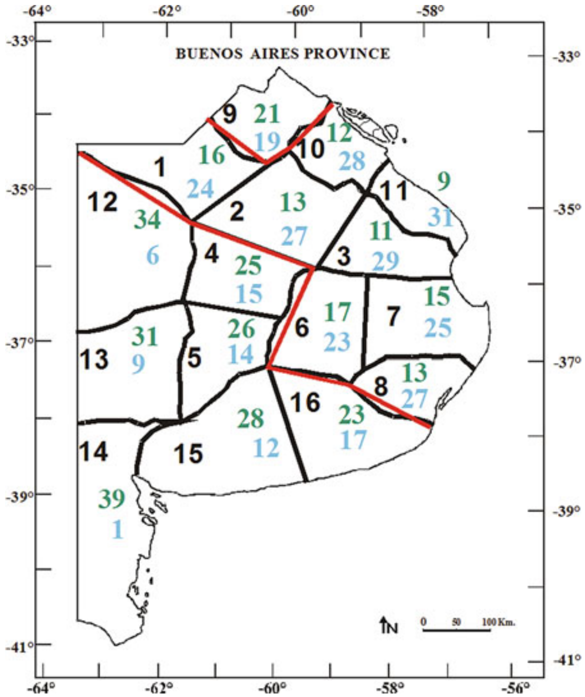

Fig. 11.6 Number of years with precipitation values equal or higher than 320 mm (blue) and lower (green) during the cold semester

Table 11.6 Drainage area S1 results for Makenses during 1971–2010

Name	S1
Test Z	−1,78
Significance	> 0.1
Q	−1.67E+00
Qmin99	−4.17E+00
Qmax99	−0.00E+00
Qmin95	−3.49E+00
Qmax95	0.00E+00
B	3.33E+02
Bmax99	3.00E+01
Bmin95	3.71E+02
Bmax95	3.00E+02

(Northwestern area of the Salado River basin), S2 (Central area of the Salado River basin), S3 (Salado River mouth), S4 (Southern area of the Salado River basin and northern area of Vallimanca River basin), S13 (Lagoon area at the Southwest), S5 (Southern area of the Salado and Vallimanca Rivers basins) and S12 (Region without surface drainage) have maximum precipitation values, higher than 900 mm, during the warm semester, while the sectors S6, S7, S8, S14, S15 and S16 never reached this value.

Sectors S2 (Central area of the Salado River basin), S3 (Salado River mouth), S4 (Southern area of the Salado River basin and northern area of Vallimanca River basin), S6 (Western Channels area at south of the Salado River basin), S7 (Channels area at south of the Salado River), S8 (Southeastern basin and streams), S9 (Arrecifes River basin), S10 (Northeastern streams basin), S11 (Drainage basin of the La Plata River at the South of Samborombon River) and S16 (Basins and Streams at South (to east)) have maximum values of precipitation, higher than 600 mm, during the cold semester while the drainage areas S1, S12, S13, S5, S14 and S15 never reached this amount.

Sectors S2, S3, S4 S9, S10 and S11 had experienced flood hazards in different occasions, while S13, S14, S15 and S16 almost every year had drought.

The Makesens results for each sector and for both semester during the period 1971–2010 show that the only drainage area with a significant statistical result is S1 (Northwestern area of the Salado River basin) for the cold semester at level $\alpha = 0.1$.

Table 11.6 presents the Makesens results.

S1 have several watersheds like Gomez lagoon (200 ha), Carpincho lagoon (400 ha) and Mar Chiquita lagoon (2600 ha). The last one in the year 2007 reached a surface of 6000 ha, almost three times its normal area. In 1997 the annual precipitation was 15% higher than the normal value considering a period of 30 year and crop production experienced losses.

Table 11.7 presents the trends of precipitation for both semesters of the year during different periods of time.

Table 11.7 Precipitation trends for the cold and warm semesters during different periods

Sector	Periods and semesters							
	1971 - 2010		1981 - 2010		1991 - 2010		2001 - 2010	
	Cold	Warm	Cold	Warm	Cold	Warm	Cold	Warm
S1	+↓	↓	+↓	↓	**↓	↓	+↓	↓
S2	↓	↓	↓	↓	**↓	↓	+↓	↓
S3	↑	↑	↑	=	+↓	↑	↓	↓
S4	↓	↑	↓	↓	*↓	↓	+↓	↓
S5	↓	↓	↓	+↓	*↓	+↓	↓	+↓
S6	↓	↓	↓	↓	+↓	↓	+↓	↓
S7	↑	↑	↑	↓	↓	↑	↓	↓
S8	↑	↓	↑	↓	↓	↓	↓	↓
S9	↓	↑	↓	↑	*↓	↑	+↓	↓
S10	↓	↑	↓	↓	↓	↑	↓	↓
S11	↑	↑	↑	↓	↓	↓	↓	↓
S12	↓	↓	↓	↓	**↓	↓	↓	↓
S13	↓	↓	↓	+↓	**↓	+↓	↓	↓
S14	↓	↑	↓	↑	**↓	↓	**↓	=
S15	↓	↑	↓	↑	+↓	↓	↓	↑
S16	↑	↑	↑	↓	↓	↓	↓	↓

References: ↓ diminution, ↑ increase and = no variation, + significant trend at level $\alpha = 0.1$, * $\alpha = 0.05$ and ** $\alpha = 0.01$. Results with different trends of those of the period 1971–2010 are in grey boxes

The results for the cold semester show that the sectors S1 (Northwestern area of the Salado River basin), S2 (Central area of the Salado River basin), S4 (Southern area of the Salado River basin and northern area of Vallimanca River basin), S5 (Southern area of the Salado and Vallimanca Rivers basins), S6 (Western Channels area at south of the Salado River basin), S9 (Arrecifes River basin), S10 (Northeastern streams basin), S12 (Region without surface drainage), S13 (Lagoon area at the Southwest), S14 (Small rivers and streams with Atlantic drainage) and S15 (Basins and Streams of South (to west)) have precipitation with decreasing trend for all the studied periods.

There were found significant statistical results for the cold semester in next sectors:

- S1 (Northwestern area of the Salado River basin) for the period 1971–2010 with a level of $\alpha = 0.1$, for the period 1981–2010 at level $\alpha = 0.1$, for the period 1991–2010 at level $\alpha = 0.01$ and, for the lat period (2001–2010) at level $\alpha = 0.1$
- S2 (Central area of the Salado River basin) for the period 1991–2010 ($\alpha = 0.01$) and for the period 2001–2010 at level $\alpha = 0.1$
- S3 (Salado River mouth) at level $\alpha = 0.1$ during 1991–2010
- S4 (Southern area of the Salado River basin and northern area of Vallimanca River basin), S5 (Southern area of the Salado and Vallimanca Rivers basins) and S9 (Arrecifes River basin) have a significant result for level $\alpha = 0.05$ for the period 1991–2010 and at level $\alpha = 0.1$ for the period 2001–2010

- S6 (Western Channels area at south of the Salado River basin) for level $\alpha = 0.1$ during the last two periods, 1991–2010 and 2001–2010
- S12 (Region without surface drainage) and S13 (Lagoon area at the Southwest) have a level of $\alpha = 0.01$ for the period 1991–2010
- S14 (Small rivers and streams with Atlantic drainage) has a significant level $\alpha = 0.01$ for the periods, 1991–2010 and 2001–2010
- S15 (Basins and Streams of South (to west)) presents a level of $\alpha = 0.1$ for the period 1991–2010

Except five sectors: S7 (Channels area at south of the Salado River), S8 (Southeastern basin and streams), S10 (Northeastern streams basin), S11 (Drainage basin of the La Plata River at the South of Samborombon River) and S16 (Basins and Streams at South (to east)), the remaining eleven ones have some statistical significance during 1991–2010.

The results for the warm semester show that S1 (Northwestern area of the Salado River basin), S2 (Central area of the Salado River basin), S5 (Southern area of the Salado and Vallimanca Rivers basins), S6 (Western Channels area at south of the Salado River basin), S8 (Southeastern basin and streams), S12 (Region without surface drainage) and S13 (Lagoon area at the Southwest) present decreasing trends for the four studied periods.

The sectors S3 (Salado River mouth) during 1981–2010 and S14 (Small rivers and streams with Atlantic drainage) during 2001–2010 had no trend in their warm semester precipitation.

There were found significant statistical results for the warm semester in next sectors:

S5 (Southern area of the Salado and Vallimanca Rivers basins) has a significance level of $\alpha = 0.1$ for the periods 1981–2010, 1991–2010 and 2001–2010

S13 (Lagoon area at the Southwest) has a level $\alpha = 0.1$ for the periods 1981–2010 and 1991–2010

In the northwest of Buenos Aires Province, a center of relative maximum precipitation appears in the end of warm semester (March), coinciding with the month in which the relation between precipitation and evapotranspiration is maximized. When it is excessive it may hamper harvesting of summer crops as well as affect the quality of the grain harvested; whereas when it is not low enough for a good reconstruction of the soil water storage after the summer months, when evapotranspiration is high.

The authors agree with Occhiuzzi et al. (2011) that increased frequency of extreme weather events constitutes a growing risk.

A number of heavy precipitation events occurred during recent years leading to flooding with important economic agricultural impacts. In 2000–2001, e.g., extended flooding in the plains of Buenos Aires caused loses attaining 700 M USD in forage output, wheat and maize yields and in milk production. Another example was the drought of 2008/2009, when precipitation in some localities was almost half of its mean value. This led to production loses of 29% in soybean, 20% in wheat, 19% in sunflower, and 12% in maize, and a 40% reduction in wheat's planted area in 2009 (Magrin et al. 2012).

The authors agree too with Hannaford (2015) that one of the biggest priorities for research should understand the drivers of interdecadal variability in water resources. To facilitate such research there is an ongoing need for efforts to ensure the preservation and stewardship of long records.

11.4 Conclusions

The paper presents a simple and clear way to analysis the distribution and evolution of precipitation. Semestral precipitation have had different behaviours over sixteen drainage areas of Buenos Aires province during a period of 40 years. This period was considered as well as whole and then was divided in others.

It is interesting to observe that, in the warm semester, the highest values of precipitation and more frequently presented, are distributed in the northern area of the province in the drainage sectors S1, S2, S4, S9, S10 and S12. The drainage sectors than in the cold semester have more possibilities of high values of precipitation are S1, S2, S3, S6, S7, S8, S9, S10 and S11.

So, it can be said that sectors S1 (Northwestern area of the Salado River basin), S2 (Central area of the Salado River basin) and S9 (Arrecifes River basin) have more precipitation over the year, and for that, they are the most important areas for rain fed agriculture of the whole province.

The precipitation of cold semester in sector S1 (Northwestern area of the Salado River basin), is the only one with statistical significance in the four periods (1971–2010, 1981–2010, 1991–2010 and 2001–2010) and decreasing trend for all of them.

The precipitation values dispersion was different according the season. In the warm semester, all the studied sectors presented the same behaviour of the precipitation; during the first studied decade (1971–1980) they had the lowest variability, during the next decade they experienced some variations among them, in the period 1991–2000 all sectors had small variability again, but during the last decade (2001–2010) there was the highest dispersion. Precipitation in the cold semester presented more variability in the different sectors than in the warm semester, with the exception of the last decade (2001–2010) when all drainages areas had high variability.

Eleven sectors had some level of statistical significance and decreasing trend for the cold semester during the period 1991–2010. In the same period, for the warm semester, only two had statistical significance and decreasing trend, S3 (Salado River mouth) and S7 (Channels area at south of the Salado River), while, S9 (Arrecifes River basin) and S10 (Northeastern streams basin) had increasing trend without statistical significance.

Six sectors had some level of statistical significance and decreasing trend for the cold semester during the period 2001–2010. In the same period, for the warm semester, S5 (Southern area of the Salado and Vallimanca Rivers basins) had statistical significance and decreasing trend, S14 (Small rivers and streams with Atlantic drainage) had no variation and S15 (Basins and Streams of South (to west)) presented increasing trend but without statistical significance.

Sectors S13 and S14 are those ones with more need of irrigation during both semesters. This region has obtained subsidies by occurrence of drought, or emergency declaration by agricultural disaster during the years 2000, 2005, 2006 and 2007. In addition, the Southwest Development Plan considered as main objective differentiate this region by its climatic and edaphic characteristics in relation to the rest of the province (Andrade and Laporta 2009).

The year 2001 had high amount of precipitation in both semesters and so, the province experienced one of the most important flood of its history.

The diversity of factors affecting water availability (mainly precipitation and soil moisture) and their variability determine the complexity of the system soil – atmosphere, because in Buenos Aires province, precipitation is the main input for soil water content.

The new System of Monitoring and Early Warning of Buenos Aires province will help to ensure greater security and predictability in face of water emergencies in real time. The need to understand climate influence and its variability over the region and more information about water resources in rain fed agricultural production is required.

In spite of the insecurity of precipitation amount the agricultural activity presents the highest productivity over national economy.

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References

Abdul Aziz OI, Burn DH (2006) Trends and variability in the hydrological regime of the Mackenzie River Basin. J Hydrol 319:282–294. https://doi.org/10.1016/j.jhydrol.2005.06.039

Andrade M, Laporta P (2009) La teoría social del riesgo. Una primera aproximación a la vulnerabilidad social de los productores agropecuarios del Sudoeste bonaerense ante eventos climáticos adversos. Mundo Agrario 10(19). Available at: https://www.mundoagrario.unlp.edu.ar/article/view/v10n19a08

Barsky A, Podestá G, Ruiz Toranzo F (2008) Percepción de variabilidad climática, uso de información y estrategias de los agentes frente al riesgo. Análisis de esquemas decisionales en agricultores de la región pampeana argentina. 8:16. Centro de Estudios Histórico Rurales. La Plata National University. http://www.mundoagrario.unlp.edu.ar/numeros/no-16-1er-sem-2008/percepcion-de-variabilidad-climatica-uso-de-informacion-y-estrategias-de-los-agentes-frente-al-riesgo-analisis-de-esquemas-decisionales-en-agricultores-de-la-region-pampeana-argentina

Capriolo AD, Scarpati OE (2012) Modeling the distribution of agricultural drought by means of soil water deficit. Energy Environ Res 2(2):1–12. Canadian Center of Science and Education. https://doi.org/10.5539/eer.v2n2p1

Celis A, Ostuni F, Kisilevsky G, Schwartz E, Fernández Bouzo S, Lopresti L (2009) Documento País: Riesgos de desastres en Argentina. In: Introducción a los riesgos de desastre en Argentina. Cruz Roja Argentina. Centro de Estudios Sociales y Ambientales, Buenos Aires

Eris E, Agiralioglu N (2012) Homogeneity and trend analysis of hydrometeorological data of the Eastern Black Sea Region, Turkey. J Water Resour Prot 4:99–105. www.SciRP.org/journal/jwarp. https://doi.org/10.4236/jwarp.2012.42012
Forte Lay JA, Kruse E, Aiello JL (2007) Hydrologic scenarios applied to the agricultural management of the Northwest of the Buenos Aires province, Argentina. GeoJournal 70:263–271
Forte Lay JA, Scarpati OE, Capriolo AD (2008) Precipitation variability and soil water content in pampean flatlands (Argentina). Geofis Int 47(4):341–354
Giraut MA, Aguglino RL, Lupano C, Bozzarello E, Cornejo JM, Rey C (2007) Regiones hídricas superficiales de la provincia de Buenos Aires – Actualización cartográfica digital. Meeting of Spanish Teledetection Society. Available at: http://www.aet.org.ar
Hannaford J (2015) Climate-driven changes in UK river flows: a review of the evidence. Prog Phys Geogr 39(1):29–48. https://doi.org/10.1177/0309133314536755
Huntington TG (2006) Evidence for intensification of the global water cycle: review and synthesis. J Hydrol 319(1):83–95. https://doi.org/10.1016/j.jhydrol.2005.07.003
Magrin GO, Travasso MI, Rodríguez GR (2005) Changes in climate and crop production during the 20th century in Argentina. Clim Chang 72(1–2):229–249. https://doi.org/10.1007/s10584-005-5374-9
Magrin GO, Travasso MI, Mehzer R (2012) Impacts of climate variability and extremes on crop production in Argentina. Planet under pressure, INTA, Argentina. http://elsevier.conference-services.net/programme.asp?conferenceID=2808&action=prog_categories
Minetti JL, Vargas WM, Poblete AG, Acuña LR, Casagrande G (2003) Non-linear trends and low frequency oscillations in annual precipitation over Argentina and Chile, 1931–1999. Atmósfera 16:119–135
Moncaut CA (2003) Inundaciones y sequías tienen raíces añejas en la pampa bonaerense (1576–2001). In: Maiola OC, Gabellone NA, Hernández MA (eds) Inundaciones en la región pampeana. Honorable Cámara de Diputados de la provincia de Buenos Aires. La Plata Nacional University Editorial, La Plata
Murphy GM, Hurtado RH (2013) Agrometeorología. Edit. Agronomy Faculty. Buenos Aires University
National Agriculture. Argentina (2015) Main webpage. http://www.minagri.gob.ar/sitio/. Agricultural statistics. http://www.siia.gov.ar/_apps/siia/estimaciones/estima2.php
National Agronomic Technology (2011) Suelos y ambiente de Buenos Aires. Mapa descriptivo del suelo y ambiente de la provincia de Buenos Aires. http://inta.gob.ar/imagenes/Buenos%20Aires.jpg/view
National Geography (2013) División Política, Superficie y Población de la República Argentina. http://www.ign.gob.ar/AreaProfesional/Geografia/DatosArgentina/DivisionPolitica
National Water Resources (2002) Atlas digital de los recursos hídricos superficiales de la República Argentina. Buenos Aires, Argentina, http://www.hidricosargentina.gov.ar/CartAct.html#1
Occhiuzzi SE, Mercuri P, Pascale C (2011) Herramientas para la evaluación y gestión del riesgo climático en el sector agropecuario, Argentina. Ministerio de Agricultura, Ganadería y Pesca de la Nación 130, Buenos Aires, Argentina
Pántano V, Spescha LB, Penalba OC, Murphy GM (2014) Influencia de la variabilidad de temperatura y precipitación en la situación hídrica del suelo, en la región oriental de secano de la Argentina. Meteor-Forschung 39(2):21–36
Penalba OC, Robledo F (2010) Spatial and temporal variability of the frequency of extreme daily rainfall regime in the La Plata Basin during the 20th century. Clim Chang 98:531–550. https://doi.org/10.1007/s10584-009-9744-6
Penalba OC, Vargas WM (2004) Interdecadal and interannual variations of annual and extreme precipitation over central-northeastern Argentina.Changes in the extreme precipitation seasonal cycle. Int J Climatol 24(12):1565–1580. https://doi.org/10.1002/joc.1069
Rusticucci M, Penalba O (2000) Interdecadal changes in the precipitation seasonal cycle over Southern South America and their relationship with surface temperature. Clim Res 1(16):1–15

Salmi T, Mata A, Anttila P, Ruoho-Airola T, Amnell T (2002) Detecting trends of annual values of atmospheric pollutants by the Mann-Kendall Test and Sen's slope estimates – the excel template application MAKESENS. Ilmatieteen laitos Meteorologiska Institutet. Finnish Meteorological Institute Painopaikka: Edita Oyj. Helsinki, Finland. http://cdn.fmi.fi/legacy-fmi-fi-content/documents/MAKESENS_MANUAL.pdf

Scarpati OE, Capriolo AD (2013) Sequías e inundaciones en la provincia de Buenos Aires (Argentina) y su distribución espacio – temporal. Investigaciones Geográficas, Boletín del Instituto de Geografía, UNAM 82:38–51

Scarpati OE, Spescha LB, Capriolo AD (2002) The impact of the heavy floods in the Salado River basin, Buenos Aires province, Argentina. Mitig Adapt Strateg Glob Chang 7(3):285–301. https://doi.org/10.1023/A:1024427613595

Chapter 12
Advanced Energy Storage Devices: Principles and Potential Applications in Sustainable Energetics

Murat Cakici, Kakarla Raghava Reddy, Robert H. Ong, and Venkata Chevali

Abstract Organic conjugated polymer based flexible sustainable storage devices have potential future applications in battery electric vehicles, rechargeable batteries, fuel cell vehicles due to their remarkable conductivity, low cost, easy fabrication in the industrial scale, stability (chemical, thermal and environmental), optical property, electroluminescence, doping-dedoping characteristics and controlling dimension (size and morphological structures) of electrode materials in the nanoscale from zero dimension (0D) to three dimension (3D). However, their application is limited due to low energy density, and loss of electrochemical properties at high temperatures. This can be overcome by functionalization of various metal oxides (e.g. TiO_2, MnO_2, ZnO, Fe_3O_4, SiO_2, etc.), and nanocarbons (e.g. 3D graphene nanosheets, 1D carbon nanotubes, 0D graphene quantum dots, carbon nanofibers, etc.) with novel organic conjugated polymers by using various synthesis methodologies. It is due to well-defined structures, large surface area, excellent electrical and mechanical properties of nanostructured metal oxides or nanocarbons-functionalized conducting polymer hybrids.

The objectives of this chapter are to summarize and discuss recent developments of low cost and highly efficient sustainable energy storage devices based on various organic conjugated polymer/nanostructured metal oxides or nanocarbon hybrid flexible electrodes. Initially, various types of organic conjugated polymers and their surface modification techniques are introduced. Later, functionalization routes of

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metal oxides or nanocarbons with various conjugated polymers (e.g. polyaniline, polypyrrole, polythiophenes, their derivatives, copolymers, etc.) are discussed and it involves various fabrication methods such as in-situ, ex-situ, electrochemical polymerization, soapless, emulsion polymerization, inverse emulsion polymerization, atom-transfer radical polymerization (ATRP), self-assembly process, etc. These fabrication techniques are depending on conjugated monomers and nanofillers types employed. Such techniques would produce novel multifunctional well-defined nanostructured hybrids consisting of metal oxides or carbons and organic conjugated polymers that have potential for applications in sustainable energy storage devices (supercapacitors, batteries, fuel cells, solar cells, and photoanodes). Structural, morphological and electrochemical (specific capacitance, capacity retention, voltage, energy density, power density, type of electrolytes, etc.) of these sustainable electrode materials are discussed. We summarize the recent work in the development of novel low cost and high-performance highly flexible nanostructured sustainable devices and their potential applications for the energy storage systems as mentioned above.

Keywords Organic conjugated polymers · Polyaniline · Polypyrrole · Polythiophene and its derivatives · Conducting polymers · Polymer synthesis · Electrical conductivity · Electrochemical properties · Electrochemistry · Energy storage devices · Supercapacitors

12.1 Introduction

In the last decade, electrochemical energy storage has gained significant interest due to the rapid transition from depleting fossil fuels to renewable and green energy sources (González et al. 2016; Wang et al. 2012a; Inagaki et al. 2010; Wang et al. 2016; Zhang and Zhao 2009). Electrochemical capacitors (ECs) are one of the promising energy storage and conversion systems to address the ever-increasing energy demand for emerging global economy. They have advanced features such as high power density, high cycle efficiency, fast charging-discharging rate, long lifecycle, and safe operation (Yan et al. 2014). However, ECs have low energy density which restricts their utilization as stand-alone energy storage units (Dyatkin et al. 2016; Simon and Gogotsi 2010). The main reason for that is the limited capacity of initial commercial ECs which store charge solely by reversible electrostatic adsorption of electrolyte ions on the surface of the porous surface of electrodes fabricated using carbon-based materials.

One way to increase the energy density of ECs is to use pseudocapacitive (PS) electrode materials which provide higher power density with fast and reversible redox reactions for charge storage in the bulk of redox material (Wang et al. 2012a; Ye et al. 2017; Abdelhamid et al. 2015). Figure 12.1 shows the difference between the charge storage using porous carbon-based and pseudocapacitive electrode materials (Snook et al. 2011). Conducting polymers (CPs) and transition metal oxides are commonly used as PS electrode materials. Among these, CPs have several

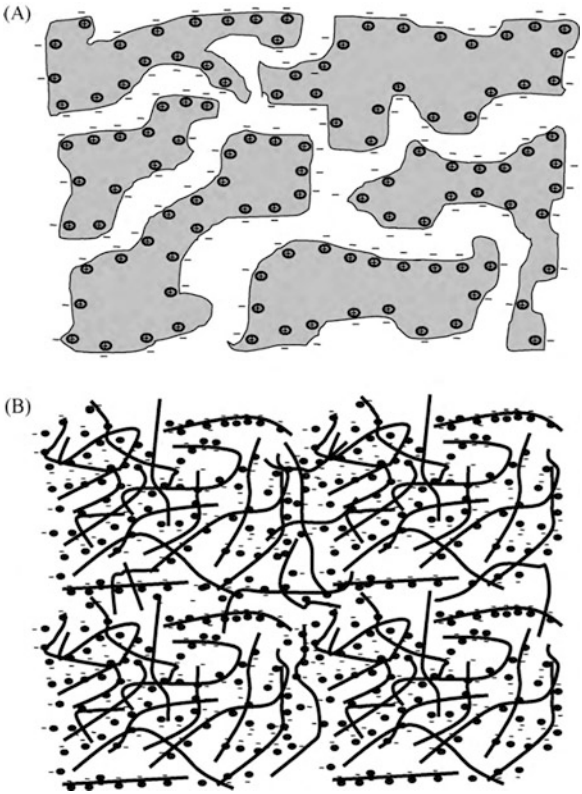


Fig. 12.1 Comparison of charge storage mechanisms of (**a**) porous carbon-based electrode and (**b**) pseudocapacitive electrode. (Reprinted with permission from Snook et al. 2011)

favourable qualities including tunable structure and electrochemical properties, low cost, flexibility, light weight, processability, and the possibility to be produced in large-scale (Abdelhamid et al. 2015; Nyholm et al. 2011; Walton 1990; Xia et al. 2015). Thus, there is growing research activity utilizing CPs as electroactive materials for electrode fabrication.

CPs are a subgroup of organic polymers and can behave as semiconductor or conductor materials (Abdelhamid et al. 2015). CPs have conducting properties through a conjugated bond system which creates a backbone of adjoining sp_2 hybridized orbitals, hence, delocalized electrons formed along their backbone (Snook et al. 2011). They are usually prepared either by chemical oxidation or electrochemical oxidation. The polymerization of conductive polymers starts with oxidation of the monomers and formation of low molecular weight oligomers (Abdelhamid et al. 2015). These oligomers further oxidized to give an undoped polymer which is neutral. The neutral polymer is doped with excess acid or oxidant to obtain CPs. Doping of CPs is a unique reversible process which grants utilization of CPs in electrochemical applications. When the CPs are doped, their backbone can be positive (p-doping) or negative (n-doping) charge carriers (Shi et al. 2015). Thus, counter ions with opposite charges would be inserted or de-inserted from the bulk of the CPs to reserve their neutral state.

In the case of an EC unit with p-dopable electrodes, during charging (oxidation), ions from the electrolyte are transferred to the polymer backbone and, on discharging (reduction) undoing takes place, ions are released back into the solution. The doping/undoping action occurs at the bulk of the electrodes, yielding the possibility of higher charge storage and higher energy density. However, insertion and deinsertion of the ions during the operation causes swelling, breaking, shrinkage, and hence, degradation of bulk CP electrodes (Shi et al. 2015; Yang et al. 2015; Yin and Zheng 2012). Therefore, the conductivity and electrochemical performance of the CPs decay rapidly.

On the other hand, there is an increasing trend in energy storage research to enhance performance and life cycle of CPs by employing their nanostructured forms, because of the novel features originated from their nanoscale size: (i) shortened pathways for better charge/mass/ion transport; (ii) large surface areas; (iii) mixed conductive mechanism of both electronic and ionic conductivity which lowers the interfacial impedance between the electrode and the electrolyte, (iv) enhanced cycling performance due to better mechanical stability (Shi et al. 2015; Pan et al. 2010).

In this review, we will focus on the CPs most commonly studied as electrode materials for ECs, namely, polyaniline (PANI), polypyrrole (PPy), and polythiophene (PTh). Recent advances on the improvement of energy storage by using nanostructured CPs and their composites with other electroactive materials will be discussed. Some selected samples will be reviewed in terms of obtaining CP based electrode materials with high capacitive performance and long cycle life.

12.2 Nanostructured Polyaniline Hybrids-Based Electrochemical Energy Storage Supercapacitors

Polyaniline (PANI), one of the most studied CPs, attracts considerable attention as a promising material in the application of ECs because of inexpensive monomer and unique proton doping mechanism. Its specific capacitance is estimated to be much higher than the carbon-based EC electrode materials. The specific capacitances reported for PANI are in the range of 163 and 1035 $F\,g^{-1}$ (Chen et al. 2003; Yu et al. 2013).

In a recent study, Li et al. calculated the theoretical specific capacitance of PANI as 2000 $F\,g^{-1}$ (Li et al. 2009). However, when they electropolymerized PANI on stainless steel (SS) electrodes to experimentally measure its specific capacitance, the results were much lower than the theoretical value. The measurements using three-electrode configuration cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS) were 608 and 445 $F\,g^{-1}$, respectively. The measurement using two-electrode configuration galvanostatic charge/discharge (GCD) analysis was 525 $F\,g^{-1}$, which was almost a quarter of the theoretical value. This was due to the limited diffusion of counter-anions in PANI during the redox which degraded the

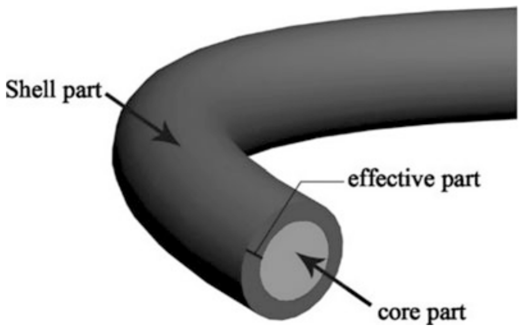


Fig. 12.2 Core-shell model of PANI utilized in charge storage. Dopants can only diffuse to few nanometer thick shell part and core part does not contribute to charge storage. (Reprinted with permission from Li et al. 2009)

charge/discharge ability. As shown in Fig. 12.2, dopants were able to diffuse only a thin layer on PANI fiber. In addition, aggregation of PANI nanofibers during their electro-polymerization on SS electrodes gave them a heterogeneous structure with conductive crystalline parts together with insulated amorphous parts which reduced the amount of electroactive material.

In an earlier study, Belanger et al. investigated the cycling performance of PANI electrodes galvanostatically formed on platinized tantalum foils (Bélanger et al. 2000). They observed the effect of different electrolytes on the capacitance retention of PANI. During cycling performance test, when tetrafluoroborate and perchlorate electrolytes were used the degradation of the electrodes were slower than when sulfuric and nitric acid electrolytes used. The decrease in the capacitance after first 5000 cycles was 33%, and then, electrodes were stable up to 100,000 cycles. The examinations showed the decrease of the electrochemical performance of PANI electrodes in charge-discharge cycling was mainly due to degradation of PANI and formation of compact PANI layers which change polymer nanostructure and decrease conductivity.

As it can be seen from above two examples, it is not possible to fully utilize PANI when it is used as the only electrode material in EC devices. Because of only a narrow layer on the surface of polymer used in charge storage and electrodes decay during intercalating/deintercalating process. PANI requires to be in a form of a thin film or nanofiber with the high surface area and needs to have a hierarchical porous nanostructure to be able to reach its high theoretical specific capacitance. Therefore, a commonly used approach to exploit high specific capacitance of PANI is to use it together with other electroactive materials which would provide flexibility, mechanical strength, high surface area, and enhanced nanostructure.

To date, a wide variety of carbon materials, such as activated carbon (Chen et al. 2003; Hu et al. 2004), mesoporous carbon (Wang et al. 2006), carbon fibre cloth (Xia et al. 2015; Yu et al. 2013; Cheng et al. 2011; Yu et al. 2014), carbon nanotubes (CNTs) (Sivakkumar et al. 2007; Wu et al. 2017a), or graphene (Salunkhe et al. 2014; Mondal et al. 2015; Hong et al. 2017; Luo et al. 2016; Zhang et al. 2017; Yu et al. 2015), were reported to be used in conjunction with PANI for fabrication of EC electrodes. CNTs have unique one-dimensional (1D) structure, good mechanical strength, and high conductivity. Sivakumar et al. reported improvement in PANI cycling performance when multi-walled CNTs were used during in situ polymerization and PANI/CNT composites were formed (Sivakkumar et al. 2007). When only in situ polymerized bare PANI electrodes were used, they had a specific capacitance of 554 F g^{-1}, which deteriorated after 1000 cycles, and measured as 57 F g^{-1}. They also suggested higher charging potentials caused degradation of the polymer. Addition of CNTs decreased the internal resistance and sustained a suitable nanostructure for charge storage. Composite electrodes, operated with a narrower potential window of 0–0.4 V, achieved a specific capacitance of 606 F g^{-1}. Capacitance retention after 1000 charge-discharge cycles were 63.6%. In another attempt to enhance the mechanical strength of PANI using CNTs, cellulose fibers were used as a supporting substrate (Ge et al. 2015). Macroporous cellulose fibers were dip coated with single-walled CNTs (SWCNT) to obtain SWCNT paper and PANI nanoribbons were in situ synthesized on the SWCNT paper. The specific capacitance of the SWCNT/PANI nanoribbon paper was 533.3 F g^{-1} while the specific capacitance of PANI nanoribbon paper was much lower with 160.3 F g^{-1}. Capacitance retention of SWCNT/PANI nanoribbon paper was 79% after 1000 cycles. The improvement in the specific capacitance was attributed to fast electron transport in SWCNTs and charge transfer of PANI obtained inside flexible cellulose fiber network. Recently, Wu et al. reported conformal deposition of PANI on vertically aligned CNTs (VA-CNTs) to obtain an ideal structure for high energy density EC units (Wu et al. 2017a). PANI was in situ grown on CNTs while the disordered CNTs were simultaneously vertically aligned by electrochemical induction (Fig. 12.3b). The optimum amount of PANI on CNTs was obtained at 60 mins of reaction. The specific capacitance of the composite material was 403 F g^{-1}. EC unit with these electrodes yielded a high energy density of 98.1 Wh kg^{-1} and good capacitance retention of 90.2% after 3000 cycles. High electrochemical performance of VA-CNT/PANI composite electrodes was attributed to straight and fast ion transport path channels, high conductivity from the good interaction of CNTs and PANI, and large pseudocapacitance of PANI.

Carbon fibre cloths (CFCs) with their remarkable chemical stability, good conductivity, low cost, flexibility, and three-dimensional (3D) microporous structure, are another choice of substrate for attaching pseudocapacitive electrode materials (Xia et al. 2015; Yu et al. 2013; Cheng et al. 2011; Wen et al. 2017). Cheng et al. used electro-etched CFC (eCFC) as a scaffold for PANI synthesis by electrochemical polymerization of aniline (Cheng et al. 2011). Electro-etching helped the nucleation of monomers and a uniform PANI nanofiber coating on eCFC was achieved. The uniform PANI nanofibers increased the contact surface area between the carbon fibers and decreased the possible contact resistance between individual carbon fibers stacked in CFC. 3D structured eCFC/PANI nanofiber composite electrode achieved a good specific capacitance of 673 F g^{-1} and good area normalized capacitance of 3.5 F cm^{-2}. In addition, capacitance retention of the composite was 90% after 1000 cycles. Yu et al. reported similar eCFC and PANI hybrid structure for EC applications (Yu et al. 2013). However, they have used nitrogen plasma etching method which doped surface of CFC with nitrogen. Nitrogen doping on CFC promoted faster nucleation and growth of PANI on eCFC during chemical

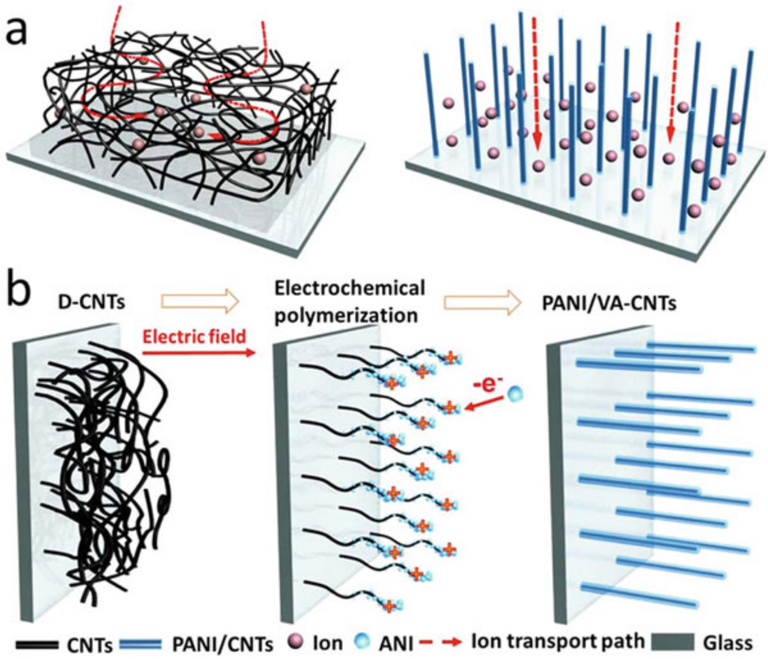


Fig. 12.3 (**a**) Design of the electrode structure. Ion transport improved after disordered CNTs were vertically aligned and coated with PANI. (**b**) Schematics of PANI/VA-CNTs film fabrication. (Reprinted with permission from Wu et al. 2017a)

polymerization of aniline. This yielded formation of narrower PANI nanowire arrays uniformly coated on eCFC. Figure 12.4 shows the structures of CFC, eCFC, and PANI/eCFC. PANI/eCFC nanowire composite electrodes had a very high specific capacitance of 1035 F g^{-1} and a good energy density of 22.9 Wh kg^{-1}. The enhancement of mechanical strength with eCFC assisted the polymer EC electrode to retain 90% of its capacitance after 5000 cycles.

