Chapter 8
An Integrated Methodological Framework to Assess Urban Resilience

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Abstract The assessment of the urban resilience should be tackled with a systemic perspective that enables an integrated analysis of the environmental, social, economic and institutional factors and their interactions characterizing urban and other complex socio-ecological systems. Here we propose an integrated framework for such assessment with the following key components: (i) The hierarchical definition of resilience objectives and indicators. (ii) A dynamic system model taking into account the key socio-economic and environment factors and their interactions, in which resilience indicators are integrated. (iii) The assessment of model potential sources of uncertainty and their impact on model outputs. (iv) The analysis of vulnerabilities to exogenous drivers (scenario analysis) and the exploration of available management and planning options (policy assessment). (v) A multi-criteria procedure, in which indicators, resilience thresholds, model outputs and scenario and policy analysis are integrated to guide decisions for an improved urban resilience. The whole framework integrates a participative approach, mainly for the initial and final steps.

Keywords Dynamic models · Policy assessment · Socio-ecological systems · Sustainability indicators

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8.1 Introduction

Urban areas can be considered a particular type of socio-ecological systems, where social, economic and environmental factors interact in a nonlinear fashion characterized by their reinforcing mechanisms. As other complex system, urban areas can face systemic changes, arising either from an external hazard event or from gradual endogenous change (Filatova & Polhill, 2012). The analysis of this dynamics, basic to understand the resilience of urban systems, requires a holistic approach, as for other socio-ecological systems (Lacitignola et al., 2007; Hodbod & Adger, 2014).

The integrated approach needed for more resilient urban systems should also consider wide time and spatial scales, to address the connections between urban systems with other surrounding socio-ecological systems. As it has been emphasised (Suárez et al., 2016), is it necessary not only to create more resilient cities, but also to reduce their environmental and social impacts on natural ecosystems and agricultural landscapes at broader scales. For example, urban sprawl constitutes one of the main factors driving the disappearance of traditional agrosystems and cultural landscapes around cities.

However, despite the increasing acknowledgement about the need for such holistic, systemic approaches, the application of integrated perspectives in urban and other socio-ecological systems are less frequent that desirable. Among the difficulties behind this, it should be emphasised (i) the need for a new conceptual perspective concerning the relationships between science and the management of real systems and (ii) the lack of tools to manage the inherent complexity of such systems. In the following sections, these two difficulties are further discussed.

8.1.1 The Need for a New Conceptual Perspective

Regarding the first difficulty, in recent years new conceptual approaches have been proposed; among them, science for sustainability or the post-normal science, as opposed to the discipline-oriented view of the positivist science. Table 8.1 synthetizes, according to Haag and Kaupenjohann (2001), the main differences between these two perspectives.

Following the perspectives emerging from the science for sustainability and post-normal science, in the approach proposed here there are two inter-connected but clearly distinctive components: The first one refers to the description of the system, making use of all necessary data and models. This description should be dynamic, to tackle not only the present state and problems but also their potential future evolution and should also be integrative, so synergies and trade-offs between different factors, objectives and actions are fully considered.

The second component refers to the definition of objectives, criteria and valuation procedures to assess the vulnerabilities of urban systems and to select the most appropriate policy measures among a set of alternatives and options, on the basis of

Table 8.1 Main differences between the positivist science and the post-normal science (Haag & Kaupenjohann, 2001)

Normal, positivist science	Post-normal science
Well defined theoretical systems	Ill-defined real problems entangled in complex ecological-socioeconomic systems. Non-equivalent descriptions are possible. Role of stakeholders in problem/system definition
Universal	Specific, unique systems
Independent of problem issues	Problem-driven. Modelling for management
Context-free	Context-sensitive
Scientific disciplines, reductionist approach	Trans-disciplinary, holistic approach
Systems to be studied: abstract, idealized	Systems to be studied: real cases
Very limited consideration (technical) or complete exclusion of uncertainty. Validation/quality control by a close community of experts	Deep consideration of different types of uncertainty, some of which are non-reductible. Extended peer community including stakeholders
Straightforward use in management. Frequently, using optimization models, assuming linear relationships and a single valuation criterium, usually defined by a close group of experts.	Increased relevance of values. Valuation procedures involving very different stakeholders. Scientific data and model results as inputs for valuation and decisión-making processes, dealing with multiple criteria, alternative valuations, incommensurability and uncertainty

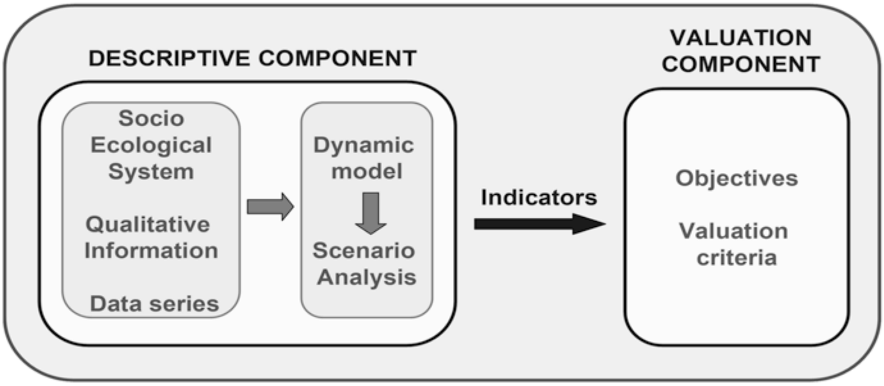

Fig. 8.1 General components for the assessment of system resilience

the best available knowledge provided by the descriptive component. The second component should answer two main questions: (i) which are the objectives to be achieved and the criteria to be considered for more resilient urban systems and (ii) which are the relative contributions of different policy options to urban resilience and which ones should be considered more beneficial to be implemented. Figure 8.1 shows the relationships between both components.

8.1.2 Integrated Tools to Assess Urban Resilience

In this chapter we propose an overall methodological framework which integrates the following components and tools:

1. The hierarchical definition of resilience objectives, along with their indicators and thresholds
2. A dynamic simulation model, where the above indicators are integrated
3. The assessment of policy options and the analysis of vulnerabilities to external scenarios
4. An uncertainty assessment concerning system behaviour and model outcomes
5. A procedure to assist decisions for an improved urban resilience

Figure 8.2 presents the relationships among the basic components. This overall approach addresses multiple purposes, including the capacity of anticipation, which is also a key property of resilient urban systems and societies (Khazai et al., 2015). The participation of involved agents, particularly in the first and last stages, is essential.

