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Michael E. Meadows
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Geomorphology and Society

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Preface

The International Geographical Union (IGU) now has more than 40 "commissions", groups of researchers who focus on a particular theme or subdiscipline of geography. Landscapes and landforms have long been objects of study for physical geographers, and an IGU commission dealing with such matters, under various guises (Geomorphological Response to Environmental Change, Geomorphological Challenges in the Twenty-First Century), has been long been active. The science of geomorphology has been through several transformations, if not revolutions, since its formal inception in the second half of the nineteenth century (Chorley et al. 1964). These include an early twentieth-century focus on "cycles of erosion" (Davis and Penck), the quantitative and systems approaches of the 1960s onward, and a concern with processes and applied geomorphology in the latter part of the twentieth century. Arguably, another transformation is under way, with the growing recognition of the nature and scale of the human impact on Earth that has led to an increasing need to examine the relationship between people and the Earth's physical environment. Analysis of the reciprocal impacts of people on geomorphology and of geomorphology on people represents an important thrust (not new, as such, but certainly rejuvenated) in the discipline.

Jamie Woodward's rather alarming evaluation[1] of the declining use of the word "geomorphology" in scholarly books published in English suggests that a new direction for geomorphology is clearly necessary. The IGU's mission is to foster the diversity of geography and to respond to new developments and iniatives, while at the same time securing its traditional roots. The geomorphic challenges commission, following several years of strong activities in the late 1990s and early 2000s appeared to be in need of some fresh ideas. And so it was, in 2012, that a proposal was put to the IGU General Assembly, at its Congress in Cologne,

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[1] Is geomorphology sleepwalking into oblivion? Earth Surface Processes and Landforms (2014).

Germany, to establish a new commission entitled Geomorphology and Society. The proposal was approved and an initial steering committee, under Professor Alcantara-Ayala as interim chair began its work. The original mission of the commission was stated as follows:

> The aim of the Commission shall be to contribute to strengthening collaborative work among scientific geomorphology networks to advance knowledge and to fostering capacity building for young researchers. Particularly, the Commission will be focused on developing applied geomorphology for the benefit of society.
>
> 1) To promote international collaboration in geomorphology within the IGU community.
> 2) To strengthen scientific cooperation with the International Association of Geomorphologists (IAG) and other international bodies related to the geomorphology field.
> 3) To support applied geomorphology research for building gateways with policy makers and societal engagement.
> 4) To stimulate the interaction among young scientists and the consolidation of leading working teams in different aspects of geomorphology.
> 5) To strengthen the scientific discussion between the numerical, experimental and field observation geomorphologists.
> 6) To foster the exchange of information and the dissemination of geomorphology.
> 7) Holding special sessions of the Commission within the IGU Congress and Conferences, as well as in other academic forums.

The inaugural meeting of the commission took place at the National Taiwan University in Taipei in September 2014. The main theme of the symposium was stated as “Earth Surface Processes in a Dynamic Environment”, with a clear emphasis on the way in which society impacts, and is impacted by, geomorphology. Earth surface processes, climatic change and land-use change are critical issues globally. Regional differences give rise to a diverse array of impacts and scenarios, requiring different approaches for more effective management solutions. The meeting provided a platform for dissemination of research findings of various geomorphologic issues and promoted meaningful discussion among scholars to develop collaboration in the future. A selection of the papers presented at that meeting comprises this volume on geomorphology and society.

We thank Irasema Alcantara-Ayala for the idea and the energy that she put in to getting the commission off the ground and R.B. Singh for suggesting that we try to publish the papers from the symposium. We wish to acknowledge the participants of that inaugural meeting for giving the IGU commission such a positive beginning. The National Taiwan University provided the venue for the sessions for the papers, and we also thank the Ministry of Science and Technology, Global Change Research Center, Department of Geography as well as the Tourist Bureau for their help during the field excursion.

Furthermore, we pay tribute to the team of referees who helped to develop the various chapters of this volume into something more coherent and scientifically sound, including Yazidhi Bamutaze, John Boardman, John Compton, Frank Eckardt, Gerry Garland, Andrew Goudie, Stefan Grab, Trevor Hill, Than van

Hoang, Peter Holmes, Jasper Knight, Olaf Slaymaker, Dieter Soyez, Tom Spencer, and Xiaoping Yang. We of course take full editorial responsibility for any errors that remain and are hopeful that the volume makes a positive contribution to emerging research on geomorphology and society.

Cape Town, South Africa Michael E. Meadows
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Chapter 1
Geomorphology and Society: An Introduction

Michael E. Meadows and Jiun-Chuan Lin

1.1 Introduction

A recent special section of the high-profile science journal *Nature* makes a strong case for the integration of social science into natural science research (for a commentary on this, see Viseu 2015). Of course, Geographers have long realised the importance of a holistic approach to the understanding of processes and problems associated with the interface of people and the environment. Grappling with the idea of developing a clearer picture of how the various factors of the physical environment interact with – and are both affected by and in turn affect – the social, political, economic and even cultural elements of populations is not a new idea. Indeed, George Perkins Marsh laid some of the foundations for this kind of thinking as long ago as the mid-nineteenth century (Marsh 1864). However, it is only recently that the sheer scale of human impact on global environments, arguably best exemplified by the record levels of atmospheric carbon dioxide and the impacts that these have had on global temperatures (IPCC 2013), has been realised. Clearly, as the *Nature* special issue argues '..we have to bring people with different kinds of skills and expertise together. No one has everything that is needed' (Nature 2015, p. 309) and that scientists must indeed '. . .work together to save the world' (Nature 2015, p. 305). This is not, however, a simple question of bolting social science expertise onto funded research projects; rather we must attempt to really integrate the social and natural sciences in a way that is not

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'deeply asymmetrical' as it currently appears to be (Viseu 2015, p. 291). As Kondolf and Piégay (2011, p. 114) have noted '. . .most models of human interactions with natural systems tend to treat the two as separate systems that interact in specific ways, such as return interval of flooding, in many cases the two are directly coupled'.