Recently, Yu et al. studied improving the performance of PANI/eCFC nanowire by covering it with a graphene layer (Yu et al. 2014). Graphene (G) is one-atom-thick two-dimensional (2D) sheet of the sp$_2$-carbon network with unique characteristics, including high electrical conductivity, surface area, and good mechanical properties. It has a theoretical specific capacitance of 550 F g^{-1} (Wang et al. 2016; Yan et al. 2014). Yu et al. dip coated PANI/eCFC nanowire composite with layers containing seven monolayers of graphene oxide (GO) sheets. They reduced these GO sheets using hydroiodic acid (HI), which is also a dopant for PANI. These reduced GO (RGO) sheets increased electrochemically active surface area, electrical conductivity, and mechanical stability of the composite electrode without preventing the contact between PANI nanowire arrays and ions inside the electrolyte. Thus, the specific capacitance of the resulting RGO/PANI/eCFC electrode was 1145 F g^{-1}.

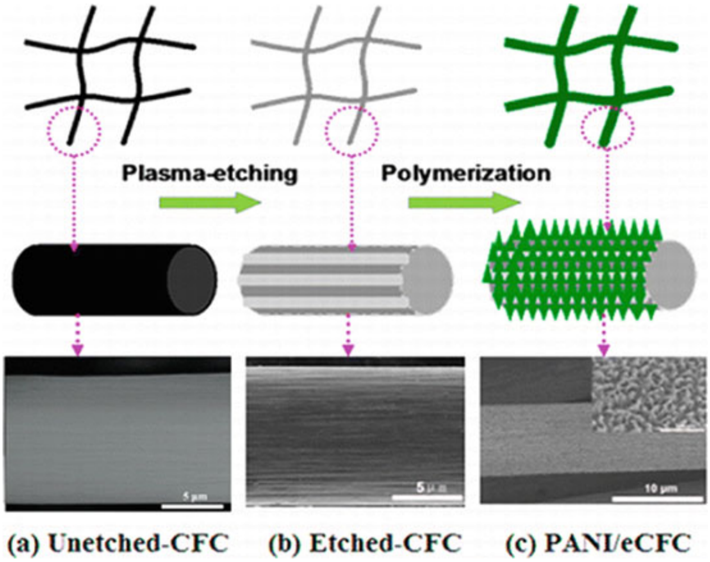


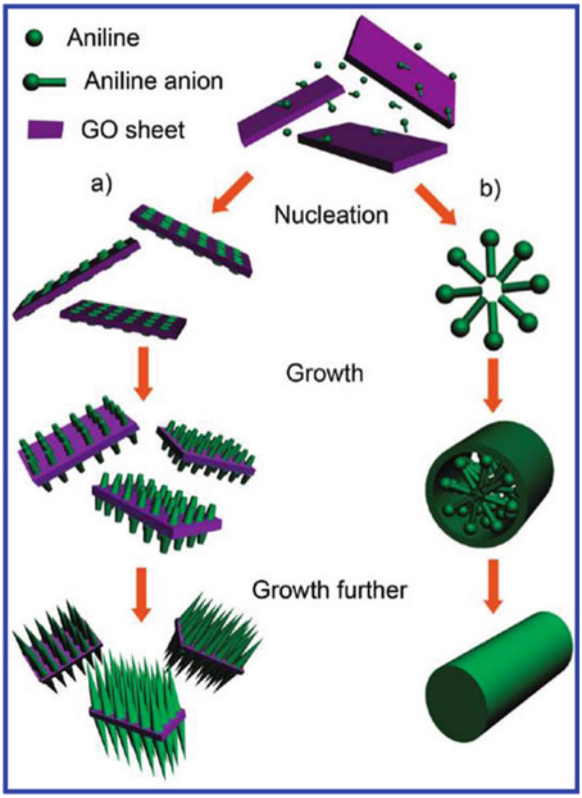
Fig. 12.4 Structures of (**a**) unetched-CFC, (**b**) nitrogen plasma etched eCFC, and (**c**) PANI/eCFC. (Reprinted with permission from Yu et al. 2013)

It also yielded an energy density of 25.4 Wh kg^{-1} while maintaining 94% of its capacitance after 5000 cycles.

In the last decade, graphene was also commonly studied as a supporting substrate to improve the electrochemical performance of PANI. Xu et al. reported the synthesis of GO/PANI nanocomposites when aniline was in situ polymerized in the presence of freeze-dried GO with a single layer of a few layer structure (Xu et al. 2010). They explained the PANI growth mechanism on GO sheets with Fig. 12.5. GO sheets have various oxygen functional groups on their basal planes and edges which assist attachment of aniline. After attachment of aniline, subsequent in situ polymerization of PANI took place on the surfaces and edges of GO sheets. Moreover, the π-π interactions between the phenyl rings and basal planes of GO further benefited in situ polymerization on the surface of GO. Thus, PANI gradually grew along the initial nuclei of PANI forming long nanowire arrays at a dilute aniline solution and a low reaction temperature. The specific capacitance of PANI nanowire arrays grown on GO was calculated as 555 F g^{-1} while the specific capacitance of PANI synthesized without GO was 292 F g^{-1}. The improved nanostructure grown on GO increased the capacitance retention from 74% to 92% after 2000 charge-discharge cycles.

Recently, Salunkhe et al. used hydrazine reduced graphene during in situ polymerization of PANI (Salunkhe et al. 2014). However, the obtained G/PANI composite yielded a specific capacitance of 286 F g^{-1}, which is probably because of the existence of stacked graphene layers. On the other hand, Hao et al. reported use of boron doped graphene (BG) for in-situ polymerization of PANI (Hao et al.

Fig. 12.5 Schematic illustration of PANI growth on GO. (Reprinted with permission from Xu et al. 2010)



2015). They achieved an improved the specific capacitance of 406 F g^{-1}. Boron doping allowed better dispersion of BG sheets followed by growth of thin PANI films at both sides of well dispersed BG sheets. The sandwich-like PANI/BG electrodes exhibited a specific energy density of 19.9 Wh kg^{-1} and excellent capacitance retention of 90% after 10,000 cycles. Mondal et al. used GO to prepare amine-functionalized graphene quantum dots (GQD) which they later used as a template for PANI growth during in situ polymerization (Mondal et al. 2015). As a result, they obtained nanotube-like structures covered with PANI nanofibers having a high specific surface area. The GQD/PANI composites achieved a high specific capacitance of 1044 F g^{-1} and a moderate cycling performance of 80.1% capacitance retention after 3000 cycles.

Construction of free-standing 3D porous structured graphene/PANI composites for the electrochemical energy storage applications has attracted considerable attention in the past few years. Several 3D G/PANI hybrid electrode materials have been prepared and exhibited unique morphology, electrical conductivity, mechanical stability, and attractive electrochemical performance. Characteristics and performance of these composites can be controlled by adjusting the hierarchical porous 3D graphene structure as well as the synergistic interactions between graphene and PANI. Wang et al. obtained PANI nanowire arrays on G/polystyrene (PS) composite film within situ polymerization of aniline (Wang et al. 2015b). PS dispersed in solution together with reduced graphene to avoid π-π interactions between individual graphene sheets and their agglomeration. After polymerization and formation PANI nanoarrays on G/PS, PS was removed with tetrahydrofuran for a 3D porous and conductive network of G/PANI structure. The specific capacitance of the hybrid electrode was measured $740\,\mathrm{F\,g^{-1}}$. G/PANI electrode yielded a high energy density of almost $66\,\mathrm{Wh\,kg^{-1}}$ with an 87% capacitance retention after 1000 cycles. Yu et al. used electrochemical deposition method to attach highly ordered PANI cones on graphene foam (GF) (Yu et al. 2015). Highly conductive GF with intact and interconnected structure was used both as a substrate to deposit PANI nanocone arrays and a current collector (Fig. 12.6). The specific capacitance of the GF/PANI nanocone arrays hybrid electrode and capacitance retention after 1000 cycles were $751.3\,\mathrm{F\,g^{-1}}$ and 93.2%, respectively. Alternatively, Luo et al. used G/PANI hydrogel electrode materials obtained by an integrated polymerization and hydrothermal process (Luo et al. 2016). p-Phelylenediamine used for aniline polymerization provided long fibrous PANI nanostructures and promoted nitrogen-doped graphene formation during the reduction of GO by hydrothermal process. In addition, freeze-drying after hydrothermal process improved mechanical properties of the composite. Foam-like G/PANI composite electrode had a specific capacitance of $610\,\mathrm{F\,g^{-1}}$ and a good cycling stability with 94.4% capacitance retention after 1000 cycles. Lately, Zhang et al. employed PANI nanofibers prepared using interfacial polymerization during steamed water regulation of high concentration

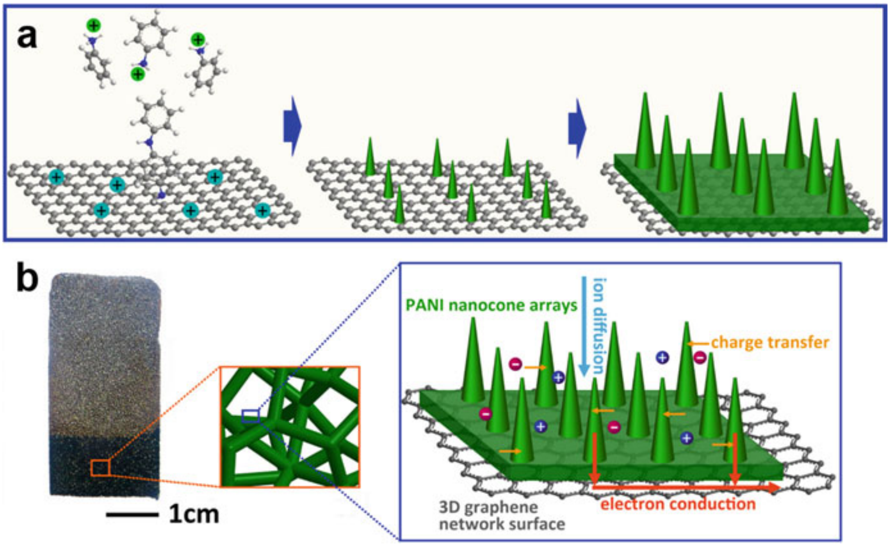


Fig. 12.6 (**a**) Schematic illustration of PANI nanocone array growth on G and (**b**) structure of 3D G/PANI nanocone arrays hybrid electrode. (Reprinted with permission from Yu et al. 2015)

GO gels (Zhang et al. 2017). The same weight of GO and PANI nanofibers were dispersed and a GO/PANI gel was prepared using rotary vacuum evaporation. The film of the gel was transferred into a Teflon-lined autoclave and heated at 200 °C for 5 h to form a unique 3D interconnected porous rGO/PANI hybrid film structure. Thus, the decrease in the electroactive surface area of graphene sheets due to parallel stacking was prevented. The specific capacitance of rGO/PANI composite film was as high as 1182 F g^{-1}. Area normalized capacitance and energy densities were 1.66 F cm^{-2} and 28.06 Wh kg^{-1}, respectively. The hybrid film had an excellent cycling performance with 8% increase in the specific capacitance after 10,000 cycles.

Additionally, energy storage performance of PANI and pseudocapacitive transition metal oxide composites attracted significant attention as they both have high theoretical specific capacitance. For example, Wang et al. investigated the application of graphene-like molybdenum disulphide (MoS_2)/PANI nanocomposites in ECs (Wang et al. 2015a). The aniline monomer was in situ polymerized inside exfoliated MoS_2 suspension which assisted intercalation of conducting macromolecules of PANI with conjugated bonds into the interlayer of MoS_2 nanosheets. Thus, the electrical conductivity of the nanocomposite was improved. The hybrid electrodes had a specific capacitance of 390 F g-1 and capacitance retention of 86% after 1000 cycles. On the other hand, Zhu et al. achieved better electrochemical performance for MoS_2/PANI composites by freezing the solution into ice during in situ polymerization of aniline inside exfoliated MoS_2 suspension (Zhu et al. 2015). While the solution was freezing during the polymerization reaction, PANI nanoneedle arrays were grown on MoS_2 nanosheets and avoided individual nanosheets to stack on each other. Conductive nanoneedle arrays grown on large surface area improved the electrode/electrolyte contact area and provided short electron/ion diffusion paths. MoS_2/PANI nanoneedle arrays hybrid electrode yielded a high specific capacitance of 853 F g-1 at a wide potential window ($\pm$1.0 V) and a good cycling performance of 91% capacitance retention after 4000 cycles within a potential window of $\pm$0.6 V. Xie et al. electrodeposited PANI on carbon/titanium nitrite nanowire arrays (C/TiN) to improve the electrochemical properties (Xie et al. 2015). PANI deposition dramatically increased the areal capacitance of the C/TiN from 86 to 480 mF cm^{-2}. PANI/C/TiN nanowire arrays yielded a very high specific capacitance of 1093 F g^{-1} and a capacitance retention of 98% after 2000 charge-discharge cycles. Xia et al. coated a thin layer RuO2 on CFC/PANI nanofibers composite using atomic layer deposition technique (Xia et al. 2015). The thin metal oxide layer on polymer improved the mechanical strength of the hybrid core-shell electrode and it achieved excellent capacitance retention of 88% after 10,000 charge-discharge cycles. The specific capacitance and areal capacitances were 710 F g^{-1} and 354 mF cm^{-2}, respectively. In addition, ternary hybrid electrode had an energy density of 11.5 Wh kg^{-1}. Table 12.1 summarizes the electrochemical performance of PANI electrode materials.

Table 12.1 Electrochemical performance of polyaniline-based electrode materials

Materials	Electrode setup	Current density or Scan rate	Specific capacitance ($F\,g^{-1}$)	Energy density ($Wh\,kg^{-1}$)	Retention ratio/No of cycles	Ref.
PANI/eCFC	2 electrode	$1\,A\,g^{-1}$	1035	22.9	90%/5000	Yu et al. (2013)
G/PANI/eCFC	2 electrode	$1\,A\,g^{-1}$	1145	25.4	94%/5000	Yu et al. (2014)
VA-CNT/PANI	3 electrode	$1\,A\,g^{-1}$	403	98.1	90.2%/3000	Wu et al. (2017a)
G/PANI	3 electrode	$5\,mV\,s^{-1}$	286	19.02	94%/2000	Salunkhe et al. (2014)
B doped G/PANI	3 electrode	$1\,mV\,s^{-1}$	406	19.9	90%/10,000	Hao et al. (2015)
G quantum dot doped PANI	3 electrode	$1\,A\,g^{-1}$	1044	117.45	80.1%/3000	Mondal et al. (2015)
G/PANI	3 electrode	$0.5\,A\,g^{-1}$	740	65.94	87%/1000	Wang et al. (2015b)
RGO/PANI	3 electrode	$1\,A\,g^{-1}$	1182	28.06	108%/10,000	Hong et al. (2017)
N doped G/PANI	3 electrode	$0.2\,A\,g^{-1}$	561	19	92%/500	Gopalakrishnan et al. (2015)
RuO2/PANI@CC	2 electrode	$5\,mV\,s^{-1}$	710	42.2	88%/10,000	Xia et al. (2015)

12.3 Nanostructured Polypyrrole Hybrids-Based Electrochemical Energy Storage Supercapacitors

Polypyrrole (PPy) received a wide attention in energy storage research due to its good processing flexibility, easy polymerization, low toxicity, high electrical conductivity, and charge storage capability. Its theoretical specific capacitance was reported as 620 F g^{-1} (Lota et al. 2004). PPy has a high volumetric capacitance (400–500 F cm^{-3}) because of its high density. However, the dense growth of PPy limits access of dopant ions to its interior sites and hinders the specific capacitance. So thin film structure of PPy is advantageous to utilize its specific capacitance. Single-charged anions such as Cl^-, ClO4$^-$, and SO_3^- are commonly used as a dopant for PPy. On the other hand, Suematsu et al. suggest using multiple-charged anion dopants, e.g. SO_4^{2-}, could cause physical crosslinking of the polymer and increase porosity during electropolymerization (Suematsu et al. 2000). Thus, the polymer would have enhanced diffusivity and capacitance. As in other CPs, the insufficient mechanical stability of PPy during charge-discharge cycling is another hurdle to overcome for its practical application in ECs. Therefore, different nanostructures of PPy have been explored to achieve an ideal EC electrode material.

1D nanostructures of CPs are attractive due to their high electrical conductivity and unique electrochemical activity. Wang et al. prepared 1D PPy nanotubes using MnO2 reactive templates and compared their electrochemical performance with PPy granules (Wang et al. 2014). They polymerized polypyrrole on the outer surface of MnO_2 with redox reaction as a MnO2 template had stronger oxidation potential (1.23 V) than the chemical oxidation potential of Pyrrole (0.7 V). HCl in the solution initiated the redox reaction and MnO_2 reduced to soluble Mn^{2+}. The resulting PPy nanotubes were 3 μm long with 50 nm diameter open tubular channels. This nanostructure allowed a higher electroactive area for short diffusion of ions and better transport of ions at the interface of the electrode and electrolyte during the charge-discharge process. However, PPy nanotubes achieved a specific capacitance of 273 F g^{-1} which was less than half of theoretical specific capacitance of PPy. On the other hand, PPy granules prepared with oxidation of $FeCl_3$ had a much lower specific capacitance of 152 F g^{-1} due to the smaller specific surface area of the PPy particles. Xu et al. also obtained 1D PPy structures on cotton fabrics using a similar in situ polymerization method with fibrillar $FeCl_3$ and methyl orange complex self-degraded template (Xu et al. 2015a). PPy nanorods uniformly coated on cotton fabrics to obtain flexible. Wearable EC electrodes were having a specific capacitance of 325 F g^{-1} and an energy density of 24.7 Wh kg^{-1}. But, the capacitance retention of the electrode was 63% only after 500 charge-discharge cycles. In another attempt, Xu et al. coated the cotton fabric using RGO followed by in situ chemical polymerization of pyrrole with $FeCl_3$ oxidant (Xu et al. 2015b). PPy granules grown on RGO coated fabric but this different structure did not improve the electrochemical performance of chemically polymerized PPy electrodes. The specific capacitance of this composite was 336 F g^{-1}. The energy density was reported as 21.1 Wh kg^{-1} and the capacitance retention after only 500 cycles was 64%.

Incorporating in situ chemical polymerized PPy with other electrochemically active materials is a trending approach to better utilizes charge storage capacity of PPy. For example, Liu et al. prepared PPy/bacterial cellulose (BC)/GO composite sheets by in situ polymerization of PPy in a suspension of BC/GO (Liu et al. 2015). PPy coating on BC/GO nanosheets formed a 3D cross-linked nanostructure wrapped with conductive PPy. Electrodes fabricated using PPy/BC/GO ternary hybrid achieved a good specific capacitance of 486 F g^{-1} with improved capacitance retention of 93.5% after 2000 charge-discharge cycles. In addition, the electrode yielded a high volumetric capacitance of 243 F cm^{-3} which was attributed to high pseudocapacitance of PPy and unique structure obtained by aggregation of PPy on nanosheets. Another nanostructure of in situ chemical oxidation polymerized PPy with improved EC performance was reported by Tang and co-workers (Tang et al. 2014). Figure 12.7 shows the fabrication method of the PPy ultrathin films on MoS_2 monolayers. They obtained ultrathin PPy films on MoS2 monolayers which were prepared by ultrasonication-assisted exfoliation of Li intercalated MoS_2. A sandwich like 2D MoS_2/PPy composite nanostructure was achieved by optimum amount of pyrrole used during polymerization. The electrochemical performance of the electrodes fabricated using MOS_2/PPy hybrids were investigated. The results revealed that PPy ultrathin films improved the overall conductivity of the nanocomposite and pseudocapacitive behavior of both PPy and MoS_2 contributed to a high specific capacitance of 700 F g^{-1}. MoS2/PPy ultrathin film electrode yielded a high energy density of 83.3 Wh kg^{-1} and cycling stability with 85% capacitance retention after 4000 charge-discharge cycles. In addition, it outperformed other electrodes prepared using G/PPy nanocomposites, MoS_2 monolayers, and pure PPy (Fig 12.7b, c).

Electrochemical polymerization is also widely used to obtain PPy electrode materials having a uniform and controlled structures. Zhang et al. obtained two different PPy structures on SS using galvanostatic method (GM) and pulse galvanostatic method (PGM) (Zhang et al. 2010). The ppy film prepared by PGM (PGM-PPy) had a uniform horn-like microporous structure while the PPy film prepared by GM (GM-PPy) was having coarser disordered particles. The specific capacitances of two PPy structures were compared. The microporous PGM-PPy yielded a good specific capacitance of 403 F g^{-1} while GM-PPy had a specific capacitance of 251 F g^{-1}. Cao et al. used an electrochemical co-deposition method to control the PPy structure electropolymerized on Ti foil (Cao et al. 2015). An electrolyte with 20 mmol L^{-1} LiCO4 and 0.1 mg mL^{-1} GO was used during the polymerization process. Hence, PPy and GO co-deposited on Ti foil forming a 3D porous interconnected nanostructure. Resulting PPy/GO electrodes achieved a specific capacitance of 481 F g^{-1} while PPy electrodeposited on Ti foil was having a specific capacitance of 345 F g^{-1}. PPy/GO hybrid electrodes also yielded a capacitance retention of almost 85% after 5000 charge-discharge cycles. As in other CPs, structural, electrical, and mechanical characteristics of the substrates used

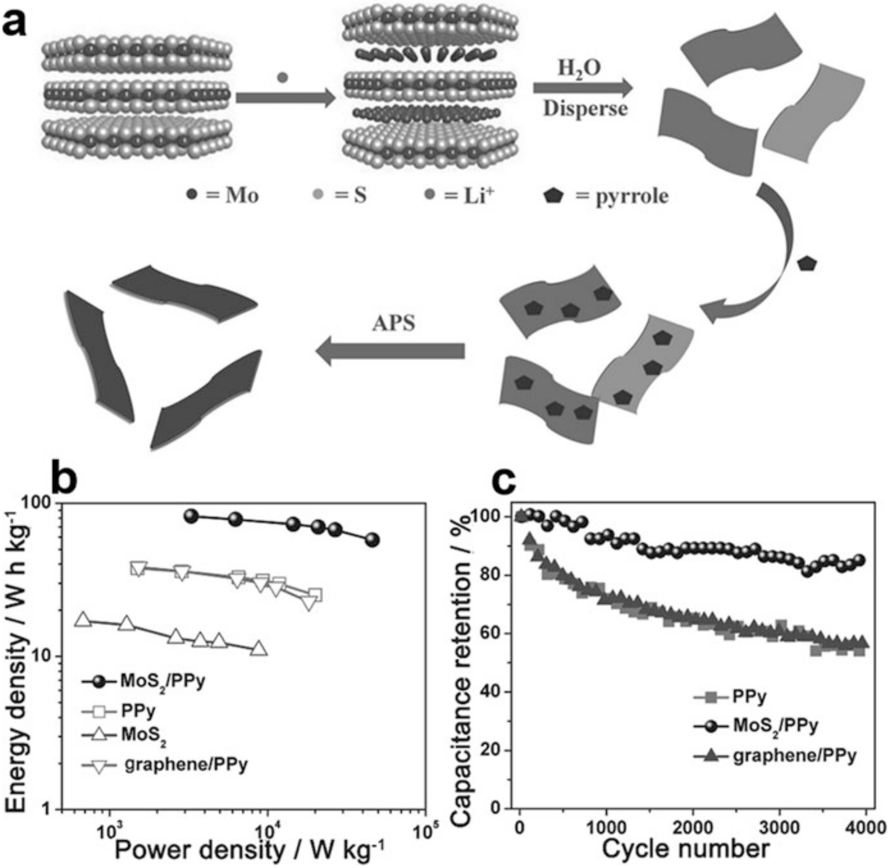


Fig. 12.7 (**a**) Schematic illustration of preparing MoS_2/PPy nanocomposite electrodes. (**b**) Ragone plots of MoS_2/PPy, PPy, MoS_2, and graphene/PPy. (**c**) Cycling performance of MoS_2/PPy, PPy, and graphene/PPy (Tang et al. 2014)

for electrochemical polymerization of PPy influence electrochemical properties of the final electrode material obtained. For instance, Chen et al. electrochemically polymerized PPy on Ti foil and 3D nickel nanoparticle film to study the effect of different substrates on the EC performance of PPy (Chen et al. 2015). PPy thin film coated on 3D nickel nanoparticles was having a higher electroactive surface area when compared with PPy grown on Ti foil substrate. Figure 12.8 shows SEM images of 3D Ni nanoparticles, PPy shell on 3D Ni core, and PPy has grown on Ti foil. Consequently, PPy core-shell on 3D Ni nanoparticle substrate achieved a high specific capacitance of 726 F g^{-1} while PPy on Ti foil had a much lower specific capacitance of 182 F g^{-1}. The EC decide built using PPy core-shell on 3D Ni nanoparticle electrodes had a good energy density of 21.2 Wh kg^{-1} and specific capacitance retention of 81.4% after 5000 charge-discharge cycles. Song

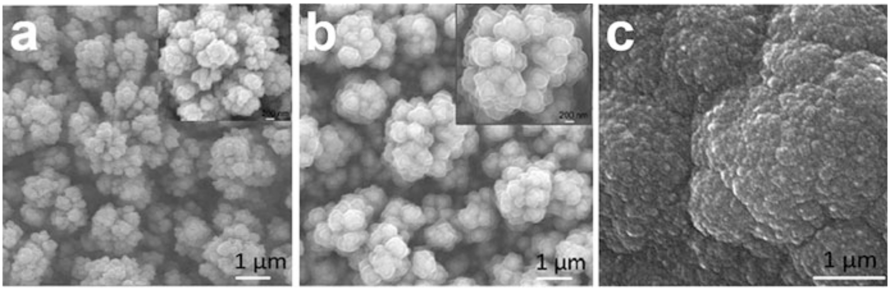


Fig. 12.8 SEM images of (**a**) 3D Ni nanoparticles on Ti foil substrate, (**b**) PPy shell on 3D Ni core on Ti foil substrate, and (**c**) PPy grown on Ti foil substrate. (Reprinted with permission from Chen et al. 2015)

et al. reported PPy film with high cycling stability which was electrochemically polymerized on functionalized partially exfoliated-graphite (FEG) substrate (Song et al. 2015). They used β-naphthalene sulfonic acid during electropolymerization to simultaneously dope PPy with β-naphthalene sulfonate (NS-) anions to decrease the mechanical deformation on polymer matrix caused by insertion/extrusion of counterions during the charge-discharge cycling process. As a result, PPy doped with NS- anions having larger sizes and low mobility had excellent capacitance retention of 97.5% after 10,000 charge-discharge cycles. Table 12.2 summarizes PPy electrode materials and their electrochemical performance.

12.4 Nanostructured Polythiophene Hybrids-Based Electrochemical Energy Storage Supercapacitors

Wang et al. (2018) fabricated the sandwich-structured poly (3,4-ethylenedioxy thiophene) (PEDOT)-A/polypropylene/Au-PEDOT through electrodeposition method, and electroless plating. The sandwich structure has two conductive surfaces and a middle insulating layer. Then, H_3PO_4/PVA gel electrolyte was added to the sandwich structure to obtain flexible supercapacitor of Au-PEDOT |H_3PO_4/PVA| PEDOT-Au. The flexible device showed the maximum capacitance of $63.4\,\mathrm{F\,g^{-1}}$ with excellent cycle stability (91.8% retention after 2000 cycles). Furthermore, the device not only showed excellent bending endurance (99.1% capacity retention after 5000 repeated bending cycles), but also can be connected in series without wires. Thus, this flexible cell has the potential for applications in portable electronics.

Novel poly(2,3,4a,9a-tetrahydro[1,4]dioxino[2,3-b]thieno[3,4-e][1,4]dioxine) (pTDTD) and poly(7-butyl-3,4a,7,9a-tetrahydro-2H-[1,4]dioxino[2,3:5,6][1,4]dioxino[2,3-c]pyrrole) (pTDDP) as redox-active electrode materials were synthesized by electropolymerization in the presence of new thiophene and pyrrole monomers containing fused two 1,4-dioxane rings (Yiğit et al. 2013). The stainless steel

Table 12.2 Polypyrrole-based electrode materials and their electrochemical performances

Materials	Electrode setup	Current Density or Scan Rate	Specific Capacitance ($F\,g^{-1}$)	Energy Density ($Wh\,kg^{-1}$)	Retention ratio/No of cycles	Ref.
PPy on fabric	2 electrodes	$0.2\,A\,g^{-1}$	325	24.7	63%/500	Xu et al. (2015a)
PPy@3D-Ni	3 electrodes	$1\,A\,g^{-1}$	726	21.2	95.8%/1000	Chen et al. (2015)
RGO/PPy on fabric	2 electrodes	$0.6\,mA\,cm^{-2}$	336	21.1	64%/500	Xu et al. (2015b)
PPy/BC/GO	2 electrodes	$0.6\,A\,g^{-1}$	486	77.2	93.5%/2000	Liu et al. (2015)
GO/PPy	3 electrodes	$0.2\,mA\,cm^{-2}$	481.1	15.1	84.8%/5000	Cao et al. (2015)
PPy/MoS2	2 electrodes	$10\,mV\,s^{-1}$	700	83.3	85%/4000	Tang et al. (2014)
Nanotubular G/PPy	3 electrodes	$0.15\,A\,g^{-1}$	509	31.6	75%/13200	Kashani et al. (2016)

(SS) modified with pTDTD and pTDDP were used as anode materials against PEDOT coated SS cathode in asymmetric devices and as both anode and cathode material in symmetric devices. The capacitive properties of the devices were tested by CV, EIS and GCD techniques in the presence of both dissolved electrolytes and ionic liquid (1-butyl-3-methylimidazolium tetrafluoroborate) as electrolytes. It was found that pTDTD exhibited the specific capacitance of $260\,F\,g^{-1}$, and specific energy of $288\,Wh\,g^{-1}$, and retain good capacitance after 8000 cycles. As shown in both Figs. 12.9 and 12.10, another novel structured one dimensional polythiophene nanofibers were synthesized inside the hollow TiO_2 nanotubes arrays (TNTs) by regulating nucleation and chain growth of polymer during the room-temperature electropolymerization of thiophene monomer molecules with different concentrations such as 0.05, 0.1, 0.5 and 1 M, along with certain concentration of tetrabutylammonium tetrafloroborate (supporting electrolyte) (Ambade et al. 2017). The polymerization was conducted at the rate of $25\,mV\,s^{-1}$ in the potential range of 2.0 to -0.6 V to control the size and nanoscale morphology of polymer, and to avoid polythiophene degradation and possible side reactions due to over-oxidation reactions. The successful formation of polythiophene nanofibers was confirmed by various microscopic and spectroscopic techniques (FE-SEM, TEM, EDX, XRD, STEM, FTIR, Raman), and then utilized it as promising electrode materials for the electrochemical energy storage supercapacitor applications. It was found that 1D polythiophene/TNT nanofibers showed the maximum specific capacitance, specific energy and specific power of $1052\,F\,g^{-1}$, $51.4\,Wh\,kg^{-1}$, and

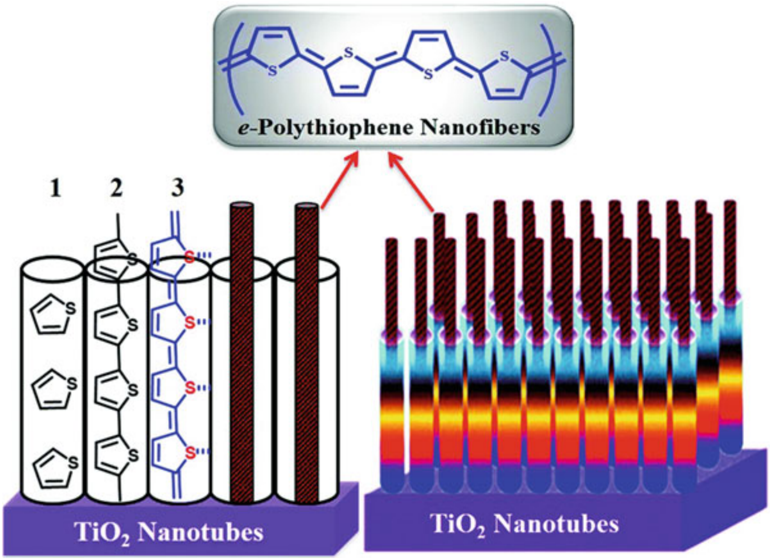


Fig. 12.9 Schematic presentation of one-dimensional polythiophene nanofibers growth in side hollow TiO_2 nanotubes arrays through controlled electropolymerization. (Reprinted with permission from Ambade et al. 2017)

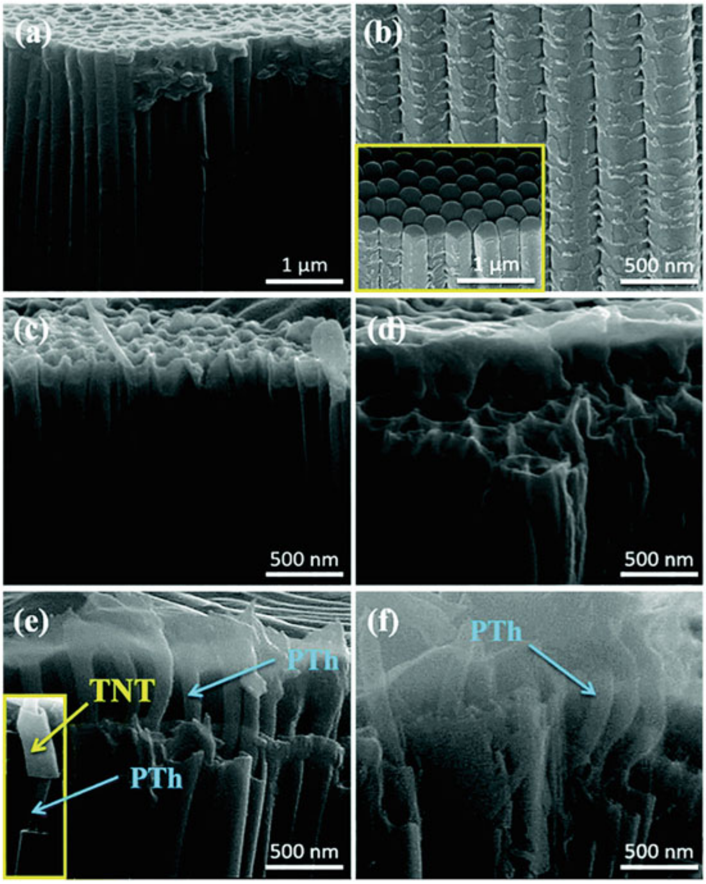


Fig. 12.10 FE-SEM images of (**a**, **b**) pristine hollow TiO_2 nanotubes, (**c**–**f**) 1D polythiophene nanofibres grew in hollow TiO_2 nanotubes at different concentrations (0.05 to 1 M) of thiophene monomer. (Reprinted with permission from Ambade et al. 2017)

255.22 W kg^{-1}. Moreover, these 1D electrode materials exhibited excellent long-term stability over 5000 cycles at a current density of 7 A g^{-1}, which were tested using galvanostatic charge-discharge (GCD). Polythiophenes (PThs) synthesized by oxidative polymerization in the presence of three types surfactants (cationic-CTAB, anionic-SDS, non-ionic-Triton X-100) and found that the specific capacitance values are 78, 93, 88 and 117 F g^{-1} for PTh, PTh-CTAB, PTh-SDS, and PTh-TRI (Senthilkumar et al. 2011).

It is known that the donor-acceptor based organic conjugated polymers show unique properties such as excellent electrical conductivity, high charge carrier mobilities, broad absorption of light in the visible wavelength, desirable semiconducting characteristics, etc., and have the potential for applications in optoelectronic devices. The conjugated donor-acceptor copolymers based on naphthalene diimide as acceptor and thiophene that is terminated with oligophenylenevinylene as donor were synthesized using the hetero arylation polymerization reaction, in which nitrile groups were introduced at the vinylene linkage in one copolymer to turning the electrochemical characteristics of polymers (Sharma et al. 2018). The synthesized two polymers further modified with 1D carbon nanotubes to fabricate composite electrodes in the presence of 0.5 M sulfuric acid as the electrolyte. It was found that the hybrid electrode material exhibits a galvanometric specific capacitance of $124\,\mathrm{F\,g^{-1}}$ with excellent stability up to 5000 cycles with almost 100% retention of initial specific capacitance in the potential range of −0.7 to 0.5 V at a current density of $5\,\mathrm{A\,g^{-1}}$, and their energy density and power density are 2, and $22\,\mathrm{kW\,kg^{-1}}$, which are in the range of the values that reported for p-type organic electrically conducting polymers. The CNT/donor-accepter polymer hybrid electrode material has better capacitance than pure polymers (84 and $61\,\mathrm{F\,g^{-1}}$) under the same conditions of electrochemical-property measurements. This electrode demonstrated as the power source to glow a red light-emitting diode (LEDs), indicating these n-type conjugated polymers have the potential for charge storage capacitor devices.