In the following sections these components and tools are described with more detail and some application examples are given.

8.2 Definition of Indicators. The IDIS Approach

8.2.1 Indicators as Tools for an Improved Resilience

One of the difficulties for an adequate understanding of resilience in urban and other socio-ecological systems is the existence of an overhelming amount of information referred to a wide number of aspects, frequently very heterogeneous in terms of

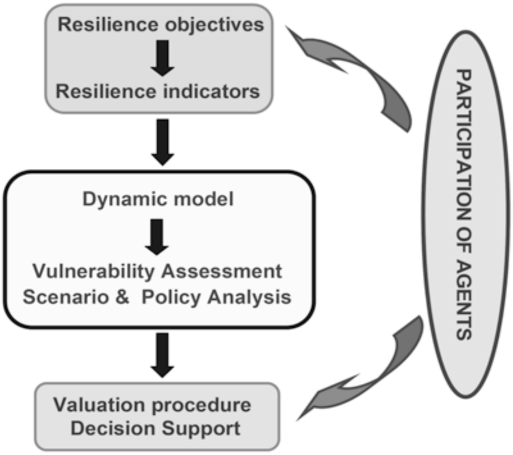

Fig. 8.2 Overall methodological framework to assess urban resilience

level of detail, spatial and temporal scales and other basic properties. To understand the multi-dimensional nature of resilience, which is a key component of sustainable systems, requires tools helping to reduce and organise the relevant information, so it can be transformed into useful knowledge. Indicators allow to monitor and assess key aspects of urban resilience in a quantitative way, to carry out comparative analysis and to provide relevant knowledge in a non-technical language to policy makers, managers, stakeholders and the general public for the decisión taking processes. Indicators should be relevant concerning the aspects they appoint to, sensible to changes, easily computed and understood, useful for communication and with a mínimum of overlap with other indicators (Adriaanse, 1993; Bell & Morse, 2008).

In recent years an increasing effort is devoted to the development of indicators of urban resilience (see for example Gonçalves & Marques da Costa, 2013; Khazai et al., 2015). Most of urban resilience indicators are directly connected to risk assessment, whereas there are few examples of indicators not linked to specific risks. These more general indicators refer mainly to energy, water and urban drainage systems (Suárez et al., 2016).

However, it is increasingly claimed that indicators just have a moderate weight on the adoption and assessment of sustainable and resilient policies and practices (Reed et al., 2006; Moldan et al., 2012). Among the limitations of conventional catalogues of indicators, we highlight:

- Its static dimension, which reduces the possibility of considering the synergies and trade-offs between indicators and the assessment of their future developments under different management options.
- Its lack of significance for each specific case of study.
- The "top-down" approach, which reduces the involvement and responsibility of different agents in monitoring objectives through such indicators
- The frequent absence of thresholds to determine whether the changes in the indicators are acceptable or not (Moldan et al., 2012).

The overall framework proposed in this chapter overcome these limitations. One crucial point is the selection of indicators, for which we propose the methodological approach outlined below.

8.2.2 *The IDIS Hierarchical Approach*

In the IDIS (Dynamic Integration of Indicators) hierarchical approach the following procedure is followed:

- Establishment of the overall resilience goals to be achieved.
- Identification of the resilience dimensions or components of the concerned system
- For each dimension, some specific objectives are defined.
- For each specific objective, it is necessary to formulate some strategic questions, relevant for the policy making process, to be answered. The answers to these

strategic questions determine whether the system is moving towards achieving the specific objective.
- Finally, to answer each strategic question, one or few relevant indicators are identified.

Figure 8.3 graphically describes the IDIS approach.

The final system of indicators derives from the objectives to be achieved, it is specific for each system, applies an integrative perspective and includes only the required indicators, avoiding redundance or indicators not connected with specific objectives. This approach also aims at carefully selecting a restricted number of indicators, since a limited and manageable number of indicators creates a more useful tool than a large number of unselected ones (Lancker & Nijkamp, 2000).

The participation of agents contributes to build confidence on the final indicators system and to increase the corresponsibility of policy makers and stakeholders in the application of the indicators. Moreover, a participatory definition of indicators also contributes to the corresponsibility in the achievement of the objectives, since an agreement on the diagnosis – from which an indicators system constitute one of the components – do not ensure but facilitates an agreement on the potential solutions to the identified problems.

The hierarchical connections between objectives, strategic questions and indicators help to define indicator systems that are truly consistent with the overall resilience goals to be achieved. For instance, efficiency indicators are very important, but an indicators system mainly based on these type of relative indicators (such as per capita or other per unit indicators) might improve while, at the same time, the system is moving away from resilience. This can be illustrated with the per capita emissions in Fuerteventura (Canary Islands), for which it is expected an improvement between 2012 and 2025, despite the rises in the consumption of resources and emissions in absolute terms (Banos-González et al., 2016). This can be explained by

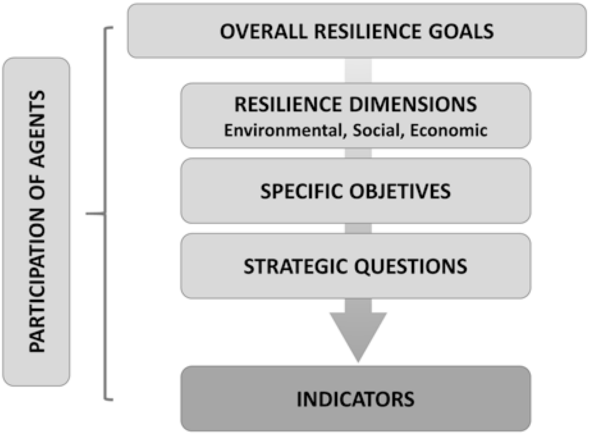

Fig. 8.3 Hierarchical approach for the definition of sustainability indicators

the even-higher expected increase in the total population over that period. Obviously, this does not imply that if more tourists come to the island, more resilient and sustainable Fuerteventura will be. This illustrates how some relative indicators, particularly many efficiency indicators, do not always give sound information, when considered alone. Therefore, these efficiency indicators and their changes over time should be taken with caution (Hanley et al., 2009), to avoid misunderstandings and errors in the diagnosis (Figge & Hahn, 2004; Mori & Christodoulou, 2012).