The need to meaningfully integrate sometimes disparate ways of thinking in order to explore complex environmental problems was at the heart of the establishment of the International Geographical Union (IGU) Commission on Geomorphology and Society, ratified by the IGU General Assembly in Cologne in 2012. The recognition of the dependence of global society on geomorphological processes, the threats that these processes represent as geohazards, and the impacts of humans on landforms and the processes that form them all act as motivation in our efforts to better comprehend the complex set of relationships that these elements entail. The inaugural conference of the new commission was held at the Taiwan National University in Taipei in September 2014 and attracted the participation of geomorphologists, both academic researchers and practitioners, from many different countries. The presentations at that conference form the basis of the current volume, which is aimed at illustrating the imperative of understanding the relationship between geomorphological processes, operating at different spatial and temporal scales, and society. While some of the contributions deal with the impact of geomorphic processes on people, others focus more on how people impact on geomorphology; still others offer a perspective that integrates both elements in suggesting more effective ways of mitigating geohazards in the future.

1.2 A Brief Outline of the Contributions

The nature and scale of human impact on environments in general has led to increasing use of the term 'Anthropocene' as the label for our current geological epoch. Of course, the International Commission on Stratigraphy of the International Union of Geological Sciences had not, at the time of writing, decided whether or not to formally ratify the use of the term as a formal stratigraphic unit. Irrespective of a formal decision to accept (or not) the term as a geological unit, there is a lively debate as to exactly when the Anthropocene actually commenced. In the opening chapter of the book, Meadows argues that, whether we like it or not, the term is here to stay and that, even if only as a pop-culture label, it is symbolic of the sheer magnitude of the accumulated impacts of society on the environment in general and, in the context of this volume, geomorphology in particular. Meadows goes on to suggest that a perspective on the Quaternary offers a foundation to understand baseline earth system conditions against which we can better evaluate the nature and scale of human impact on geomorphology now and in the future.

Soyez chooses a very particular anthropogenic impact to focus on, one that appears to have been rather neglected, if not ignored, by geomorphologists. He outlines various issues associated with the extraction of sand and gravel materials, principally for construction work. Population growth and increasing urbanisation have resulted in an exponential rise in the extraction of sand and gravel resources globally, much of which is not adequately monitored and, in an alarming number of instances, is even illegal. The deleterious environmental effects of this kind of mining are diverse and, since many of these are quite obviously geomorphological, it is interesting that civil society actors, rather than geomorphologists, currently play the dominant role in highlighting the issue and the threats that it poses to sustainability. There is no doubt that the diverse problems associated with aggregate extraction pose challenges (and offer opportunities) that demand research at the interface of human and physical geography.

Taiwan provided a most suitable locational context for the inaugural conference of the IGU Commission on Geomorphology and Society. In his chapter, Lin introduces us to the extraordinary combination of physical environmental and societal factors that yield such dynamic geomorphological conditions in this small sub-tropical island. A combination of earthquakes – the island sits on the northwestern margin of the Philippine tectonic plate – steep togography, high relief, frequent summer and early autumn typhoons together with high urban population densities is a concoction that all too can induce catastrophe. The geomorphic conditions manifest as frequent landslides, river channel dynamics and coastal changes that demand detailed technical knowledge to be combined with a deeper understanding of societal response if such catastrophe is to be avoided in future. In this sense, Taiwan represents an ideal 'laboratory' for the study of geomorphology and society.

Indeed, several other chapters develop case studies that demonstrate the need for closer cooperation between geomophologists, politicians, planners and county and municipal decision-makers in the country. Jen and co-authors document the landslides and debris flows initiated by one of the largest typhoons in Taiwan's recent history, Typhoon Morakot, which brought record rainfall to the country in 2009 and initiated excessive mass movement that had significant impacts on the population. The chapter explores the use of a GIS-based mapping technique to identify areas of landslide concentration (hotspots) as a step in the direction of preventing future problems arising from events of similar nature and magnitude. Shen then examines the need for systematic and accurate land development controls in regard to flood mitigation. She demonstrates, using examples from four selected river reaches in the country, that the delineation of so-called historical fluvial territories (i.e. the geomorphologically active parts of the river floodplain historically prone to inundation during flood events) is an important element of avoiding future disasters related to flooding. Su's chapter explores a slightly different element of the geomorphology and society interface, although the motivation to introduce a solar energy plant to a low-lying part of coastal Taiwan lay in the devastation caused by Typhoon Morakot. She presents a political economy approach to understanding why and how the decision to establish the plant was taken. The various parties include national, regional and local policy-makers as well as individual landowners –all acting out against a background of changes in policy in the face of land subsidence caused principally by tectonic activity.

Japan is, of course, a country that is also associated with high levels of tectonic activity and high relief and so clearly offers pertinent examples of the need to understand landscape morphodynamics with a view to geohazard mitigation. Hayakawa and co-authors utilise very high resolution laser-scanning to produce a recent time series of a mega-landslide, the Ohya-kuzure mass movement feature in central Japan, and in so doing reveal the spatial and temporal pattern of sediment production that provides information vital to the mitigation of possible future sediment-related risks to communities in downstream areas. The chapter by Le et al. presents yet another effective methodology for documenting landslide impacts, this time based on a case study from central Vietnam. The mapping technique employs available aerial photography and reveals that a landslide typology based on morphology can be a useful tool as a preliminary step in determining the susceptibility of populations in different localities. The mass movement theme is further developed by Keiler and Fuchs who, in taking the European Alps region as an example, focus more on the societal/behavioural issues that need to be addressed if a more robust understanding of future geohazard risk is to be obtained. The combination of vulnerability and exposure, along with their connections with mountain geomorphology, emerge as key considerations.