Liu and Reynolds (2010) were employed the transesterification reaction between 2,2-dimethyl-1,3-propanediol and 3,4-dimethoxythiophene to synthesize 2,2-Dimethyl-3,4-propylenedioxythiophene, and then polymerized it through an electropolymerization in the three-electrode cell containing 10 mM of monomer and 0.1 M LiBTI/acetonitrile supporting electrolyte. It was used to fabricate the supercapacitive device by coating polymer on gold-deposited Kapton electrode ($1 \times 2\,\mathrm{cm^2}$) as a flexible conductive working electrode, Ag/Ag^+ as the counter electrode (anode), and an ionic liquid as an electrolyte. It was found the electrochemical supercapacitor device fabricated using poly(2,2-Dimethyl-3,4-propylenedioxythiophene) displayed the supercapacitance of $55\,\mathrm{F\,g^{-1}}$ and the capacitance retention of 85% of its storage capacity after 32000 redox cycles. Moreover, it showed good energy density $6\,\mathrm{Wh\,kg^{-1}}$ along with rapid capacitive responses to 1 V between 5 to $500\,\mathrm{mV\,s^{-1}}$. This electroactive conjugated polymer electrode is used to assemble tandem four electrochemical supercapacitors in the series, which showed a 4.0 V charging/discharging window with 4-fold enhancement in capacitance, demonstrating it has potential to develop as an individual, flexible, and lightweight supercapacitor modules. Another type thiophene-based conjugated polymer, poly(3,3’ ’ ’ -dialkylquarterthiophene) flexible films with enhanced electrical charge transport properties were fabricated through the self-assembly process (Pandey et al. 2014). Novel conjugated monomers (thiophene, carbazole)-based rigid type monomers (tectons) have been used to fabricate 3D microporous structured polymer films having smooth surface morphology (Zhang et al. 2015). These conjugated polymer microporous films were produced through potentiodynamic electrochemical oxidative polymerization of tetracarbazole-substituted zinc-porphyrin monomer in the dichloromethane solvent. Cyclic voltammograms (CV) results confirmed that the peak current displayed a linear relation with the scan rate. This demonstrated the occurrence of surface-limited redox reactions. Galvanostatic charge-discharge (GCD) electrochemical tests showed that this polymer electrode has maximum supercapacitance of

$142\,\mathrm{F\,g^{-1}}$ at a current density of $5\,\mathrm{A\,g^{-1}}$ with good capacitance retention at higher current densities. N and p-doped PEDOT showed the specific capacitance of $121\,\mathrm{F\,g^{-1}}$ at a scan rate of $10\,\mathrm{mV\,s^{-1}}$ (Bhat and Kumar 2007).

Conductive 3D structured porous organic conjugated polymers (POCP1 and POCP2) were synthesized by the condensation of tetra(4-aminophenyl)methane and 2-thenaldehyde or 2,2-bithiophene-5-carboxyaldehyde, and their subsequent polymerization reaction (Li et al. 2018). The resulting POCP1 and POCP2 have a higher BET surface area of 342 and $260\,\mathrm{m^2\,g^{-1}}$. POCP2 electrode was used to test the supercapacitor device and it showed the specific capacitance of $332\,\mathrm{F\,g^{-1}}$ with good cycle stability (capacity retention of 94% after 10,000 successive cycles). This study reveals that the electrochemical performance of the device can be further improved effectively by altering the monomers and porosity properties of conjugated polymers. Another new electrode, poly(2-(thiophene-2-yl)furan) (PTFu) was fabricated by an electropolymerization of monomer in acetonitrile solution containing 0.1 M lithium perchlorate ($LiClO_4$) as monomer in this medium has an oxidative onset potential of 0.9 V, which is lower than those of thiophene (1.47 V) and furan (1.28 V) (Mo et al. 2015). The PTFu electrode in ionic liquid showed the enhancement of specific capacitance of $392\,\mathrm{F\,g^{-1}}$ from $249.4\,\mathrm{F\,g^{-1}}$ at $5\,\mathrm{A\,g^{-1}}$. It was found that the cycling stability of device was also enhanced to 67% retention from 25.5% retention after 500 cycles when the equivalent boron trifluoride diethyl etherate (BFEE) was added into the acetonitrile electrolyte. The electrode showed a lower capacitance ($209.4\,\mathrm{F\,g^{-1}}$ at $5\,\mathrm{A\,g^{-1}}$) and improved stability (67.6% retention after 600 cycles) in the presence of ionic liquid 1-butyl-3-methylimidazolium hexafluorophosphate. This study demonstrates that PTFu polymer electrodes display good capacitive properties when the electrolyte based-BFEE is used. Another new type thiophene-based polymer, poly(1-(pyren-1-yl)-2,5-di(thiophene-2-yl)-1H-pyrrole) (PThP) was synthesized on the surface of pencil graphite electrode by electropolymerization, and it showed highest specific capacitance of $25\,\mathrm{mF\,cm^{-2}}$ in 0.1 M tetrabutylammonium perchlorate/dichloromethane solution for 30 cycles at $25\,\mathrm{mV\,s^{-1}}$ scan rate (Çelik et al. 2014). New dendritic thiophene-based conjugated polymers with porous morphological structures (Potphode et al. 2017), polytris[4-(2-thienyl)phenyl]amine (P1), polytris(4-(3-methylthiophene-2-yl)phenyl)amine (P2), polytris (4-(selenophen-2-yl)phenyl)amine (P3) and poly(tris(4-thieno[3,2-b]thiophene-2-yl)phenyl amine) (P4) were synthesized by chemical oxidative polymerization of synthesized organic monomers in the presence of anhydrous $FeCl_3$ as an oxidizing agent and $CHCl_3$ as solvent, and they showed specific capacitance of 278, 257, 246 and $315\,\mathrm{F\,g^{-1}}$ for P1, P2, P3 and P4 with low internal resistance. This research demonstrates that the electrodes have potential as new redox-active pseudocapacitors and other electrochemical devices. Another novel electrodes, poly(4-methyl-3,4-dihydro-2H-thieno[3,4-b][1,4]oxazine) and poly(4-ethyl-3,4-dihydro-2H-thieno[3,4-b][1,4]oxazine) were synthesized by electrochemical polymerization of N-alkyl-dihydro-1,4-oxazine ring fused thiophene monomers on the surface of a stainless steel electrode (Ermiş et al. 2013). Stainless steel coated electrodes-coated these conjugated polymers have been used as an anode material against PEDOT-coated cathode in an asymmetric pseudocapacitor cell and as both anode and cathode material in a symmetric pseudocapacitor cell. The electrochemical capacitive properties of n/p type pseudocapacitors were tested by CV, EIS, and GCD, and the results showed the specific capacitance of pseudocapacitor cells in the range of 285.6 and 325 $F\,g^{-1}$, with specific energy values for the symmetric and asymmetric pseudocapacitor cells in the range of 64.26–86.74 $Wh\,kg^{-1}$.

Aradilla et al. (2016) reported the fabrication of poly (3,4-(ethylenedioxy)thiophene) (PEDOT) nanowires-coated diamond/silicon electrodes through the electrochemical polymerization. They found that the mass of polymer coated on the electrode was found to be 0.31 mg by calculating the difference in the masses before and after electrodeposition process by using a METLER balance. The symmetric planar microcapacitor developed using this electrode materials in the presence of N-methyl-N-propylpyrrolidinium bis((trifluoromethyl)sulfonyl)imide ionic liquid, and the capacitor device exhibited outstanding energy and power densities 26 $mJ\,cm^{-2}$ and 1.3 $mW\,cm^{-2}$ within a large voltage cell of 2.5 V. The device also showed the specific capacitance of 140 $F\,g^{-1}$ at 1 $mV\,s^{-1}$ to 24 $F\,g^{-1}$ at 200 $mV\,s^{-1}$, with 80% of capacity retention after 15000 galvanostatic charge-discharge cycles at a higher current density of 1 $mA\,cm^{-2}$, and 100% of Coulombic efficiency. Therefore, such a new type of electrodes can be used for a high-energy cutting-edge on-chip supercapacitive electronic devices. A new type thiophene-based electroactive polymer, poly 2-[(thiophene-2-yl)-4-(thiophene-2- lmethylene)oxazol-5(4H)-one] (PTTMO) was coated on pencil graphite electrode (PGE) through an electrochemical polymerization by using chronoamperometric (CA) technique in an acetonitrile solution containing 0.01 M 2-[(thiophene-2-yl)-4-(thiophene-2- lmethylene)oxazol-5(4H)-one] monomer and 0.10 M tetrabuthylammonium perchlorate, and the electrochemical performance of a hybrid electrode was analyzed using CV, EIS, and GCD with two or three electrode systems (Hür et al. 2016). The device showed the highest specific capacitance of 193 $F\,g^{-1}$ at a scan rate of 10 $mV\,s^{-1}$, with good charge-discharge cycle stability with the capacity retention of 90.8%. In another case, the films of polythiophene (PTh), poly(3-methylthiophene) (PMeT) and poly(3,4-ethylenedioxythiophene) (PEDOT) were grown on PGE using cyclic voltammetry in an acetonitrile solution containing LiClO4 and HClO4 (Hür et al. 2013). The electrochemical properties of the electrodeposited polymer films were analyzed using CV and EIS methods. The CV results exhibited the specific capacitance of PTh/PGE, MeT/PGE, and PEDOT/PGE are 1503, 2621 and 8668 $mF\,g^{-1}$ at a scan rate of 10 $mV\,s^{-1}$. Repetitive chronopotentiometry (RCP) test results showed that the hybrid electrode films have excellent cycling stability even after 1000 consecutive cycles. Three different types of thiophene-based polymers, poly(3-p-fluorophenylthiophene) (PFPT) and poly(dithieno[3,4-b:3V,4V-d]thiophene) (PDTT1) were galvanostatically grown on carbon paper electrodes and poly(3-methylthiophene) (PMeT) on Pt electrodes was grown by the oxidation of monomer (Mastragostino 2002), and utilized them as n/p type supercapacitors. Naphthaleneamidinemonoimide-modified polythiophene battery electrode showed specific charges of 38 $mAh\,g^{-1}$ (Otero et al. 2011).

An aqueous polymerization route has been employed to synthesize copolymer of aniline-thiophene nanofibers in the presence of monomers, ammonium persulfate as an initiator, and sulfuric acid as inorganic dopant (Male et al. 2015). The same pathway has been used to synthesize copolymer using sodium lauryl sulfate that function as both organic dopant and surfactant (self-organizing molecules). The copolymer nanofibres displayed the specific capacitance of 614 F g^{-1} at 1 mV s^{-1}, with the capacitance retention of 78% after 1000 cycles and almost 100% of columbic efficiency. The capacitance values are measured in the low-frequency region at 10 mHz and calculated to be 267 and 240 F g^{-1} at 0.6 and 0.8 V. Moreover, the electrical conductivity of the copolymer samples were tested by measuring the resistance of pressed polymer pellets (13 mm in diameter and 1.5 mm in thickness, pressure of 120 kg cm^{-2}) using a constant current source (6220) and nanovoltameter (2182 A) (Keighley conductivity meter), and it showed the electrical conductivity of 1.3 S cm^{-1}. Another new nanoscale porous structured different thiophene-based conjugated polymers were developed by Li's group (Li et al. 2015). They developed phenyl heterocyclic thoiphene, selenophene and tellurophenes (PT, PSe, PTe)-based 3D organic frameworks and utilized them in organic electronic devices (asymmetric supercapacitors) using the polymer as positive electrode and carbon black as the negative electrode. The electrochemical supercapacitor device showed a pseudo-rectangular cyclic voltammogram, indicative of the pseudocapacitive behavior of the electrode. The capacitive device showed an areal capacitance of 4 mF cm^{-2} at a current density of 0.1 A g^{-1}, with the peak current that is 80% of its initial value. They suggested that the capacitance can be further improved by optimizing the electrode fabrication, device fabrication, controlling pore properties (pore size and pore volume) and by using a redox electroactive material on the surface of the negative electrode. Another nanohyrid electrode, poly(o-methoxyaniline)/poly(3-thiophene acid) fabricated through the layer-by-layer (LBL) method, and measured the electrochemical performance using CV and EIS (Christinelli et al. 2016). The results showed that the specific capacitance of LBL polymer films increases linearly with a number of bilayers due to the self-doping effect between the conjugated polymers, i.e. carboxylate groups in the poly(3-thiophene acid) and the amine group in the poly(o-methoxyaniline). The LBL film showed the maximum capacitance of 140 F g^{-1} in the presence of 0.1 mol L^{-1} $LiClO_4$ electrolyte. Ordered poly(3-hexylthiophene):[6,6]-phenyl C_{61}-butyric acid methylester (PCBM) nanowire electrode showed maximum capacitance of 0.14 F cm^{-2} (Wang et al. 2012b). Poly(tris(thiophenylphenyl)amine) electrode showed the capacitance of 950 F g^{-1} in 100 mM tetrabutylammonium tetrafluoroborate in acetonitrile (Roberts et al. 2009).

Wu et al. (2017b) fabricated the piled-layer heterostructured films (Fig. 12.11) of two-dimensional thiophene nanosheets and electrochemically exfoliated graphene (<3 layers) through the self-assembly process and used 2D nanohybrid as solid-state pseudocapacitors with enhanced volumetric capacitance and superior rate capability. Such hybrid devices are portable and wearable electronics that have features of thin, lightweight, highly mechanically flexible, low-cost with outstanding electrochemical properties. They showed an areal capacitance of 3.9 mF cm^{-2}, a volumetric

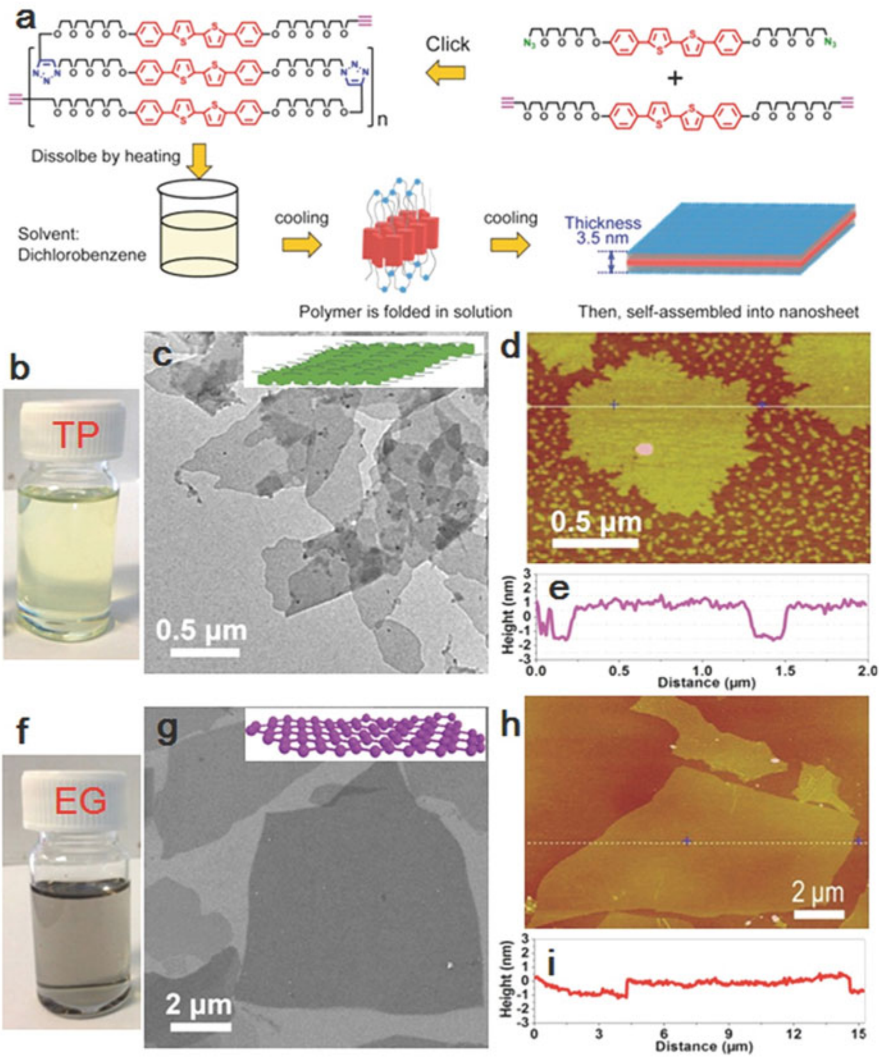


Fig. 12.11 (**a**) Fabrication of 2D polythiophene nanosheets, (**b**) optical image of the stable thiophene solution, (**c**) TEM image of polythiophene nanosheets, (**d**) AFM image, (**e**) height profile of polymer sheets, (**f**) optical image of graphene solution, (**g**) SEM image of graphene nanosheets, (**h**) AFM image, and (**i**) height profile of graphene nanosheets (thickness of 1 nm). (Reprinted with permission from Wu et al. 2017b)

capacitance of 375 F cm^{-3}, the energy density of 13 mWh cm^{-3} and power density of 776 W cm^{-3}. Furthermore, this supercapacitor device can be further developed at the high rate up to 1000 V s^{-1}, providing remarkable rate capability (areal

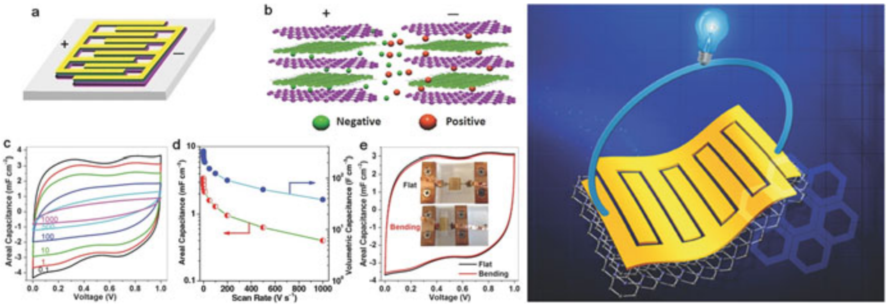


Fig. 12.12 Electrochemical characterization (CV) of the thiophene polymer/graphene nanosheet hybrid capacitive device at different scan rates, tested under flat and bending states. (Reprinted with permission from Wu et al. 2017b)

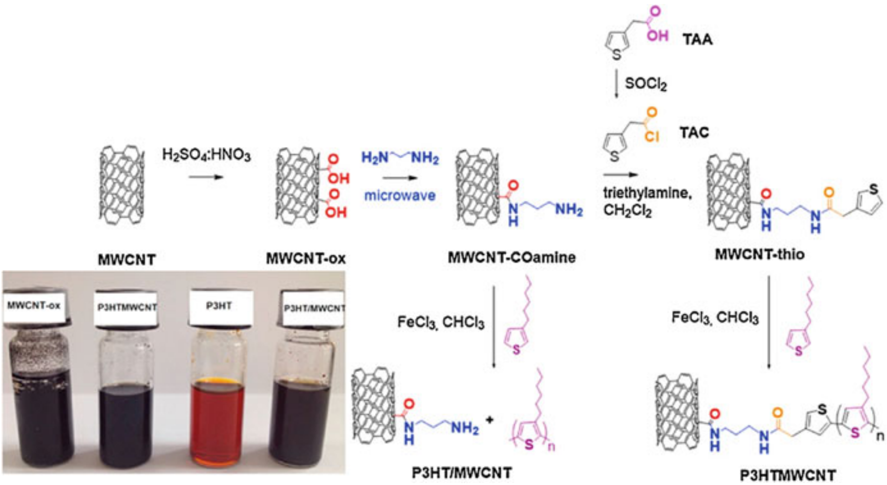


Fig. 12.13 Polythiophene-based electrode materials and their electrochemical performances

capacitance of 1.3 mF cm^{-2} and volumetric capacitance of 123 F cm^{-3} at 100 V s^{-1}), as well as flexibility under various blending modes (Fig. 12.12).

Another hybrid electrode, poly(3-hexylthiophene)-covalently functionalized with multi-walled carbon nanotubes (MWCNTs) were synthesized by polymerization of MWCNTs-modified with monomeric thiophene derivative and the monomer 3-hexylthiophene (1:1 mass ratio) through an in-situ oxidative polymerization as shown in Fig. 12.13 (Alves et al. 2016). The covalent hybrid showed an electrical conductivity of 0.46 S cm^{-1}, which is 5 times higher than that of the hybrid prepared by physically mixing of CNTs and polymer, indicating that the enhancement of charge transfer in the covalently CNTs-linked polymer hybrids. The capacitor device showed a specific capacitance of 239 F g^{-1} at a current density of 3 Ag^{-1}, which is 585% higher than the supercapacitor developed based on

Table 12.3 Polypyrrole-based electrode materials and their electrochemical performances

Materials	Current density or Scan rate	Specific capacitance ($F\,g^{-1}$)	Energy density ($Wh\,kg^{-1}$)	Retention ratio/No of cycles	Ref.
Polypyrrole/poly(3-(4-tert-butylphenyl)thiophene) copolymer	$5\,A\,g^{-1}$	291	36	91%/1000	Yue et al. (2012)
PEDOT nanotubes	$5\,mA\,cm^{-2}$	140	5.6	–	Liu et al. (2008)
PTh films	$0.3\,mA\,cm^{-2}$	300	11.4	87%/1000	Patil et al. (2014)
MECNTs/Poly(3-methylthiophene)	$0.6\,mA\,cm^{-2}$	296	33.4	80%/1000	Sivaraman et al. (2013)
Poly(3-methylthiophene)/PVDF hybrid	$10\mu A\,cm^{-2}$	616	7.3	84%/150	Fonseca et al. (2006)
Graphene/PEDOT	$5\,A\,g^{-1}$	201	–	–	Kumar et al. (2012)
MWCNTs/Polythiophene	$1\,A\,g^{-1}$	216	–	74%/500	Zhang et al. (2014)
MnO2/PEDOT	$5\,mA\,cm^{-2}$	210	–	–	Liu and Lee (2008)
TiO2/Polythiophene	$2\,A\,g^{-1}$	640	237	89%/1100	Ambade et al. (2013)
Zn-doped Poly (3-methyl thiophene)	$2\,A\,g^{-1}$	235	–	92%/500	Karthikeyan et al. (2011)

pure MWCNTs electrodes at 1 Ag^{-1}. LBL strategy has been employed to develop novel ternary hybrid electrode material through the combination of conducting poly(3,4-ethylenedioxy thiophene):poly(styrene sulfonate) (PEDOT:PSS), few-layer graphene (FLG) and magnetite iron oxide raspberry nanostructures (Pardieu et al. 2015), and tested their electrochemical properties in 0.5 M Na_2SO_3 aqueous electrolyte using CV and EIS. The hybrid Fe_3O_4@FLG@PEDOT:PSS multilayered electrode provide a high specific capacitance of 153 F g^{-1} at 0.1 A g^{-1} with good cycling stability (114% retention after 3500 cycles). This LBL method can be extended to the synthesis of even higher capacitive electrodes using other types of metal oxides and conjugated polymers. Another hybrid type electrochemical supercapacitive electrode, $Li_4Ti_5O_{12}$/poly(methyl)thiophene asymmetric hybrid-activated carbon counter-electrode was fabricated and it displayed a specific energy of 10 Wh kg^{-1} with better cycle life (Pasquier et al. 2004). Likewise, numerous polythiophene derivatives and its hybrids-based supercapacitor devices were fabricated through various strategies, and their electrochemical properties were summarised in Table 12.3.

12.5 Conclusion

This chapter discussed the recent developments on various synthesis methodologies of different nanostructured conducting polymers such as polyaniline, polypyrrole, polythiophene and their derivatives, and their hybrids functionalized with various nanoscale 0D – 3D metal oxides and carbon nanomaterials (e.g. graphene, carbon nanotubes, porous carbons, graphene quantum dots, carbon fibres, carbon cloth), influencing parameters on the control of morphological structures and dispersion of nanostructured inorganic particles into polymer matrix, and electrochemical energy storage supercapacitive characteristics such as specific capacitance, capacity retention, cyclic stability, energy density and power density. The design of efficient large scale fabrication methods for new structured conducting polymers-based hybrid electrodes for low cost and high-performance, energy storage devices (super capacitors and rechargeable batteries) need to be developed to meet the technological requirements.

References

Abdelhamid ME, O'Mullane AP, Snook GA (2015) Storing energy in plastics: a review on conducting polymers & their role in electrochemical energy storage. Rsc Adv 5:11611–11626

Alves APP, Trigueiro JPC, Calado HD, Silva GG (2016) Poly(3-hexylthiophene)-multi-walled carbon nanotube (1:1) hybrids: structure and electrochemical properties. Electrochim Acta 209:111–120. https://doi.org/10.1016/j.electacta.2016.04.187

Ambade RB, Ambade SB, Shrestha NK, Nah YC, Han SH, Lee W, Lee SH (2013) Polythiophene infiltrated TiO2 nanotubes as high-performance supercapacitor electrodes. Chem Commun 49:2308. https://doi.org/10.1039/c3cc00065f

Ambade RB, Ambade SB, Shrestha NK, Salunkhe RR, Lee W, Bagde SS, Kim JH, Stadler FJ, Yamauchi Y, Lee SH (2017) Controlled growth of polythiophene nanofibers in TiO2 nanotube arrays for supercapacitor applications. J Mater Chem A 5:172–180. https://doi.org/10.1039/c6ta08038c

Aradilla D, Gao F, Lewes-Malandrakis G, Müller-Sebert W, Gentile P, Boniface M, Aldakov D, Iliev B, Schubert TJS, Nebel CE, Bidan G (2016) Designing 3D multihierarchical heteronanostructures for high-performance on-chip hybrid supercapacitors: Poly(3,4-(ethylenedioxy)thiophene)-coated diamond/silicon nanowire electrodes in an aprotic ionic liquid. ACS Appl Mater Interfaces 8:18069–18077. https://doi.org/10.1021/acsami.6b04816

Bélanger D, Ren X, Davey J, Uribe F, Gottesfeld S (2000) Characterization and long-term performance of polyaniline-based electrochemical capacitors. J Electrochem Soc 147:2923–2929

Bhat DK, Kumar MS (2007) N and P doped poly(3,4-ethylenedioxythiophene) electrode materials for symmetric redox supercapacitors. J Mater Sci 42:8158–8162. https://doi.org/10.1007/s10853-007-1704-9

Cao J, Wang Y, Chen J, Li X, Walsh FC, Ouyang JH, Jia D, Zhou Y (2015) Three-dimensional graphene oxide/polypyrrole composite electrodes fabricated by one-step electrodeposition for high performance supercapacitors. J Mater Chem A 3:14445–14457. https://doi.org/10.1039/c5ta02920a

Çelik B, Çelik İ, Dolaş H, Görçay H, Şahin Y, Saraç AS, Pekmez K (2014) Electrochemical synthesis, characterization and capacitive properties of novel thiophene based conjugated polymer. React Funct Polym 83:107–112. https://doi.org/10.1016/j.reactfunctpolym.2014.07.014

Chen WC, Wen TC, Teng H (2003) Polyaniline-deposited porous carbon electrode for supercapacitor. Electrochim Acta 48:641–649

Chen GF, Su YZ, Kuang PY, Liu ZQ, Chen DY, Wu X, Li N, Qiao SZ (2015) Polypyrrole shell@3d-ni metal core structured electrodes for high-performance supercapacitors. Chem A Eur J 21:4614–4621. https://doi.org/10.1002/chem.201405976

Cheng Q, Tang J, Ma J, Zhang H, Shinya N, Qin LC (2011) Polyaniline-coated electro-etched carbon fiber cloth electrodes for supercapacitors. J Phys Chem C 115:23584–23590

Christinelli WA, Gonçalves R, Pereira EC (2016) A new generation of electrochemical supercapacitors based on layer-by-layer polymer films. J Power Sources 303:73–80. https://doi.org/10.1016/j.jpowsour.2015.10.077

Dyatkin B, Gogotsi O, Malinovskiy B, Zozulya Y, Simon P, Gogotsi Y (2016) High capacitance of coarse-grained carbide derived carbon electrodes. J Power Sources 306:32–41

Ermiş E, Yiğit D, Güllü M (2013) Synthesis of poly(n-alkyl-3,4-dihydrothieno[3,4-b][1,4]oxazine) derivatives and investigation of their supercapacitive performances for charge storage applications. Electrochim Acta 90:623–633. https://doi.org/10.1016/j.electacta.2012.12.052

Fonseca CP, Benedetti JE, Neves S (2006) Poly(3-methyl thiophene)/PVDF composite as an electrode for supercapacitors. J Power Sources 158:789–794. https://doi.org/10.1016/j.jpowsour.2005.08.050

Ge D, Yang L, Fan L, Zhang C, Xiao X, Gogotsi Y, Yang S (2015) Foldable supercapacitors from triple networks of macroporous cellulose fibers, single-walled carbon nanotubes and polyaniline nanoribbons. Nano Energy 11:568–578

González A, Goikolea E, Barrena JA, Mysyk R (2016) Review on supercapacitors: technologies and materials. Renew Sust Energ Rev 58:1189–1206

Gopalakrishnan K, Sultan S, Govindaraj A, Rao C (2015) Supercapacitors based on composites of pani with nanosheets of nitrogen-doped RGO, bc1. 5n, MoS2 and ws2. Nano Energy 12:52–58

Hao Q, Xia X, Lei W, Wang W, Qiu J (2015) Facile synthesis of sandwich-like polyaniline/boron-doped graphene nano hybrid for supercapacitors. Carbon 81:552–563

Hong X, Zhang B, Murphy E, Zou J, Kim F (2017) Three-dimensional reduced graphene oxide/polyaniline nanocomposite film prepared by diffusion driven layer-by-layer assembly for high-performance supercapacitors. J Power Sources 343:60–66

Hu CC, Li WY, Lin JY (2004) The capacitive characteristics of supercapacitors consisting of activated carbon fabric–polyaniline composites in nano3. J Power Sources 137:152–157
Hür E, Varol GA, Arslan A (2013) The study of polythiophene, poly(3-methylthiophene) and poly(3,4-ethylenedioxythiophene) on pencil graphite electrode as an electrode active material for supercapacitor applications. Synth Met 184:16–22. https://doi.org/10.1016/j.synthmet.2013.09.028
Hür E, Arslan A, Hür D (2016) Synthesis and electrochemical polymerization of a novel 2-(thiophen-2-yl)-4-(thiophen-2-ylmethylene)oxazol-5(4h)-one monomer for supercapacitor applications. React Funct Polym 99:35–41. https://doi.org/10.1016/j.reactfunctpolym.2015.12.001
Inagaki M, Konno H, Tanaike O (2010) Carbon materials for electrochemical capacitors. J Power Sources 195:7880–7903
Karthikeyan G, Sahoo S, Nayak GC, Das CK (2011) Investigations on doping of poly(3-methylthiophene) composites for supercapacitor applications. Macromol Res 20:351–357. https://doi.org/10.1007/s13233-012-0020-7
Kashani H, Chen L, Ito Y, Han J, Hirata A, Chen M (2016) Bicontinuous nanotubular graphene–polypyrrole hybrid for high performance flexible supercapacitors. Nano Energy 19:391–400. https://doi.org/10.1016/j.nanoen.2015.11.029
Kumar NA, Choi HJ, Bund A, Baek JB, Jeong YT (2012) Electrochemical supercapacitors based on a novel graphene/conjugated polymer composite system. J Mater Chem 22:12268. https://doi.org/10.1039/c2jm30701d
Li H, Wang J, Chu Q, Wang Z, Zhang F, Wang S (2009) Theoretical and experimental specific capacitance of polyaniline in sulfuric acid. J Power Sources 190:578–586
Li PF, Schon TB, Seferos DS (2015) Thiophene, selenophene, and tellurophene-based three-dimensional organic frameworks. Angew Chem Int Ed 54:9361–9366. https://doi.org/10.1002/anie.201503418
Li T, Zhu W, Shen R, Wang HY, Chen W, Hao SJ, Li Y, Gu ZG, Li Z (2018) Three-dimensional conductive porous organic polymers based on tetrahedral polythiophene for high-performance supercapacitors. New J Chem 42:6247–6255. https://doi.org/10.1039/c8nj00667a
Liu R, Lee SB (2008) MnO2/poly(3,4-ethylenedioxythiophene) coaxial nanowires by one-step coelectrodeposition for electrochemical energy storage. J Am Chem Soc 130:2942–2943. https://doi.org/10.1021/ja7112382
Liu DY, Reynolds JR (2010) Dioxythiophene-based polymer electrodes for supercapacitor modules. ACS Appl Mater Interfaces 2:3586–3593. https://doi.org/10.1021/am1007744
Liu R, Cho SI, Lee SB (2008) Poly(3,4-ethylenedioxythiophene) nanotubes as electrode materials for a high-powered supercapacitor. Nanotechnology 19:215710. https://doi.org/10.1088/0957-4484/19/21/215710
Liu Y, Zhou J, Tang J, Tang W (2015) Three-dimensional, chemically bonded polypyrrole/bacterial cellulose/graphene composites for high-performance supercapacitors. Chem Mater 27:7034–7041. https://doi.org/10.1021/acs.chemmater.5b03060
Lota K, Khomenko V, Frackowiak E (2004) Capacitance properties of poly (3, 4-ethylenedioxythiophene)/carbon nanotubes composites. J Phys Chem Solids 65:295–301
Luo J, Zhong W, Zou Y, Xiong C, Yang W (2016) Preparation of morphology-controllable polyaniline and polyaniline/graphene hydrogels for high performance binder-free supercapacitor electrodes. J Power Sources 319:73–81
Male U, Singu BS, Srinivasan P (2015) Aqueous, interfacial, and electrochemical polymerization pathways of aniline with thiophene: nano size materials for supercapacitor. J Appl Polym Sci 132:n/a–n/a. https://doi.org/10.1002/app.42013
Mastragostino M (2002) Conducting polymers as electrode materials in supercapacitors. Solid State Ionics 148:493–498. https://doi.org/10.1016/s0167-2738(02)00093-0
Mo D, Zhou W, Ma X, Xu J (2015) Facile electrochemical polymerization of 2-(thiophen-2-yl)furan and the enhanced capacitance properties of its polymer in acetonitrile electrolyte containing boron trifluoride diethyl etherate. Electrochim Acta 155:29–37. https://doi.org/10.1016/j.electacta.2014.12.110

Mondal S, Rana U, Malik S (2015) Graphene quantum dot-doped polyaniline nanofiber as high performance supercapacitor electrode materials. Chem Commun 51:12365–12368

Nyholm L, Nyström G, Mihranyan A, Strømme M (2011) Toward flexible polymer and paper-based energy storage devices. Adv Mater 23:3751–3769

Otero TF, Arias-Pardilla J, Herrera H, Segura JL, Seoane C (2011) Electropolymerization of naphthaleneamidinemonoimide-modified poly(thiophene). Phys Chem Chem Phys 13:16513. https://doi.org/10.1039/c1cp21837a

Pandey RK, Singh AK, Prakash R (2014) Directed self-assembly of poly(3,3'''-dialkylquarterthiophene) polymer thin film: effect of annealing temperature. J Phys Chemis C 118:22943–22951. https://doi.org/10.1021/jp507321z

Pan L, Qiu H, Dou C, Li Y, Pu L, Xu J, Shi Y (2010) Conducting polymer nanostructures: template synthesis and applications in energy storage. Int J Mol Sci 11:2636–2657

Pardieu E, Pronkin S, Dolci M, Dintzer T, Pichon BP, Begin D, Pham-Huu C, Schaaf P, Begin-Colin S, Boulmedais F (2015) Hybrid layer-by-layer composites based on a conducting polyelectrolyte and fe3o4 nanostructures grafted onto graphene for supercapacitor application. J Mater Chem A 3:22877–22885. https://doi.org/10.1039/c5ta05132k

Pasquier AD, Laforgue A, Simon P (2004) Li4ti5o12/poly(methyl)thiophene asymmetric hybrid electrochemical device. J Power Sources 125:95–102. https://doi.org/10.1016/j.jpowsour.2003.07.015

Patil BH, Patil SJ, Lokhande CD (2014) Electrochemical characterization of chemically synthesized polythiophene thin films: performance of asymmetric supercapacitor device. Electroanalysis 26:2023–2032. https://doi.org/10.1002/elan.201400284

Potphode DD, Mishra SP, Sivaraman P, Patri M (2017) Asymmetric supercapacitor devices based on dendritic conducting polymer and activated carbon. Electrochim Acta 230:29–38. https://doi.org/10.1016/j.electacta.2017.01.168

Roberts ME, Wheeler DR, McKenzie BB, Bunker BC (2009) High specific capacitance conducting polymer supercapacitor electrodes based on poly(tris(thiophenylphenyl)amine). J Mater Chemis 19:6977. https://doi.org/10.1039/b916666a

Salunkhe RR, Hsu SH, Wu KC, Yamauchi Y (2014) Large-scale synthesis of reduced graphene oxides with uniformly coated polyaniline for supercapacitor applications. ChemSusChem 7:1551–1556

Senthilkumar B, Thenamirtham P, Selvan RK (2011) Structural and electrochemical properties of polythiophene. Appl Surf Sci 257:9063–9067. https://doi.org/10.1016/j.apsusc.2011.05.100

Sharma S, Soni R, Kurungot S, Asha SK (2018) Naphthalene diimide copolymers by direct arylation polycondensation as highly stable supercapacitor electrode materials. Macromolecules 51:954–965. https://doi.org/10.1021/acs.macromol.7b02425

Shi Y, Peng L, Ding Y, Zhao Y, Yu G (2015) Nanostructured conductive polymers for advanced energy storage. Chem Soc Rev 44:6684–6696

Simon P, Gogotsi Y (2010) Materials for electrochemical capacitors. In: Rodgers P (ed) Nanoscience and technology: a collection of reviews from nature journals. World Scientific, Singapore, pp 320–329

Sivakkumar S, Kim WJ, Choi JA, MacFarlane DR, Forsyth M, Kim DW (2007) Electrochemical performance of polyaniline nanofibres and polyaniline/multi-walled carbon nanotube composite as an electrode material for aqueous redox supercapacitors. J Power Sources 171:1062–1068