8.2.3 Resilience Thresholds

In terms of interpretation of the indicators and in order to represent a useful tool for the decision processes, a quantitative notion of what is acceptable for sustainability or for resilience – a threshold – is needed (Rodríguez-Rodríguez and Martínez-Vega, 2012; Banos-González et al., 2016). Without thresholds, indicators can describe, but are less useful as valuation tools to help decisions. Thresholds allow to track not only the direction and magnitude of changes but also to determine whether such changes are acceptable or not in terms of resilience or sustainability (Lancker & Nijkamp, 2000; Moldan et al., 2012; Proelss & Houghton, 2012). Indeed, the notion of threshold is key for an operative application of the concept of resilience (Gonçalves & Marques da Costa, 2013).

How can resilience thresholds be identified? A threshold may be a background value or it can be a meaningful reference value related to the irreversibility of the system. Depending on the nature of the indicator, threshold values can be provided by mandatory legal standards, guidelines from different institutions, benchmarking (best practices and experiences from other sites) and reference values taken from historical values of the system.

8.2.4 The Case of Galapagos Islands

The application of the IDIS approach to develop the water indicators system in the Galapagos Islands (SIAG, Martínez-Fernández et al., 2016) allows to discuss some of the limitations of conventional indicator catalogues, as explained below.

Static Versus Dynamic Indicators The static catalogues of indicators cannot take into account the interactions and trade-ofs among indicators, by which the improvement in some indicators may cause a worsening in others (Banos-González et al., 2016). Therefore, it is important to integrate the indicators within a dynamic model (Vidal-Legaz et al., 2013; Liu et al., 2014; Banos-González et al., 2015). The SIAG indicators are being integrated into a dynamic model covering the key dimensions for sustainability and resilience of the Galapagos Islands.

Need of Context-Specificity The SIAG includes several indicators regarding the resilience to climate change in the urban areas of Galapagos, characterized by a very arid climate. One of these indicators is the proportion of houses and other buildings which have devices for rainwater collection, a traditional water system which is being lost during the last decades. This system of water supply has other advantages, as the provision of high quality water for the most basic human needs with no or very low input of energy. However, other works have included as indicator of poverty in Galapagos the existence of water supply systems different to the public network (Granda Leon et al., 2013), since this is one of the indicators of poverty being applied in the continental Ecuador. This exemplifies how the direct translation of indicators to other areas can be inadequate to specific contexts, such as the Galapagos Islands, where rainwater collection is not related to poverty and, in fact, it should be promoted to increase Galapagos resilience to climate change. Moreover, the consideration of rainwater collection as an indication of poverty contributes to a negative perception of this device (Guyot-Tephany et al., 2013) and therefore is counterproductive to increase the overall resilience of the urban areas in Galapagos.

Participatory Versus Top-Down Approach The implication of agents are crucial in the development of urban resilience indicators (Khazai et al., 2015). A top-down, non-participatory approach, does not facilitate the co-responsibility of all agents in the effective application and follow-up of the indicators. In the case of SIAG, water managers and stakeholders have participated in its development, which has contributed to improve the initial proposal and to increase the interest of involved agents on an effective application of the indicators system.

Need of Thresholds A frequent weakness of many catalogues of indicators is the lack of reference values. Without thresholds, the indicators can describe, but are less useful as valuating tools to help decisions. In addition to monitor the direction and magnitude of change, thresholds allow us to determine whether such change is acceptable or not regarding resilience (Lancker & Nijkamp, 2000; Moldan et al., 2012; Proelss & Houghton, 2012). In the case of SIAG, a threshold was identified for each of the 34 indicators, what allowed to get some measure of the distance to goal and therefore to better prioritize the actions to be taken.

8.3 Dynamic Simulation Models

8.3.1 The System Dynamics Approach

System dynamics models (SD) allow us to understand the structure and behaviour of complex systems, by means of the causal relationships, feedback loops, delays and other processes of the system (Kampmann & Oliva, 2008; Li et al., 2012; Martínez-Moyano & Richardson, 2013). Negative feedback loops, which tend to absorb disturbances and maintain the overall behaviour within certain ranges, are also essential features for the resilience of socio-ecological systems. These feedbacks constitute, therefore, an important core urban resilience factor (Suárez et al., 2016).

The application of system dynamics modelling tools allow to facilitate the comprehension of complex systems (Martínez-Moyano & Richardson, 2013; Kelly et al., 2013) aimed at generating useful information for decision-making (Jakeman & Letcher, 2003; Voinov & Shugart, 2013). Another important feature of SD is its context-specific approach. Context-specific or context-adapted models are needed to be able of addressing the concrete problems, challenges and needs of real systems and, therefore, to provide proper solutions. Dynamic system models are particularly appropriate to visualize the overall system, to consider a long run perspective, to present factors and relationships in a transparent way and to integrate resilience indicators. All this make dynamic models valuable tools for a participatory management, helping in the communication among the scientific-technical, management and social agents' sides.

The modelling process involves several stages (Fig. 8.4): conceptualisation, formulation of model equations and calibration, in which the model is iteratively improved through calibration against the observed data of main variables. Finally, the model is tested by means of structural tests (Barlas, 1996), including dimensional consistence tests, sensitive analysis and extreme condition tests. After successful testing, the model is applied to define and assess the expected effects of different policies and scenarios. Figure 8.4 shows how these methodological steps are related.