Two of the chapters present cases related to lakes, one describing how land use change and geo-engineering has impacted on sedimentation, the other outlining the impacts of hydroclimate dynamics on lake levels and their subsequent effects on people. Nagao and colleagues describe a situation in central Japan in which changes in the drainage system arising from land reclamation efforts aimed at facilitating food production significantly altered deposition, particularly in relation to increased organic matter inputs. Although this is less obviously a ‘geomorphological’ perspective, it does illustrate how human actions, often aimed at increasing productivity of the land, can have unintended consequences for sediment supply in vulnerable low-lying lakes and wetlands. In the central Rift Valley of Kenya, a series of lakes which are of vital importance to livelihoods of the local population are shown by Obando and her co-workers to be very sensitive to hydroclimate dynamics. More particularly, rainfall in the catchments of these four lakes has, since 2010–2011, been well above the long-term mean, most likely associated with El Niño conditions. This has significantly increased lake levels and applied considerable stress to several aspects of the natural environment such that local communities have been severely impacted as a consequence. Of course the trend in rainfall amount and distribution is a key element of soil erosion and needs to be carefully accounted for in modelling soil loss. Sumner et al. review our understanding of the issue of rainfall erosivity and its importance for accelerated soil erosion risk assessment. They note that, in the case of Mauritius (incidentally another small subtropical island), where cyclonic rainfall events (these would be called ‘typhoons’ in Asia) would usually be thought as most significant in the context of soil loss are supplemented by rainfall from winter cold fronts and can also be very important drivers of increased erosion.

The last two chapters of the book deal with coastal geomorphology, a sub-category of the discipline that classically illustrates the interdependency of landforms and people. Coastal morphodynamics are very strongly impacted by both the direct (e.g. coastal development) and indirect (e.g. sea level caused by anthropogenic climate change) effects of people. Regnauld and colleagues use an example from western Brittany to illustrate that even major human-induced geomorphic impacts (in this case the almost complete removal of a coastal gravel bar for construction during the second world war) can be effectively managed in a way that enables natural environmental processes to recover. This involved a complex series of management (and mismanagement) interventions over time but has culminated in a situation whereby the coastal barrier and marsh system is now an important and valuable site of conservation. The need to integrate our understanding of sediment systems in relation to estuaries and coasts is the focus of the study by French et al. for a part of the Suffolk coast of England. They employ a new coastal mapping approach that captures not only the natural dynamics of the system under varying environmental conditions (including sea level rise of course) in a robust way, but also accounts for the multiplicity of human responses that interact with the predicted shoreline changes. The authors document an innovative participatory approach that can be applied to a more complete understanding of the challenges of living at the coast and, in this way, provide an excellent example of what it means really to integrate geomorphology and society.

1.3 Prospective

Geomorphology is a complex science that requires multiple levels of understanding of a wide array of features and processes operating at a range of spatial and temporal scales. The individual and unique nature of the geomorphology of the earth's surface led Schumm (1991) to employ the term 'singularity' in relation to landforms. His argument in essence is that that the sensitivity of landforms to external forcing (including human activity) varies to some degree between apparently similar systems and even within the same system under the same conditions. Phillips (2015) has even gone as far as to suggest that geomorphology is 'badass' in that its processes, illustrated in his case by the meandering of a section of the Kentucky river, is individualistic, non-conformist in a way that makes their understanding additionally difficult (but also more interesting). The various chapters in this volume illustrate that the challenges of resolving geomorphological processes are in themselves substantial but that, as soon as the societal element is introduced, the complexity and challenge escalates further. Thus, integrating geomorphology and society is no trivial exercise, but the efforts to do so are all the more important in these times of rapid change in environmental processes and, indeed, in global society at large. That these contributions are brought together in the form of a book, rather than as a special issue of a specialised journal, is all the more important given Woodward's (2015) quite alarming observation that the use of the term 'geomorphology' in monograph titles has dramatically declined in the last few years. We hope that this volume will in some small way help to communicate the importance of our discipline to a broader community of scientists and social scientists.

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Chapter 2
Geomorphology in the Anthropocene: Perspectives from the Past, Pointers for the Future?

Michael E. Meadows

Abstract The term Anthropocene has been introduced to highlight the fact humans have, directly or indirectly – accidentally or intentionally – profoundly transformed the earth system. There is much debate as to whether the magnitude and extent of such change is geologically distinctive and, accordingly, warrants formal designation as a new epoch although, irrespective of this, the magnitude of change is undoubtedly significant. In order to put the Anthropocene into perspective, the chapter briefly reviews various systemic and cumulative drivers of geomorphic change before going on to explore the time-transgressive impacts of humans on virtually all environments of the earth. This is followed by a consideration of three instructive case studies of how the deleterious effects of growing numbers of people using increasingly sophisticated technologies are expressed geomorphologically across a range of environments. The problems of accelerated soil erosion, the impact of large dams and the nature and extent of artificial ground are used to highlight the important role that geomorphology plays in understanding the burgeoning footprint of humanity on earth systems. The Quaternary record offers a foundational understanding of baseline conditions of earth system processes and responses and facilitates increased confidence in evaluating the magnitude of past and future global climate change and its diverse effects. A quarter of a century on from the first IPCC report, the degree to which the strength of its statements, and the confidence with which they are made, is rooted in a better understanding of longer-term past changes should not be underestimated. The fact that geomorphology may still be a 'Cinderella' in relation to studies of environmental change is ongoing cause for concern and, if we are to illuminate the range of options available to mitigate and adapt to future change, we need systematically to incorporate a stronger geomorphological perspective into global change science; the Anthropocene represents an appropriate platform from which to inject that perspective.

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2.1 Introduction: The Anthropocene

The term ‘Anthropocene’ was introduced to the world of science at the turn of the new millennium (Crutzen and Stoermer 2000) and it is now very widely employed, although not without controversy, to describe the current geological age. There are now three academic journals using the word in their titles (*Anthropocene*, *Elementa – Science of the Anthropocene* and *Anthropocene Review*) and it is clear that, notwithstanding heated debate around its definition, Anthropocene as a label is here to stay. The term was originally proposed to highlight the increasing impact of humans on the environment to the point of their dominance over other ‘natural’ processes. Thus, anthropogenic activities were considered global in their extent and so potent in their effects that geologists of the future would be able to examine the sedimentary record and see a marked shift from a dynamic world dominated by natural processes to an even more dynamic one characterised by processes directly affected by people. Hence, in the future it would be possible to look back and see in the geological record where the Holocene ended and the Anthropocene began. In essence, this led to the concept of ‘a geology of mankind’ (Crutzen 2002).