Sivaraman P, bhattacharrya AR, Mishra SP, Thakur AP, Shashidhara K, Samui AB (2013) Asymmetric supercapacitor containing poly(3-methyl thiophene)-multiwalled carbon nanotubes nanocomposites and activated carbon. Electrochim Acta 94:182–191. https://doi.org/10.1016/j.electacta.2013.01.123

Snook GA, Kao P, Best AS (2011) Conducting-polymer-based supercapacitor devices and electrodes. J Power Sources 196:1–12

Song Y, Liu TY, Xu XX, Feng DY, Li Y, Liu XX (2015) Pushing the cycling stability limit of polypyrrole for supercapacitors. Adv Funct Mater 25:4626–4632. https://doi.org/10.1002/adfm.201501709

Suematsu S, Oura Y, Tsujimoto H, Kanno H, Naoi K (2000) Conducting polymer films of cross-linked structure and their qcm analysis. Electrochim Acta 45:3813–3821

Tang H, Wang J, Yin H, Zhao H, Wang D, Tang Z (2014) Growth of polypyrrole ultrathin films on MoS2monolayers as high-performance supercapacitor electrodes. Adv Mater 27:1117–1123. https://doi.org/10.1002/adma.201404622

Walton D (1990) Electrically conducting polymers. Mater Des 11:142–152

Wang YG, Li HQ, Xia YY (2006) Ordered whiskerlike polyaniline grown on the surface of mesoporous carbon and its electrochemical capacitance performance. Adv Mater 18:2619–2623

Wang G, Zhang L, Zhang J (2012a) A review of electrode materials for electrochemical supercapacitors. Chem Soc Rev 41:797–828

Wang YZ, Wang Q, Xie HY, Ho LP, Tan DMF, Diao YY, Chen W, Xie XN (2012b) Fabrication of highly ordered P3HT:PCBM nanostructures and its application as a supercapacitive electrode. Nanoscale 4:3725. https://doi.org/10.1039/c2nr30486d

Wang JG, Wei B, Kang F (2014) Facile synthesis of hierarchical conducting polypyrrole nanostructures via a reactive template of MnO2 and their application in supercapacitors. RSC Adv 4:199–202

Wang J, Wu Z, Hu K, Chen X, Yin H (2015a) High conductivity graphene-like mos2/polyaniline nanocomposites and its application in supercapacitor. J Alloys Compd 619:38–43

Wang S, Ma L, Gan M, Fu S, Dai W, Zhou T, Sun X, Wang H, Wang H (2015b) Free-standing 3D graphene/polyaniline composite film electrodes for high-performance supercapacitors. J Power Sources 299:347–355

Wang Q, Yan J, Fan Z (2016) Carbon materials for high volumetric performance supercapacitors: design, progress, challenges and opportunities. Energy Environ Sci 9:729–762

Wang N, Han G, Song H, Xiao Y, Li Y, Zhang Y, Wang H (2018) Integrated flexible supercapacitor based on poly (3, 4-ethylene dioxythiophene) deposited on au/porous polypropylene film/au. J Power Sources 395:228–236. https://doi.org/10.1016/j.jpowsour.2018.05.074

Wen L, Li K, Liu J, Huang Y, Bu F, Zhao B, Xu Y (2017) Graphene/polyaniline@ carbon cloth composite as a high-performance flexible supercapacitor electrode prepared by a one-step electrochemical co-deposition method. RSC Adv 7:7688–7693

Wu G, Tan P, Wang D, Li Z, Peng L, Hu Y, Wang C, Zhu W, Chen S, Chen W (2017a) High-performance supercapacitors based on electrochemical-induced vertical-aligned carbon nanotubes and polyaniline nanocomposite electrodes. Sci Rep 7:43676

Wu ZS, Zheng Y, Zheng S, Wang S, Sun C, Parvez K, Ikeda T, Bao X, Müllen K, Feng X (2017b) Supercapacitors: stacked-layer heterostructure films of 2D thiophene nanosheets and graphene for high-rate all-solid-state pseudocapacitors with enhanced volumetric capacitance (adv. mater. 3/2017). Adv Mater 29. https://doi.org/10.1002/adma.201770020

Xia C, Chen W, Wang X, Hedhili MN, Wei N, Alshareef HN (2015) Highly stable supercapacitors with conducting polymer core-shell electrodes for energy storage applications. Adv Energy Mater 5:1401805

Xie Y, Xia C, Du H, Wang W (2015) Enhanced electrochemical performance of polyaniline/carbon/titanium nitride nanowire array for flexible supercapacitor. J Power Sources 286:561–570

Xu J, Wang K, Zu SZ, Han BH, Wei Z (2010) Hierarchical nanocomposites of polyaniline nanowire arrays on graphene oxide sheets with synergistic effect for energy storage. ACS Nano 4:5019–5026

Xu J, Wang D, Fan L, Yuan Y, Wei W, Liu R, Gu S, Xu W (2015a) Fabric electrodes coated with polypyrrole nanorods for flexible supercapacitor application prepared via a reactive self-degraded template. Org Electron 26:292–299

Xu J, Wang D, Yuan Y, Wei W, Duan L, Wang L, Bao H, Xu W (2015b) Polypyrrole/reduced graphene oxide coated fabric electrodes for supercapacitor application. Org Electron 24:153–159. https://doi.org/10.1016/j.orgel.2015.05.037

Yan J, Wang Q, Wei T, Fan Z (2014) Recent advances in design and fabrication of electrochemical supercapacitors with high energy densities. Adv Energy Mater 4:1300816

Yang C, Wei H, Guan L, Guo J, Wang Y, Yan X, Zhang X, Wei S, Guo Z (2015) Polymer nanocomposites for energy storage, energy saving, and anticorrosion. J Mater Chem A 3:14929–14941
Ye Z, Li T, Ma G, Peng X, Zhao J (2017) Morphology controlled MnO2 electrodeposited on carbon fiber paper for high-performance supercapacitors. J Power Sources 351:51–57
Yin Z, Zheng Q (2012) Controlled synthesis and energy applications of one-dimensional conducting polymer nanostructures: an overview. Adv Energy Mater 2:179–218
Yiğit D, Güngör T, Güllü M (2013) Poly(thieno[3,4-b][1,4]dioxine) and poly([1,4]dioxino[2,3-c]pyrrole) derivatives: p- and n-dopable redox-active electrode materials for solid state supercapacitor applications. Org Electron 14:3249–3259. https://doi.org/10.1016/j.orgel.2013.09.037
Yue B, Wang C, Wagner P, Yang Y, Ding X, Officer DL, Wallace GG (2012) Electrodeposition of pyrrole and 3-(4-tert-butylphenyl)thiophene copolymer for supercapacitor applications. Synth Met 162:2216–2221. https://doi.org/10.1016/j.synthmet.2012.09.024
Yu P, Li Y, Yu X, Zhao X, Wu L, Zhang Q (2013) Polyaniline nanowire arrays aligned on nitrogen-doped carbon fabric for high-performance flexible supercapacitors. Langmuir 29:12051–12058
Yu P, Li Y, Zhao X, Wu L, Zhang Q (2014) Graphene-wrapped polyaniline nanowire arrays on nitrogen-doped carbon fabric as novel flexible hybrid electrode materials for high-performance supercapacitor. Langmuir 30:5306–5313
Yu M, Ma Y, Liu J, Li S (2015) Polyaniline nanocone arrays synthesized on three-dimensional graphene network by electrodeposition for supercapacitor electrodes. Carbon 87:98–105
Zhang LL, Zhao X (2009) Carbon-based materials as supercapacitor electrodes. Chem Soc Rev 38:2520–2531
Zhang J, Kong LB, Li H, Luo YC, Kang L (2010) Synthesis of polypyrrole film by pulse galvanostatic method and its application as supercapacitor electrode materials. J Mater Sci 45:1947–1954. https://doi.org/10.1007/s10853-009-4186-0
Zhang H, Hu Z, Li M, Hu L, Jiao S (2014) A high-performance supercapacitor based on a polythiophene/multiwalled carbon nanotube composite by electropolymerization in an ionic liquid microemulsion. J Mater Chem A 2:17024–17030. https://doi.org/10.1039/c4ta03369h
Zhang H, Zhang Y, Gu C, Ma Y (2015) Electropolymerized conjugated microporous poly(zinc-porphyrin) films as potential electrode materials in supercapacitors. Adv Energy Mater 5:1402175. https://doi.org/10.1002/aenm.201402175
Zhang L, Huang D, Hu N, Yang C, Li M, Wei H, Yang Z, Su Y, Zhang Y (2017) Three-dimensional structures of graphene/polyaniline hybrid films constructed by steamed water for high-performance supercapacitors. J Power Sources 342:1–8
Zhu J, Sun W, Yang D, Zhang Y, Hoon HH, Zhang H, Yan Q (2015) Multifunctional architectures constructing of pani nanoneedle arrays on MoS2 thin nanosheets for high-energy supercapacitors. Small 11:4123–4129

Chapter 13
Spatial Variability of Reasonable Government Rebates for Rainwater Tank Installation: A Case Study for Adelaide, Australia

Upendra R. Paudel and Monzur A. Imteaz

Abstract Rainwater harvesting is a sustainable alternative water source in urban and suburban areas. So government authorities are encouraging the households to install rainwater tank in their premises by providing the subsidies. However, with increasing demand and financial constraint many government authorities are struggling to maintain such subsidy. As such, a prudent and optimum government rebate needs to be derived. This chapter presents the spatial variability of reasonable government rebates for rainwater tanks installations with a case study for an Australian coastal city, Adelaide. It is shown that significant variations among the regions are expected in regards to rainwater savings, even with the same tank size, same roof connection and same rainwater demand. Providing a double-sized tank and double-sized roof is likely to increase the savings only up to 1.19 times and 1.78 times respectively. It is found that the payback periods of total rainwater tank related costs widely vary depending on region, tank, roof and demand scenario; a variation from 15 to 79 years without government rebate is expected. However, with reasonable government rebates these payback periods can be brought down to 8 years. To optimise government's spending a variable rebate scheme can be introduced based on the current findings.

Keywords Rainwater tank · Water balance · Water savings · Spatial variability · Cost analysis

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13.1 Introduction

13.1.1 Background

Rainwater is popular alternative water source in Australia. The use of domestic rainwater harvesting in Australia has a long history that commenced with early white settlement (Coombes 2006). According to Australian Bureau of Statistics (ABS), around 2.3 million households in Australia are using rainwater as an alternative source. To promote the rainwater harvesting system in urban and suburban areas, government authorities are providing incentives to the eligible households. In 2009, Australian Federal Government has introduced a rebate scheme under the Water for Future Initiative (WFI) to help residents to install rainwater harvesting systems for non-potable purpose which was ended in June 2011. Out of total \$7 million rebate, 55% of the rebates were provided in New South Wales, 13.7% in Victoria, 18.2% in South Australia and 0.3% was offered in Tasmania (Chubaka et al. 2018). City of Adelaide is currently giving \$500 incentives to the households installing minimum 2 kL rainwater tank plumbed into at minimum of a toilet or hot water service or washing machine. But for apartment, office and education buildings, city of Adelaide is providing a rebate of \$0.25 per litre of storage capacity up to a maximum of \$3000 if the rainwater is used for communal internal purpose. Despite these several campaigns and incentives, in general a positive willingness towards the widespread installations of rainwater tanks is often missing, mainly due to lack of convincing information/understanding of effectiveness of any proposed on-site stormwater harvesting system from end-users' side (Imteaz et al. 2011). Further confusions and uncertainties arise among the end-users due to inter-annual variations of water-savings due to climatic conditions, which is often very significant for Australian cities (Imteaz et al. 2013).

13.1.2 Research Related to Cost Analysis

Most of the studies on rainwater tank dealt with the potential water savings, however from end-users' point of view 'cost effectiveness' is the prime concern, which not only depends on potential water savings, but also on water price, tank installation and maintenance costs. For remote areas without having any centralized water supply system, residents are bound to use rainwater to augment their water demands. However, for urban areas where centralized water supply exists, installation of rainwater tanks may not always turn out to be cost-effective. Implementation of rainwater tank will be cost-effective for cities having relatively moderate to high rainfalls and where water price is relatively high considering a several years of design life. Whereas, if the water price is comparatively lower, as it is the case for many cities, implementation of rainwater tank may not turn out to be cost-effective even considering a longer design life (i.e. 25 years). Tam et al. (2010) studied cost effectiveness of installing rainwater tank as compared to the use of other water sources (i.e. water from dams, desalination, purchase irrigation water, groundwater, and non-potable water recycling) for seven Australian cities. In order to do so, various costs were computed including installation and maintenance costs, and compared with unit costs from other sources. The average costs of using rainwater tank and monetary savings in compared to other sources were then calculated for combinations of outdoor plus indoor or sole outdoor uses only. It was found that between the two studied uses, sole outdoor use turned out to be more beneficial compared to 'outdoor plus indoor' use. They have reported that with the sole outdoor use, annual costs savings (compared to other water sources) depending on roof and tank sizes are \$83~\$240 for Gold Coast, \$65~\$181 for Sydney and \$0~\$36 for Brisbane. However, surprisingly for other studied cities (Melbourne, Adelaide, Perth and Canberra) for any reasonable combination of roof and tank sizes, annual cost savings are negative. Khastagir and Jayasuriya (2011) have presented cost analysis through calculating payback periods of rainwater tanks situated in Melbourne, Australia. They found that the cost of accessories alone contributed almost half of the cost of rainwater harvesting system if it is connected with toilet, laundry and irrigation. It was found that payback periods ranged from 14 to 40 years depending upon tank size, discount rate, inflation rate and rainfall characteristics of different areas across Melbourne. A 14 years' payback period can be achieved with a 5 kL tank size for area having annual rainfall about 1000 mm. Whereas, the payback period can be as high as 40 years with a tank of 1 kL in an area having low annual rainfall (454 mm).

Ghisi and Schondermark (2013) studied investment feasibility of rainwater harvesting system for five towns in Brazil. Through using average historical year rainfall data, they have calculated discounted payback periods for all the five regions. It was found that payback periods less than 10 years are achievable with a smaller roof connection (90 m^2); even a lowest payback period of 2 years can be achieved for a tank size of 3–4 m^3. However, the payback periods can be more than 10 years, for bigger roof connections (150~300 m^2) with larger tank sizes but lower demand. Matos et al. (2015) calculated payback period of highly effective rainwater harvesting system for a large commercial building located in Portugal. Three different scenarios with the variations in tank size, rainfall and demand were tested for the same building, and then annual water savings and financial benefits were computed. It was found that with a discount/interest rate of 10% depending on tank size and connected roof area, payback periods of 2–6 years can be achieved; with a lower discount/interest rate payback periods will be further reduced. However, for single residential rainwater tank, where space for the bigger tank is an issue, in most cases the payback period turns out to be very high.

13.1.3 Research Gaps

As mentioned earlier government authorities are giving incentives to implement rainwater system in their dwellings. But with the global financial crisis, many countries/governments are struggling to continue/introduce such rebate for a longer period. If provided, offered incentives are not sufficient in terms of investment cost.

Studies carried out by Imteaz et al. (2013, 2015, 2017) found significant variations of potential water savings and reliabilities within large cities Sydney, Melbourne and Adelaide. So, reasonable rebate amount within the city is often debatable. This paper presents evaluation of reasonable rainwater tank rebates, which would be attractive to the residents. Also, as potential water savings are expected to vary within a large city, this paper summarizes reasonable variations of such government rebate with a case study for Adelaide metropolitan area in Australia.

13.2 Methodology

Potential annual water savings for a particular scenario is calculated for payback period analysis. Daily water balance model "eTank" developed by Imteaz et al. (2011) was used for calculation of expected annual savings. Daily rainfalls data, roof area, daily water demand and tank size are the major input variables in this model. In this analysis, 5 years daily rainfall data for each dry, average and wet year climatic conditions were selected. So, altogether 15 years annual savings value for each selected region were calculated for different combinations of tank sizes (5 kL and 10 kL), daily water demands (300 L and 500 L) and roof areas (100–400 m^2) and average of these 15 years annual savings values were used in the calculation of payback period. To minimize the effect of unusual rainfall pattern (sporadic burst and/or longer dry periods) compare to usual pattern of occurrences, this study has used 5 years data for each climatic condition to represent an average year.

Average annual water savings were converted to annual monetary savings through multiplying the water savings values with the unit cost charged by the South Australian water authority (SA Water). Then net present value of future water savings were calculated by using the following formula:

$$PV = S_t/(1+i)^t, \tag{13.1}$$

where i is the discount rate, PV is the present value of a particular savings in a year t, S_t is the savings in a year t. Discount rate of 3% is used in this study as it reflects the risk free rate of return which is based on govenernment bond rate (Hall 2013).

Total costs for 5 kL and 10 kL tank sizes, including the maintenance cost were evaluated; then payback period for a particular scenario was calculated using accumulated monetary savings and total installation & maintenance costs over the years. Payback period of a particular installation is the number of years (since installation) when accumulated water savings value is equal to or higher than accumulated costs.

13.3 Study Area and Data

Australian coastal city Adelaide has been selected for the assessment of spatial variations of reasonable government rebate within its boundaries. Adelaide, which is the capital city of South Australia, has Mediterranean climate usually hot dry summers and cold winters. Annual average rainfall of Adelaide is approximately 585 mm and the population is around 1.26 million (www.abs.gov.au).

Rain water harvesting system is very popular in Adelaide. In Adelaide, 44% of households have a rainwater tank installed at their dwelling (ABS 2013). This number is going to increase as government is requiring rainwater to be plumbed in the newly constructed households.

On the basis of availability of data and its location/direction, four rainfall stations covering the Adelaide city were selected for this study. Map of Adelaide City with selected rainfall stations are shown in Fig. 13.1. Precipitation data used were downloaded from the Bureau of Meteorology (www.bom.gov.au). Details of the selected rainfall stations and its mean annual precipitation are shown in Table 13.1. Rainwater tank installation and maintenance cost details were taken from Urban Water Security Research Alliance website, Bunning's Warehouse and Adelaide's local rainwater tank manufactures. Details of installation and maintenance cost of 5 kL and 10 kL tank are shown in Table 13.2.

Fig. 13.1 Map of Adelaide metropolitan area with selected rainfall stations

Table 13.1 Selected rainfall stations and years of Adelaide city

	Rainfall stations	Data period	Mean annual precipitation (mm)	Direction	Remarks
1	Adelaide airport	1956–2012	442	Western	9 km from Kent town
2	Happy valley reservoir	1892–2015	635	Southern	18 km from Kent town
3	Kent town	1978–2015	550	Central	–
4	Edinburgh RAAF	1973–2012	430	Northern	24 km from Kent town

Table 13.2 Rainwater tank installation cost based on Adelaide market

Items	5kL tank	10kL tank
Storage tank cost	$1000	$1600
Plumbing & installation cost	$1600	$2100
Electric Pump	$700	$700
Pump Installation	$200	$200
Total Investment	$3500	$4600

13.4 Results

13.4.1 Spatial Variations of Potential Water Savings

eTank was used to evaluate the spatial variability of potential water savings in northern, southern, eastern and central regions of Adelaide city as in Table 13.1. Figs. 13.2, 13.3, 13.4 and 13.5 show the comparison of potential annul water savings among these four regions for daily water demand 400 L, tank sizes 2.5 kL, 5 kL, 7.5 kL and 10 kL and roof areas ranging from 100 m^2 to 400 m^2.

These figures clearly depict that there are substantial variations of water saving exists among different regions of Adelaide city. It can be seen that Kent Town which is centrally located has highest potential of water savings whereas Happy Valley Reservoir which is located in the southern region has lowest potential of water savings for higher roof area condition ($\geq$300 m^2) and bigger tank sizes (5 kL, 7.5 kL and 10 kL).

This expected difference in water savings in central and southern region is about 9.09 kL-18.48 kL depending upon the tank size and roof areas. But for lower roof area input (<200 m^2), Happy Valley Reservoir has highest potentials and Edinburgh RAAF which is in the Northern regions has lowest potentials of water savings. The expected difference of water savings between these two regions was ranging from 10.21 kL to 25.17 kL depending upon the roof areas and tank size.

It is to be noted that Happy Valley Reservoir receives highest amount of rainfall 635 mm among the selected regions followed by Kent Town 550 mm, Adelaide Airport has 442 mm and Edinburgh RAAF receives the least amount of rainfall which is 430 mm. Interesting findings here is that even Happy Valley Reservoir has the highest rainfall among the selected regions, its water savings potential is not highest in all scenarios. Its water savings potential is much lower than other regions for bigger roof areas ($\geq$ 300 m^2) situation.

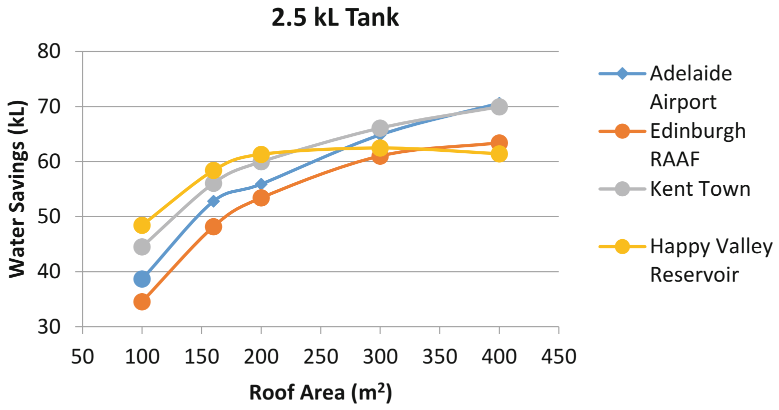

Fig. 13.2 Annual water savings vs Roof area for 2.5 kL tank and 400 L water demand

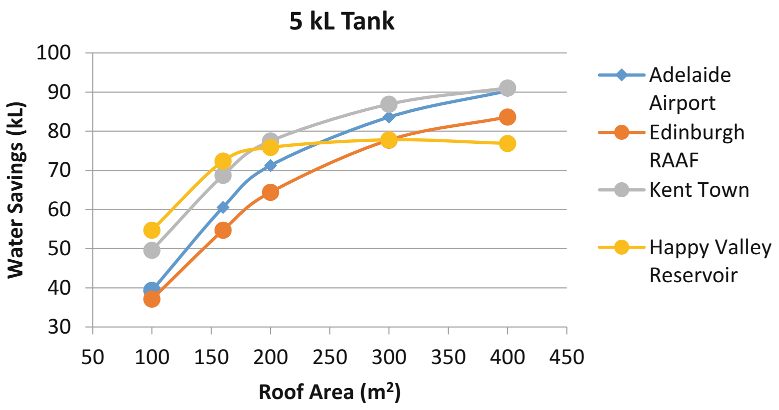

Fig. 13.3 Annual water savings vs Roof area for 5 kL tank and 400 L water demand

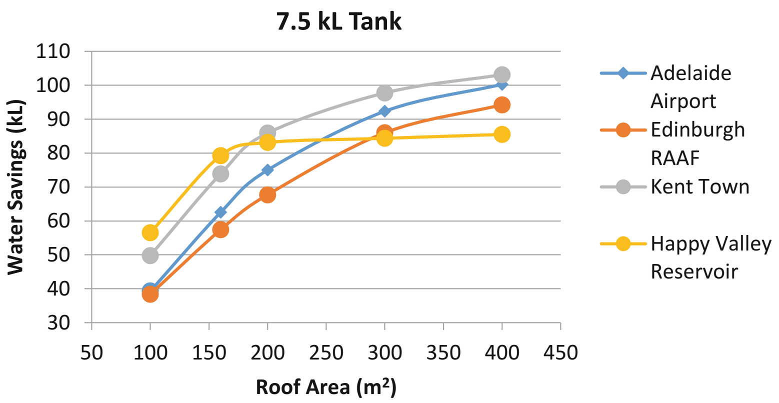

Fig. 13.4 Annual water savings vs Roof area for 7.5 kL tank and 400 L water demand

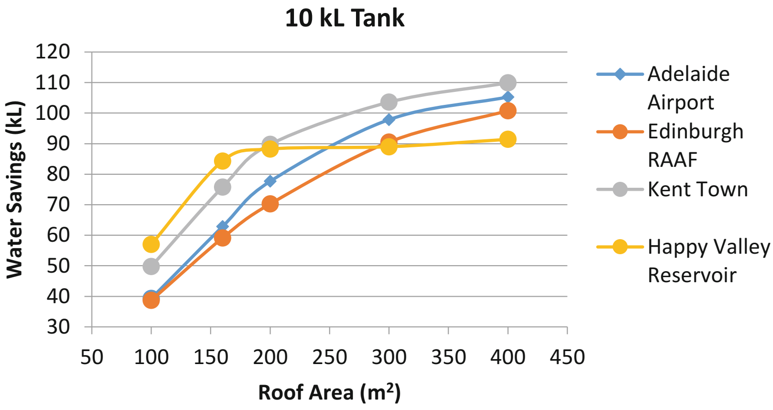

Fig. 13.5 Annual water savings vs Roof area for 10 kL tank and 400 L water demand

Table 13.3 Ratios of annual water savings to average annual rainfalls in different regions of Adelaide for a roof area of 150 m^2 and daily water demand of 300 L

Tank size (kL)	Adelaide airport	Happy valley reservoir	Kent town	Edinburgh RAAF
5	121.81	97.12	109.20	117.89
10	131.90	111.17	119.50	128.56

Table 13.4 Ratios of annual water savings to average annual rainfalls in different regions of Adelaide for a tank size of 10 kL and daily water demand of 500 L

Roof area (m^2)	Adelaide airport	Happy valley reservoir	Kent town	Edinburgh RAAF
150	134.11	131.09	131.87	131.02
300	233.03	173.86	209.95	233.20

Table 13.3 shows the ratios of annual water savings potentials (in kL) to annual rainfall amounts (in m) of all the studied regions for a roof area of 150 m^2 with a daily rainwater demand of 300 L for two tank sizes (5 kL and 10 kL). Although, as a broad theoretical concept these ratios are expected to be same under similar conditions (roof area, tank size and demand), in reality ratios are varying from 97.12 to 121.81 for a 5 kL tank and from 111.17 to 131.9 for a 10 kL tank. Also, in regards to effect of tank size, it can be concluded that although someone may expect to save double amount of water using a double-sized tank (i.e. 10 kL, instead of 5 kL), in reality with such double-sized tank increase in water savings would be approximately 1.03–1.19 times.

Similarly, Table 13.4 shows the ratios of annual water savings potentials (in kL) to annual rainfall amounts (in m) of all the studied regions with a tank size of 10 kL and a daily rainwater demand of 500 L for two roof sizes (150 m^2 and 300 m^2). Again, in regards to effect of roof size, it can be concluded that although someone may expect to save double amount of water using a double-sized roof (i.e. 300 m^2, instead of 150 m^2), in reality with such double-sized roof increase in water savings would be approximately 1.10–1.78 times.

Interesting findings from these tables are that even though Edinburgh RAAF's annual rainfall amount is lowest among all the studied regions, its water savings efficiency (compared to the total rainfall received) is second highest and on the other hand although Happy Valley Reservoir is having highest (among the studied regions) annual rainfall, its water savings efficiency (compared to the total rainfall received) is the lowest. The reason for lower savings with higher rainfalls is the rainfall pattern and subsequent tank overflow loss, which happens when there are significant rains in consecutive days or big burst of rain in a day.

13.4.2 Cost Analysis

In this cost analysis, Payback periods of total installation and maintenance costs of two normally used tank sizes (5 kL and 10 kL) were calculated. Repayment of the investment cost depends on annual water savings which will vary according to the tank size, roof area and daily water demand. As such, combination two tank sizes (5 kL and 10 kL) with daily water demand of 300 L and 500 L and three roof sizes (100, 200 & 300 m^2) were considered.

Tables 13.5, 13.6, 13.7 and 13.8 show the calculated payback periods under different scenarios for all the selected regions. As mentioned earlier, in many cases payback period without government rebate may not turn out to be attractive for the end-users, tables also show required government rebates to achieve a payback period of 8 years, which is considered to be lucrative/acceptable for the end-users.

From the tables, it is evident that without government rebate with a smaller roof area (100 m^2) payback periods for all the regions are not really attractive. Payback periods for Edinburgh RAAF (having lowest water savings potential) vary from 64

Table 13.5 Annual water savings, payback period and suggested government rebate for Adelaide airport

Adelaide airport							
		Tank Size = 5			Tank Size = 10		
Roof area (m^2)	Demand (L)	Annual savings (kL)	Payback period (yrs)	Reasonable govt rebate ($)	Annual savings (kL)	Payback period (yrs)	Reasonable govt rebate ($)
100	300	39	64	3378	39.7	75	4487
200	300	62	32	2782	71	33	3628
300	300	68.1	28	2654	78.7	28	3329
100	500	39.5	63	3380	39.7	75	4487
200	500	71.7	26	2571	77.7	29	3442
300	500	86.6	19	2040	103	19	2616

Table 13.6 Annual water savings, payback period and suggested government rebate for happy valley reservoir

Happy valley reservoir							
		Tank Size = 5			Tank Size = 10		
Roof area (m^2)	Demand (L)	Annual savings (kL)	Payback period (yrs)	Reasonable govt rebate ($)	Annual savings (kL)	Payback period (yrs)	Reasonable govt rebate ($)
100	300	52.9	41	3053	56.6	46	4064
200	300	65.6	29	2633	74.3	31	3550
300	300	67.6	28	2622	77.9	29	3455
100	500	55.8	37	2881	57.1	45	3996
200	500	85.6	20	2195	99.9	20	2744
300	500	95	17	1897	110.4	18	2608

Table 13.7 Annual water savings, payback period and suggested government rebate for Kent town

Kent town							
		Tank size = 5			Tank size = 10		
Roof area (m^2)	Demand (L)	Annual savings (kL)	Payback period (yrs)	Reasonable govt rebate ($)	Annual savings (kL)	Payback period (yrs)	Reasonable govt rebate ($)
100	300	34.2	78	3576	46.5	58	4268
200	300	70.3	26	2491	78.2	29	3474
300	300	78.9	22	2283	85.8	25	3178
100	500	49.8	45	3147	48.6	57	4278
200	500	84.1	20	2140	90.0	23	2986
300	500	102.2	15	1641	115.5	17	2509

Table 13.8 Annual water savings, payback period and suggested government rebate for Edinburgh RAAF

Edinburgh RAAF							
		Tank size = 5			Tank size = 10		
Roof area (m^2)	Demand (L)	Annual savings (kL)	Payback period (yrs)	Reasonable govt rebate ($)	Annual savings (kL)	Payback period (yrs)	Reasonable govt rebate ($)
100	300	36.9	70	3487	34.7	79	4422
200	300	62.8	31	2712	68.3	34	3565
300	300	75.3	24	2445	89.2	26	3232
100	500	39.2	64	3410	38.1	78	4426
200	500	68.6	27	2541	74.2	31	3484
300	500	90.4	18	1968	100.3	20	2758

to 79 years, whereas payback periods for Kent Town (having highest water savings potential) vary from 45 to 78 years.

Even with a large roof area (300 m^2), payback periods for Kent Town vary from 15 to 25 years and for Edinburgh RAAF vary from 18 to 26 years, none of which are really attractive to the end-users.

From the tables it is also found that with some reasonable government rebates, payback period of expenses from the end-users can be brought down to 8 years for all the options. For Kent town, with larger roof (300 m^2) area connection, a payback period of 8 years can be achieved with rebate of $1641 for a 5 kL tank and $2509 for a 10 kL tank. For Edinburgh RAAF, under same scenario to achieve the same payback period it would require a rebate of $1968 for a 5 kL tank and $2758 for a 10 kL tank. Variations of the optimum Government rebate for Adelaide City is shown in Fig. 13.6.

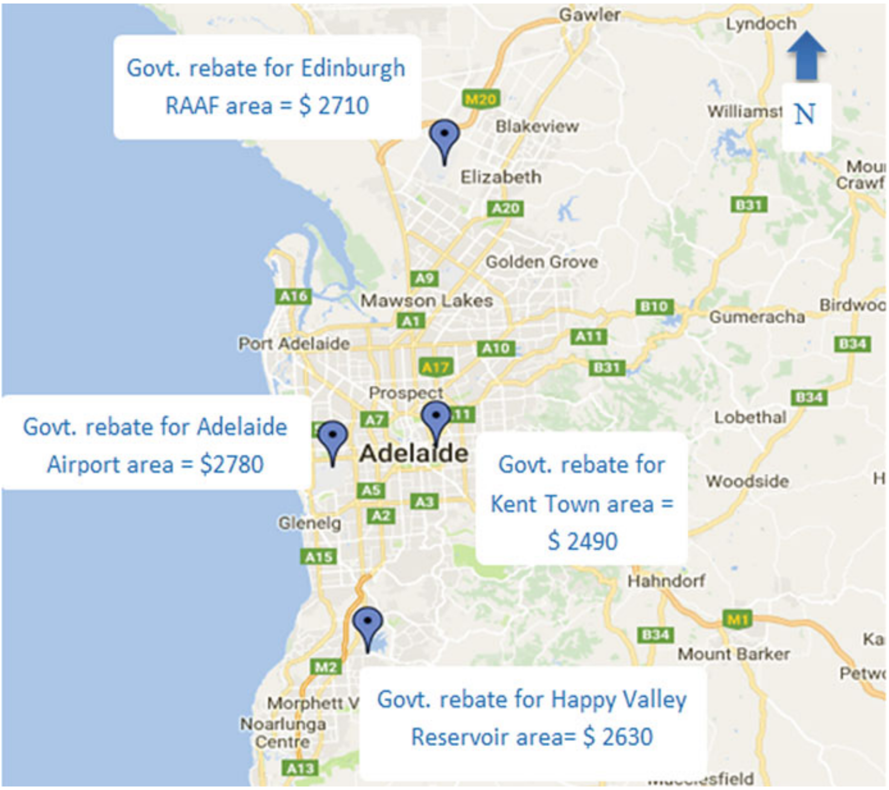

Fig. 13.6 Reasonable government rebates for different regions of Adelaide metropolitan

13.5 Conclusions

Findings from the previous section showed that spatial variation of potential rainwater savings is significant within the different regions of Adelaide city. Households having same roof area, tank size and water demand within the selected regions: a difference of 25.70 kL in annual water savings can be expected. Annual water savings not only depends on the amount of annual rainfall, rather it also depends on rainfall distribution as well as roof area, tank size and water demand. Rainwater savings efficiencies, which is the ratio of potential water savings to annual rainfall amount for a particular locality, are also found varying significantly within the regions. In general, these ratios are expected to be the same. Water savings efficiencies variation is primarily due to the pattern/distribution of rainfall within a year. During the continuous rainy day or day having big burst of rainfall, overflow loss from the tank will be huge. Even an area having high annual rainfall amount will not provide high rainwater savings because of overflow loss. From the outcomes of this study it can be seen that regions having lower precipitation not necessarily rendering lower amount of water savings.

Another interesting finding is that for few common scenarios it is found that through providing a double-sized tank, rainwater savings can be increased only 1.03~1.19 times and similarly through providing double-sized roof, rainwater savings can be increased only 1.10~1.78 times. From the above-mentioned findings, it can be concluded that in regards to maximizing rainwater savings, increasing roof area is more effective than increasing tank volume.

Furthermore, payback periods for the tank installation and maintenance cost were found quite high. Depending upon the roof area, tank size, demand and selected regions, payback periods were found varies from 15 to 79 years without any government rebate. Edinburgh RAAF, having lowest rainwater savings potential (for roof area $\leq$ 300 m^2), payback periods vary 64~79 years, 27~34 years and 18~26 years for roof area of 100, 200 and 300 m^2 respectively. However, for Kent Town, having highest rainwater savings potential, payback periods vary 45~78 years, 20~29 years and 15~25 years for roof area of 100, 200 and 300 m^2 respectively. From these data it can be concluded that the payback periods of rainwater tank will not be really worthy unless a reasonable government rebate is given to achieve a wider implementations of rainwater tanks. For the optimization of government's monetary support, they can implement such different rebates depending on the region as discussed in the previous section.

References

Australian Bureau of Statistics (2013) Environmental Issues: Water use and Conservation. https://doi.org/10.1155/2018/6471324. Accessed on 21 may 2018

Chubaka CE, Whiley H, Edwards JW, Ross KE (2018) A review of roof harvested rainwater in Australia. J Environ Public Health. https://doi.org/10.1155/2018/6471324

Coombes P (2006) Guidance on the use of rainwater harvesting systems, 3 May 2006
Ghisi E, Schondermark PN (2013) Investment feasibility analysis of rainwater use in residences. Water Resour Manag 27:2555–2576
Hall MR (2013) Review of rainwater tank cost-effectiveness in South East Queensland, urban water security research alliance technical report no. 105 (2nd Edition)
Imteaz MA, Paudel U, Ahsan A, Santos C (2015) Climatic and spatial variability of potential rainwater savings for a large coastal city. Resour Conserv Recycl 105:143–147
Imteaz MA, Karki R, Shamseldin A, Matos C (2017) eTank and contemporary online tools for rainwater tank outcomes analysis. Int J Comp Aided Eng Technol 9:372–384
Imteaz MA, Ahsan A, Shanableh A (2013) Reliability analysis of rainwater tanks using daily water balance model: variations within a large city. Resour Conserv Recycl 77:37–43
Imteaz MA, Shanableh A, Rahman A, Ahsan A (2011) Optimisation of rainwater tank design from large roofs: a case study in Melbourne, Australia. Resour Conserv Recycl 55:1022–1029
Khastagir A, Jayasuriya N (2011) Investment evaluation of rainwater tanks. Water Resour Manag 25:3769–3784
Matos C, Bentes I, Santos C, Imteaz M, Pereira S (2015) Economic analysis of a rainwater harvesting system in a commercial building. Water Resour Manag 29:3971–3986
Tam VW, Tam L, Zeng S (2010) Cost effectiveness and tradeoff on the use of rainwater tank: An empirical study in Australian residential decision-making. Resour Conserv Recycl 54:178–186

Chapter 14
Strategic Planning of Socio-Economic Development in Russian Regions on the Basis of Sustainability Principles

Roman V. Shekhovtsov, Nikolay A. Dimitriadi, and Marina A. Ponomareva

Abstract Incorporating principles of sustainable development in long-term socio-economic planning at regional and municipal levels requires novel methodology and its supporting tools. In the chapter, the best practices of strategic planning of sustainable initiatives have been investigated based on the thorough analysis of the dynamics of sustainability indicators, major stakeholders, and organizations involved in the process. The approaches supporting sustainable planning and corresponding tools have been identified using planning activities in a large industrial and agricultural area – the Rostov region. As a result, the recommendations on strategic planning supporting sustainability at the local and regional levels are formulated. These recommendations can be useful for strategic planning in other regions with similar socio-economic characteristics.