In the next section the role of dynamic models is exemplified with the case of the periurban agro-ecosystem of Murcia, which has an essential role on the climatic

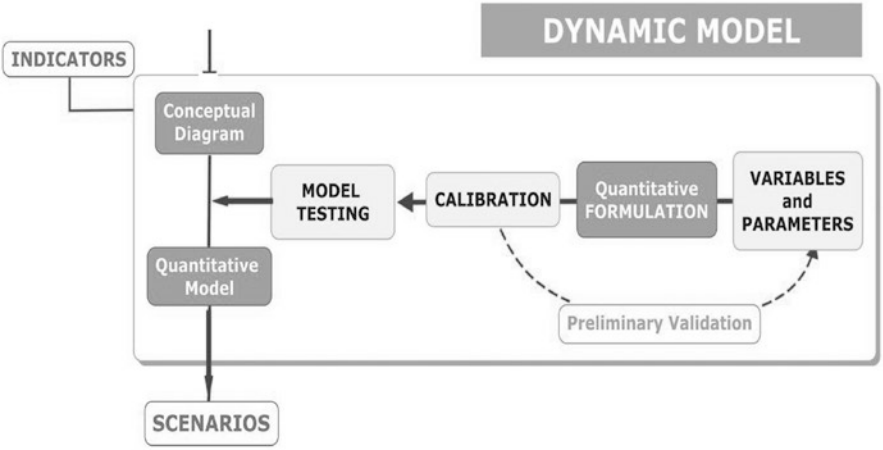

Fig. 8.4 Methodological steps to develop dynamic models

comfort of the city and is therefore essential to preserve the resilience of Murcia to climate change.

8.3.2 The Case of Murcia City and Its Periurban Agro-ecosystem

Dynamic models can help to better understand and improve the resilience of urban systems from an integral perspective. This is illustrated in the case of the city of Murcia (Southeastern Spain) and its periurban agro-ecosystem, called "huerta", a type of Mediterranean traditional irrigated land. Ancient elements like the irrigation ditches, dating from before 1000 AD, exist alongside modern elements associated to urban development. This irrigated agro-ecosystem plays a key role to substantially moderate the urban heat island effect of the city. The available regionalised climate change scenarios point to an increase in the intensity and frequency of heat waves, which will seriously impact on the public health and the thermal comfort of the city. Therefore, the preservation of the Huerta agro-ecosystem around Murcia is essential to improve the resilience of this urban system to the ongoing climate. Moreover, this traditional agro-landscape, called Huerta, has important environmental and cultural values.

Nevertheless, the preservation of this agrosystem is seriously threatened. In order to assess the factors involved in the progressive loss of this agroecosystem, it has been developed a dynamic system model (Fig. 8.5). The model takes into account the area occupied by the Huerta agro-ecosystem, the area occupied by new irrigated lands, located outside the river valley, the number of landowners, the average farm size, the population, the amount and quality of water resources used for irrigation and the profitability index. Several factors contribute to the decreasing profitability of the Huerta agro-ecosystem. The main factor is the reduction in the average farm size, caused by the permanent increase in the number of landowners in Huerta de Murcia. The consequent reduction in the average farm size strongly affects the profitability of Huerta. The scarcity and low quality of water resources used for irrigation also affects the profitability. Figure 8.5 shows a simplified diagram of the model. More details can be found in Martínez-Fernández et al. (2013).

In 1932 the Huerta de Murcia had 13,500 ha, area which progressively decreases to around 11,500 ha in 1995 (Fig. 8.6a). By the end of the period, around 15% of the initial area of Huerta had been lost, value which doubles the proportion of high quality soils lost in Spain (Comisión de las Comunidades Europeas, 1992).

One of the reasons for the loss of Huerta is the increase in total population by around 150% (Fig. 8.6b). Population demands land uptake for infrastructures and especially for residential uses. The other reason for the loss of huerta is the reduction of profitability due to the increase in the number of landowners (Fig. 8.7a), leading to the decrease in the average size per farm (Fig. 8.7b).

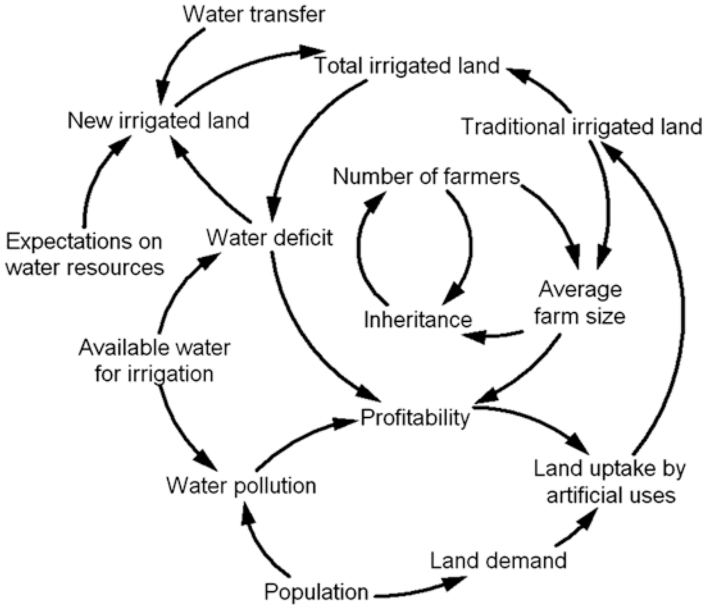

Fig. 8.5 Simplified diagram of the Huerta dynamic model

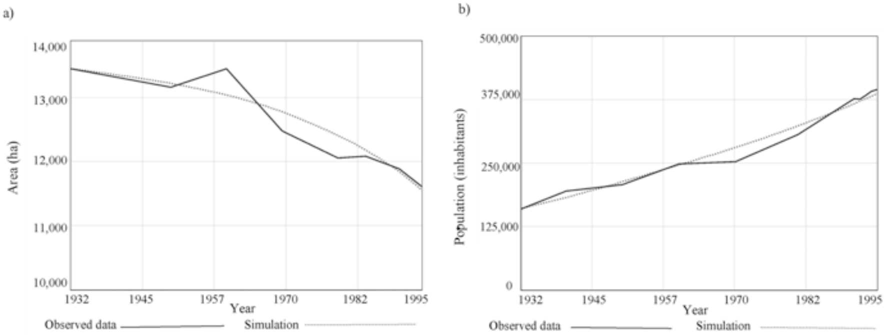

Fig. 8.6 Observed data and simulation results for (**a**) traditional irrigated lands around the city of Murcia, (**b**) total population

Under the base trend scenario, the traditional irrigated land would be lost between 1995 and 2025 at a rate which doubles the average annual land uptake in the previous 30-years period.