Although the idea of human impact is not new, since George Perkins Marsh wrote the first systematic account of how people transformed the earth surface through deforestation and the like 150 years ago (Marsh 1864), it is the idea that human effects now outweigh natural changes that has prompted the need to consider the naming of a new geological epoch. While much of the debate has focused on what criteria should or could be used to identify the Anthropocene (see Steffen et al. 2011; Ruddiman 2013) and, accordingly, how and when should its starting point be defined (Smith and Zeder 2013; Foley et al. 2013), this chapter rather focuses on the nature and scale of impact in relation to geomorphological processes and landforms in particular. It is not my intention here to enter the debate as to whether or not use of the term is valid or, if so, when the epoch actually began. As Braje and Erlandson (2013, p. 116) put it ‘. . .Designating a starting point for the Anthropocene may be less important than understanding the cultural processes that contributed to human domination of Earth’s natural systems’ and in any case, formal ratification is in the hands of the International Union of Geological Sciences (IUGS) through a working group of its International Commission on Stratigraphy (and see Waters et al. 2014). Indeed, rather than arguing about the precise identification of an Anthropocene ‘beginning’, Butzer (2015) suggests that a more flexible, time-transgressive approach would more fruitfully stimulate study of human disturbance of the global environment. It is, nevertheless, important to understand the environmental processes by which human impacts were manifested and that geomorphologists need to play their part in elucidating these. The aim here, therefore, is to use the idea of the Anthropocene as a lens through which geomorphologists can develop research which contributes more directly to a better understanding of the relationship between society and landforms and the processes that shape them. Brown et al. (2013) suggest that there could well be a ‘geomorphological case’ for the Anthropocene and Lewin and Macklin (2013) have already assessed the possible value of a formally defined Anthropocene for geomorphologists. Whether we recognise the Anthropocene or not, further exploration is still needed of the nature and magnitude of societal impact on geomorphic processes in a variety of geographical contexts and at a range of scales. Only through such studies can we begin to understand and address the resultant problems and seek the means to a more sustainable future.

To begin this discussion, it is first necessary to consider the different ‘drivers’ of geomorphic change and to explore their relative importance in shaping landforms. Following a brief consideration of the magnitude of human impact on the earth’s system, the chapter moves to an exploration of several key case studies illustrating the nature and scale of human modification of landscapes. In considering the use of evidence from the late Quaternary, the relatively recent geological past, the scale of human-induced change can perhaps be benchmarked. Finally, there is contemplation of how prospective environments may develop and how geomorphologists can usefully contribute to current thinking about a more sustainable future.

2.2 Drivers of Geomorphic Change

In relation to global environmental change, Slaymaker et al. (2009) recognise two major forms of ‘driver’ in geomorphology, sets of processes that have shaped, and continue to shape, the landforms around us. These are the so-called ‘systemic’ and ‘cumulative’ drivers of change. Paramount among the systemic drivers are those related to the hydroclimate and its relationship to surface runoff. The hydrological cycle is obviously sensitive to change in global climate but the geomorphic effects are strongly scale-dependent and not necessarily easily accounted for. Runoff is influenced by such processes as land use change, which is spatially discontinuous and complex. Land use change can have net positive effects on runoff volume, for example when forest is replaced by agriculture with much lower biomass and land cover (Muñoz-Villers and McDonnell 2013), but can equally restrict runoff volumes in situations where the change results in increased biomass and evapotranspiration, such as when Mediterranean-type shrublands are invaded by alien trees (le Maitre et al. 1996) or through afforestation (Iroumé and Palacios 2013). Substantial geomorphic impacts are produced by other common human interventions, such as the construction of impoundments which in some cases stop even major rivers from running to the sea altogether (Biemans et al. 2011). Therefore, in so far as people can manipulate the hydrological cycle and climate, intentionally or otherwise, such processes are an important means by which society affects geomorphology.

The second major systemic driver according to Slaymaker et al. (2009) is sea level change. Through the global effects of anthropogenic climate change, sea level is rising mainly through the combined influence of increased runoff due to ice sheet melt-out and thermal expansion of the ocean itself as a result of higher temperatures. There are obvious implications here for coastal geomorphology, with impacts likely on estuaries, coastal marshes and dunes, beaches, cliffs, deltas and coral reefs that can all be considered, indirectly at least, geomorphological consequences of human-induced climate change.

Topographic relief and human activity are classified as cumulative drivers of the earth system by Slaymaker et al. (2009). Except perhaps at the local scale, topographic relief, despite its marked importance for denudation, is essentially a longer-term, if dynamic, influence on geomorphology and is not considered further here. But human activity as a cumulative driver, over and above the secondary effects wrought through climate change and associated effects on the hydrological cycle and sea level, is patently an essential focus in the context of this chapter in particular and the book in general. In regard to this, Slaymaker et al. (2009) divide the important factors into direct and indirect. Indirect factors include the essential social and economic features of the human society, for example population growth, cultural practices, trade and industry. These are obviously highly complex issues and spatially extremely dynamic although the authors point to the growth of the world's population, especially in the second half of the twentieth century, as perhaps the most potent indirect driver in this category. The world's people are increasingly urbanised and increasingly concentrated at or rather near the coast or regions otherwise prone to flooding (Jongman et al. 2012) with implications for the location of geomorphic impacts.