Keywords Sustainable development · Strategic planning · Socio-economic development · Region · Rostov region · Rostov-On-Don

14.1 Introduction

The concept of sustainable development in its classical interpretation is defined as "development that meets the needs of the present [generations] without compromising the ability of future generations to meet their own needs". This model allowed to perceive social and ecological imperatives at a new qualitative level having considered intergenerational problems and interlinked ecological, economic and social priorities of social development (Khaiter and Erechtchoukova 2009, 2010, 2018). This idea demanded the leading world countries to combine their efforts in raising the role of natural and human capital in the controlling of sustainable development

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of the national and regional socio-economic development and making up effective economic mechanisms of transition to the trajectory of sustainable development. As the experience of developed countries shows, socio-economic policy built on the bases of sustainability leads to substantial positive results in reducing of social stratification caused by income level, poverty problem eradication, raising the local opportunities in forming conditions for human potential realization and improving environmental condition.

At the same time, understanding of the instruments and methods of practical realization of sustainability principles can be substantially different in different countries and regions. It is determined by several factors reflecting in specific features of governmental regulation of socio-economic development in a particular country, by existing institutional conditions, general macroeconomic situation and governmental opportunities in conducting specific reforms, and the allocation of funds for their implementation.

Some of the contemporary research is aimed at clarifying the situation with sustainable development goals – either in general or in certain countries. Some papers are devoted to examining an interaction between different sustainable development goals in Coastal Bangladesh (Hutton et al. 2018), combining the development of a foresight approach with Sustainable Development Goals (SDGs) (Kuribayashi et al. 2018), developing a composite baseline indicator of the agriculture-related SDGs in Southern Africa (Nhemachena et al. 2018], developing indicators for monitoring of implementation and digitalization of SDGs in Russia (Bobylev et al. 2018). At the same time, some authors (e.g. Zimm et al. 2018) suggest reducing a level of complexity of SDGs.

A question on acceleration of sustainable development is still pretty urgent (Baral et al. 2017). Some authors discuss a role of contemporary companies as drivers of sustainable development (Gazzola et al. 2018), and a role of the entrepreneurial activity to simultaneously enhance economic growth, advance environmental objectives, and improve social conditions in developing countries (Dhahri and Omri 2018).

Efforts directed at finding and creating of the usable knowledge for sustainable development are very important (Clark et al. 2016). Some authors (e.g. Vargas-Hernández et al. 2018) discuss a new paradigm of sustainable development related to bio-economy.

At the same time, the specialists are trying to find a real basis for sustainable development of different countries, for example, by analyzing a possible role of metal recycling in Nigeria sustainable development (Ojonimi et al. 2018) or developing a framework permitting to compare industries in terms of their sustainable development potential (Du Plessis and Bam 2018).

In the Russian Federation and in its regions, much attention is given to the principles of socio-economic sustainability realization. Sustainable development and human development are the main basic concepts for developing most of strategic documents at the federal, regional and municipal levels. Within the framework of socio-economic development, strategies worked out by different medium-term programs in social and ecological spheres are realized and they are aimed at the solving of the most urgent social and ecological territorial problems. At the same time, it's necessary to note that despite declared aims and tasks in the area of sustainable development in regional strategies, often social and ecological problems are considered isolated from economic ones and related tasks are solved mostly by means of costly methods supplied by budgets of the different levels. The connection between social, economic and ecological indicators is rarely seen, and in general, at present, the indicator system of sustainable development allowing to track the effectiveness of steps being taken in the given sphere hasn't been formed, either at the federal or at the regional levels. This obstructs the assessment of how close or far one or other regions have advanced in solving the task of transition to sustainable development.

The Rostov region, as one of the most developed industrial and agricultural centers in the south of Russia, during the transition economy faced the range of transformations that negatively affected the sustainability of economic system of the region. Presently, the process of strategic planning is mainly based on the concept of sustainable development. There are attempts to develop strategic documents including the implementation of sustainable initiatives taking into account the interests of all parties concerned (i.e. stakeholders) including local authorities, businesses, general public, non-commercial organizations, scientific sector, etc.

As a result, the task of regional sustainable development comes down to the studying of two basic problems. On the one hand, this is about the opportunities to increase the quality of strategic planning at the regional level, baseline of the methodological approaches in working out of sustainable development of the region, justification of their goal-setting and priorities defining, and suggesting the mechanisms of realization. On the other hand, this is about a deeper understanding of concept of sustainable development, its principles transformation to the level of regional management, forming the system of practical steps providing the inclusion of sustainability principles into regional strategies of development.

14.2 Theoretical, Informational, Empirical and Methodological Fundamentals of the Study

Within the framework of this study, the concepts of sustainable development and human development are being used as the leading theories included in the goal-setting of strategic documents of the Russian regions and Rostov region, in particular. Different methodological approaches to the analysis of sustainable socio-economic development of Rostov region and justification of suggestions and recommendations on using sustainable initiatives in strategic planning of the region development have been used, in particular: observation and abstraction, deduction and induction, economic, logical and comparative analysis, data grouping, normative and systematical methods, generalization of actual and theoretical material, methods of tabular and graphical data visualization, dynamic series, indexes and index system building.

Informational and empirical fundamentals of this research consist of data obtained from official statistical collections, the website of Federal Service of State Statistics and its regional branches, including Rostov region, regulatory documents managing the process of strategic planning at the federal and regional levels and also the implementation of principles of sustainable socio-economic development of Rostov region, methodological working-out used in the current process of designing the new strategies of the regional and municipal (Rostov-on-Don) development, in which the authors are taking an active part as developers.

14.3 Results

14.3.1 Historical Background of Forming the Global Model of Sustainable Development and the Specific of its Realization in Russian Conditions

The concept of sustainable development originally occurred as the reaction of the international society to rising global environmental problems in the second half of the twentieth century, which caused the necessity of searching a new model of societal development. This necessity was justified by negative forecasts on the basis of global economic and mathematical models predicting environmental and social crises caused by the rising man-produced load on the environment (Forrester 1971; Meadows et al. 1972, 2004).

Practical emergence of the concept of sustainable development is connected with the establishment of the United Nations World Commission on Environment and Development (WCED) in 1983 at the initiative of the Secretary-General of the United Nations. The Prime Minister of Norway H. Brundtland led the Commission. WCED's task was to reveal the problems combining ecological and socio-economic concerns in different regions of the world, first of all, in the developing countries. In 1987, WCED strongly sharpened the question of the necessity in searching a new civilization model having published the report "Our common future", in which the impossibility to put forward and solve large environmental problems without their connection with social, economic and political problems was brightly shown. Since the Brundtland Report publication and its approval by the United Nations General Assembly, the new term "sustainable development" has come into use.

The concept of sustainable development offers such a model of socio-economic development with which a high coefficient of the future is realized and satisfaction of the life needs of the present generation of people is achieved without depriving this opportunity for future generations. In contrast to other concepts that somehow take into account the ecological factor in economic and social development (eco-development, co-evolution, noosphere), two key concepts were pointed out in the sustainable development model: (1) the concept of needs necessary for the existence of the poorest layers of the population, which should be a priority; and (2) the notion of restrictions due to the state of technology and the organization of society, imposed on the ability of the environment to meet current and future needs.

Such problems of sustainable socio-economic development include overcoming the territorial differentiation of the population in terms of the level of well-being and quality of life, reducing the territorial unevenness of population dispersal, smoothing out the demographic territorial disparities, etc. Their pendency can lead to significant destabilization of the relevant socio-economic systems, to limit the opportunities for transition to sustainable development, and, therefore, requires the formation of mechanisms that regulate territorial development (for example, ensuring the equal availability of vital natural resources – water, clean air, high-quality food products, energy resources, etc.).

In this sense, the concept of sustainable development has shown that current environmental and social problems are the result of a generally inefficient and unfair system of redistribution of income and capital flows that does not take into account the interests of individual social groups and vulnerable segments of the population. Such inefficiency comes out both within the framework of separate territorial systems (countries, regions) in the form of expanding negative processes of excessive differentiation of different levels of the population according to their income and potential for realizing their goals (education, self-realization and decent wages, high-quality medical care, favorable quality of natural environment, etc.) and globally in the form of extremely high disparities in the living standards of the population of highly developed and developing countries.

Without solving the problem of social injustice and uneven socio-economic development of different countries, territories and population groups, it is impossible to provide solutions to environmental problems, where the latter often result from the former. In this regard, the socio-economic aspect of sustainability involves studying and solving the problems of poverty, increasing the incomes of the population, and developing human potential. It can be said that sustainable socio-economic development is based on the concept of "human development" (Kolesov 2008), which considers the three main components of a full-fledged human life: decent income, high life expectancy and the opportunity to receive education.

Approximately at the end of the last century, new concepts of state public administration began to appear (such as the concepts of "political networks", a new method of governance, a synergetic approach to public administration, etc.), which mainly began to carry out the tasks of involving familiar management objects (population, business, territory, etc.) into the subjects of management. This allowed to form a joint "image of the future" for the development of specific territories and to include the priorities of the previously disparate parties in strategic documents.

In Russia, these processes in their practical application became in-demand much later. This is due to both the complex transformational processes caused by the transition from a centralized to a market-based economic system occurring in the late 1980s – the beginning of the XXI century, as well as a more extensive spatial extent of the territories. Also important is the fact that the territories (regions) of the Russian Federation faced with the lack of natural resources much later than it occurred in the developed countries of the European Union and the United

States. Despite the fact that in the scientific community the ideas of sustainable development have been understood and developed by a number of researchers (Bobylev et al. 2018), in practice of management at both the federal and regional levels they have been used very narrowly. The greatest emphasis in the implemented programs was still made on the social aspects of the development of the territories, since historically, the public administration system was set up to maximize the state support to vulnerable segments of the population. However, the effectiveness of such support was extremely low and could not effectively smooth out the differentiation of the population in terms of living standards being formed in the country as a whole and in individual regions.

It should also be noted that the system of strategic planning in Russian Federation got into a new stage of its development in 2014 when a Federal Law "About the strategic planning" (Federal Law of the Russian Federation of June 28, 2014 No. 172-FZ) was passed. It became a starting point of regular and systematic strategic documents elaborating on all state management levels (federal, regional and local). And today in the Russian regions, some experience in methodical support for the development and implementation of strategic documents has been already accumulated.

14.3.2 Analysis of the Main Indicators of Sustainable Social and Economic Development of the Rostov Region

The analysis of the main indicators of sustainable social and economic development of the Russian Federation and regions was carried out on the material of the Rostov region, one of the industrial and agricultural regions in the South of Russia (Fig. 14.1).

The results of the analysis reflect a number of positive tendencies in the implementation of the principles of social-economic sustainability related to conducting in Rostov region a complex of medium-term targeted programs aimed, among other things, at addressing social issues.

At the same time, there are some issues in the social sphere of the region which still demand an attention on the management part.

The dynamics of the main indicators of social and economic development is presented in Fig. 14.2 and Table 14.1.

As can be seen from the data presented in Fig. 14.1, the overall macroeconomic situation in the region is characterized by an annual growth of the gross regional product by approximately 3–4% per year over the period under review. The social development indicators also reflect the improving situation in the Rostov region (Table 14.1).

Thus, the region shows an increase in life expectancy which testifies the improved living conditions. Positive dynamics is demonstrated by the infant mortality rate. Over the analyzed period, it decreased by almost 1.5 times. Migration

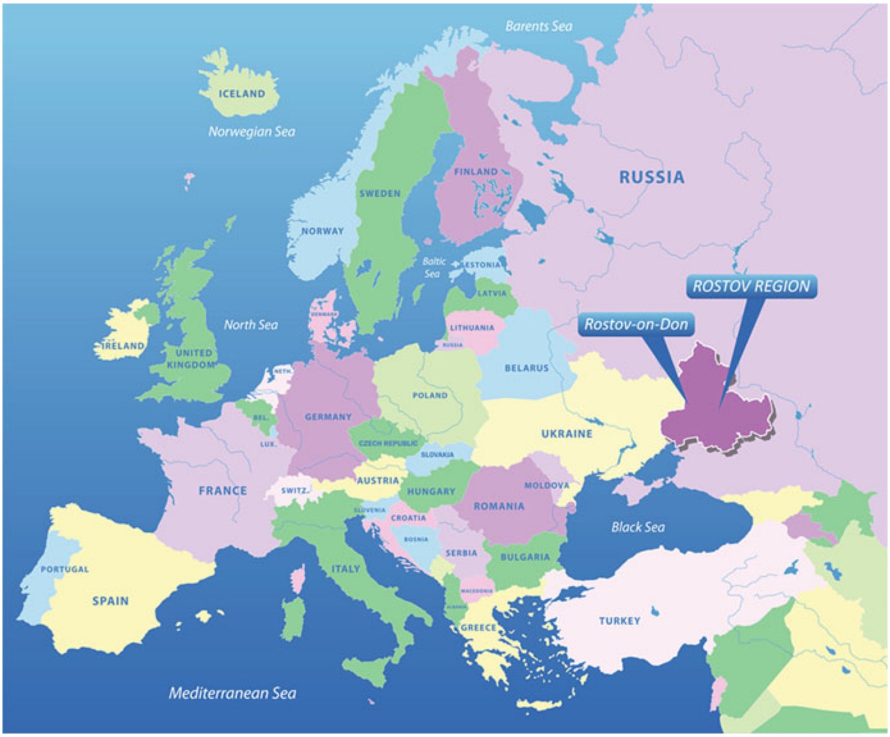

Fig. 14.1 Map of Rostov region in the context of Europe Source: https://www.ipa-don.ru/presentation/mapeurope/

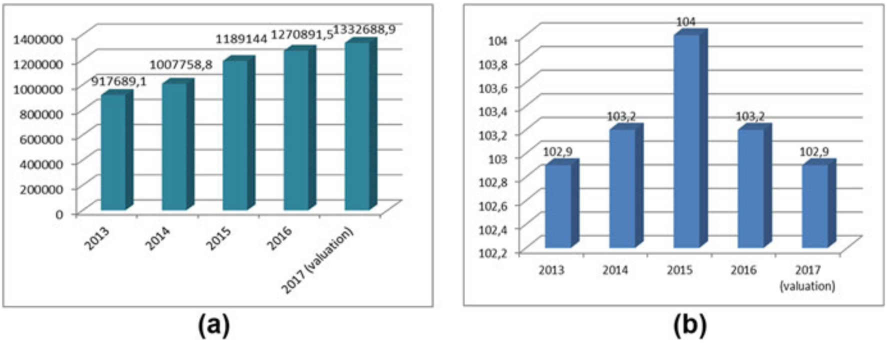

Fig. 14.2 Dynamics of indicators of the gross regional product: (**a**) gross value added, in basic prices, million rubles; (**b**) the physical volume index of the gross regional product, %, 2013–2017 Source: Materials of the official portal of the Government of the Rostov region.URL:http://www.donland.ru/Donland/Pages/View.aspx?pageid=124053&mid=128713&itemId=127331

Table 14.1 Dynamics of the main demographic indicators of social and economic development in the Rostov region, 2013–2016

Indicator	2013	2014	2015	2016
Population change, annual increase,%	−0,2	−0,1	−0,1	−0,1
Mortality per 100,000 population	1292,5	1317,9	1299,9	1303,9
Infant mortality per 1000 live newborns	9,5	7,9	6,6	6,6
Natural population growth per 1000 population	−2,1	−2,0	−1,8	−2,3
Migration growth per 10,000 population	−0,3	12	4	12
Life expectancy at birth, years	71,39	71,30	71,90	72,20

Source: Regions of Russia. Socio-economic indicators 2017. http://www.gks.ru/wps/wcm/connect/rosstat_main/rosstat/en/statistics/publications/catalog/doc_1138623506156

Table 14.2 Dynamics of income indicators of the population in the Rostov region, 2013–2016

Indicator	2013	2014	2015	2016
Average per capita monthly monetary income of the population, rubles	20,995	23,355	26,558	27,104
Average monthly nominal accrued wages of employees, rubles	21,867	23,818	25,008	26,689
Average size of the assigned pensions, rubles	9204	9943	10,995	16,283
Amount of the monthly subsistence minimum, on average per capita, rubles	6988	7967	9109	9414
The population with cash income below the subsistence minimum, % of the total population	12,9	12,9	14,0	14,0
Gini coefficient	0,392	0,398	0,392	0,392

Source: Regions of Russia. Socio-economic indicators 2017. http://www.gks.ru/wps/wcm/connect/rosstat_main/rosstat/en/statistics/publications/catalog/doc_1138623506156

growth, provided mainly by the influx of migrants from troubled border areas, also does not compensate for the natural population decline, which generally affects the continuing decline in the total population.

The indicators of monetary income considered under the sustainable development concept are growing up in the Rostov region (Table 14.2).

Wages and social benefits (pensions, allowances, etc.) still are the predominant share in the structure of the population's incomes. In general, the country and the region do not have enough tools to ensure personal financial security. There is also an increase in the proportion of the population with cash incomes below the subsistence minimum. In 2016, 7.2% of the population of the Rostov region had incomes above 60 thousand rubles per month. More than 45.3% of the total monetary income of the population is attributed to 20% of the population with the highest incomes (Fig. 14.3).

At the same time, the Gini Coefficient in the Rostov Region remains unchanged over the entire period under review. In general, the analysis carried out shows a tendency of poverty increasing and reducing of the income of the population in the Rostov region, the stratification increasing of the population according to the level and quality of life. This suggests that the economic growth ensured in the region

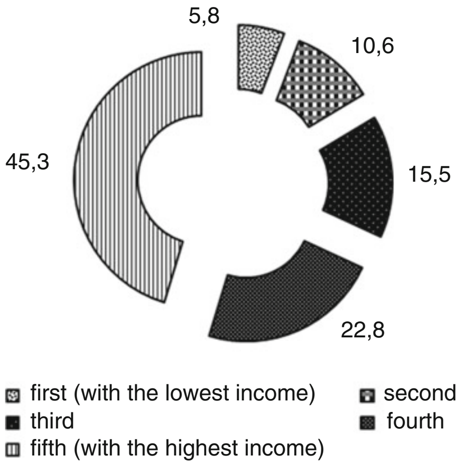

Fig. 14.3 The share of the total monetary income attributed to the relevant groups of the population, in the total amount of cash income, %, 2016 Source: Regions of Russia. Socio-economic indicators 2017. http://www.gks.ru/wps/wcm/connect/rosstat_main/rosstat/en/statistics/publications/catalog/doc_1138623506156

is characterized by a parallel increase in the social differentiation and calls for a stronger attention to the implementation of social programs aimed at creating a more equitable system of income redistribution.

14.3.3 Modern Trends in the Development of Strategic Planning for the Socio-Economic Development of Russia and the Regions on the Basis of the Principles of Sustainability (Rostov Region Case Study)

The Rostov region is a constituent entity of the Russian Federation in the Southern part of the European Russia belonging to the Southern Federal District. Among other major territorial entities of the Russian Federation, the region is distinguished by its high scientific, production, resource and financial potential. The development of the regional economy is based on the impact of such factors as the favorable economic and geographical situation (as the connection hub linking the Central Russia with the North Caucasus and Transcaucasia), the availability of natural resources, historically favorable development conditions, high labor supply, and well-developed transport infrastructure. In terms of the economic transformations over the recent years and the volume of output of goods and services, the region occupies one of the leading positions, both in the Southern Federal District and in Russia as a whole (Materials of the official portal of the Government of the Rostov region, Brief description of the Rostov region. – http://www.donland.ru/O-regione/?pageid=75187).

The capital of the Rostov region and the Southern Federal District is the city of Rostov-on-Don, an administrative center with a population of more than one million people and an area of 348.5 square kilometers. Positioning as the capital of the

South of Russia and localization of industrial enterprises and structures of the South-Russian scale in the city stipulates additional concentration of jobs in Rostov-on-Don, provides a higher level of economic activity and investment attractiveness. A factor that is favorable to the socio-economic development of the city is its positioning as a "core" of the Rostov agglomeration with a demographic potential of up to two million people forming the largest local consumer market in the South of Russia, which concentrates a large part of the scientific, educational, industrial and financial investment potential of the region (Materials of the official portal of the City Duma and the Administration of the city of Rostov-on-Don, http://rostov-gorod.ru/ourcity/aboutrostov/aboutcity/).

At present, the Rostov Region and Rostov-on-Don are developing new strategies for their socio-economic development. So, in the region the Strategy of socio-economic development of the Rostov region is being developed until 2030 and in the city – the Strategy of socio-economic development of the city of Rostov-on-Don until 2035. An important principle in the development of these strategic documents at various levels is their continuity, which ensures the strengthening of the role of city strategy in implementing the development goals of the region. At the same time, between the working groups formed for the development of strategies, methodological interaction is established, ensuring the unity of conceptions and methodological means for their realization.

The concepts of sustainable development and human development are the core basis for the development of these strategies. The developers emphasize the need to harmonize the interests of present and future generations, operational and strategic goals. In the framework of the new Strategy of the Rostov region, the concept ensures the coordination of the long-term goals of the three components "Society", "Economy" and "Territory". These components form the directions of strategic development of the region, which will be realized through three regional state policies: economic, social, spatial (Conceptual framework of the Strategy 2030, http://don2030.mineconomikiro.ru/) (Fig. 14.4).

At this stage, the mission of the Rostov region is defined as follows: ensuring the social well-being of the population; playing the role of the supporting region of the "new economy" of Russia; implementation of the functions of the scientific and technological as well as political and administrative center of the South of Russia; preservation of the unique ecosystem of the Don region; preservation and development of its unique cultural space. The mission created in such a way allows to fit organically the Rostov region into the regional system of Russia, while preserving the identity and specific advantages of the region, making it unique and competitive.

The advantage of the methodological approach used in the development of the Rostov Region Strategy is an attempt to build a system of goals and relevant targets, taking into account the relationship between the identified social, economic and spatial subsystems (Tables 14.3 and 14.4).

Currently, the Strategy is in the process of development, so the final ideas on specific priority tasks and strategic project initiatives that will be incorporated into

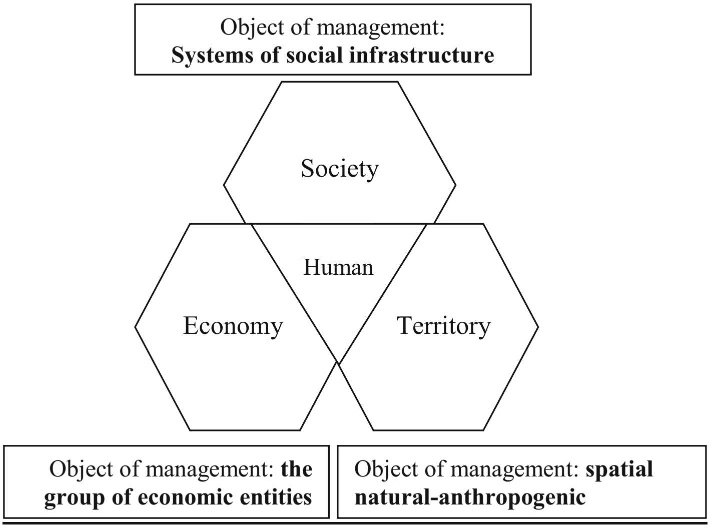

Fig. 14.4 Conceptual framework for the development of the Strategy for Social and Economic Development of the Rostov Region until 2030 Source: Conceptual framework of Strategy 2030, http://don2030.mineconomikiro.ru/

the Strategy implementation mechanism have not yet been formed. The principle of priority is defined as fundamental in the development of strategic documents.

In the strategy considered, the identification of priorities is carried out in two main directions: the removal of the most urgent restrictions of the growth relevant to the modern state of the strategic objects, and also the definition and realization of development opportunities in the long term. Thus, the methodology used reflects the two most important aspects of strategic planning: the priority and direction for development.

The process of developing such priority tasks and project initiatives is carried out in working groups, which are formed in all supervised priority areas. The working groups include representatives of the executive power of the Rostov region (no more than half of the total number of the group), officials who are responsible for methodological support, coordination and interaction of its participants; representatives of subordinate institutions and organizations, public councils, local self-government bodies, the deputy corps, the business community, as well as representatives from the public and science.

Algorithms and forms have been developed to justify systematically the views and interests of various concerned stakeholders in the development of the strategy, allowing to reconcile the priorities, goals, indicators and activities necessary to achieve the target indicators. Working groups function in a variety of formats, starting with desk research, brainstorming and finishing-up foresight technologies, which are relatively new to Russian strategic planning practice.

Table 14.3 The system of goals that link the results of interaction between the social, economic and spatial subsystems of the Rostov Region

Subsystem/policy	Subsystem's goals	Goals of interaction with other subsystems	Goals of human development
Social	Ensuring the competitiveness of the social sphere in the struggle for human capital	Providing the economy with quality labor resources	Providing the population with quality social services
		Formation of territorial accessibility of social services	
Economic	Increasing competitiveness and consolidating the leading positions of economic entities at the sectoral markets	Providing an economic basis for the development of the social sphere	Ensuring the material well-being and self-realization of the population
		Balanced territorial economic development	
Spatial	The development of a global effective framework and preservation of the ecosystem	Removing infrastructure limits for social development	Creating conditions for comfortable living
		Removing infrastructure limits for economic development	

Source: compiled from http://don2030.mineconomikiro.ru/

14.4 Conclusions and Recommendations

The set goals of sustainable development of the Rostov region will require, in addition to resolving the current most urgent problems of the region in its main spheres, cardinal structural changes in the economy and social sphere and introducing appropriate instruments for their achievement in the management practice.

The situation in the social sphere requires strengthening the implementation of programs in the field of health, promoting healthy lifestyles, as well as increasing attention to the growth of incomes of the population and reducing the differentiation of the population in terms of living standards.

Among indicators of sustainable development, the human development index (HDI or the index of human development) is often used in international practice. This indicator is not considered by the Russian statistics, but the existing methodology for its calculation (Human Development Report 2010) makes it quite easy to calculate it for the regions of the Russian Federation using official state statistics. In our opinion, taking into account that the concept of sustainable development and human development was based on the development of the strategy of the Rostov region, it is necessary to use this indicator in the system of target indicators.

Table 14.4 The system of target indexes, mutually linking the results of interaction of the social, economic and spatial subsystems of the Rostov Region

	Target indexes for the implementation of the Strategy			
	2016		2030	
Indexes on subsystems/politicians	Index meaning	Place among RF entities	Index meaning	Place among RF entities
Common indexes				
Gross regional product, mln., rub.	1,264,452,9	12	3,828,331,6	TOP-10
Investments in the basic capital, mln., rub.	287,412,5	11	1,035,388,7	TOP-5
Average per capita monetary income, rub.	27,228	35	99,733,7	TOP-30
Life expectancy, years	72,2	21	76,93	TOP-20
Social sphere				
The number of permanent residents, thousand people	4231,3	6	5077,6	TOP-5
The number of births per 1000 people	11,6	64	15,0	TOP-40
Mortality caused by different reasons, people, per 1000 people	13,9	34	9,1	TOP-20
Unemployment rate, %	5,8	45	4,6	TOP-30
Economic sphere				
Number of enterprises and organizations, units	90,596	11	113,245	TOP-10
Profit from profitable organizations, mln., rub.	112,559,6	24	436,971,1	TOP-20
Export volume, mln. USD	5543	10	11,649	TOP-10
Average monthly accrued wages, rub.	26,689,1	51	100,417	TOP-40
Spatial				
Share of used and neutralized waste,%	46,7	48	100	TOP-20
Freight turnover of public transport, million t-km	54,576	–	65,491	–
Share of urban population,%	67,9	52	74,7	TOP-40
Territory coverage with cellular network,%	89	–	100	–

Its advantage over the other indicators, now offered in the strategy as target ones, is to reflect the relationship between specific measures implemented in the region within the framework of socio-economic policy and its end results for the people living in the area. The concept of human development and the HDI, reflecting the degree to which a high level of well-being of the population is achieved, is more focused on people's needs for decent income, good health and access to education as the main components of a full and happy life. The growth of this indicator will mean that the implemented policy makes it possible to improve the development conditions of the inhabitants of the region, and consequently the region as a whole will be more competitive in terms of attracting flows of human capital.

Particular importance should be attached to the development of rural areas, since most of the negative factors affecting the overall results of the social development of the region are common for the regions remote from Rostov-on-Don and other cities of the region.

Today, the strategy is designed to increase the proportion of urban population, which corresponds to the global development trends. However, this goal can be realized in various ways. It should be noted the unfavorable migration situation in the city of Rostov-on-Don itself, which reflects in the outflow of highly qualified personnel, who in most cases received higher education in higher educational institutions of the city, to other cities of the Russian Federation (mainly to Moscow and St. Petersburg), as well as to other countries. In fact, in regard to the Rostov region and the city of Rostov-on-Don, one can speak of "the export of human capital" as a product of the education system in the region. In this regard, it is possible and necessary to develop urban areas and urban agglomerations, ensuring an inflow of people from outside and providing the local population with a high standard of living and a favorable urban environment, which will increase the birth rate, reduce mortality, and stay with highly skilled personnel from the city, as there will be all conditions for their self-realization. It is desirable that the inflow to urban agglomerations is carried out not only at the expense of the rural territories of the region, but more at the expense of flows external to the region. Moreover, in our opinion, in addition to the development of urban centers and growth points in the region, it is necessary to pay attention to improving the quality of living space for the population of rural areas. It should not be forgotten that the Rostov Region is not only an industrial, but also an agricultural center, with favorable conditions for farming, considered as the granary of Russia. The lack of population in rural areas, in its turn, reduces the opportunities for entrepreneurship, farming, and infrastructure construction there. It is necessary to switch to a qualitatively new model for the development of agriculture, built on modern technologies, highly automated work that provides decent income and living conditions for farmers and the rural population. We should also concentrate on the tools that provide the transition to the newest models of the post-industrial economy, and introduce exact sustainable initiatives, including those built on the principles of the "green economy", the introduction of "green standards." From foreign practice, such tools often have a triple effect: economic, social, environmental. In particular, the priority of implementing the "best available technologies" while providing support for the development of industry and other sectors of the economy, such as construction, agriculture and agribusiness, allows us to change the structural qualitative characteristics of the economic development model. These qualitative changes provide the basic principles of sustainable development through modernization based on energy efficiency, a comprehensive reduction of the negative anthropogenic impact on the environment, and generally ensure an increase in the efficiency and competitiveness of production. For the local population, this becomes a more effective way of realizing their labor potential, a guarantee of improving the quality of the environment and the standard of living in general.

Using the strategic approach in the sustainable development planning suggests taking into account the results of the following steps when choosing industrial priorities (it takes estimating some quantitative characteristics of the environment):

– a stage of macroeconomic analysis of the industries being found as high priorities in the Russian Federation;
– a stage of macroeconomic analysis of the industries having high priorities in the world economy;
– a stage of estimation of the industries being analyzed from a viewpoint of provision of necessary resources.

Taking into account the stage of the industry life cycle helps avoiding investing into the industries which are going to reduce in the near future. Putting the resources (the investments, first of all) into developing industries can produce powerful drivers of the regional economy.

Weight coefficients could be used when calculating the industries attractiveness level as per the following formula:

$$Po = \sum\nolimits_i c_i * M_i,$$

where Po is the potential priority level of the industry (on an appropriate scale), c is the value of the weight coefficient, M is the score of the industry's characteristic being estimated, i is the number of the industry in the group of industries being analyzed.

Implementation of the approach described above can allow transferring the regional socio-economic policy priorities to industries related to new and developing markets and create a basis for the sustainable development of the region.

References

Baral KP, Yadav UN, Baral G (2017) Accelerating progress towards reaching sustainable development goals. Nepal J Obstet Gynaecol 12(1):5–7

Bobylev SN, Chereshnya OY, Kulmala M, Lappalainen HK, Petäjä T, Solov'eva SV, Tikunov VS, Tynkkynen V-P (2018) Indicators for digitalization of sustainable development goals in PEEX program. Geogr Environ Sustain 11(01):145–156

Clark WC, van Kerkhoff L, Lebel L, Gallopin GC (2016) Crafting usable knowledge for sustainable development. PNAS 113(17):4570–4578
Dhahri S, Omri A (2018) Entrepreneurship contribution to the three pillars of sustainable development: what does the evidence really say? MPRA Paper No. 84504. Munich Personal RePEc Archive. https://mpra.ub.uni-muenchen.de/84504/
Du Plessis J, Bam W (2018) Comparing the sustainable development potential of industries: a role for sustainability disclosures? Sustainability 10:878
Federal Law of the Russian Federation of June 28, 2014 No. 172-FZ "On Strategic Planning in the Russian Federation" (as amended). http://base.garant.ru/70684666/#friends#ixzz5Cw8kmlFw
Forrester J (1971) World dynamics. Wright Allen Press, Cambridge, Mass
Gazzola P, Sepashvili E, Pezzetti R (2018) How sustainable enterprises can drive the sustainable development. Eur Sci J:26–36
Hutton CW, Nicholls RJ, Lázár AN, Chapman A, Schaafsma M, Salehin M (2018) Potential trade-offs between the sustainable development goals in coastal Bangladesh. Sustainability 10:1108
Khaiter PA, Erechtchoukova MG (2009) Model aggregation and simplification in sustainable environmental management. Int J Environ Cult Econ Soc Sustain 6(1):227–242
Khaiter PA, Erechtchoukova MG (2010) Simulating the hydrological service of forest for sustainable watershed management. Int J Environ Cult Econ Soc Sustain 6(3):227–240
Khaiter PA, Erechtchoukova MG (2018) Conceptualizing an environmental software modeling framework for sustainable management using UML. J Environ Inf. https://doi.org/10.3808/jei.201800400
Kolesov VP (ed) (2008) Human development: a new dimension of socio-economic progress, 2nd edn. Prava cheloveka, Moscow
Kuribayashi M, Hayashi K, Akaike S (2018) A proposal of a new foresight platform considering of sustainable development goals. Eur J Futur Res 6:4
Materials of the official portal of the City Duma and the Administration of the city of Rostov-on-Don. http://rostov-gorod.ru/ourcity/aboutrostov/aboutcity/
Materials of the official portal of the Government of the Rostov region. The gross regional product of the Rostov region. http://www.donland.ru/Donland/Pages/View.aspx?pageid=124053&mid=128713&itemId=127331
Materials of the official portal of the Government of the Rostov region. Brief description of the Rostov region. http://www.donland.ru/O-regione/?pageid=75187
Meadows DH, Meadows DL, Renders J, Behrens WM III (1972) The limits to growth. Universe Book, Chicago
Meadows DH, Renders J, Meadows DL (2004) Limits to growth: the 30-year update. Chelsea Green, Vermont
Nhemachena C, Matchaya G, Nhemachena CN, Karuaihe S, Muchara B, Nhlengethwa S (2018) Measuring baseline agriculture-related sustainable development goals index for southern Africa. Sustainability 10:849
Ojonimi IT, Onimisi M, Ocheri C, Onuh CY (2018) Sustainable development of Nigeria's solid minerals through metal recycling: a review. J Degraded Min Lands Manag 5(2):1019–1026
Regions of Russia. Socio-economic indicators (2017). http://www.gks.ru/wps/wcm/connect/rosstat_main/rosstat/ru/statistics/publications/catalog/doc_1138623506156
Report on Human Development in the Russian Federation (2010) Millennium development goals in Russia: looking to the future: 152. http://www.undp.ru/nhdr2010/Nationa_Human_Development_Report_in_the_RF_2010_RUS.pdf
The conceptual basis of Strategy 2030 http://don2030.mineconomikiro.ru/
Vargas-Hernández JG, Pallagst K, Hammer P (2018) Bio-economy at the crossroads of sustainable development. Revista Iberoamericana de Bioeconomia y Cambio Climático (Rev iberoam bioecon cambio clim) 4(7):800–815
Zimm C, Sperling F, Busch S (2018) Identifying sustainability and knowledge gaps in socio-economic pathways Vis-à-Vis the sustainable development goals. Economies 6:20

Chapter 15
Resilience of Desalination Plants for Sustainable Water Supply in Middle East

Furqan Tahir, Ahmer A. B. Baloch, and Haider Ali

Abstract Desalination produces fresh water from seawater. Given that seawater accounts for 97% of water on the earth, it is the most reliable source of fresh water production, especially for water-stressed countries on the coasts. Middle East is an example for that since it faces arid climate and relies on desalination for fresh water supply. However, heavily relying on desalination as a nation makes it vulnerable. In the case of a disaster, countries like Qatar would have only 48-hours emergency water supply for its 2.4 million population. Therefore, the capacity to recover quickly from failures is vital to this industry. This chapter will highlight the most recent and proactive approaches to resilience by evaluating the possible vulnerabilities and measures for desalination plants. Technological diversification will ensure it can maintain its constant water supply without relying on fossil fuel-based desalination plants. The outlook of national programs in the region looks positive as they are already on the path towards a resilient and sustainable society as realized by the ongoing projects such as Mega Reservoirs, and research programs in solar desalination and pretreatment techniques. The chapter will focus on these issues related to resilience and sustainability dimensions applicable to desalination plants.