However, which has been the actual behaviour of the system after 1995? Results obtained show that the area of traditional irrigated land expected under the Base trend scenario by year 2025, has actually been reached 18 years earlier. One key factor for such acceleration is the new municipal land use policy implemented after 1995, which has shifted from weak or no controls on land uptake to an even worse

Fig. 8.7 Observed data and simulation results for (**a**) number of landowners of traditional irrigated lands, (**b**) average farm size

situation characterised by the successive reduction in the legally preserved area of the Huerta. Between 1998 and 2001 the legally preserved area of the Huerta was reduced by around 38%. Although the change in legal status from preserved to buildable area does not imply an immediate transformation into urban use, the expectations about this potential future urban population might be the key factor for the observed accelerated loss of the Huerta. To assess this, we have defined and implemented a new scenario corresponding to the actual trend 1995–2010 with two main aims: (i) to test whether the changes in the municipal land plan can explain the observed loss of the Huerta in 1995–2010 and (ii) to test whether the dynamic model, developed and calibrated with data from the 1932–1995 period, can resemble the observed trends in the 1995–2010 period without further calibration. The potential effect of the municipal land plan as been implemented by including the expected increase in population associated to the successive changes in the municipal land plan for years 1995, 2001 and 2005, taking into account the official values in each plan of buildable area, floor area ratio, average number of inhabitants per home and the time period required to reach the saturation of such buildable area. The area of the Huerta, number of landowners, population, average farm size and water quality index were updated for the period 1995–2010 for comparison purposes with simulation runs, but no new calibration against observed data was performed.

Results show that the actual trend scenario is able of resembling the observed data series. The area of traditional irrigated lands decreases to values around 7500 ha in response to the increase in both the real population but also the potential new population according to the successive land plans, confirming that this is effectively the key driving force inducing the accelerated loss of huerta in Murcia (Fig. 8.8).

The model ability to replicate the basic behaviour pattern of the system in the period 1995–2010 with no further model calibration against observed data, may be considered a sort of model validation with an independent dataset. This constitutes a valuable and rather uncommon feature regarding models of socio-ecological systems.

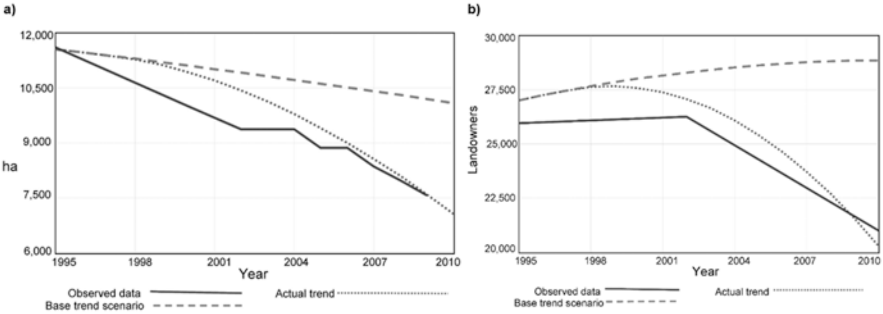

Fig. 8.8 Observed data and simulation results under the base tren scenario and the actual trend simulation for (**a**) the Huerta agroecosystem and (**b**) the number of landowners

In synthesis, obtained results show that the traditional irrigated land around Murcia is being lost at an accelerated rate. This will impact on the urban resilience of Murcia to climate change, regarding the capacity of the huerta to moderate the heat island effect of city. As a consequence, Murcia will be more vulnerable to the heat waves, which are expected to increase in intensity and frequency under the ongoing climate change. In order to improve the resilience of the city to the climate change impacts, the Huerta model will be applied to explore different land use and agricultural policy measures and their effectiveness in maintaining and recovering the Huerta periurban agro-ecosystem.

8.4 Vulnerability and Policy Assessment

8.4.1 Policies, Scenarios and Vulnerability

Dynamic simulation models are particularly useful as prospective tools (as opposed to predictive or forecasting tools). These kind of models capture the general structure and behaviour of models and are intended to explain the general dynamics of the system in the long run, not precise details in the short term. In coherence with this, dynamic models are not developed to tell what will happen, but to answer "what-if" questions. They are particularly useful at the level of strategic decisions and planning, more than at the managerial or operational level.

In the case of socio-ecological systems, including urban areas, these "what-if" questions can refer to actions that can be taken within the modelled system or to changes in the boundary conditions, this is, in the factors that condition the system but whose behaviour cannot be determined or decided within the system. These two different situations are usually distinguished with the terms *policies* (actions which can be implemented within the system to achieve certain objectives) and *scenarios* (external changes in the boundary conditions). Dynamic models can be applied to assess the expected effects of different policy measures and to explore the vulnerability of the system to certain scenarios, such as climate change or an economic recession.

Regarding resilience, there is a remarkable need of dealing with long-term dynamics, since resilient policies can only be successful if they consider long time horizons. Long-term planning is especially important when short-term decisions have long-term consequences, since it makes it possible to visualise key issues that may otherwise be missed. For this purpose, scenario development and policy assessment is one of the major tools to compare the potential outcomes of a variety of alternatives and to anticipate the long-term consequences of scenarios, policy decisions and actions (Banos-González et al., 2016).

In relation to policy measures, dynamic simulation models can be applied to (i) analyse the measures proposed by different agents and action plans; (ii) quantify their effects in terms of resilience indicators and thresholds; (iii) identify side-effects and trade-offs among objectives; (iv) determine the degree of uncertainty of the simulation results and (v) prioritize among measures.

The role of scenarios and policy assessment is illustrated with the water and energy nexus. Urban areas are highly dependent on other socio-ecological systems for the provision of resources, as water and energy. This dependence makes urban areas potentially vulnerable to possible shortages of such resources. The increasing proportion of urban population is emphasising this potential vulnerability. Therefore, it is important to anticipate the effects of different management options regarding resilience, as well as the urban vulnerability under different socio-economic and environmental scenarios, such as climate change. In the following section it is shown the combined use of dynamic simulation models, resilience indicators and thresholds to explore policies and scenarios regarding the water and energy nexus in the case of Fuerteventura.