2.3 Time-Transgressive Human Impacts on the Earth System

The debate around use of the term Anthropocene has in part centred on the difficulty of establishing when it actually commenced. This a common kind of problem in stratigraphy, where one geological time unit ends and another begins is always a cause for deliberation and sometimes a source of dispute, but the case for the Anthropocene is especially challenging because substantial impact of humans on the earth system has been spatially uneven and time-transgressive. Human modification of the earth has arguably been significant for more than 8000 years (Ellis 2011) with major land use changes a characteristic of the Neolithic 'revolution'. Mass extinction of mega-fauna, a process in which humans certainly played their part through hunting, occurred even earlier. But the scale of transformation was not of a similar magnitude everywhere in these earlier phases of impact and the 'palaeoanthropocene' (Foley et al. 2013) is equally difficult to pin down. Ruddiman (2013) makes the point that the first major human impact on atmospheric greenhouse gas concentrations occurred in the mid-Holocene as a result of land use changes, more especially deforestation, and that it was at this point that the atmospheric condition of the current interglacial began to diverge from the pattern typical of other interglacials of the late Quaternary. However, many others argue that the most profoundly global human impacts have occurred since industrialisation of the global economy and especially in the post second world war period increasingly referred to as the ‘Great Acceleration’ (Costanza et al. 2007) because of the directional trends observed in so many diverse parameters related to human activity and the parallel trends in features of the earth system.

The geomorphological implications of such dramatic changes are important as landscapes have become transformed through the combined effects of agriculture, forestry, mining, water storage and diversion and urbanisation as well as the indirect consequences of changing climate and sea level. Land use change is perhaps the most obvious direct form of human intervention with immediate geomorphic consequences. To put this into context, Ellis (2011) has modelled the degree of transformation across global biomes and arrived at the conclusion that people had already converted substantial proportions of the earth’s terrestrial biomes into what he terms ‘anthromes’ (see Ellis et al. 2010) by the year 1750. Hooke et al. (2012) review the scale of land transformation and suggest that rather more than 50 % of the earth’s terrestrial surface had been modified by the year 2007 (Table 2.1). Human appropriation of global net primary productivity has doubled in the last century and now more than 25 % of every gram of carbon fixed through photosynthesis is directed to human use (Kraussman et al. 2013). Of course, this human ‘footprint’ is spatially irregular and regions within the tropical and temperate woodland biomes have been especially impacted along with vast areas of the Middle East and the Indian subcontinent (Kareiva et al. 2007). Such statistics prompted Ellen Wohl (2013) to lament that, in effect, ‘wilderness is dead’.

2.4 Human Impact on Geomorphology

Some examples of geomorphic changes that have accompanied the monumental dimensions of this scale of modification are apt here (Table 2.1). Syvitski et al.’s (2005) analysis suggests that, while accelerated soil erosion has increased sediment transport by rivers globally by 2.3×10^9 t a^{-1}, this has been accompanied by substantial reductions in sediment flux to the oceans (by 1.4×10^9 t a^{-1}) because of sediment storage in reservoirs. Indeed, reservoirs around the world now store more than 100 billion metric tons of sediment (Syvitski et al. 2005). Globally, large impoundments retain more than 2.3 Gt of sediment annually, resulting in sediment starvation of deltas which, combined with the extraction of water, oil and gas, results in a situation whereby deltas are sinking at four times the rate of sea-level rise (Syvitski 2012). More than 50 % of Earth’s ice-free land area has been directly modified by human actions involving moving earth or changing sediment fluxes (Hooke et al. 2012).

Table 2.1 Land area modified by human action (Hooke et al. 2012)

Activity	Area involved 10^6 km^2	% of earth's land surface
Human modified land		
Cropland (mostly cultivated or ploughed land)	16.7 ± 2.4	12.8 ± 1.8
Permanent meadows and pastures	33.5 ± 5.7	25.8 ± 4.3
Land area modified by deposition of eroded sediment	5.3 ± 2.0	4.1 ± 1.5
Land area modified by logging	2.4 ± 1.2	1.8 ± 0.9
Plantation forestry area	2.7	2.1
Sub-total agriculture and forestry	**60.6 ± 6.5**	**46.6 ± 5.0**
Urban areas (including urban roads)	3.7 ± 1.0	2.8 ± 0.8
Rural housing and commercial developments	4.2 ± 1.4	3.2 ± 1.1
Highways and roads in rural areas	0.5 ± 0.1	0.4 ± 0.1
Reservoirs	0.2 ± 0.1	0.2 ± 0.1
Railways	0.03	0.02
Mining and quarrying	0.4 + 0.4/−0.1	0.3 + 0.3/−0.1
Sub-total human infrastructure	**9.0 ± 1.7**	**53.5 ± 5.1**
Total land area modified by humans	**69.6** ± **6.7**	**53.5** ± **5.1**
Natural lands (mostly)		
Forest area (natural, if not necessarily virgin)	36.2 ± 2.9	27.8 ± 2.2
Other land (mainly high mountains, tundra, deserts etc.	24.3	18.7
Total natural land area	**60.5**	**46.5**
Total land area (excluding ice sheets)	130.1	100.0

Table 2.2 Human actions that modify geomorphic systems (After Syvitski and Kettner 2011)

Deforestation and its associated role in soil erosion, slope failure and downstream sedimentation,
Farm-animal grazing leading to gully development and soil erosion,
Agriculture, including tillage, terracing, irrigation systems and subsurface
Water extraction, leading, respectively, to increased soil erosion, creep, siltation and subsidence,
Mining and its associated role in river channel and hill slope alteration, slope instabilities and subsidence,
Transportation systems, including gully development, soil erosion and riverbed scouring,
Waterway re-plumbing, including reservoirs and dams, diversions, channel levees, channel deepening, discharge focusing and ultimately coastline erosion,
Coastal management through groynes, jetties, seawalls, breakwaters and harbours, leading to unnatural coastal erosion or sedimentation, wetland, mangrove and dune alterations,
Warfare that magnifies many of the above activities for a duration that extends beyond the period of combat, and
Global climate warming and its impact on coastal inundation, precipitation intensity, including the intensity of cyclones, desertification and an accelerated hydrological cycle

A diverse range of human actions is known to modify geomorphology (Table 2.2). Some of these impacts warrant exploring in greater detail as they are symbolic of the scale, magnitude and complexity of geomorphic challenges imposed by humans and point geomorphologists in the direction of where to focus their efforts. The three examples chosen here to elaborate on this are: (a) accelerated soil erosion; (b) the impacts of large dams; and (c) the growth in artificial ground.