Keywords Resilience Measures · Water Security · GCC · Desalination · Sustainability

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Abbreviations

AC	Activated carbon
AVC	Absorption vapor compression
CAPEX	Capital expenditure
DAF	Dissolve air flotation
GCC	Gulf Co-operation Council (Qatar, Saudi Arabia, United Arab Emirates, Bahrain, Kuwait, Oman)
GW	Giga watts
HABs	Harmful algal blooms
ICBA	International Center for Biosaline Agriculture-UAE
MF	Micro filtration
Mm^3/y	Millions cubic meter per year
NF	Nano filtration
PR	Performance ratio (fresh water produced with unit kg of steam supply)
RO	Reverse osmosis
SFLA	Shuffled frog leaping algorithm
SWCC	Saline Water Conversion Corporation (Saudi Arabia)
SWRO	Sea water reverse osmosis
TD	Thermal desalination
TSE	Treated sewage effluent
TVC	Thermal vapor compression
TWW	Treated waste water
UAE	United Arab Emirates
UF	Ultra filtration

15.1 Introduction

Desalination produces fresh water from seawater. Knowing that seawater accounts for 97% of water on the earth, it is the most reliable source of fresh water production, especially for water-stressed countries on the coasts. Middle East is an example for that since it has arid climate and relies on desalination for fresh water supply. With an expected population of 633 million in Arab region by 2050, water resources are estimated to be 470 m^3/ca, which will be 10% of world's average (Abouhatab 2018). The renewable water resources of Gulf Co-operation Council (GCC) are very low and declining as shown in Fig. 15.1. All of the GCC countries have renewable water resources less than 100 m^3/year/capita, which falls into minimum survival level as shown by Fig. 15.2. The aquifers' level in Saudi Arabia are dropping at a rate of 3~6 m/year for the last 30 years. In GCC, the average rainfall is around 20 cm per year, which makes this region driest and water scarce. With increasing population and decreasing water resources, dependency on surrounding countries has been increased for energy, food and water nexus.

Despite water scarcity, water needs in GCC countries are met by desalination plants which are coupled with large-scale fossil fuel based power plants (Mohammed and Darwish 2017; Alhanaee et al. 2017). Middle East's reliance on desalinated water is increasing, however, this reliance has some serious disadvan-

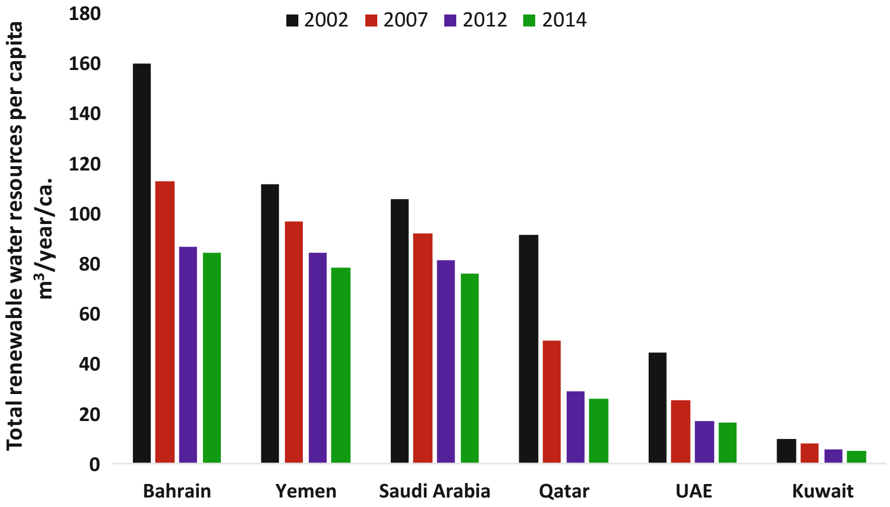

Fig. 15.1 Total renewable water resources (m^3/year/ca) for GCC countries. (FAO 2018)

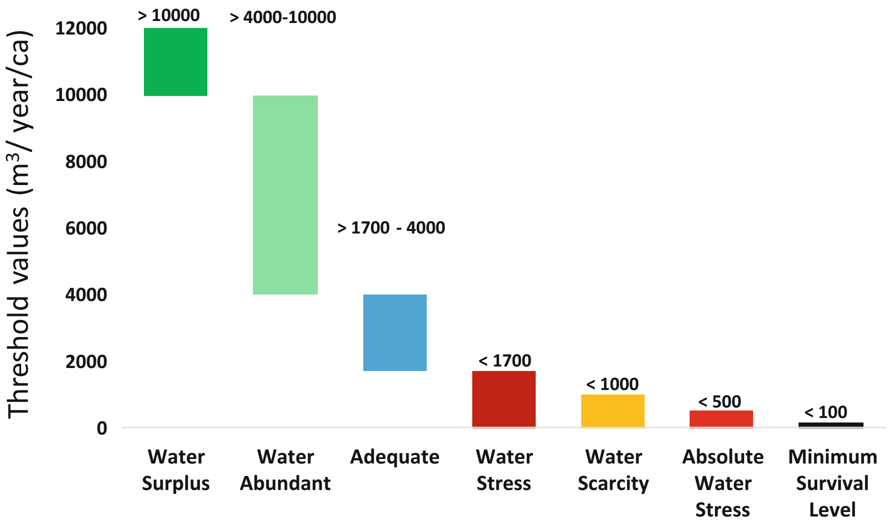

Fig. 15.2 Threshold values of water resources (m^3/year/ca). (Parveena 2010)

tages (Darwish and Mohtar 2013). What if there's a natural disaster resulting in Desalination plant failure or an oil spill in the vicinity of desalination plants? In such events, for instance, Qatar has only 48-hours emergency water supply for its 2.4 Million people. Hence, completely relying on desalination would result in vulnerable water security due to any unexpected turn off time of the plants. Events like oil spills or harmful algal blooms, though unlikely, have high risk due to its lethal consequences.

If water supply is cut-off or disturbed for more than 2 days then it is termed as long-term interruption. Long-term interruption may happen due to adverse climatic conditions or if the main plants are disabled. The causes for plant shut down can come from external impact, failure, accidental impacts or malicious activity. This can establish a critical scenario in the country if the susceptible desalination plant become non-operational for any reason. The capacity to quickly recover from failures is vital to this industry. Whether it is an equipment failure or process failure, the key to keeping the water supply on is its resiliency (WHO and DFID 2009). Agricultural and domestic sectors in Middle East are the main water consumers whereas ground water is over-exploited which is not sustainable. Desalination process is costly and energy demanding, the energy is usually taken from power plants which results in increased carbon emissions. Therefore, these plants are contributing to greenhouse gases and global warming. Also rejected brine with increased salinity and temperature disturbs the marine ecology (Kim and Jeong 2013). This is primarily because the Arabian Gulf is narrow with low depth so continuous brine rejection is causing salinity level to rise and formation of algal blooms (Meshkati et al. 2016).

To understand the desalination plants, it is important to familiarize with different desalination types currently operating. There are two main type of desalination technologies, thermal and membrane desalination. Reverse Osmosis (RO) membrane-based desalination is energy efficient and has lower cost but the pretreatment is required to avoid membrane degradation. Thermal desalination, which includes Multi-Stage Flash (MSF) and Multi Effect Desalination (MED), has more market shares in GCC countries because of the harsh sea water conditions and lower steam cost. MSF technology is matured but MED has still room for improvements (Tahir et al. 2015).

Considering the importance of sustainable water production especially in Middle Eastern region, the chapter highlights the most recent and proactive approaches to resilience by evaluating the possible vulnerabilities and resilience measures for desalination plants.

15.2 Resilience and Sustainability Dimensions

Resilience is a feature of a system "that offers flexibility and scope for adaptation whilst maintaining certain core functions" (Pelling 2003). It is essentially the ability of any system to bounce back to its original state after any unlikely event. The capacity of countries to have adaptability for a change while managing the existing risks without compromising the future goals is a connection between resilience and sustainability. For example, the construction of solar desalination plants can be a resilience dimension as it reduces risk of water supply from conventional fossil-fueled power desalination plant and allows the system to adapt and recover more

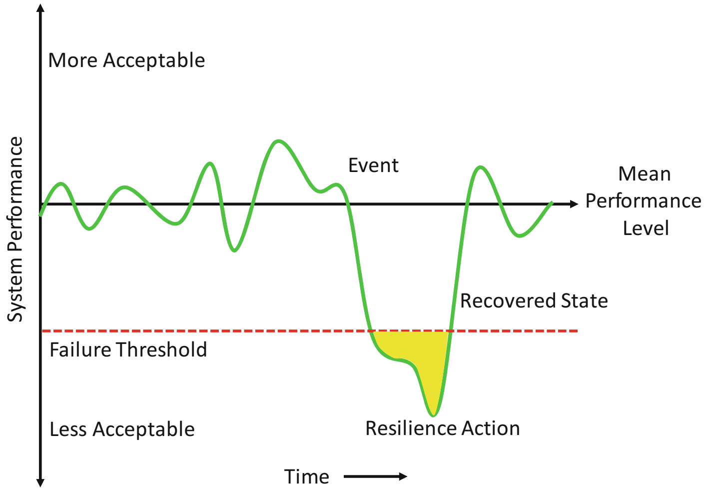

Fig. 15.3 Performance of a system under shock from an event with threshold level and resilience action for recovery. (Modified from Hashimoto et al. 1982)

quickly. Resilience is shown by adaptability of the system and its dynamic change to come back to equilibrium while a sustainable system aims for healthy social, economic, and ecological structures (Folke et al. 2002). Sustainability and resilience includes three dimensions – social, environmental and economic (Handmer and Dovers 1996).

For a resilient and sustainable water supply system, careful consideration must be given to current and future water demands by analyzing the possible events that may alter the operational stability and productivity of the system. Figure 15.3 graphically demonstrates system performance under shock from an event with threshold level and resilience action. For a system to perform at its main level, it needs to employ resilience measures after the threshold limits. An optimal resilient system should ensure that the system does not cross the threshold limit, while the recovery mechanism from failure should react as swift as possible to the stress event. In the background of desalination plant failure, threshold level is the measure of emergency water supply before any harm and disturbance prevails. This includes precautionary measures required for limiting the threshold behavior such as building infrastructure or risk-based inspection of desalination plant. Coping measure shows the capacity of a system to perform its duty despite going beyond the threshold level. Recovery measure is associated to the swiftness and efficiency of the system to return to regular operational level after a serious failure in water scarcity. Furthermore, adaptive measure represents the capacity of the system to utilize the recovery time and the period amidst events to improve the three mentioned measures.

15.3 Vulnerabilities and Resilience Measures

Sustainability of desalination plants can be studied by understanding the resilience of these systems under possible vulnerabilities. These natural or artificial vulnerabilities should be reduced while designing the plants to counter the issue of water scarcity for individual and nations. Middle Eastern climate serves as the prime example due to its terrain and limited availability of water resources. To understand the importance of resilience, case studies and examples have been showed. Measures are carefully selected and discussed built on an assessment of open literature and industrial reports (Missimer et al. 2013a, b; Darwish et al. 2016a, b, c). This integrates the idea of resilience and vulnerability by highlighting the significance of risk assessment and preventive/reactive steps for strengthening water supply from desalination plants. To reduce the likelihood of events of plant failure, possible vulnerabilities and adaptive measures are shown in Fig. 15.4:

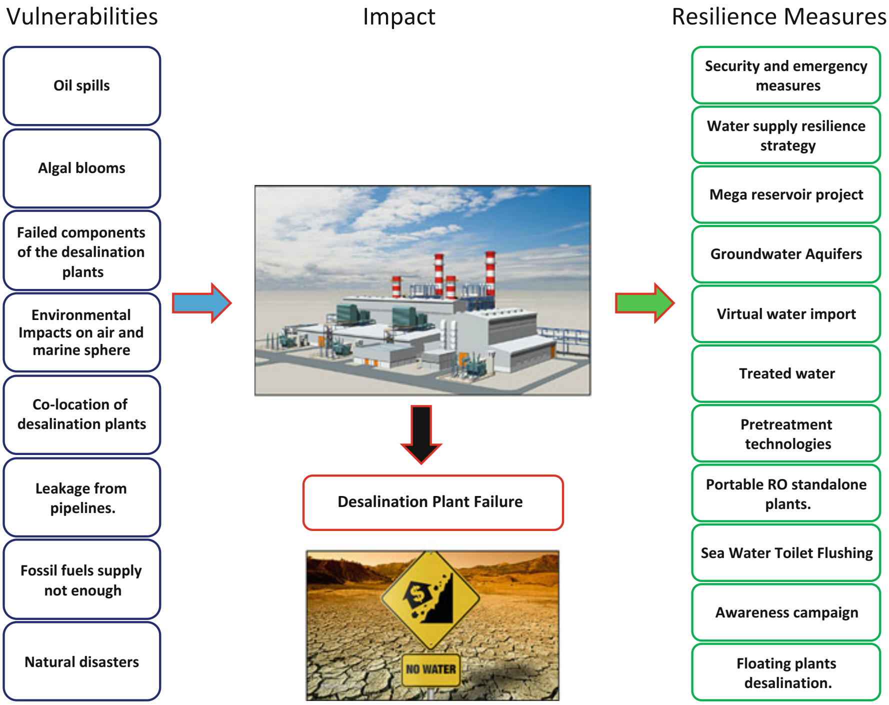

Fig. 15.4 Desalination plant resilience strategy identifying vulnerabilities and adaptive measures

15.4 Vulnerabilities

Actions are required to remove vulnerabilities and to ensure that water supply is constant to people by considering possible risks. Although, the likelihood of plant failure due to forced majeure are unlikely. There are enough evidences to suggest plant failures may result in a severe consequence if it ever occurs. With the ever-changing dynamics of desalination industry and increasing water supply, scenarios which may result in technological weakness must be examined. This may include growing problems such as algal blooms, oil spill impact or malfunctioning of industrial equipments. The most important vulnerabilities that may result in plant failure and subsequent water supply in the Gulf region are discussed below:

15.4.1 Harmful Algal Blooms (HABs)

Harmful algal blooms (HABs), also called as red tides, are a serious concern in the countries dependent on desalination technologies (Al Muftah et al. 2016; Darwish et al. 2016c; Hess et al. 2017). HABs are organisms that can reduce the oxygen level of natural water thereby affecting the marine ecosystem and producing neurotoxins (Hess et al. 2017). As a result, even the treated water from desalination can be contaminated with chemicals causing skin allergies, foul smell, and bad taste. HABs are sub-divided in two categories: Toxic with low biomass and non-toxic with high biomass. Both of these HABs deter the operation of the desalination plants. Non-toxic with high biomass can clog the filters in the membranes used for pretreatment as well as fouling issues. Toxic HABs, on the contrary, can enter into the food cycle which can be extremely harmful for the human health (Darwish et al. 2016b). Essentially, the HABs pose two operational dangers for desalinated water viz. Safety of water and Security of water supply. The security of water supply can be altered by these blooms from unscheduled outages and shutdown of plants due to intake or pretreatment failure problems. Such HABs can have direct implication on the water security and may result in financial losses as well.

HABs, mainly phytoplankton, have been reported in the warm seawater of the Gulf of Middle East. The recent extraordinary event of algal blooms in the Gulf of Oman caused a partial shutdown of the desalination plant leading it to reduce water production (Hess et al. 2017). Some plants were shut down for 32–55 days as an outcome of massive fouling in the filtering medium and an inability of pretreatment processes to remove them from reverse osmosis (RO) membranes as shown in Fig. 15.5 (Darwish et al. 2016c). Case studies from industries show the impact of HABs is more vulnerable to Sea Water Reverse Osmosis (SWRO) plants than Thermal Desalination (TD) Plants. This is due to easy passing of blooms from intake screens in TD based factories. TD plants in Fujairah showed this behavior when they were continued to operate despite the red tides whereas the co-located SWRO plant had to shut down. Despite this situation, toxins may be available in desalinated water,

Fig. 15.5 Reported algal bloom incidents in the Middle East for the period 2005–2012. (ROPME 2013)

which needs to be taken care of before supplying it to consumers. Other prominent case study for occurrence of HAB and operational issues is the Shuwaikh plant in Kuwait located near seaport with poor water quality near intake systems (Hess et al. 2017). Precautionary methods in terms of continuous monitoring for algal bloom, forecasting and exploring possible measures of reducing the impact of HABs are being tested. Dissolve Air Flotation (DAF) and Ultra Filtration methods have been employed in contemporary times to control this problem. Selection of site and water intake (subsurface intake such as beach wells) may as well decrease the vulnerability to desalination plants.

15.4.2 Oil Spill Impacts

Middle Eastern countries heavily depend on desalination technology for supplying water to domestic and industrial use. These oil-rich states hold 47.2% of world's known oil reserves despite covering only 3.4% of the total world area (BP 2018). The high-volume production, as shown in Fig. 15.6, from petroleum industries combined with the loading and logistics pose serious threats to water, energy, and food security. Moreover, the geographical location and condition of seawater with shallow depth and high residency time, around 2–3 years, also increases the potential risk from the oil leakage. In the year 2016, Middle Eastern gulf had an estimated 800 offshore plants with an approximately 50,000 oil ships for transportation. Oil spill in this region is a critical problem that can have a significant impact on the operational capability of desalination plants. These oil spills can be caused either by accidents, operational issues from the oil production facilities, illegal discharging, oil smuggling or by military action as highlighted by the (Elshorbagy and Elhakeem 2008). It is a chronic issue in the area with an assessed long-term average of 8958 tons of spilled oil every year (El-Sayed Elshorbagy and Elhakeem 2012; ROPME 2013). The major contribution has been from military action during the gulf war with 840 kTon of oil entering the sea body and affecting marine sphere. Clearly, major spills, although with less likelihood, still remains a risk to the strategic and development plans for these water-stressed countries.

The polluted oil has direct effect on the feed water and intake system for desalination plants. The oil slick water reduces the intake performance of filters, causes biofouling due to the present hydrocarbons and restricts the flow to the main intake manifold by clogging screens. As the seawater is mixed with oil, its thermo-physical property changes. This, in turn, reduces the thermal performance of heat exchangers leading to a decrease in the productivity of distilled water. For SWRO plants, the membranes have to undergo a major overhaul due to contamination from oil. These adverse effects force the plants to shut down for rigorous cleaning and

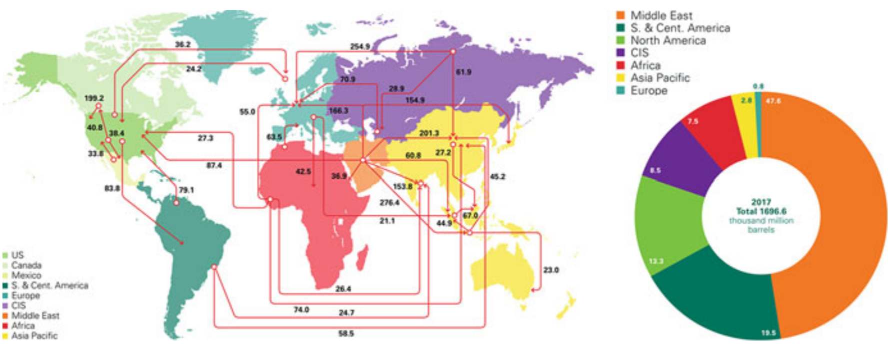

Fig. 15.6 Transportation routes of oil around the world (left) and Share of oil resources in the world (right). (BP 2018)

Table 15.1 Causes for oil spilling in Arabian Gulf with individual percentage contribution

Oil Spill Reason	Percentage Contribution (%)
Grounding	0.004
Leakage	0.005
Internal discharge	0.078
Sinking	0.263
Explosion	2.403
Unspecified	5.125
Collision	5.796
Unknown (not reported)	8.275
Military action	78.051

Reproduced from Elshorbagy and Elhakeem (2008)

maintenance. Recently, Az-Zour North desalination plant in Kuwait was shut down temporarily for 48 hours due to an estimated 35 thousand barrels of oil leak in the vicinity. A major contamination of water supply in treated water was reported in 1997 in Sharjah when the grounded barge spilled diesel along the coast. Collision between oil tankers in Fujairah (1994) resulted in a crude oil spill of 16 thousand ton (Pearson et al. 1998) which would have caused a huge catastrophe had this oil slick water reached the desalination plant intake (Elshorbagy and Elhakeem 2008). Considering the impact, it is of vital importance to consider risk and measures for an oil spill accident affecting the desalination plants operating along the coast. Contingency plans should be developed based on the modeling of oil leakage motion and pattern considering the sea currents. Risks associated for different locations based on past events and current data for oil production and shipment can assist in providing timely mitigating measures (Elshorbagy and Elhakeem 2008; El-Sayed Elshorbagy and Elhakeem 2012) (Table 15.1).

15.4.3 Co-located Desalination Plants

Co-location of desalination plants with power plant facilities offer significant advantages in terms of permit and energy cost savings along with the reduction for an additional intake system (Gude 2015). Hybrid thermal desalination and seawater reverse osmosis can be employed with these large power plants to further decrease the price of desalted water. However, for water-stressed countries in Middle East with high density of desalination plants as shown in Fig. 15.7, additional risks are presented by constructing sites near to each other. The risk associated has high consequences and less likelihood due to co-location of desalination plants. This is because if there is any power outage due to natural or man-made disaster such as algal blooms or oil spills, all the plants in chain will be stopped leading to catastrophic impact on water supply.

Thermal desalination plants are more resilient towards force majeure events due to their favorable high temperature operating conditions. During an algal

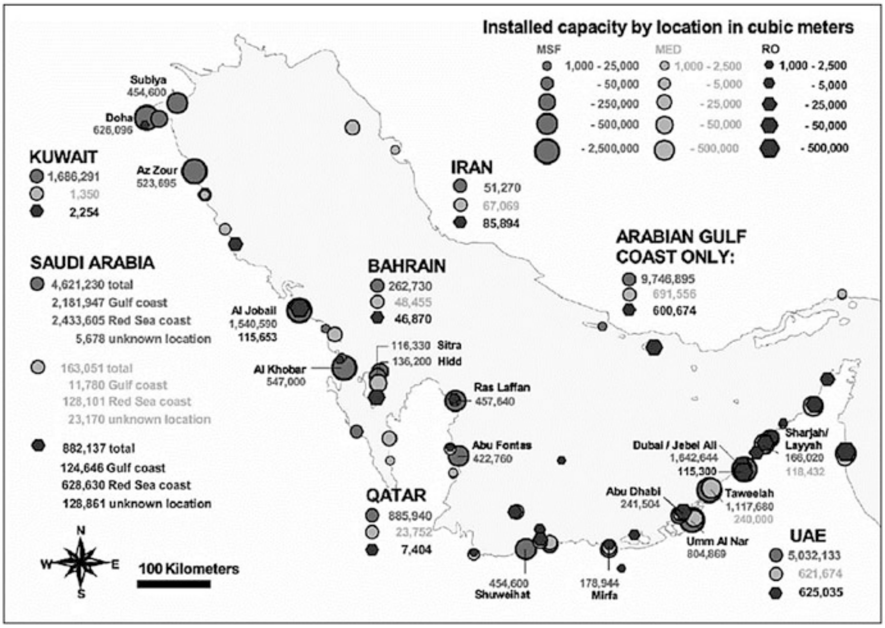

Fig. 15.7 Location of installed desalination plants in the Gulf of Middle East. (Dawoud and Al Mulla 2012)

bloom occurrence in Fujairah 1 hybrid desalination plant, thermal desalination plant (Multi-stage flash) was operated continuously without any major issue whereas seawater reverse osmosis was shut down (Darwish et al. 2016c). This is due to ease of passing of blooms from intake screens in thermal desalination units. Jeddah Desalination plants have faced similar issue and proposed to solve it temporarily using floating desalination plant. Desalination units situated near Abu Dhabi, Mina Jebel Ali and Dubai are extremely sensitive due to possible oil spills (ROPME 2013). Therefore, strategic location of desalination units should also include the risks associated with the causes and consequences of co-location.

15.4.4 Environmental Impact

Several environmental issues can decrease the viability of the desalination plants by affecting the intake system. Algal blooms and numerous organic nature biomasses can severely influence the desalination operation, which may constrain a plant to close down. In harsh climates, such as in Middle East, cyanobacteria due to their toxin production pose a growing risk to water security. For sustainable water supply, the protection of resources and the reduction of possible causes of pollution is necessary for safe water. Furthermore, oil slick from hydrocarbon fuel spills may also result in restricting the flow in the intake screen (Al Hashar et al. 2004). These organic nature masses produce contaminants which can be passed onto the water supply or increase turbidity of the feed water (Darwish et al. 2016c). This results in partial plant shutdown or suspending pretreatment faculties for proper operation within safe consumption limits for machines and human usage.

Arabian Gulf is a relatively small sea body with shallow water and high evaporation rate making it the most saline water in the world. Moreover, continuous brine discharge also poses a threat to aquatic life and feed water salinity (Darwish 2015). This high saline water pose an operational risk and demands energy-intensive process to desalt water. Moreover, due to the natural ocean current, Arabian Gulf is exposed to only narrow opening channel resulting in water replenishment every 8–9 years. This implies that polluted water from sewage, power plants and oil tankers takes a longer time to flush out of the system.

Brine also increases locally the temperature of the seabed thereby affecting the marine life. Marine ecosphere is extremely sensitive to the seasonal changes. In some seasons, saltwater from sea comprises of plankton, which has suspended particles not appropriate for intake systems. Moreover, desalination sites also heavily produce air pollutants such as carbon and sulfur dioxides emissions (Dawoud and Al Mulla 2012). All these causes may force a factory to partially shut down and reduce the productivity to meet the environmental limitations.

15.4.5 Plant Equipment Failure

The failure of equipment in a desalination plant may be the result of a problem with the reliability of machineries, failure modes, or man-made errors. These machinery failure events can assist in identifying the critical components and procedures leading to the shutdown of the plant. A reliable plant can reduce the maintenance costs, smoothen the operations and decreases the unplanned outages. To assess the failure of the equipment, the effect of equipment breakdown on system failure must be examined. The reliability of the plant depends on the design of the equipment, maintenance schedule, failure rates, and likelihood. The reduced plants performance could be due to operating conditions and ineffective instruments. These subsystems include pumps, heat exchangers, evaporators, valves, membranes, and electronic faults.

Major startup difficulties and plant stoppages in the desalination units usually arise from (Kutbi et al. 1981)

- Failure of pumping and acid injection system
- Electrical issues like faulty power cable
- Malfunctioning of inverters and electronic boards due to substantial oxidation
- Oil spill in the sea
- Fire in the lining of the generator
- Improper operation of the fiberglass housing on Reverse Osmosis plants

Table 15.2 Failure probabilities and intensities of seawater reverse osmosis systems and intake systems with individual components

Component	Failure probability 10^{-3}	Failure intensity 10^{-2}
Seawater intake system		
Pump	3.2	2.7
Piping	2.5	4.2
Valves	4.4	4.0
Intake screen	2.7	2.2
Overall system	18	20.0
Reverse osmosis system		
Pump	12	9.4
Piping	2.4	3.7
Valves	3.7	3.4
Engine	12	9.4
Overall system	220	98.0

Reproduced from Kutbi et al. (1981)

- Intake system issue
- Electronic issues related to control panels

In both seawater intake system and reverse osmosis system in the complete desalination unit, the major contribution to plant's failure results from malfunctioning of pumps. This is caused by erosion, corrosion and cavitation in the pumps. After pump, pipe leakage and faulty valve results in operational problems (Kutbi et al. 1981). Table 15.2 shows the failure probabilities and failure intensities of seawater reverse osmosis systems and intake systems with individual components. Based on the analysis and reports, preventative maintenance schedule can be optimized for smooth operations to reduce the occurrence of plant failure.

15.4.6 Urban Pipe Network Vulnerability

Most of the cities in Middle Eastern countries transport water through long network of pipes from coastal areas to inland cities. For example, Riyadh, a city in the middle of Saudi Arabia, currently meets half of its urban demand using desalted water from shoreline through a network of hundreds of kilometers using pumps. (Owens et al. 2017) Therefore, the resilience study should include water network as a part of desalination system for the end product of urban water supply. These networking of pipes are spread on a large area under extreme conditions of temperature and pressure. As a result, risks related to leakage and pipe rupture are inevitable and may reduce the urban water security. Low ground areas pose a serious threat to water leakage from these networks. Pipe joints are also susceptible to failure resulting in ingress of impurities and seepage.

High-pressure pumps employed for fluid transfer may also be damage by water hammering phenomenon which is caused by sudden change in pressure or cavitation. (Ghidaoui et al. 2005) This remove the pipes from their supports and may cause damage to pump's components such as impeller. Issues like leak and irregular water supply phases intensifies the probability for contamination. Moreover, storing water supply for urban usage is not consumer friendly due to the possible contamination of water quality (WHO and DFID 2009). Natural disaster such as earthquakes and floods should be taken into consideration where storm water retention basins should be utilized for leaks and floods. Water system resilience can be modeled using system's approach by evaluating and analyzing failures for this particular region. (Da Silva et al. 2012)

15.5 Strategies for Desalination Water Resilience

Above discussion shows that desalination plants are vulnerable and may be affected by various factors. In order to establish robust and reliable technology, resilience measures should be implemented to overcome disastrous situation. Following are some resilience measures discussed in detail:

15.5.1 Groundwater Management and Strategic Water Storage

With the depletion of renewable ground water, most of non-renewable aquifers have also been exhausted in GCC region. Wajid aquifer which is located in the south of Saudi Arabia and shared by Saudi Arabia and Yemen is projected to be exhausted within 10 years (ESCWA and BGR 2013). Around two-thirds of groundwater aquifers are dried in Saudi Arabia but situation in other GCC countries is also not good. UAE water levels in aquifers have been dropping with the rate of 1 m/year for last 30 years causing seawater intrusion and increased salinity resulting in unfit ground water for domestic and agricultural use (ESCWA and BGR 2013; Kader 2015). Umm-er-Radhuma aquifer is located in east side of Saudi Arabia and stretches to Bahrain and Qatar. Most of the water is drawn from Dammam for agricultural development projects. The renewability of Umm-er-Radhuma aquifer is very low, from 0~20 mm/yr. and it will be depleted within 30 years. Currently, there are no written agreements between countries for shared aquifers management (Darwish 2015). A joint management system is needed to ensure sustainable use of aquifers, to reduce salination and to avoid potential conflicts between countries. Developing resilience system would result in policy implications. Furthermore, joint policies are needed for ground water resource management which should consist of transparent allocation of resources and necessary compensation between different usages.

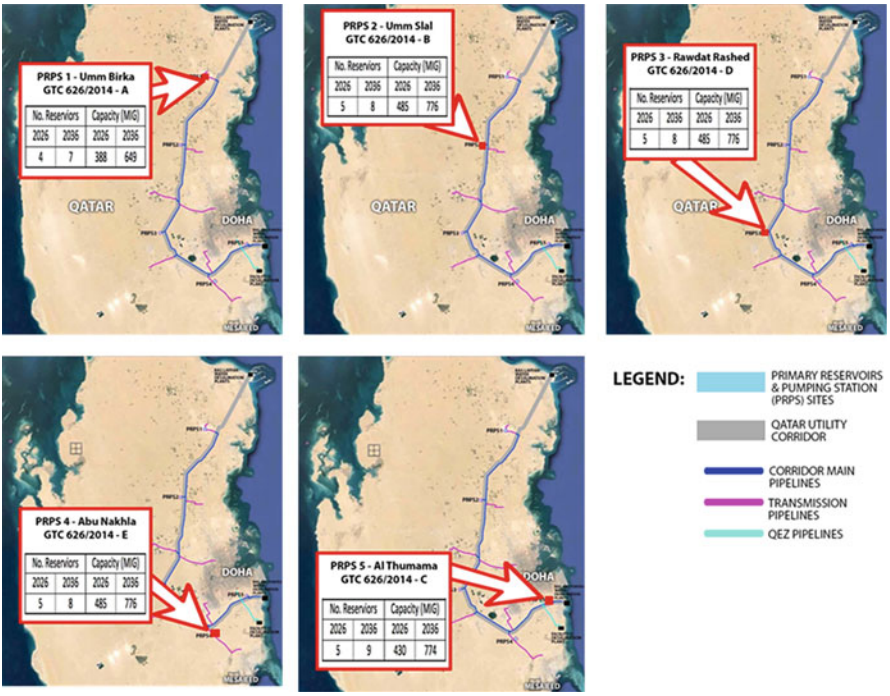

Fig. 15.8 Mega reservoir projects in Qatar by KAHRAMAA. (KAHRAMAA 2018)

Qatar has now 2 days of water supply in case of emergency but Qatar general electricity and water corporation (KAHRAMAA) is working on mega reservoir projects to extend this supply to 7 days. The project is divided into two phases; first phase consists of reservoirs having cumulative capacity of 2300 million gallons while the second phase consists of 3800 million gallons capacity and is expected to be completed by 2026 and 2036 respectively (KAHRAMAA 2018). Figure 15.8 shows project reservoir locations and piping connection. This project will play a crucial role in water security and making water distribution more resilient for country. Similar strategies are required by other countries for water management, storage assessment and monitoring.

15.5.2 Pretreatment

Pretreatment plays a critical role in reverse osmosis (RO) plant as compared to thermal desalination plants. Correct pretreatment in RO plants ensure membrane robustness and plant reliability. RO membranes can face deterioration and fouling if they come in contact with organic/inorganic compounds, particulate matter,

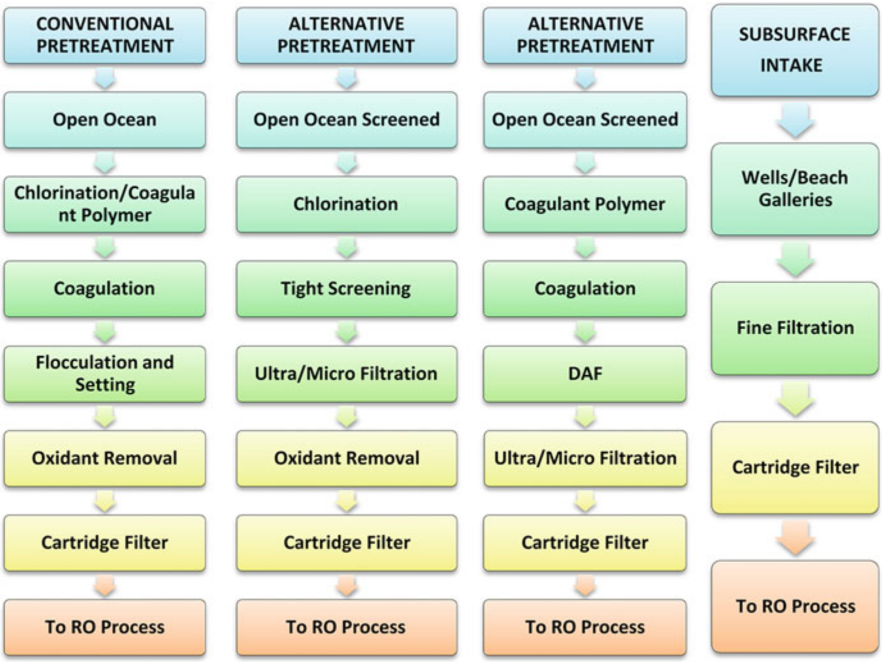

Fig. 15.9 Different pretreatment processes for RO plants

suspended solids, bacteria, microorganisms, and colloidal particles etc. (Wilf and Bartels 2005; Wolf et al. 2005; Valavala et al. 2011). Pretreatment CAPEX may account from 10 to 20% of total plant expenditure (Sutzkover-Gutman and Hasson 2010). Therefore, it is important to choose correct pretreatment processes and sequence for lower cost and better reliability. Figure 15.9 shows pretreatment processes that can be selected based on available resources and plant durability.

Many plants have implemented combination of MF/UF, which reduces the fouling index and footprints as compared to conventional pretreatment processes. With lower fouling probability, RO membranes can have longer life and lower cleaning frequency (Vedavyasan 2007). Water quality, process complexity, and operating cost are the key factors that should be considered in the feasibility study for SWRO plants. Considering these factors, subsurface beach well intake system is one of the feasible methods available in the literature (Voutchkov 2005). The utilization of subsurface beach well intake for seawater reverse osmosis (SWRO) desalination plants improves raw water quality, lessens chemical utilization and ecological effects, diminishes the carbon impression, and decreases the cost of treated water. The utilization of chlorine, coagulants, and different chemicals can be eliminated by employing subsurface intake facilities. Subsurface intake systems produce improved quality feed water by removing approximately all of the algae, a high percentage of the bacteria, organic carbon, and marine biopolymers that participates in membrane biofouling. The improved quality feed water allows the use of a simpler, less expensive pretreatment system. The performance of beach wells is site-specific and depends largely on the local hydrogeology (Missimer et al. 2013a; Rachman et al. 2014; Dehwah and Missimer 2016).

The pretreatment technology should be adopted after considering resilience measures to climate change, cost and social grounds. Preference should be given to technologies, which are resilient to climate change such as beach wells or subsurface intake systems. Less resilient technologies should only be deployed where regional conditions demonstrate enough resilience to predicted climate changes or where more resilient technologies cannot be implemented due to economics and other factors (Dehwah and Missimer 2016).