8.4.2 Assessing Policy Measures for Urban Resilience in Fuerteventura

Energy and water are firmly interconnected and interdependent. Understanding this connection of water and energy has created a strong interest in exploring what Madani and Khatami (2015) named “the water-energy nexus”. Water is used in energy mining and production, running turbines, cooling power plants, construction and operation of energy generation facilities and disposing their waste products. On the other hand, we need energy to purify, desalinate and transfer water (Hadian & Madani, 2013). This reciprocal dependency of water and energy is the core idea of the water-energy binomial.

Despite its high interdependence, managers of water and energy resources have conventionally operated independently (Madani & Khatami, 2015). There is a serious need for balancing the trade-offs between the different aspects of water-energy nexus management. A successful balance requires a good understanding, assessment and communication of the possible effects of different policy options and to share visions among policy makers, stakeholders and other agents, based on sound scientific knowledge.

This idea is even more challenging in the case of arid islands, such as Fuerteventura (The Canary Islands). In Fuerteventura, declared as Biosphere Reserve in 2009, there is a potential tradeo-off in terms of urban resilience objectives: on one hand, the marine water desalination increases the island resilience towards droughts and to an unexpected reduction in available resources in Fuerteventura; on the other hand, the dependence of a basic need as urban water supply from marine water desalination can be considered a vulnerability to the energy supply system, particularly if allochthonous, non-renewable energy sources are mainly used. In order to gain insights on the water and energy nexus, it has been applied the Fuerteventura Sustainability Model (FSM, Fig. 8.9), developed following the system dynamics methodology. It has been calibrated for the 1996–2011 period (Further details can be found in Banos-González et al., 2015). The FSM integrates five sectors: land use changes, socio-tourist sector, environmental quality, biodiversity and water resources. The model testing results (Banos-González et al., 2015) offer an adequate degree of model confidence to use it as a tool to analyse the main sustainability and resilience issues in Fuerteventura.

In Fuerteventura, urban water supply, both for resident (Fig. 8.10a) and tourist population, represents around 69% of the total water demand (around 12.5 Hm^3 in 2011). The net consumption per resident was 180 l per person and day, whereas tourists consumed around 378 l and 221 l per person and day in hotels and non-hotel tourist accommodations, respectively.

Surface water and groundwater pumping in Fuerteventura are clearly insufficient to fit the total water demands for the tourist and resident population, covering less

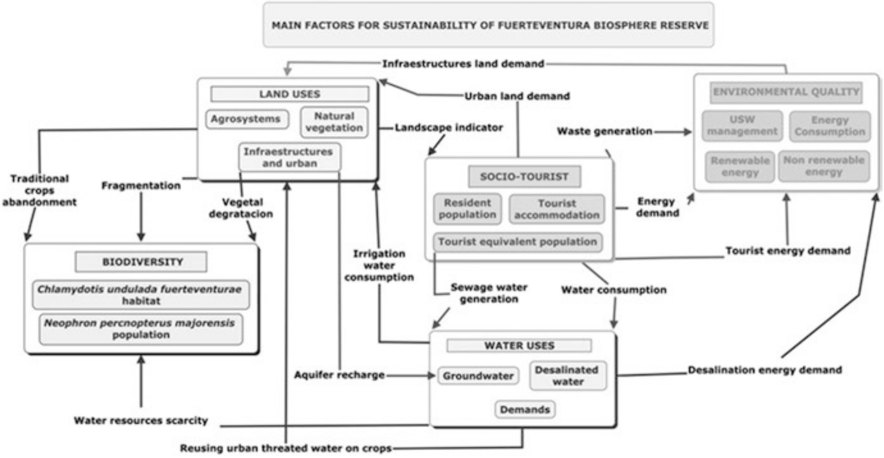

Fig. 8.9 Overview of the Fuerteventura Sustainability Model, FSM. (Further details can be found in Banos-González et al., 2015)

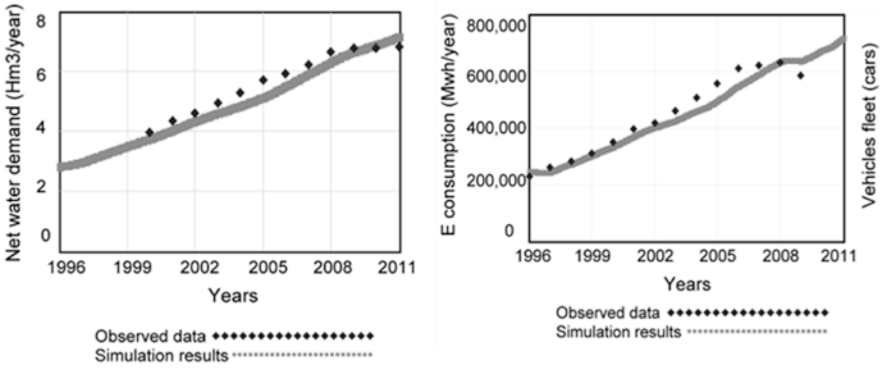

Fig. 8.10 Observed data in Fuerteventura and model simulation results for (**a**) Net water demand for water supply of resident population and (**b**) Total electric energy consumption

than 20%, in average. Therefore, seawater desalination is required to satisfy the remaining 80% of urban water demand. Moreover, desalination doubled along the 1996–2011 period. Although water desalination represents a minor component of total electricity demand (around 8.6% in 2011), such increase in water desalination also contributed to the rise in the total electric energy consumption (Fig. 8.10b). The share of renewable energy is around 2% of total energy use along the 1996–2011 period, meaning that practically all energy demands are fitted with external, non-renewable resources.

The FSM model has been applied to assess the objectives and policy measures contained in the Fuerteventura Biosphere Reserve Action Plan (AP, 2013), including those involving the water-energy nexus. This Plan includes the measure “100% renewable water”, whose aim is to cover 100% of the electricity demand required for the supply of desalinated water with renewable energy in 2025, one of the basic guidelines of the AP. The FSM model, along with the integrated indicators and their thresholds, has allowed the assessment of the effectiveness of this policy measure (100% renewable water), as compared with the Business As Usual (BAU) run, under which no increase in renewable energy is implemented.

Three sustainability indicators related to energy and emissions of the Fuerteventura Biosphere Reserve Action Plan (Table 8.2) were selected and integrated into the FSM. A reference value or threshold was defined by each one of these three indicators.