2.4.1 Accelerated Soil Erosion

Dotterweich (2013) recently reviewed global evidence of the long-term history of soil erosion in humid and semi-humid landscapes and records; the earliest available historical documents describing soil erosion are from Greece and China from about 2500 years ago and the process is widespread in many types of environments. The initiation of accelerated rates of soil loss is most often land use change, in particular the clearance of forest in woodland in environments that support such vegetation but it is also prevalent in semi-arid regions as well, albeit not always confined to soil erosion by water because wind too is a potent geomorphic force. In order to assess the degree to which agriculture and other activities have resulted in increased soil loss and sediment delivery, it is instructive to consider how the process of natural erosion operated in the 'pre-human' era. Wilkinson and McElroy (2007) have engaged in such an exercise for the contiguous United States and compared the estimated spatial distribution and magnitude of long-term 'natural' soil erosion with those of the latter part of the twentieth century as measured, or modelled to be more precise, on cropland. The resulting maps are strikingly akin to mirror images of each other in that the denudation rates have highest values in the western half of the country whereas the cropland map shows elevated rates in the central and eastern states. Beyond the contrast in the spatial distribution of denudation, the magnitude is also markedly different; rates of erosion on agricultural land are estimated at an average of 600 m Gyear^{-1} and, in some places exceeding 2000 m Gyear^{-1} in comparison with values below 15 m Gyear^{-1} or less in equivalent areas prior to the land use change (Wilkinson and McElroy 2007). The analysis indicates an acceleration directly due to human modification of more than an order of magnitude and leads the authors to the conclusion '...that farming practices are the most important processes of erosion acting on the surface of modern Earth' (p. 150). Wilkinson and McElroy (2007) go on to argue that, combined with the accelerated erosion of the sediment itself, subsequent deposition of the material of floodplains '...is the most important geomorphic process...currently shaping the landscape of Earth (p. 140)'. The significance of this surpasses even the effect of continental glaciation during the Quaternary or the modern rates of erosion by glacio-fluvial processes.

In semi-arid and arid environments (Goudie and Middleton 2006), but also under agricultural land use in sub-humid or even humid regions (Borrelli et al. 2014; Biemans et al. 2014), accelerated soil loss due to wind erosion is a significant geomorphic force. Globally, large volumes of mineral dust enter the atmosphere and an increasing proportion of these aerosols emanate from areas that have been significantly impacted by humans. Undoubtedly the rate of erosion of fine particles is significantly increased where vegetation cover is reduced in grazing and croplands. Furthermore, increased temperatures and reduced soil moisture due to anthropogenic climate change is likely to exacerbate the problem. For example, conditions that resulted in the North American ‘Dust Bowl’ in the 1930s were certainly amplified by agricultural mismanagement (Cook et al. 2009) and evidence suggests that such conditions are more likely to occur again as a result of climate change (Seager et al. 2007).

Soil erosion is, of course, not necessarily an irreversible environmental problem and there are many cases of degraded land being rehabilitated. Accelerated erosion that occurred in the wheat farming regions of the Cape Town (South Africa) hinterland in the 1930s was addressed through investment in soil conservation works and farmer education; gullies were reclaimed, contours constructed and the land once again became productive (Meadows 2003). It is becoming increasingly clear that soil conservation efforts need to address more than the basic biophysical processes and that solutions founded on an enabling policy environment that integrates the land-user perspective are much more likely to be effective (Dumanski 2015).

2.4.2 Geomorphic Impacts of Dams

Large dams have diverse effects on a range of geomorphological characteristics that have been widely reported, especially in the downstream direction. Graf (2006) analyses above and below impoundment reaches of 72 large North American rivers and documents impacts that amount to a ‘shrunken and geomorphologically simpler’ downstream environment (p. 336). Regulated reaches have significantly less active flood plain areas and greater inactive flood plain areas. The cumulative effect of reservoir management and irrigation extractions leads to a mean annual decrease in global discharge of almost 1000 km^3 (Biemans et al. 2011; Gerten 2011) and, although this represents only about 2 % of discharge, there are seasonal fluctuations resulting in periodically more substantial effects and many rivers where the hydrological impact is of geomorphic significance.

Rather than reduction in discharge per se, geomorphologically it is the impact of impoundments on river sediment load that is of most importance. This is exacerbated by the fact that the number of dams, both small and large, has grown exponentially in the last century or so, both in the developed and developing world. There were no dams in North America in the year 1800, although there has been extremely rapid increase in construction across the region since then; indeed, humans ‘. . .have engineered how most water and sediment are discharged into the coastal ocean’ (Syvitski and Kettner 2011, p. 957) and the global influence on sediment flux is considerable. Gupta et al. (2012) review the situation in southeast Asia where there are now 250 mega-dams and tens of thousands of smaller impoundments that have decreased sediment flux in the order of 20–90 %. In some rivers, sediment flux has been so interrupted by impoundments that only negligible amounts of sediment now reach the coast from their catchments, for example the Ebro in Spain (Walling 2006). In the case of the Three Gorges Dam, the world's largest, 1.8 Gt of sediment were trapped within the first decade following its construction and there were some periods when more than 90 % of the upstream sediment load was deposited; sediment thickness already exceeds 60 m in places (Yang et al. 2014).

There are numerous detailed examples in the literature of the potential geomorphological and hydrological implications of sediment starvation downstream of reservoirs. Petts and Gurnell (2005) note the changes in channel form that dams invoke and the knock-on impacts of this for irrigation ecology of riparian vegetation. For south-east Asia, one large-scale outcome, among many others, is the marked reduction in the extent of some of the largest deltas in the continent (Gupta et al. 2012). All five of the major rivers that drain into the East Pacific Ocean have experienced dramatic reductions in sediment delivery to the sea (Wang et al. 2014). Delta shrinkage is predicted to accelerate in the future; Syvitski et al. (2009) have estimated that, globally, delta surface area vulnerable to flooding could increase by 50 % under projected sea-level rise estimates due to losses in aggradation and other processes (Syvitski et al. 2009). There are obvious implications of this for the large populations living or obtaining their livelihoods on deltas. Downstream channel incision is also an important issue resulting from clearwater erosion due to sediment trapping by the impoundments. The balance of erosion or sedimentation in rivers is complex and dynamic with a number of controlling factors, but there is little doubt that sediment retention in impoundments can dramatically alter the equilibrium.