15.5.3 Water Distribution Network

For establishing resilient water distribution network, it is necessary to consider all focal stages such as plant location, intakes, and distribution. Water distribution system is considered as inherently vulnerable to climatic changes because of the complexity, leakages, intermittent supply and large dimensions. One example is of 2007 floods in Gloucester (United Kingdom) which flooded Myhte pumping station and entire water supply was disturbed (WHO and DFID 2009). Water safety plan can be used to identify vulnerabilities at each level of the network and it can be an effective way in evaluating impacts and adaptation options (Bartram 2009). Also, new risk assessment tools can be implemented to determine uncertainty. Availability of water supply system and assets are two main components that should be considered in calculating likelihood of a long-term interruption to supply occurring.

Smart urban planning is required to reduce leakages, complexity and capital cost. For example, if there is a long water supply line between two cities then new city may be developed between them. A lot of research has been carried out in optimizing water supply network for robust and resilient design. Savic and Walters (Savic and Walters 1997) applied genetic algorithm to water supply network and they concluded that least cost system can be designed using optimization. A similar study was carried out by Cunha and Sousa but they used simulated annealing based stochastic optimization (Cunha and Sousa 1999). Eusuff and Lansey (2003) found shuffled frog leaping algorithm (SFLA) promising in optimizing supply network expansion and new distribution system. Vasan and Simonovic (2010) proposed that differential evolution algorithm can be used as an alternative to other optimizations for designing economical and resilient water supply networks.

15.5.4 Efficient Agricultural Practices

Agriculture places heavy burdens on GCC ground water system as most of the ground water is used for irrigation. In 2005, water consumption for agriculture sector in Qatar was 261.5 Mm3/y out of which 83% of the water was from ground water resources and rest was from treated sewage effluent (TSE) (Darwish and Mohtar 2013). Figure 15.10 shows that agriculture sector accounts for 45% and 59% of the total water needs in Bahrain and Qatar respectively. While for Saudi Arabia, Kuwait, Oman, and UAE it accounts for more than 80% and for whole GCC 85% of the water is used in irrigation which should be minimized for water security of the region (Sadik 2012; Darwish et al. 2015). After diplomatic crisis in Qatar, vegetables production has been increased by 100% and constant supply of dairy products to local markets have been made since last year. However, it affected water demands from ground and desalination plants, so for sustainable water supply Qatar is planning to increase wastewater and treatments plants for agriculture and construction purposes. It is estimated that 95% of agriculture crops can be produced by using treated sewage effluent (TSE) (Ali et al. 2016).

Targeted cultivation and modern irrigation techniques could enhance domestic crops production. Mekonnen and Hoekstra reported that through effective irrigation approaches global water savings of 39% can be achieved with 54% reduced water pollution (Mekonnen and Hoekstra 2014). Some of the needed cultivation techniques for GCC countries from literature are as follows:

- Selecting crops that use less water per metric, that are compatible with local soil quality and can adhere elevated temperature in GCC countries would reduce the overall water demands and load on desalination plants and energy sector.

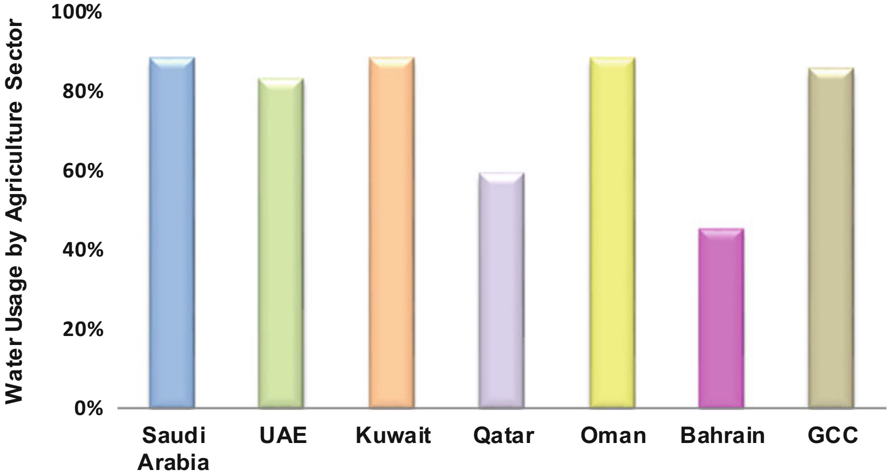

Fig. 15.10 Water usage by agriculture sector. (Sadik 2012; Darwish et al. 2015)

- Reducing unwanted evapotranspiration by managing plant spacing, crop scheduling and reducing tillage (Ventura and Sagi 2013).
- Using plant mulches and residue for better nutrient recycling (Ventura and Sagi 2013).
- Management of soil nutrients through erosion control, optimized crop rotation and proper application of fertilizer (Ventura and Sagi 2013).
- Yield increment by weed and pest control.
- Implementing enhanced farming techniques such as drip and sub surface irrigation (Ventura and Sagi 2013).
- Increasing soil sanitization in gulf region requires crops cultivation that are edible and can grow in salty environment such as halophyte salicornia and sarcocornia (Ventura and Sagi 2013). UAE established International Center for Biosaline Agriculture (ICBA) in 1999 that focuses on biosaline crop cultivation and food security of gulf region (Pirani and Arafat 2016).
- Investments in foreign agricultural lands with better fertility and water availability. GCC countries have already acquired lands mainly in Sudan, Morocco, South Sudan, Zimbabwe, Pakistan and other countries and started crop production. This step will reduce water and energy burdens on the GCC region (Pirani and Arafat 2016).

15.5.5 Desalination Using Low Carbon Energy

As more desalination plants are being installed due to increasing demand, water intakes near coastal areas may have become vulnerable to increased salinity. This leads to high energy consumption resulting escalated carbon footprints, which needs to be minimized. There can be two options; one is to use renewable energy source like solar Photovoltaics (PV), solar thermal, wind etc. and second is to develop energy efficient desalination plants. First option will diminish carbon burden on the environment and second will reduce carbon footprints to some extent, combination of both will result in sustainable and energy efficient systems.

GCC countries accounts for 3.8% of the total CO_2 emissions in the world but these countries have highest CO_2 emissions per capita due to high energy and water consumption with poor efficient systems (BP 2018). Saudi Arabia contributes to 56% of CO_2 emissions in gulf as shown in Fig. 15.11. However, due to increase in energy and water demands, several steps have been taken to use efficient system and renewable energy resources to overcome carbon footprints. Kuwait and Qatar are targeting 15% and 20% respectively of their energy demands via renewable sources by 2030. UAE will add 5 GW solar plant in Dubai by 2030 and Saudi Arabia will add 54 GW of renewable energy by 2040. Qatar is also planning to establish solar desalination plants, to meet agriculture water needs and to reduce dependence on its diminishing aquifers. Small units like humidification and dehumidification (HDH) desalination units can be operated with low-temperature heat source from cooling of solar panels (Bahaidarah et al. 2014, 2016; Baloch et al. 2015). Therefore, solar

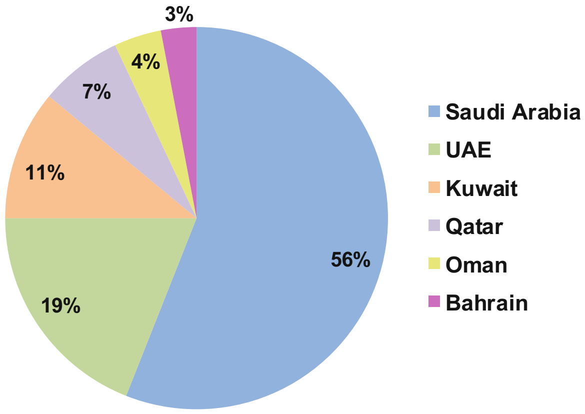

Fig. 15.11 Carbon emissions by countries in GCC. (BP 2018)

desalination can be a feasible option to accommodate water gap by considering the required change in terms of financing, policy, and regional cooperation to make this alternative method of desalination a success (Darwish 2014).

In existing desalination plants, performance ratio ‘PR’ is limited to 8–10. As MED plants are more efficient than MSF plants in terms of specific power consumption and no further improvement is expected in MSF plants as MSF technology is matured (Tahir et al. 2018). So researchers are focusing on improving MED design and some new designs are reported in the literature, which can raise PR more than 50% as compared to existing output. Mabrouk et al. modified evaporator design and integrated MED with absorption vapor compression (AVC) instead of thermal vapor compression (TVC) system (Mabrouk et al. 2017a, b) because the thermal efficiency of TVC is lower than AVC system. Theoretical results showed lower specific power consumption, less plant footprint (lower CAPEX), reduced evaporator losses, and more than 50% water production depending on seawater quality, ambient and operating conditions. In an another design by Ng et al. (Ng et al. 2015), TVC is replaced by silica gel based adsorption vapor compression (AdVC) which also showed enhanced water production similar to MED-AVC.

15.5.6 Floating Desalination Plants

Floating desalination plants are ship based desalination plants that can be moved from one place to another depending on the requirement. Mitenkov et al. (Mitenkov et al. 1997) studied floating SWRO desalination plant using nuclear power generation proposed by ministry of Russian Federation of atomic energy. The advantages of proposed plant included:

- Cheap source of clean energy as compared to fossil fuels
- Long term reliability and can be moved to required place in minimal time period.

- Can be anchored in various coastal region of the world.

This plant had the proposed capacity of 80,000 m^3/day having refueling interval of 2~3 years. Therefore, a floating desalination plant can be a feasible option in case of temporary water shortage problems. As was in the case of Jeddah plant failure, SWCC setup two desalination barges having total capacity of 50,000 m^3/day at Yanbu, these floating plants provided fresh water to Madinah and Yanbu (Rasooldeen 2010).

As discussed in above section, harmful algal blooms (HABs)/red tide can cause desalination plant to shut down. Floating desalination plants can also be used to encounter HABs detrimental effects as explained in (Owen and Owen 2013). In their study, they discussed that HABs are affected by sudden environmental perturbations, which can be made possible by floating desalination plants. The discharge of desalination unit consists of hyposaline (fresh water), hypersaline (high salinity) and heated water. These discharges can disrupt seawater stratification in water column which leads to momentary cysts formation and minimizes population growth of motile and dinoflagellates. So discharges from floating desalination plants can be fashioned in such a manner that would eventually cause HABs elimination.

15.5.7 Technology Mix

All of the desalination technologies have some advantages and disadvantages. Such as RO plant is vulnerable to HABs and turbidity. The overall performance of RO plants is affected by salinity, which is high in the Gulf region and pretreatment is required. In state of the art technologies, RO offers least cost of distillate and energy consumption. On the contrary, thermal desalination can withstand seawater with harsh conditions. In the area of thermal desalination, MSF plant has higher energy consumption and top brine temperature ‘TBT’ than its counterpart MED. However, MSF offers additional advantages such as smooth operation, longer plant life and absence of fouling. MED uses low-grade energy with TBT of around 65 °C, which makes it feasible to utilize waste heat but this technology, is more susceptible to fouling. Therefore, relying on one technology makes system vulnerable and combination of these different desalination types is needed for resilient water supply. Figure 15.12 shows schematic of RO and thermal desalination plant coupled with CCPP. In case of plant failure, thermal desalination system will go down but RO can be run from substation with electricity from outside. In case of HABs or high turbidity, RO plant cannot run but there will be water supply from thermal desalination unit.

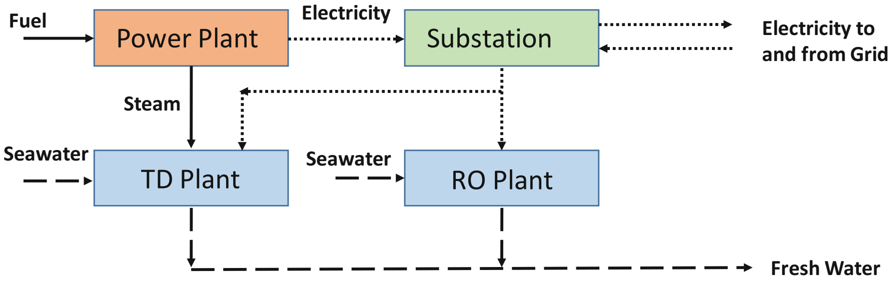

Fig. 15.12 Thermal desalination and RO plant coupled with power plant

15.5.8 Virtual Food Water Import

One of the resilience measures is the virtual water trade in food imports. Virtual water is defined as the volume of water used to produce unit crop in a particular region (Same crop may have different virtual water content depending on the region, where it was produced). GCC countries are heavily dependent on food imports and the cost of growing food locally is more vulnerable for water supply and involves higher risk to water level. Therefore, virtual water trade is the best option for water-scarce regions. Virtual water import quantity can be calculated for each type of food by following expression:

$$\mathrm{VW_i}(\mathrm{m}^3) = \mathrm{Food_i}(\text{in tons}) \times \text{virtual water contents } (\mathrm{m}^3/\text{ton}) \tag{15.1}$$

Countries in Middle East like UAE, Kuwait, and Qatar fulfill almost all of their cereals needs from imports (AOAD 2012). Imported virtual food water items in GCC include rice, barley, pulses, maize, dairy, meat, fruits, vegetables, wheat, eggs and fish as shown in Fig. 15.13 (Darwish et al. 2015). For Qatar, only 6% of land mass is fit for agriculture due to biophysical constraints (MDPS 2015). Qatar traded virtual water with an average of 1360 Mm3/year from 1998 to 2015 and it covered 70% of the total water requirement (Mohammed and Darwish 2017). On average, 15.5% of the virtual water import was from Saudi Arabia but after diplomatic crisis with neighboring countries that began in 2017, Qatar has faced virtual water trade deficit, which she has covered by trading with other countries and developing agriculture/dairy farms within the country. GCC countries have to develop proactive policies in order to address virtual water trade to overcome water crisis.

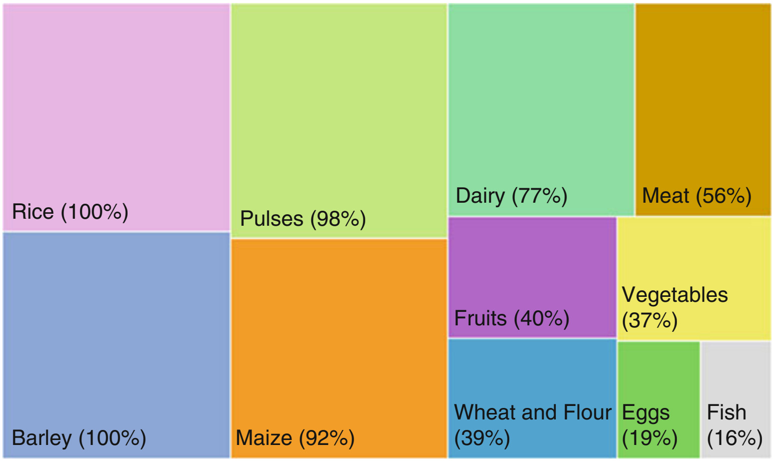

Fig. 15.13 Imported food items as a proportion of consumption in GCC (%). (Darwish et al. 2015)

15.6 Recommendations for Resilient System

A sustainable and resilient desalination system will ensure water and food security of the GCC region. The recommendations and measures for resilience are summarized below:

- Agriculture practices heavily burdens Middle Eastern ground water system due to the over usage for irrigation and less replenishment. This should be practically substituted by virtual water trade in food imports. Food import with less virtual water content should be recommended.
- For a resilient water distribution network, it is necessary to consider all focal stages such as plant location, intakes, and distribution.
- Pretreatment plays a critical role in RO plant as compared to thermal desalination plants. Correct pretreatment in desalination plants ensures membrane robustness and plant reliability. Preference should be given to technologies, which are resilient to climate change such as beach wells or subsurface intake systems.
- Technological diversification must be adopted ensure constant water supply without relying on fossil fuel-based desalination plants.
- Desalination plants with lower energy consumption and unit distillate cost like hybridization or MED-AVC should be employed to reduce energy based risks.
- Floating desalination ships have also been employed as emergency measures and can be considered for water security depending on the requirement.
- Social awareness campaigns for water usage and savings must be adopted for local population.
- Sea water toilet flushing can be employed to reduce load on desalination plants.
- Desalination plants should be located such that the impact for collocated oil plants and oil spills from marine traffic is minimal.

- Contingency plans should be established based on the modeling of oil leakage motion and pattern considering the sea currents.
- Potable water solution for remote areas such as PV with RO should be encouraged to reduce the reliance on main desalination plants and pipeline associated issues.
- Water storage and reservoirs for population must be developed as a preventive measure to counter natural or man-made disasters.
- Based on the failure probabilities and intensities of seawater reverse osmosis systems and intake systems with individual components, preventative maintenance schedule should be optimized for smooth operations to reduce the occurrence of plant failure.

15.7 Conclusion

Sustainability of desalination plants can be studied by understanding the resilience of these systems under possible vulnerabilities. For a sustainable water supply system, careful consideration must be given to current and future water demands by analyzing the possible events that may alter the operational stability and productivity of the system. Considering the need, this chapter addresses the most recent and proactive approaches to resilience by evaluating the possible vulnerabilities for desalination plants. These natural and artificial vulnerabilities should be reduced while designing the plants to counter the issue of water scarcity for individual and nations. Middle eastern climate serves as the prime example due to its terrain and limited availability of water resources. To understand the importance of resilience, case studies and examples have been showed. Oil spill, harmful algal blooms and plant equipment failure were found to be the most dominant vulnerabilities leading to downtime of desalination plants. The reliability of the plant depends on the design of the equipment, maintenance schedule, failure rates and likelihood. The impact of co-located desalination plants and piping network poses a chronic threat to water security in the region. Several environmental issues can also decrease the viability of the desalination plants by impacting the intake system. Desalination plant results in failure of equipment due to reliability of machineries, failure modes, and man-made errors. To assess the failure of the equipment, the effect of equipment breakdown on system failure must be examined. The outlook of nationwide plans and policies in the region looks encouraging as they are already on the path towards a resilient and sustainable society realized by the ongoing projects such as Groundwater Management and Strategic Water Storage, and research programs in desalination using low carbon energy and pretreatment techniques. With the ever-changing dynamics of desalination industry and increasing water supply, adaptive measures presented should be adopted and risk-based inspections should be carried out to address any conceivable technological issue.

References

Abouhatab A (2018) Water scarcity and water trade: an analysis of the determinants of virtual water flows to the GCC countries. In: Qatar foundation annual research conference proceedings. Doha

Al Hashar N, Anisuddin S, Sadik T, Tahseen S (2004) Oil spill pollution in seawater – a hindrance for desalination. Desalination 166:305. https://doi.org/10.1016/j.desal.2004.06.085

Al Muftah A, Selwood AI, Foss AJ et al (2016) Algal toxins and producers in the marine waters of Qatar, Arabian Gulf. Toxicon 122:54–66. https://doi.org/10.1016/j.toxicon.2016.09.016

Alhanaee G, Sanders K, Meshkati N (2017) Rising temperatures, rising risks: the food-energy-water nexus in the Persian Gulf. Environ Sci Technol 51:4117–4118. https://doi.org/10.1021/acs.est.7b00688

Ali H, Mohamed H, Hamar Y, Al-Murikhi A (2016) Current and future water resources for agriculture in Qatar state. Br J Appl Sci Technol 18:1–13. https://doi.org/10.9734/BJAST/2016/17881

AOAD (2012) Arab agricultural statistics yearbook. Khartoum

Bahaidarah HM, Gandhidasan P, Baloch AAB et al (2016) A comparative study on the effect of glazing and cooling for compound parabolic concentrator PV systems – experimental and analytical investigations. Energy Convers Manag 129:227–239. https://doi.org/10.1016/j.enconman.2016.10.028

Bahaidarah HMS, Baloch AAB, Gandhidasan P (2014) Modeling and comparative analysis of jet impingement cooling and conventional channel cooling for photovoltaic strings. In: 2014 IEEE 40th photovoltaic specialist conference (PVSC). IEEE, pp 0748–0753

Baloch AAB, Bahaidarah HMS, Gandhidasan P, Al-Sulaiman FA (2015) Experimental and numerical performance analysis of a converging channel heat exchanger for PV cooling. Energy Convers Manag 103:14–27. https://doi.org/10.1016/j.enconman.2015.06.018

Bartram J (2009) Water safety plan manual: step-by-step risk management for drinking-water suppliers. World Health Organization, Geneva

BP (2018) BP statistical review of world energy

da Cunha MC, Sousa J (1999) Water distribution network design optimization: simulated annealing approach. J Water Resour Plan Manag 125:215–221. https://doi.org/10.1061/(ASCE)0733-9496(1999)125:4(215)

Da Silva J, Kernaghan S, Luque A (2012) A systems approach to meeting the challenges of urban climate change. Int J Urban Sustain Dev 4:125–145. https://doi.org/10.1080/19463138.2012.718279

Darwish M (2015) Desalination engineering, 1st edn. Balaban Desalination Publications, Hopkinton

Darwish M (2014) Qatar water problem and solar desalination. Desalin Water Treat 52:1250–1262. https://doi.org/10.1080/19443994.2013.815684

Darwish MA, Abdulrahim H, Mohammed S, Mohtar R (2016a) The role of energy to solve water scarcity in Qatar. Desalin Water Treat 57:18639–18667. https://doi.org/10.1080/19443994.2015.1103666

Darwish MA, Abdulrahim HK, Hassan AS, Shomar B (2016b) Reverse osmosis desalination system and algal blooms part II: seawater intake technologies. Desalin Water Treat 3994:1–37. https://doi.org/10.1080/19443994.2016.1159619

Darwish MA, Abdulrahim HK, Hassan AS, Shomar B (2016c) Reverse osmosis desalination system and algal blooms part I: harmful algal blooms (HABs) species and toxicity. Desalin Water Treat 57:25859–25880. https://doi.org/10.1080/19443994.2016.1159618

Darwish MA, Abdulrahim HK, Mohieldeen Y (2015) Qatar and GCC water security. Desalin Water Treat 55:2302–2325. https://doi.org/10.1080/19443994.2014.947782

Darwish MA, Mohtar R (2013) Qatar water challenges. Desalin Water Treat 51:75–86. https://doi.org/10.1080/19443994.2012.693582

Dawoud MA, Al Mulla MM (2012) Environmental impacts of seawater desalination: Arabian Gulf case study. Int J Environ Sustain 1:22–37. https://doi.org/10.24102/ijes.v1i3.96

Dehwah AHA, Missimer TM (2016) Subsurface intake systems: green choice for improving feed water quality at SWRO desalination plants, Jeddah, Saudi Arabia. Water Res 88:216–224. https://doi.org/10.1016/j.watres.2015.10.011

El-Sayed Elshorbagy W, Elhakeem AA (2012) Forecasting the oil spill impacts on coastal desalination plants in United Arab Emirates. pp 263–274

Elshorbagy W, Elhakeem A-B (2008) Risk assessment maps of oil spill for major desalination plants in the United Arab Emirates. Desalination 228:200–216. https://doi.org/10.1016/j.desal.2007.10.009

ESCWA, BGR (2013) Inventory of shared water resources in Western Asia. Beirut

Eusuff MM, Lansey KE (2003) Optimization of water distribution network design using the shuffled frog leaping algorithm. J Water Resour Plan Manag 129:210–225. https://doi.org/10.1061/(ASCE)0733-9496(2003)129:3(210)

FAO (2018) Water resources. http://www.fao.org/nr/water/aquastat/water_res/index.stm

Folke C, Carpenter S, Elmqvist T et al (2002) Resilience and sustainable development: building adaptive capacity in a world of transformations. AMBIO A J Hum Environ 31:437–440. https://doi.org/10.1579/0044-7447-31.5.437

Ghidaoui MS, Zhao M, McInnis DA, Axworthy DH (2005) A review of water hammer theory and practice. Appl Mech Rev 58:49. https://doi.org/10.1115/1.1828050

Gude VG (2015) Energy and water autarky of wastewater treatment and power generation systems. Renew Sust Energ Rev 45:52–68. https://doi.org/10.1016/j.rser.2015.01.055

Handmer JW, Dovers SR (1996) A typology of resilience: rethinking institutions for sustainable development. Organ Environ 9:482–511. https://doi.org/10.1177/108602669600900403

Hashimoto T, Loucks DP, Stedinger J (1982) Reliability, resilience and vulnerability criteria for water resource system performance evaluation. Water Resour Res 18:14–20

Hess P, Villacorte Loreen O, Dixon Mike B et al (2017) Harmful algal blooms (HABs) and desalination: a guide to impacts, monitoring, and management. Intergov Oceanogr Comm UNESCO 539:53–88

Kader BA (2015) Abu Dhabi's groundwater to run out in 50 years. Gulf News

KAHRAMAA (2018) Water security mega reservoirs project. In: www.watermegareservoirs.qa

Kim BK, Jeong YH (2013) High cooling water temperature effects on design and operational safety of NPPS in the Gulf region. Nucl Eng Technol 45:961–968. https://doi.org/10.5516/NET.03.2012.079

Kutbi II, Metwally AM, Sabri ZA, Husseiny AA (1981) Reliability of the Jeddah seawater RO desalination plant based upon operations experience. Desalination 39:179–191. https://doi.org/10.1016/S0011-9164(00)86123-8

Mabrouk A, Abotaleb A, Abdelrehim H, et al (2017a) High performance MED desalination plants, part II: novel integration MED-absorption vapor compression. In: IDA world congress on water reuse and desalination. Sao Paulo, Brazil

Mabrouk A, Abotaleb A, Tahir F, et al (2017b) High performance MED desalination plants part I: novel design MED evaporator. In: IDA world congress on water reuse and desalination. Sao Paulo, Brazil

MDPS (2015) National accounts bulletin. Doha

Mekonnen MM, Hoekstra AY (2014) Water footprint benchmarks for crop production: a first global assessment. Ecol Indic 46:214–223. https://doi.org/10.1016/j.ecolind.2014.06.013

Meshkati N, Tabibzadeh M, Farshid A et al (2016) People-technology-ecosystem integration. Hum Factors J Hum Factors Ergon Soc 58:43–57. https://doi.org/10.1177/0018720815623143

Missimer TM, Ghaffour N, Dehwah AHA et al (2013a) Subsurface intakes for seawater reverse osmosis facilities: capacity limitation, water quality improvement, and economics. Desalination 322:37–51. https://doi.org/10.1016/j.desal.2013.04.021

Missimer TM, Ghaffour N, Dehwah AHA et al (2013b) Subsurface intakes for seawater reverse osmosis facilities: capacity limitation, water quality improvement, and economics. Desalination 322:37–51. https://doi.org/10.1016/j.desal.2013.04.021

Mitenkov FM, Polunichev VI, Zverev KV (1997) Floating nuclear power-desalination complex using a nuclear power plant of the KLT-40 type and the reverse osmosis process. In: Nuclear desalination of seawater. Republic of Korea, Taejon, pp 255–269

Mohammed S, Darwish M (2017) Water footprint and virtual water trade in Qatar. Desalin Water Treat 66:117–132. https://doi.org/10.5004/dwt.2017.20221

Ng KC, Thu K, Oh SJ et al (2015) Recent developments in thermally-driven seawater desalination: energy efficiency improvement by hybridization of the MED and AD cycles. Desalination 356:255–270. https://doi.org/10.1016/j.desal.2014.10.025

Owen KC, Owen JL (2013) Floating desalination and water pumping plants as harmful algal bloom control technologies. J Mar Sci Res Dev 03. https://doi.org/10.4172/2155-9910.1000140

Owens A, Doufene A, Design CS, et al (2017) Assessment of resilience in desalination infrastructure using semi-markov models

Parveena P (2010) The electric energy – water nexus: managing the seasonal linkages of fresh water usein energy sector for sustainable future WP-2010-017

Pearson WH, Neff JM, Brandt CJ, et al (1998) Assessment of damages to commercial fisheries and marine environment of Fujairah, United Arab Emirates, resulting from the Seki oil spill of March 1994: a case study

Pelling (2003) The vulnerability of cities: natural disasters and social resilience. Earthscan

Pirani SI, Arafat HA (2016) Interplay of food security, agriculture and tourism within GCC countries. Glob Food Sec 9:1–9. https://doi.org/10.1016/j.gfs.2016.05.002

Rachman RM, Li S, Missimer TM (2014) SWRO feed water quality improvement using subsurface intakes in Oman, Spain, Turks and Caicos Islands, and Saudi Arabia. Desalination 351:88–100. https://doi.org/10.1016/j.desal.2014.07.032

Rasooldeen M (2010) Floating desalination plant launched in Yanbu. Arab News

ROPME (2013) State of the marine environment report 2013. pp 1–31

Sadik A-K (2012) Food security and agricultural sustainability, in the Arab environment 5, Survival option: ecological footprint of Arab Countries. In: Saab N (ed) Report of the Arab forum for environment and development, 2012

Savic DA, Walters GA (1997) Genetic algorithms for the least-cost design of water distribution networks. ASCE J Water Resour Plan Manag 123:67–77

Sutzkover-Gutman I, Hasson D (2010) Feed water pretreatment for desalination plants. Desalination 264:289–296. https://doi.org/10.1016/j.desal.2010.07.014

Tahir F, Atif M, Antar MA (2015) The effect of fouling on performance and design aspects of multiple-effect desalination systems. Recent Prog Desalin, Environ Mar Outfall Syst:35–52. https://doi.org/10.1007/978-3-319-19123-2_4

Tahir F, Mabrouk AA, Koc M (2018) CFD analysis of spray nozzle arrangements for multi effect desalination evaporator. In: Proceeding of 3rd thermal and fluids engineering conference (TFEC). Begellhouse, Connecticut, pp 935–941. https://doi.org/10.1615/TFEC2018.fip.021685

Valavala R, Sohn J-S, Han J-H et al (2011) Pretreatment in reverse osmosis seawater desalination: a short review. Environ Eng Res 16:205–212. https://doi.org/10.4491/eer.2011.16.4.205

Vasan A, Simonovic SP (2010) Optimization of water distribution network design using differential evolution. J Water Resour Plan Manag 136:279–287. https://doi.org/10.1061/(ASCE)0733-9496(2010)136:2(279)

Vedavyasan CV (2007) Pretreatment trends — an overview. Desalination 203:296–299. https://doi.org/10.1016/j.desal.2006.04.012

Ventura Y, Sagi M (2013) Halophyte crop cultivation: the case for salicornia and sarcocornia. Environ Exp Bot 92:144–153. https://doi.org/10.1016/j.envexpbot.2012.07.010

Voutchkov N (2005) SWRO desalination process: on the beach – seawater intakes. Filtr Sep 42:24–27. https://doi.org/10.1016/S0015-1882(05)70657-1

WHO, DFID (2009) The resilience of water supply and sanitation in the face of climate change

Wilf M, Bartels C (2005) Optimization of seawater RO systems design. Desalination 173:1–12. https://doi.org/10.1016/j.desal.2004.06.206

Wolf PH, Siverns S, Monti S (2005) UF membranes for RO desalination pretreatment. Desalination 182:293–300. https://doi.org/10.1016/j.desal.2005.05.006

Chapter 16
Managing the Forest Fringes of India: A National Perspective for Meeting Sustainable Development Goals

Manoj Kumar, Savita, and S. P. S. Kushwaha

Abstract Forest fringes are the outer reach of the forests which witness majority of the extraction pressure from the community living near to it. For a country like India, where most of the lands are rainfed and lack sufficient irrigation facilities for the agricultural activities, the dependence of the communities is significantly high on the forests for meeting their subsistence needs. When compared to the overall area of the forests, the fringe areas are more vulnerable to extraction pressure. Fringe forests safeguard the interior core forests as long as the anthropogenic pressure does not exceed their resilience. However, the phenomenal increase in human and cattle populations over time and lack of effective management interventions is acting as a barrier in meeting the goals of sustainable development. Over-exploitation of the forest resources had led to the diminishing supply of goods and services. A quantitative assessment of the dependence of the fringe communities on forests is essential for formulating the sustainable actions. We present here a national perspective of the current status of fringes in meeting the goals of sustainable development. We emphasise that forest fringes demand an urgent site-specific prioritised intervention to improve livelihood as well as the ecological health for addressing the goals of sustainable development.

Keywords Fringe forest · Fodder · Fuelwood · Agroforestry · Forest degradation · Socio-economic

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16.1 Introduction

India is one of the most diverse nations in the world, be its societal and cultural setup or the natural ecosystems. The ever increasing population of the country and the dependence of the rural forest fringe communities upon forest resources pose an alarming situation. Country's population was 1.21 billion as per Census of India (2011) with a population density of 382 per km^2. The projected growth of population indicates that India will be the first most populous country in the world and China will be second by 2050 (PRB 2001). Having 18% of the world's population on 2.4% of its land area exerts tremendous pressure on its natural resources. Forest cover of the country as per FSI (2017) is 7,08,273 km^2 which is 21.54% of the geographical area of the country. There has been a stable to slightly increasing trend of forest cover as per the biennial assessments by Forest Survey of India (FSI), Dehradun, India. FSI is an organisation in India under the Ministry of Environment, Forest & Climate Change, Government of India whose mandate is to conduct survey and assessment of forest resources in the country. FSI (2017) assessment report highlighted an increase of 6778 km^2 in the forest cover at the country level compared to the preceding assessment of 2015. Report further states that hilly districts of the country have 40.22% forest cover of their total geographical area that makes them short by nearly 26% for achieving two-third area under forests. The tribal districts have 37.43% area under forests, which acts as one of the major sources for the local tribal population. Hilly areas of the country had a net increase of 754 km^2 in the forest cover while the same was 86.89 km^2 in tribal areas. Areas within 1000 m elevation had net increase in forest cover while those above this elevation witnessed a net decrease.

Ashraf et al. (2017) showed divergent trends from decline to an expansion of country forest areas and *vice-versa* depending on the local socio-environmental conditions. Forest expansion was found to be correlated with the level and the long-term sustainability of the socio-economic development (Moretti et al. 2014; Redo et al. 2012; Rodríguez and Pérez 2013). Looking at the close linkages between the forest and the society, it is imperative to understand the relationship and the extent of resource extraction for prioritising goals of the sustainable development. Sustainable development has been variously conceived in terms of vision expression (Lee 1993), value change (Clark 1989), moral development (Rolston 1994), social reorganization or transformational process (Viederman 1994) toward a desired future or better world (Gladwin et al. 1995). The core idea was defined most influentially by The World Commission on Environment and Development (i.e., The Brundtland Commission) as "development which meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland 1987), which is more widely and universally accepted definition (Gladwin et al. 1995).

Definition of sustainable development encompasses sustainable use of natural resources including forests. Forests and the communities have a close linkages and there always exists a risk of imbalance between them. To improve the forest quality together with the livelihood support in the country in an effective way, there is a need to identify the present status of the forests not only in the form of its canopy density, type of forests but also in the form of information about the extent of dependence of the fringe communities for their livelihood and other essential commodities. Information on identification and mapping of the fringe forest, extent and distribution of forestlands in rainfed areas, identification of forest fringe villages, areas supporting open and/or dense forests, forest vegetation community structure, species diversity, regeneration status, dominant species, socio-economic parameters of human population like land holding, cropping pattern, occupational status, income and household size, livestock population, distance between fringe villages and the nearest town, irrigation facilities, energy consumption/energy use pattern, extent of dependence on forests for fuelwood and fodder, forest products extraction, etc. has recently been studied by Forest Research Institute (FRI), Dehradun (FRI 2017). The information generated by FRI is relevant for the policy makers and would serve as a vital input in planning especially the site-specific planning to address the goals of sustainability.

We present in brief the results of above mentioned study conducted by FRI compiled at the state level (an administrative unit next below the country) that could be helpful in prioritising actions of sustainable development for a country like India. The chapter makes special effort to understand the wider perspective of fringes with reference to sustainability and planning. The overall objective of this chapter is to illustrate how one can compile extensive information at a larger national scale and work out the dimensions or components that could be helpful for the managers to plan sustainable development and management strategies for the forest fringes. The broader theme relates to the communities' dependence at household level for their subsistence needs and their influence on the ecological state of the fringes. The study also provides an understanding on the relationship of the forest fringe villages with the fringe forests summarised at the State level to rank them as low, medium and high categories of dependence. Each State has also been ranked on the basis of use of non-wood forest products (NWFPs) for self-consumption/sale and Shannon's index of diversity representing ecological status. We illustrate various levels of household dependence of respective States which can contribute in prioritising State-specific actions to achieve the overall goals of sustainable development. This task could be achieved by visualising the priority States, which need urgent interventions for the forest conservation, livelihood improvement of forest dependent communities, reducing dependence of the communities upon forest resources and the major forest resources which supports the livelihood. Once these interlinked components are identified and measured, this will certainly help manage our forest fringes in a better way for improving the health of the forests as well as the economic status of the fringe communities.

16.2 Case Study: Forest Resource Dependence of Fringe Communities in Selected Rainfed Districts of India

16.2.1 Background

Rainfed areas are those areas which have scanty rainfall and very often socio-ecological systems of these areas suffer due to lack of sufficient irrigation facilities (Savita et al. 2018). Social as well as ecological systems of these regions depend heavily on rains. Agriculture-dependent communities of rainfed areas are especially at greater risks due to the lack of sufficient irrigation facilities. This forces the communities to look for alternate sources of livelihood for meeting their subsistence needs and this trend is increasing significantly. However, rainfed agriculture plays an important role in India’s economy. The crop-wise analysis shows that major coarse cereals are grown in rainfed areas. The crop productivity in rainfed areas is low and people are dependent on alternative sources including common property resources such as forests for their livelihood. There is, therefore, a need to look into feasible solutions for improving the productivity of rainfed areas along with the other means of livelihood. The serious question being faced by the policymakers is “how to improve the productivity of land while maintaining the ecological equilibrium”. Looking at the implications of the situation and for addressing the emerging issues, National Rainfed Area Authority (NRAA) was constituted as an attached office of the Department of Agriculture, Cooperation, and Farmers Welfare, Ministry of Agriculture and Farmers Welfare, Government of India with an objective to prepare perspective plan and guidelines for effective management with special focus on rainfed areas. Soon after its establishment, NRAA has been successfully developing and implementing various management plans for tackling the emerging issues of the rainfed areas in consultation with various agencies including premier research institutes. One of the mandates of the authority is to serve as a knowledge platform and connect research, academic, and other institutions for the effective planning and implementation of the identified activities through various implementing agencies. NRAA also focuses on the issues of livelihood opportunities for the landless and marginal farmers who constitute a large proportion of the rainfed area population.