Table 8.3 shows the simulation results for the three considered indicators under the policy measure of 100% Renewable Water, as well as under the Business As Usual (BAU) simulation for the 2012–2025 period. The estimated uncertainty for the expected results is also expressed, as 95% confidence intervals around the mean value of simulations, according to the Monte Carlo analysis.

The results under the Business As Usual simulation show that the urban demand for desalinated water would double between 2012 and 2025 due to the increase in population (both resident and tourist-equivalent population). The same increase

Table 8.2 Sustainability indicators on energy and emissions. Units and thresholds are also specified

Indicators	Units	Threshold	Meaning of the threshold	References of the thresholds
Per capita primary energy consumption (*PEpc*)	GJ/year*pc	<42	Minimum energy use required to reach a Human Development Index of at least 0.8, recommended by United Nation Development Programme.	Johansson and Goldemberg (2004)
Share of renewable energy (*SER*)	Dimensionless	>0.2	Renewable energy to represent at least 20% of total energy use in 2020 and 27% in 2030.	EC (2008 2015)
Per capita CO_2 emissions (CO_2pc)	metric tons CO_2/year*pc	<9.52	A 20% reduction in the per capita CO_2 emissions from 1990 levels. Based on 1999 value.	EC (2008)

Table 8.3 Simulation results in 2025 for the considered indicators under BAU and under the 100RW policy measure

Indicator	PEpc (GJ/ year*pc)	SER(dimensionless)	CO_2pc (metric tones CO2/ year*pc)
Threshold	<42	>0.2	<9.52
BAU	281.97±42.07	0.011±0.004	17.04±4.21
100RW	275.73±2.17	0.017±0.003	16.89±4.21

BAU Business As Usual, *100RW* Policy measure: 100% Renewable Water

would be expected for the electrical energy consumption. The total primary energy consumption would also increase, by around 52%. If all the power demand of desalination processes would be provided by renewable power, the SER indicator would increase by around 54%. However, the three indicators would exceed their thresholds under both simulations, even though the policy measure 100RW explicitly addresses the improvement of such indicators.

Whereas the seawater desalination, the main source of water on the island, has enabled to overcome the limitations of water scarcity on the socioeconomic activities, its negative side – a high energy consumption, an increased energy dependence and greenhouse and brine emissions – must be addressed (Meerganz von Medeazza & Moreau, 2007; Lattemann & Höpner, 2008; Melián-Martel et al., 2013), particularly in an island system with a low SER indicator. This dependence on allochthonous, non-renewable energy resources in Fuerteventura has not improved in the period 1996–2011, which represents a clear sign of unsustainability. Even more, the strong dependency of water availability for urban supply on energy consumption – more than the 80% of urban and tourist population water demand is covered by seawater desalination, – implies a high vulnerability of the whole socio-ecological system, even for basic needs, to socioeconomic changes such as those in the energy policies and markets, and to the ongoing global change (Kruyt et al., 2009). Climate change is expected to exacerbate the situation by increasing energy and water demands while at the same time available water resources are expected to decrease in Fuerteventura.

In synthesis, the combined use of the Fuerteventura dynamic model, along with the indicators and thresholds, allow to assess the relative effectiveness of planned policy measures, showing in this case that regarding the water-energy nexus such measures are far from achieving the proposed objectives. This type of assessment is essential to reorientate and better focus the actions aiming at substantially improving the urban resilience in Fuerteventura.

8.5 Uncertainty Assessment

8.5.1 Uncertainty and Urban Resilience

The assessment of socio-ecological system generally suffers from high levels of uncertainty. Complex models with many interactions among individual sources of uncertainty can increase the overall model uncertainty (Perz et al., 2013). Therefore, there is a need to identify potential sources of uncertainty and to quantify their impact on model outputs and on the application of each considered policy option. However, the existing models are often deterministic (Holzkämper et al., 2015; Uusitalo et al., 2015) highlighted that models which include the uncertainties related to management options may be of considerable added value for the decision makers. In fact, one of the properties of resilient systems is their ability to accept and cope with the inherent and ever-increasing uncertainty and change in today's world.

Regarding socio-ecological modelling, there are two different types of uncertainty. The first type arises from the lack of knowledge about the precise value of certain parameters and variables (for example the per capita net water consumption in certain urban typologies). This type of uncertainty can be reduced by specific studies aiming at improving the available information and data about such parameters and variables. This is particularly necessary in the case of parameters having a strong influence in model outcomes (high sensitivity parameters). The second type of uncertainty derives from intrinsic, non-reductible sources of variability in the socio-ecological system (for example the annual rainfall in Mediterranean environments). These sources of uncertainty should be explicitly accounted for in socio-ecological modelling, by determining appropriate uncertainty ranges to each parameter. Moreover, the interactions among variables can minimise or exacerbate the model response to all combined sources of uncertainty.

Among the methods across literature that enable to cope with uncertainty the Sensitivity Analysis (SA) is highlighted. SA is broadly used identify the key input variables and parameters that control model outputs (Schouten et al., 2014). An overview of SA methodologies can be found in Saltelli et al. (2005), Cariboni et al. (2007) and Refsgaard et al. (2007). The sensitivity analysis allows: (i) On one side, a detailed assessment of model robustness and, therefore, of the reliability of model outputs. (ii) On the other side, the quantification of the specific uncertainty associated to each model outcome under the considered scenarios and policies. The SA allows to answer questions as the following: How robust the conclusions derived from the model are?, How does uncertainty affect the assessment of policies and the vulnerability to certain external changes?

Different sensitivity analysis techniques can be applied, more specifically local sensitivity analysis or "One factor at a time" (OAT) and general sensitivity techniques by means of Monte Carlo simulation. OAT techniques allow us to determine the model sensitivity to each individual parameter. The sensitivity index ($S_{i,j}$, Jørgensen & Fath, 2011) is calculated as follows:

$$S_{i,j} = \left(\frac{OM_{i,t} - Om_{i,t}}{Ob_{i,t}} \right) / \left(\frac{PM_j - Pm_j}{Pb_j} \right) * 100$$

Where $S_{i,j}$ represents the sensitivity index of the target variable i to the parameter j; $OM_{i,t}$ and $Om_{i,t}$ are the maximum and minimum values of the *ith* target variable at time t; $Ob_{i,t}$ represents the base (default) model value of the *ith* target variable at time t; PM_j and Pm_j represent the maximum and minimum values of the *jth* parameter, respectively; and Pbj is the base model value of the *jth* parameter. The sensitivity index allows to discriminate between parameters with low ($Si,j < 10\%$), moderate ($10\% \leq Si,j < 50\%$), high ($50\% \leq Si,j < 100\%$) and very high sensitivity ($Si,j \geq 100\%$).