2.4.3 Excavation and the Creation of Artificial Ground

The magnitude of rock and soil material moved around the surface of the earth by humans in mining or construction, for example, is a geomorphic effect of humans that manifests as landforms. Ever since the first people began to excavate stone to make implements or discard waste material in 'middens', there has been direct and intentional human modification of the actual land surface of the earth. Price et al. (2011) report the scale of this to be enormous, with almost 60Gt of excavated material annually translocated, sometimes long distances from its source, and that this is almost three times the amount transported by the world's rivers. This represents deliberate modification arising from the creation of made ground, worked ground or infilled ground resulting from a range of activities including mining, construction, industry, ore-processing, solid waste generation, transport infrastructure development and land reclamation. Of course inadvertent movement of material also occurs due to processes of accelerated soil erosion (see above) and this also needs to be taken into consideration when assessing the magnitude of human effects on landforms.

Table 2.3 Summary of artificial ground in a selected regions of Great Britain based on 1: 50,000 scale geological map sheet areas and the maximum coverage of artificial ground shown by BGS DiGMapGB10 10,000 maps (After Price et al. 2011)

UK location	Sample area (km^2)	Mapped artificial ground area (km^2)	% artificial ground in sample area	Principal sources of artificial ground
Manchester city (large industrial conurbation)	559	99	17.8	Subsurface and open cast mineral extraction, textiles and engineering, industrial development, canals, construction and demolition
London area (large urban and peri-urban conurbation with multiple industrial centres)	2196	181	8.2	Dockland development, open cast mineral extraction, commercial development, construction and demolition
Midland Valley, Scotland (rural with multiple urban and industrial centres)	2297	185	6.2	Coastal industrial development, opencast and subsurface mineral extraction, metal processing

These effects are indeed so prominent that there is now a formal proposal to recognise so-called anthropostratigraphic and technostratigraphic units of classification for Holocene deposits (Howard 2014). Peloggia et al. (2014) have suggested the use of the term ‘geotechnogenic ground’. Ford et al. (2014) also argue for the need for a separate classification scheme for such sediments and Lewin (2013) has even gone as far as to suggest that some landscape elements, for example, modern floodplains, have in effect been ‘genetically modified’. There are practical difficulties in accurately assessing the distribution of such artificial landforms and associated sediments, either because the excavation or the resultant landforms are often obscured by the very activity that creates them, although Jordan et al. (2014) have developed a possible methodology and applied it to a case study of the Norfolk coast.

Some examples from Britain are helpful in revealing the scale of this process, at least for the industrialised world. In some cities, for example, Manchester, artificial ground occupies as much as 18 % of the urban area, although this may be an underestimate (Burke et al. 2009 after Price et al. 2011) and includes colliery spoil, infilled gravel and brick pits, industrial waste and reclaimed river valleys (Table 2.3). Such assessments have benefitted from the use of remotely sensed spatial data (aerial photographs, satellite imagery, digital elevation models) which increasingly allow time-series to be mapped, especially if used in conjunction with other documentary sources. Made ground in Salford, which may exceed 10 m in thickness, includes material, mainly colliery spoil and furnace waste, used to infill the former course of the River Irwell and deposited next to the Manchester Ship Canal (Price et al. 2011) during the late nineteenth century. The identification and mapping of artificial ground is but one further means by which we may judge the nature and magnitude of the human geomorphic footprint. As with anthropogenic soils, such deposits may yet represent the ‘golden spike’ of the Anthropocene (Certini and Scalenghe 2011).

2.5 Perspectives from the Past: The Quaternary Benchmark

In deliberating as to whether or not the term Anthropocene should be formalised, one of the key issues is to assess the degree and extent to which human activities have come to dominate global earth system processes. In other words, have humans transformed global environmental processes in such a way as to deflect the natural course of events in some clearly identifiable way? In reality, such a question is unanswerable without recourse to evidence from the past, for if we do not know what is the longer-term ‘pulse’ of the earth system, i.e. what indeed is the ‘natural course of events’, we cannot begin to evaluate the magnitude of human impact. This is not a novel idea of course, since geomorphologists have long recognised that understanding landforms and the processes that shape them cannot be comprehensive if it is based only on ‘snapshots’ of the contemporary situation or recent past. As Meadows (2012) argues, reliable reconstructions of palaoenvironments are essential to our meeting the environmental challenges of the future. The recently published Intergovernmental Panel on Climate Change Fifth Assessment Report (AR5) (IPCC 2013) fully accepts this and, for the first time, contains a chapter dedicated to the use of palaeoclimate archives, in particular from the Quaternary, as a benchmark of earth system sensitivity. ‘This offers a foundational understanding of baseline conditions of climate and on other components of the earth system and allows increased confidence in evaluation of the magnitude of past and future global climate changes’ (Meadows 2014, p. 1). In other words, to quote Winston Churchill: ‘The farther back you can look, the farther forward you are likely to see’.

However, this is not simply a matter of applying reconstructions of the Quaternary past to predict the future. Knowledge of the way environments changed, even in the geologically recent past, cannot be a kind of ‘plug and play’ to foresee how landscapes will respond, for example, to a given range of predicted climate parameters. Knight and Harrison (2013) have, however, gone as far as to argue that earth scientists may need to abandon the concept of uniformitarianism altogether as it pertains to the Anthropocene and that ‘…traditional systems’ properties such as equilibrium and equifinality are increasingly irrelevant (p. 5). This is certainly a provocative view and to accept it uncritically would be to ignore a great deal of evidence about the sensitivity of the earth to wide range of perturbations beyond those invoked by human activity. There are in fact several ways in which developing robust analyses of past environmental changes can provide a valuable perspective that may lead to more effective management of the environmental challenges of the future, although this requires continued improvement both in methodologies and in the way in which data are provided (McCarroll 2010; Meadows 2014).