While there have been various attempts to define and demark the rainfed areas in the country, there is still a general lack of understanding and consensus for a commonly acceptable definition. According to NRAA, rainfed areas are those where irrigation is $\leq$ 30% of the net sown area (NRAA 2012). Regions with an extent of irrigation exceeding 30% are often defined as “irrigated areas”. According to official statistics, about 86 million ha of the total cultivated area of 143 million ha is rainfed (NRAA 2011, 2012). Rainfed areas are characterized by low agricultural productivity in terms of crop yields as compared to irrigated areas (NRAA 2011, 2012; Kumar et al. 2017). The extent of the rainfed area varies from year to year depending upon the rainfall and water availability in the reservoirs. Most of the rainfed districts of the country suffer from lack of sufficient irrigation facilities making agriculture a cumbersome activity. Consequently, people explore other means of livelihood and forests serve as one of the option to be explored. The prevailing situation exerts pressure on the forests by fringe communities, specifically in the rainfed areas. Thus, there is a need to be more pragmatic while addressing the issues of the rainfed areas for achieving the goals of sustainable development. Identification of the issues and its prioritisation for the effective solution seems to be the top agenda for all of the rainfed districts falling in all agro-climatic zones. Majority of these areas are located in arid and semi-arid regions of the country with a relatively larger population of low-income people.

Foremost identified key issues of the rainfed areas include the degradation of the land mainly because of the unplanned activities, over-exploitation of the natural resources, and an ever-increasing pressure of human and livestock populations on the resources. As a result, even marginal lands are being cultivated by the communities with little support to the livelihood. This has resulted in the degradation of forests because of livestock grazing, fodder extraction and heavy dependence of the local people for fuelwood, timber and non-wood forest resources. The communities of the region have various levels of annual income, agriculture land holding, education and engagement in terms of government and private jobs, thereby making various levels of hierarchical dependence defined by these respective attributes. Landholding and income from agriculture lands are also inadequate and at various levels. This frames various socio-economic hierarchy in these regions, which actually form one of the criteria for ranking of the districts. In rainfed areas, most of the farmers are small land holders. Phenomenal increase of human and cattle populations and lack of effective management interventions in the fringe areas is affecting not only the fringe but also the core forests (FRI 2017). Overexploitation of the forest resources has resulted in vast trails of degraded forests in turn leading to diminishing supply of goods and services from the forests. Hence, there is an urgent need to develop a system in which food, fodder, and fibre can be grown in an integrated manner on the same unit of land. One such system is agroforestry which is a climate-smart solution with many significant co-benefits. In other words, agroforestry can serve as a useful practice in rainfed areas to increase the productivity from land and also to mitigate the climate change impacts. Authorities may also act proactively to implement management interventions that would help in improving the regeneration, thereby improving the health of the forests and the flow of ecosystem services.

This case study focused on the socio-economic assessment with reference to forest resource dependence and ecological status of the fringe forest lands in the rainfed areas. The study will help in prioritising the states for addressing the issues of sustainability and evolving an effective plan at country level to manage forest fringes in a better way. In-depth understanding of the fringe forest areas and the communities depending on these forests will help decision-makers to undertake the meaningful interventions to achieve the goals of sustainability in a more pragmatic manner.

16.3 Materials and Methods

16.3.1 Study Area

The study was conducted in 275 districts of India identified for this study (Fig. 16.1).

Villages located within 1 km distance along the outer periphery of the forest boundary identified for the survey were considered as "forest fringe villages" and has been referred as "forest fringe", where the forest boundaries were derived from the FSI (2011) and represents the forest cover densities mapped using remote sensing signatures of the forests. Whereas, forest areas within reach of 1 km distance inside the forest from outer periphery (i.e. boundary) of the forest were defined as

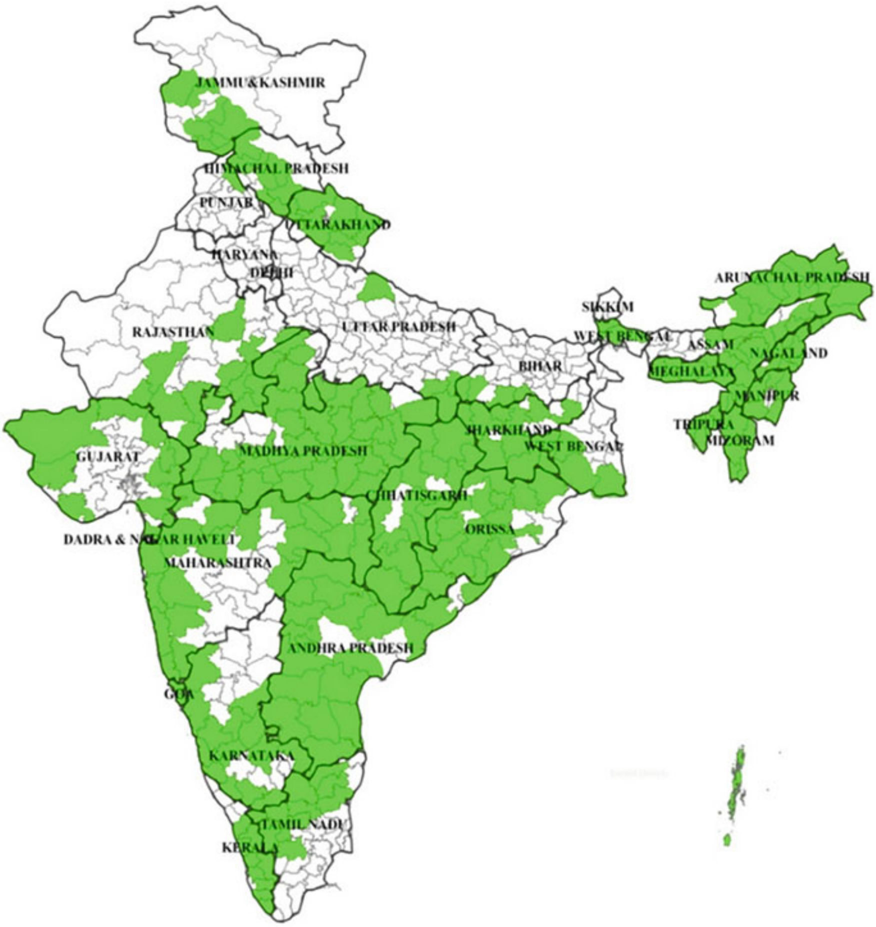

Fig. 16.1 Distribution of rainfed study districts in India (in green colour)

'fringe forests'. For the representation of both outer as well as the inner buffer area of 1 km as a combined representation, word "fringes" has been used throughout the chapter.

16.3.2 Sample Size Selection

Sample size selection for the complete enumeration was tested by conducting initial pilot survey. The number of samples (sample size) appropriate for selecting the number of villages in a district was derived using formula suggested by Cochran (1977) as indicated below.

$$n = \left(\frac{CV(Y) * t}{\varepsilon} \right)^2, \tag{16.1}$$

where n = number of sample plots, CV = coefficient of variation, Y = character under study (magnitude of extraction of forest resource or the degradation/deforestation of forest), t = confidence interval, ε = margin of error. A precision level of $\pm 5\%$ at 95% probability level was achieved.

16.3.3 Socio-Economic and Phytosociological Survey

Socio-economic conditions of the forest fringe communities were assessed by collecting information at the village as well as household level through a standard questionnaire developed specially for this study. Field survey-based information was collected for the sociological and ecological study across more than 100,000 fringe villages spread across 275 districts. Both qualitative, as well as quantitative information were compiled from survey data. For collecting information on the ecological status of the fringe forests, nested quadrat method was followed. The layout of the sample plots for the phytosociological study was adopted from the Forest Survey of India forest inventory manual (FSI 2002) (Fig. 16.2).

Stratified Random Sampling was used for collecting information of socio-economic parameters where first stage sampling units were the villages and the second stage sampling units were households. The first sampling units, i.e. villages within each district were stratified based on the population of the villages available in the population census data of 2011 (Census of India 2011). All the villages in the said districts were arranged in the descending order of population. If '*n*' villages were to be selected, then the list of villages was grouped into n/5 groups and 5 villages were randomly selected from each group using a random number table. In the selected villages, the households were categorized into three groups based on their economic status, i.e., affluent, less affluent, and others. Twelve households in a village were selected randomly for the survey to collect desired information

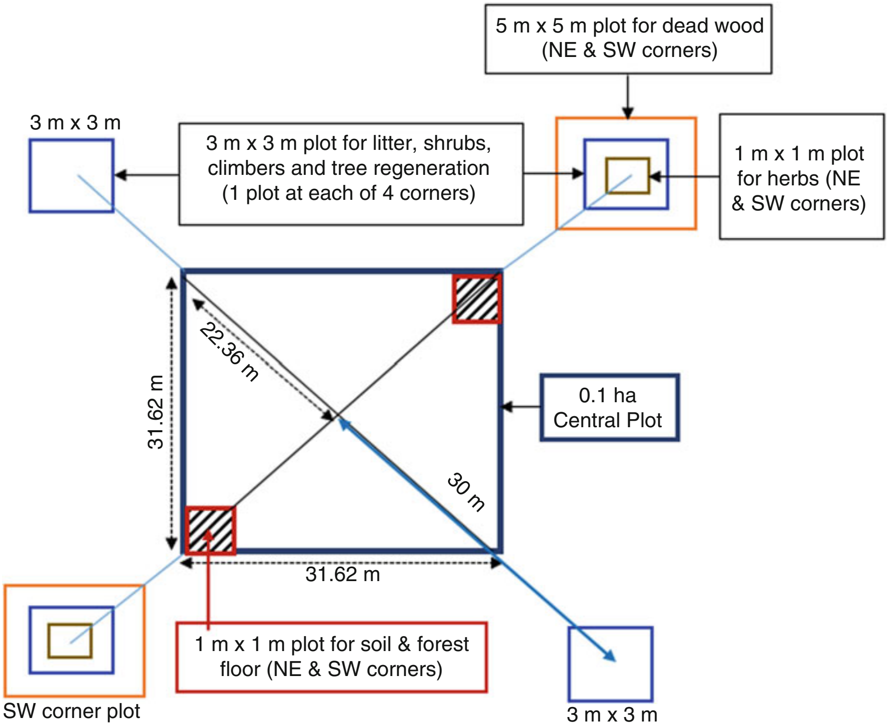

Fig. 16.2 The layout of the sample plots for the phytosociological study (NE: North-East, SW: South-West)

Table 16.1 Selection of household class for the survey

S. No.	Condition	Selection of household classes		
		Affluent	Less affluent	Other
1.	If all 3 household classes are available	Two families from this category	Five families from this category	Five families from this category
2.	If affluent class is not available	Nil	Six families from this category	Six families from this category
3.	If less affluent class is not available	Six families from this category	Nil	Six families from this category
4.	If other class is not available	Four families from this category	Eight families from this category	Nil

in a way so that two, five, and five households are selected from affluent, less-affluent and other class, respectively. The shortfall, if any, in any of the category, was compensated from other classes (Table 16.1).

The ecological study focused for the observation on the importance value index (IVI) (Curtis 1959) and index of diversity (Shannon's Index) (Shannon 1948). Regeneration status of important species was also enumerated while the focus primarily remained to assess regeneration of dominant species only. Shannon's index of diversity has only been discussed in this case study for the sake of simplicity.

Species diversity is an expression of community structure and is unique to the community. The number of species in a community is referred to as species richness when the topography of compartment is homogeneous. The relative abundance of all species is called evenness. Species diversity includes both species richness and evenness. A community demonstrates a high species diversity if many equally or nearly equally abundant species are present. Plant communities with a large number of species that are evenly distributed are the most diverse and communities with fewer species that are dominated by one species are the least diverse. Species diversity was calculated using Shannon's Index of diversity (Shannon 1948).

$$Shannon's\ Index\ of\ diversity\ (H) = -\sum_{i=1}^{s} (P_i * \ln P_i)\,, \tag{16.2}$$

where, P_i = fraction of the entire population made up of species, i; s = numbers of species encountered; ln = natural logarithm and $\sum$ = sum from species 1 to species s.

The diversity of the study area was grouped into low, moderate, high and very high based on the calculated Shannon's value using criteria; low (up to 1.50), medium (1.60–2.50), high (2.60–3.50), and very high (>3.50).

16.4 Results and Discussion

The total number of villages in the studied districts is 310,434, of which 147,127 were identified as forest fringe villages. State-wise distribution of total geographical area, total area under forest, total number of villages and the number of villages identified as fringe villages is presented in Fig. 16.3.

The total geographical area includes 3,233,442 km^2 which is having a total forest cover of 702,819 km^2 comprising 21.73% area under forests. Whereas, the total area demarcated as fringe forests is 386,079 km^2 which is nearly 55% of the total forest area. This indicates that more than half of the forest area is vulnerable to the pressure of extraction by the fringe people. This is primarily witnessed in the form of fuelwood extraction, non-wood forest product (NWFP) collection and fodder usage. Annual fodder consumption from the fringe forest is 45,074,032 Mt., of which 41,577,706 Mt. is grazed and 3,496,326 Mt. is stall-fed.

There is variation in the state-wise pattern of dependence for each of the resources among households. The pattern of dependency for the resource extraction or utilization from the fringe forest areas is not similar among all of the states. This signifies that selection and utilization of the resources are governed by other attributes of the communities which could be their economic status, literacy and the

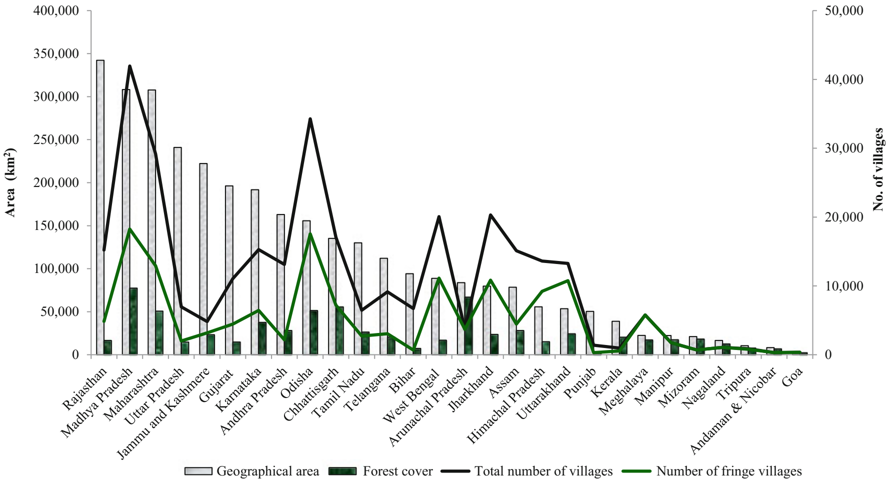

Fig. 16.3 Profile of the States including names, geographical area, forest area, number of villages and the number of villages identified as fringe villages

way of living. While analyzing the percentage of households in respective states for extracting resources from the fringe forests, it was observed that states could be categorized into high, medium and low level of dependency. The categorization of different states for their dependency of fodder in the form of grazing, fodder in the form of stall-fed and the extraction of fuelwood is shown in Figs. 16.4, 16.5 and 16.6, respectively.

Extraction and utilization of NWFP is one of the most hunted activity by the forest fringe communities in many of the fringe areas. The communities make use of NWFP for self-consumption as well as trading them in the market. Self-consumption of NWFPs is more prevalent than using it in trades for cash income (Fig. 16.7). Trade routes for most of the NWFPs are not well understood and therefore the collection of information on the quantity being extracted is a little bit difficult. In many of the cases, communities do not want to reveal the information in anticipation and apprehension of facing legal issues; whereas sometimes people don't have any idea about the exact quantum of stuff they extract. However, an attempt was made to distinguish between the consumption and sale out pattern prevalent among the states (Fig. 16.7).

Cattle provide one of the major support to the livelihood of the fringe communities. Most favoured livestock in the fringe villages is cow throughout India, while chickens and pigs are preferred in the north-eastern States and goats in the states of Rajasthan, Madhya Pradesh (MP), Jharkhand, and Andaman & Nicobar (A & N). A large number of cattle are owned by the majority of the households, thus making nearby forests as one of the priority choices for the grazing or stall-feeding. Due to lack of availability of alternate sources of fodder in the form of fodder grown on the

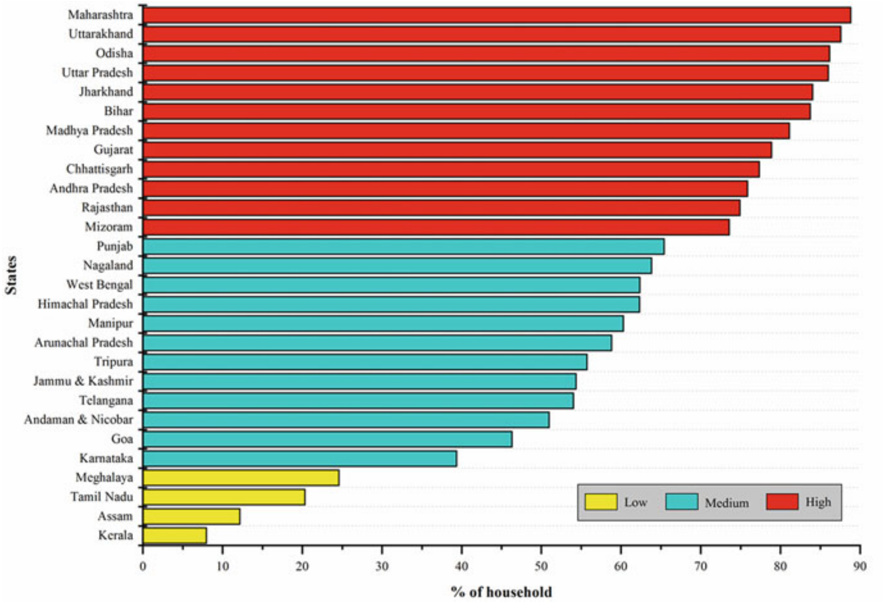

Fig. 16.4 Households (%) in different States where dependence for fodder is in the form of grazing

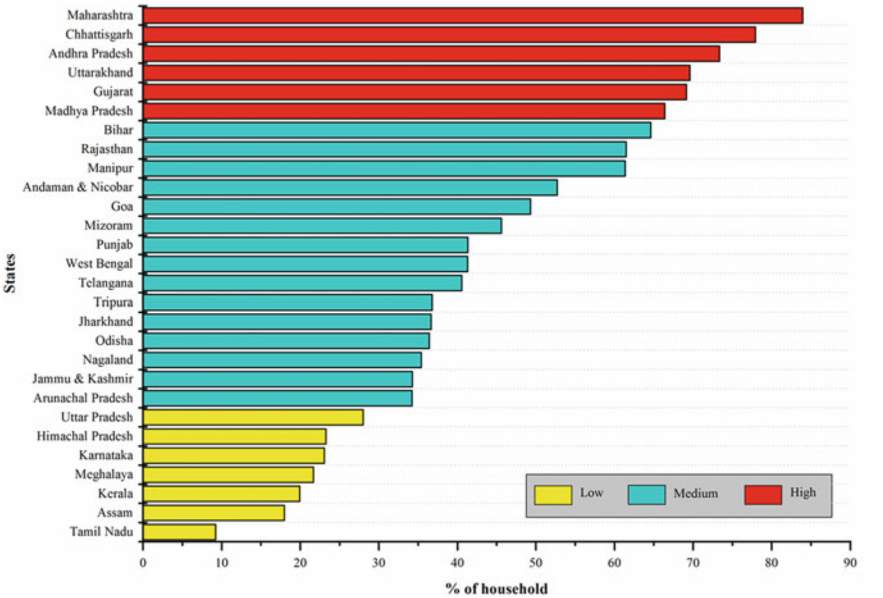

Fig. 16.5 Households (%) in different States where dependence for fodder is in the form of stall-feeding

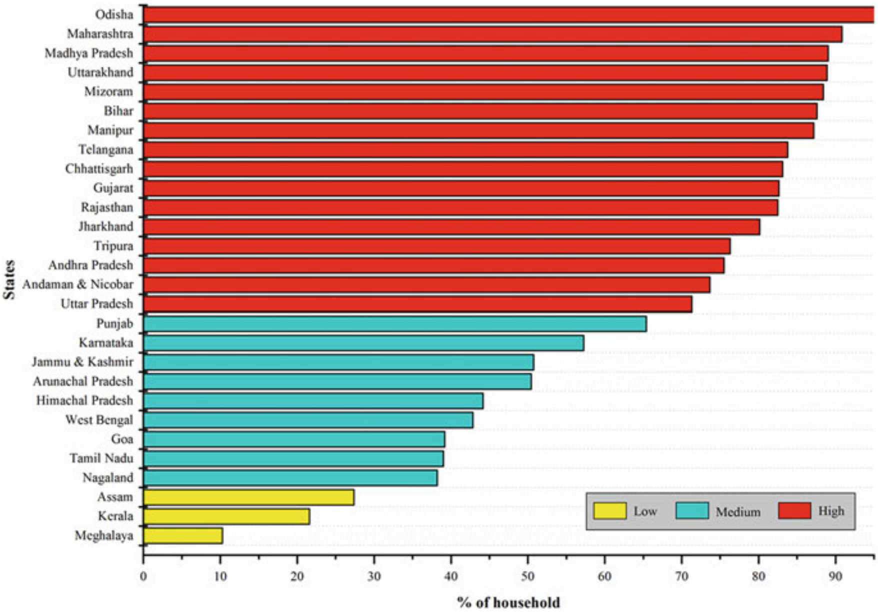

Fig. 16.6 Households (%) in different States that extracts fuel wood from the forests

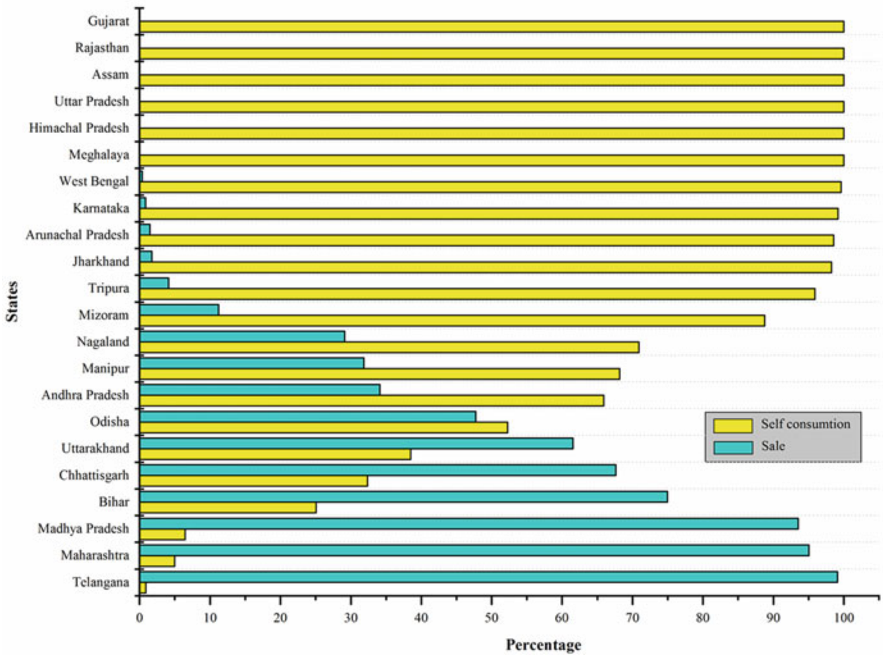

Fig. 16.7 Households (%) in different States making use of NWFP for self-consumption and sale

individual fields or community-owned lands, this has further increased dependency of communities for fodder upon fringe forests. The tree species found in the forests, which are not at all meant for the fodder resources also bear the brunt of fodder extraction and their leaves and branches are chopped for the stall-feeding. Species like *Aegle marmelos* and *Mangifera indica* also become choice of fodder for stall-feeding. This calls for immediate intervention to provide the alternate source(s) of fodder to support cattle population that will help to protect natural forests of the fringes.

The most used species for fodder in the country are *Acacia catechu, Acacia senegal, Apluda mutica, A. varia, Bambusa vulgaris, Brachiaria mutica, Caulanthus pilosus, Chionachne koenigii, Chrysopogon montanus, Cymbopogon martini, C. ambiguous, Cynodon dactylon, Cyperus rotundus, Dactyloctenium aegyptium, Dendrocalamus calostachyus, D. strictus, Desmostachya bipinnata, Diospyros melanoxylon, Echinochloa colona, Eleusine coracana (residue), Eragrostis tenella, Eulaliopsis binate, Exbucklandia populnea, Ficus religiosa, Grewia optiva, Hardwickia binata, Heteropogon contortus, Imperata cylindrica, Mangifera indica, Mussaenda frondosa, Oryza sativa (residue), Panicum notatum, Podocarpus neriifolius, Quercus leucotrichophora, Saccharum officinarum (residue), S. spontaneum, Schima wallichii, Schleichera oleosa, Shorea robusta, Sorghum bicolor, Trifolium alexandrinum, Triticum aestivum (residue) and Zea mays.*

Due to lack of alternate sources of fuel for cooking, a majority of the fringe communities ultimately have to rely upon the forests. Although fuelwood is mainly used for the purpose of cooking while in most of the cold regions of the country, it is also used for heating to combat the cold. Dependence of the communities upon forests for the fuelwood has emerged as one of the top cause of forest degradation in the country. Additionally, such dependency also has engaged the community into the drudgery of collecting firewood where women have the major stake. At the same time, smoke generated from such fuels causes serious health implications to the women and children in the form of respiratory disorders, poor health and a decrease in average life expectancy. Communities engaged in fuelwood collection from fringe forests are more at the risk of death because they are highly vulnerable to the attacks of wild animals and snake bites. Looking at intricacies of the situation, Government of India has recently launched Pradhan Mantri Ujjwala Yojana (PMUY) (www.pmujjwalayojana.com) initiated through the Ministry of Petroleum and Natural Gas for the distribution of relatively clean fuel in the form of Liquid Petroleum Gas (LPG) cylinders. The PMUY aims for distribution of clean cooking fuel to protect health of the communities who are otherwise exposed to smoky kitchens and have to engage themselves in the drudgery of fuelwood collection.

The preferred species for fuelwood in the fringes are *Ailanthus malabarica, Albizia lebbeck, Alnus nepalensis, Azadirachta indica, Bambusa vulgaris, Bauhinia variegata, Cedrus deodara, Dalbergia latifolia, Dendrocalamus hamiltonii, Grewia optiva, Mangifera indica, Schima wallichii, Shorea robusta, Terminalia myriocarpa, Acacia arabica, A. catechu, A. nilotica, A. planifrons, Albizia lebbeck,* *Anogeissus latifolia, Artocarpus chaplasha, Artocarpus heterophyllus, Azadirachta indica, Bambusa vulgaris, Bassia latifolia, Boswellia serrata, Buchanania lanzan, Butea monosperma, Cajanus cajan, Casuarina equisetifolia, Chloroxylon swietenia, Cocos nucifera, Dalbergia sissoo, Dendrocalamus strictus, Diospyros melanoxylon, Gmelina arborea, Hevea brasiliensis, Lagerstroemia parviflora, Lantana camara, Madhuca indica, Mangifera indica, Pinus kesiya, P. roxburghii, Populus tremula, Prosopis juliflora, Shorea robusta, Syzygium cumini. Tamarindus indica, Tectona grandis, Terminalia arjuna, T. tomentosa* and *Toona ciliata*.

The choice of species for the fuelwood is governed by the non-availability of alternate options. Cow dung (including that of buffaloes) is extensively used by the communities as cooking fuel. However, in absence of sufficient quantity of fuel from alternate sources communities extract fuelwood from the fringe forests. Similar to the choice of species for fodder, selection of species for fuelwood is also guided by non-availability of appropriate species and sometimes villagers also extract these by chopping useful species.

The highest number of forest fringe households practice agriculture while the number of skilled and non-skilled labourers are also very high. Paddy, wheat, and tapioca among major food and rubber among the plantation crops are the dominant crop cultivated across the study area. Average monthly income of the households in a state is as low as $ $\leq$ 422,[1] while few also have the income above $ 2535. Generally, the average household size in fringe villages is larger than the State average. Average monthly household income at state level ranges between $ 46 to 297.

The species regeneration is adequate in A & N, Meghalaya, and Karnataka fringe forests while it is inadequate in Arunachal, Assam, Kerala, Mizoram, Punjab, Rajasthan, Tripura, Uttar Pradesh (UP), and West Bengal (WB). Generally, arid to semi-arid states have inadequate regeneration. Only Arunachal and Assam are an exception. This is also true for Shannon's Index of plant diversity. Highest index value was noticed in A&N (4.5) while Maharashtra had the lowest value of 0.79 (Fig. 16.8).

It was observed that in the majority of the state forests serve as the major source of livelihood to the fringe communities in the form of fuelwood, fodder and NWFP. Fringe forests also act as a guard to the inner core of the forests and the majority of the activities of the fringe communities is restricted to these fringe areas for their daily basic requirement. Hence, the significance of the fringe forests has emerged as the top priority for managing forests to meet the goals of sustainable development. This demands an early intervention to manage the fringes (both fringe forests as well as forest fringe communities) through the application of site-specific way-out that fulfils the goals of sustainability.

[1]Conversion done from INR (₹) to US $ considering 1 US $ = 71 INR

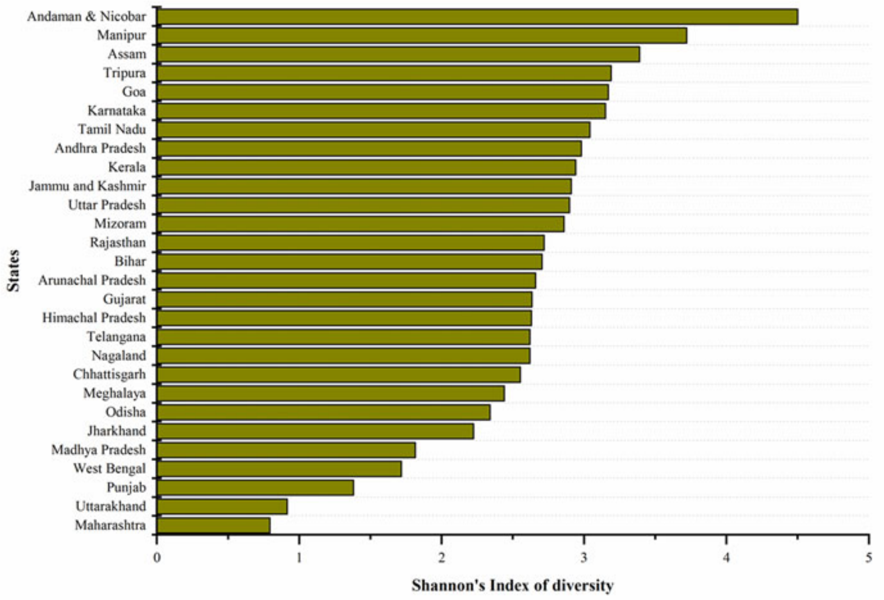

Fig. 16.8 Shannon's index of diversity in the fringe forests of different States

16.5 Conclusions and the Way Forward

Looking at the present need to develop appropriate management strategies for reducing extraction pressure posed on the forests by fringe communities, the present study provides ample scope to formulate viable options to safeguard and improve the fringes. The study is expected to help in developing strategies to check the unsustainable resource extraction from the fringe forests. The findings suggest that there is an urgent need to manage the fringes to fulfil the goals of sustainability. The areas where the sign of degradation is quite evident require immediate attention. The areas where gaps in tree density are visible and the vegetation has deteriorated, planting activity with an active involvement of local people could be taken up to fulfil the gaps. The planting should invariably use local plant species. The present case study provides a baseline in the country to prioritise site-specific interventions, although there can be multiple strategies for improving the ecological status of forest fringes. However, considering the pressure emerging mainly as fuelwood and fodder extraction, agroforestry can play a significant role. This will not only reduce the pressure on forests but also augment the livelihood of the fringe communities by providing the additional source of income.

Agroforestry is a land use practice which involves the combination of trees with agricultural production systems with social, economic and environmental benefits. Agroforestry term can be used for any part of the land, whereas, "Rainfed Agroforestry" may be referred exclusively for those specific agroforestry models which can successfully be implemented in rainfed areas and are effective in the management of rainfed areas. Rainfed agroforestry can act as a decisive tool for compatible livestock management, integrated land development, improving the livelihood of communities by increasing income, improving biomass productions, improving regeneration and fetching multiple benefits from the available marginal lands. The development of non-forest areas for their sustainable use would call for regenerating or recreating an integrated and interdependent land management system. Rainfed agroforestry may help in enhancing sustainable livelihood security through the simultaneous production of food, fodder and firewood. Management of trees in synchrony with crops in rainfed areas would decrease the risks associated with stress period through the efficient use of the limited natural resources. Rainfed agroforestry will also help in conserving soil, water, and in providing security against a fast changing climate.

In order to implement agroforestry at country level successfully, dissemination of knowledge and capacity building of people at the various hierarchical levels of implementation involving both the planner as well as executors is imperative. Categorically, the knowledge dissemination and orientation of action can be in the form of:

(a). information related to the identification of suitable sites and models of agroforestry,
(b). testing the applicability of selected models for its implementation on specific sites, and
(c). skill up-gradation of stakeholders through training programmes for the transfer of technologies to implement agroforestry models.

In view of the above facts, there is a considerable scope for managing the forest fringes in the country for meeting the sustainable development goals. There is an urgent need for advocating land use diversification and crop intensification in identified selected areas having various levels of natural resources and livelihood support. Fringes may require a combination of natural resource protection and livelihood support systems that are not heavily dependent on water. Authorities may plan to provide support services in the form of improved technology, innovations, infrastructure support, capacity building, credit, institutional linkages, knowledge dissemination, forward and backward linkages with concerned agencies, etc. The packaging of technologies is the need of the hour while the pragmatic approach for wider acceptability needs to be explored for successful implementation of proposed activities in the prioritized fringe areas. As solutions to rural fringe community problems become increasingly sophisticated with every passing day; the institutional and management models including the external support agencies have to evolve and adapt site-specific interventions and policies to abstain from any significant loss to communities as well as forests.

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References

Ashraf J, Pandey R, de Jong W (2017) Assessment of bio-physical, social and economic drivers for forest transition in Asia-Pacific region. For Policy Econ 76:35–44

Brundtland GH (1987) Report of the world commission on environment and development: "our common future". United Nations

Census of India (2011) House listing and housing census schedule. Ministry of Home Affairs. Office of Registrar General and Census Commissioner, Government of India, New Delhi

Clark WC (1989) Managing planet earth. In: Global climate change. Springer, London, pp 1–12

Cochran WG (1977) Sampling Techniques, 3rd edn. Wiley, Hoboken

Curtis JT (1959) The vegetation of Wisconsin: an ordination of plant communities. University of Wisconsin Press, Wisconsin

FRI (2017) Forest resource dependence and ecological assessment of forest fringes in rainfed districts of India. Forest Research Institute. Ministry of Environment, Forest and Climate Change, Government of India, Dehradun

FSI (2017) India state of forest report 2017. Forest Survey of India, Ministry of Environment, Forest and Climate Change, Government of India, Dehradun

FSI (2011) India state of forest report 2011. Forest Survey of India. Ministry of Environment & Forests. Government of India, Dehradun

FSI (2002) The manual of instructions for field inventory. Forest Survey of India Dehradun, Dehradun

Gladwin TN, Kennelly JJ, Krause T-S (1995) Shifting paradigms for sustainable development: implications for management theory and research. Acad Manag Rev 20:874–907

Kumar MD, Reddy VR, Narayanamoorthy A et al (2017) Rainfed areas: poor definition and flawed solutions. Int J Water Resour Dev:1–14

Lee KN (1993) Greed, scale mismatch, and learning. Ecol Appl 3:560–564

Moretti V, Ferrara A, Colantoni A et al (2014) Forest transition and changes in the socio-economic structure of a developed country: a long-term analysis. Mod Econ 5:932–938

NRAA (2012) Prioritization of rainfed areas in India (Study Report 4). National Rainfed Area Authority, New Delhi

NRAA (2011) Hallenges of food security and its management. National Rain-fed Area Authority, New Delhi

PRB (2001) Population reference bureau. World Population Data Sheet, Washington, DC

Redo DJ, Grau HR, Aide TM, Clark ML (2012) Asymmetric forest transition driven by the interaction of socioeconomic development and environmental heterogeneity in Central America. Proc Natl Acad Sci 109:8839–8844

Rodríguez LG, Pérez MR (2013) Recent changes in Chinese forestry seen through the lens of forest transition theory. Int For Rev 15:456–470

Rolston H (1994) Conserving natural value. Columbia University Press, New York

Savita, Kumar M, Kushwaha SPS (2018) Forest resource dependence and ecological assessment of forest fringes in rainfed districts of India. Indian For 144(3):211–220

Shannon CE (1948) A mathematical theory of communication. Bell Syst Tech J 27:379–423. & 623–656, July & October

Viederman S (1994) The economics of sustainability: challenges. Jessie Smith Noyes Foundation, New York