The general sensitivity analysis by means of Monte Carlo simulation (MC) allows us to assess the effects of a simultaneous variation of all sensitive parameters for each target variable. The variation coefficient (VC_i) of the target model variables shown by the Monte Carlo simulation is calculated as follows:

$$VC_{i,t} = \left(\frac{OM95_{i,t} - Om95_{i,t}}{\bar{O}_i} \right) * 100$$

Where VC_i represents the relative variation of the target variable i respect to its mean value using 95% confidence bounds; $OM95_i$ and $Om95_i$ are the maximum and minimum values of the ith target variable at time t using 95% confidence bound, and $\bar{O}_i$ is the mean value of the target variable i. According to the variation coefficient, the target model variables can show a low ($VCi < 50\%$), moderate ($50\% \leq VCi < 100\%$) and high response ($VCi \geq 100\%$) to changes in their respective most sensitive parameters.

The next section illustrates the uncertainty analysis using the FSM model in the Fuerteventura island.

8.5.2 Assessing Uncertainty under Policy Measures and Scenarios in Fuerteventura

As presented in the previous section, the FSM model was applied to assess different policy measures and scenarios in the Fuerteventura island (Banos-González et al., 2016). An extensive sensitivity analysis was also carried out to explore how uncertainty affects the model outcomes. One of the key issues in Fuerteventura is the rapid tourist development shown during the last decades. This Biosphere Reserve faces important challenges regarding its rural and urban resilience and the overall vulnerability of the island to this external driver. Using the FSM model, the embedded indicators and their thresholds, it has been assessed the Business As Usual simulation for the period 1996–2025. Figure 8.11 shows the results of the Montecarlo simulation in the period 1996–2025 under BAU for three key variables: the built-up urban area, the resident population and the equivalent tourist population.

The model includes three important indicators regarding the socio-tourist development: the ratio of tourist to resident population, the ratio between the tourist accommodation and resident population and the artificial land proportion (Table 8.4). Results show that the expected value of the ratio of tourists to residents would exceed the threshold value, whereas the two other indicators would not. However, when uncertainty is taken into account, it is clear that another indicator, the ratio between tourist accommodation and resident population, might also exceed the threshold.

In Fuerteventura this has been found not only in the case of the BAU simulation but also with different policy options and scenarios, as climate change, which have shown to be riskier than expected when only mean values are considered, since, when uncertainty is considered, such policies and scenarios present higher number of indicators exceeding their thresholds.

This highlights the importance of considering uncertainty in the decision process, when assessing different policy options. Some authors state that the precautionary principle should not represent a brake to decision-making, since inaction could have costly and unforeseeable impacts (Gee & Krayer von Krauss, 2005; Van der Sluijs, 2007). Uncertainty should be considered a normal component of decisions and, instead of inaction, it should appeal to the prudence of policy makers. In this sense,

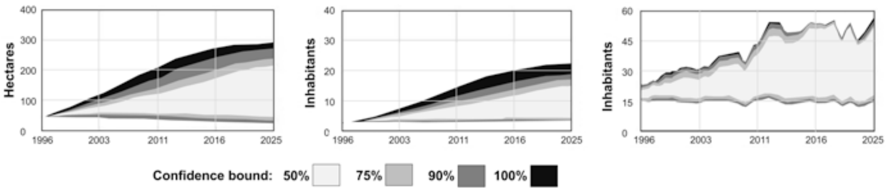

Fig. 8.11 Monte Carlo sensitivity analysis to changes in sensitive parameter values (local sensitivity over 50%) for the target model variables (left to right): Built-up urban area, Resident population and Equivalent tourist population

Table 8.4 Results of indicators related to the tourist development in Fuerteventura under the Business as Usual (BAU) simulation in the period 1996–2025

Indicator	Units	Threshold	Meaning of threshold	References for thresholds	BAU expected value and 95% confidence bound
Ratio of tourists to residents	Dimensionless	<0.3152	The ratio of tourist to local inhabitants should be lower than the threshold	Government of Canary Islands (2010)	0.329 ± 0.277 (0.053–0.606)
Ratio between tourist accommodation and resident population	Tourist beds/ inhabitant	<0.97	Ratio between tourist accommodation and resident population	Government of Canary Islands (2010)	0.618 ± 0.643 (0–1.261)
Artificial land proportion	%	<20	Proportion of area occupied by agriculture, urban use and infrastructures	Graymore et al. (2010)	6.83 ± 4.74 (2.09–11.57)

Units, threshold, references of thresholds, expected value and 95% confidence bounds are indicated

the precautionary principle should be applied taking into account the uncertainty analysis: the higher the uncertainty, the less risky the policy should be.

8.6 Conclusions. A Framework to Support Decisions for an Improved Resilience

In this chapter it has been presented an overall methodological framework to assess resilience in urban and other types of socio-ecological systems with the combined use of indicators, thresholds, dynamic simulation models, the assessment of policies and scenarios and the effects of uncertainty on model outcomes. As opposed to conventional Decision Support Systems (DSS), frequently based on assigning weights to each criteria, which are then combined into mixed indexes to find an optimal solution, here a different approach is proposed.

This approach allows to explicitly address the complex nature of real problems and the interactions and trade-offs among variables, by means of the indicators embedded in the model. The establishment of threshold values for each indicator provides a way to identify those policies that would exceed the concerned resilience thresholds. Following the rule “Threshold out, Measure out”, any policy exceeding a threshold should be rejected or assigned the lowest priority. This approach avoids the use of indexes mixing non-reducible dimensions and, instead, keeps track of the positive and negative effects of each policy or scenario on the different environmental, economic and social factors involved in the concerned socio-ecological system. Finally, the participation of involved actors, particularly in the first stage (definition of objectives and indicators) and the final stage (assessment of policies and scenarios) is essential to ensure that the process effectively influences the decision process.

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