Are reconstructions of the Quaternary past helpful in evolving scenarios of future responses of the earth to climate change and does that have geomorphological relevance? The fifth assessment report of the IPCC (AR5; IPCC 2013) adopts reconstructions of past climate as benchmarks which can be used to train climate models. Put crudely, complex ocean-atmosphere models need to be able adequately to reconstruct known climates of the past otherwise we can hardly expect them to be able to accurately predict climates of the future. Climate models are required that generate credible scenarios of the future, making available data of relevance to geomorphic processes at a range of different spatial scales. This can best be done through identifying how landforms and the processes that shaped them responded to changes in the past and indicates the degree to which geomorphology is sensitive to the dynamics of climate and other variables, including human activity.

In essence, the past is a reference or archive against which to quantify the anthropogenic effect. Benito-Garzón et al. (2013), for example, have computed long-term climate anomalies between the mid-Holocene and IPCC-generated future climate scenarios to provide a comparative perspective on the magnitude of differences in climate across time. This is then applied to a model of biome changes but it could just as easily be adapted to deal with key geomorphological parameters such as sediment flux. In reality, landscape sensitivity can only really be properly assessed by examining the response to perturbations of the past.

Ecologists utilise the concept of a ‘historical range of variability’ and this is also applicable to assessing the geomorphic response to what may be considered the ‘natural’ amplitude and frequency of environmental dynamics (Wohl and Rathburn 2013). The degree to which human activities might result in exceeding historical thresholds of equilibrium represents yet another possible palaeoenvironmental line of inquiry for geomorphologists interested in applying their minds to issues of more practical significance, such as the susceptibility of channels to incision (Florsheim et al. 2013).

Arguments have been made for utilising past environmental analogues, in particular the identification of periods of time when the earth’s climate was as warm, or warmer than today. What transpired geomorphologically during those times? Obviously at a rudimentary level this is far too simplistic, not least because past boundary conditions are usually very different from the modern and, as is evident throughout this volume, the impact of humans on the global environment is so profound that any information about, say, past rates of soil erosion in response to warmer temperatures may be meaningless. Indeed, ‘. . .no interval during the last 650,000 years is extreme enough to be an indicator of late twenty-first century climate’ (Haywood et al. 2009, p. 5). Surprisingly, then, the search for analogues is ‘not over yet’ (Meadows 2012, p. 542). One especially promising candidate for a ‘palaeoanalogue’ is is the so-called Palaeocene-Eocene Thermal Maximum (PETM) event (Bowen and Zachos 2010). Enormous amounts of carbon were released into the earth’s atmosphere around this time (c 55 Ma) over a relatively short period (perhaps 20 ka) and, indeed, the effects were long-lasting, as has been posited for the current interglacial (Stager 2010), persisting for up to 200 ka and associated with higher global temperatures of the order of 5–6° C. A deeper investigation of the climate, vegetation and geomorphic relationships of this period could provide useful insights into a future warmer earth.

2.6 The Future of the Anthropocene?

Much of this chapter has dwelt on environments of the past and the imperative of quantifying, or at least clarifying the nature and extent of human activities on the landscape and it is clear that these activities have had impacts that are global in extent, highly diverse in character, mostly unintended and possibly even irreversible. Disagreement still seems to dominate the discourse around use of the term Anthropocene, particularly in relation to whether or not it should be declared a formal stratigraphic unit (Rull 2013). Indeed, the first formal meeting of the Anthropocene Working Group of the International Union of Geological Sciences' (IUGS) International Commission on Stratigraphy took place in Berlin, Germany in September 2014 (see: Sub-commission on Quaternary Stratigraphy 2014) and any formal proposal can only be ratified at the earliest in 2016 at the next IUGS General Assembly. However, even if the IUGS does not decide to adopt a formal definition, the fact of the matter is that the term is in widespread use in science, in the media and even in 'pop culture' (Autin and Holbrook 2012).

Geomorphologists have entered the fray of this argument (Brown et al. 2013, 2016) but I sense we are better off expending our, time, energies and hard-won research grants addressing some of the problems that have emerged from human impact on the landscape with a view to ensuring a more sustainable future. We should surely engage in the science of a significantly modified global environment irrespective of a formal designation for the new epoch. The 'Anthropocene narrative' (Berkhout 2014) is shaping decisions about investments, development, lifestyles and even livelihoods. As Ellis and Trachtenburg (2013) put it: 'Anthropocene science is cast in the vital role of helping people make the choices that will realize a morally acceptable future. This role should not be a passive one, restricted to objectively predicting outcomes, or even posting warnings about bad choices' (p. 60). The authors envision an active role for Anthropocene science, in which we try to identify more favourable outcomes and pathways to attaining them. One of the most important roles for scientists, as Slaymaker et al. (2009) argue, is to clarify the options that will enable us to respond to global environmental change in a sustainable way; the complex set of relationships between geomorphology and society surely need to be considered in choosing such options. Understanding human-landscape systems should indeed be a high priority research initiative that requires participation from the social, behavioural and economic sciences in full collaboration with geosciences, biosciences and engineering (Harden et al. 2014).

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Chapter 3
Society and Geomorphology: Addressing the (Mis-)Use of Aggregate Resources

Dietrich Soyez

Abstract Society and geomorphology are mutually dependent. The scientific gaze on society's and geomorphology's common fields of interest was for a long time, however, clearly dominated and continuously refined by geomorphologists. A corresponding involvement on the part of social scientists was unusual. This paper addresses interlinked fields of major importance for both society and geomorphology, but mainly from an intradisciplinary social science/human geography perspective. After an introductory section on the evolution of the subfield of anthropogenic geomorphology, the main focus is on an emerging topic of arguably worldwide influence for both bio-physical and socio-political systems: the rapidly increasing extraction and (mis-)use of aggregates (sand and gravel) and the ways of addressing related issues from a variety of geographical perspectives. The discussion directs the attention to problematic developments, apparent knowledge gaps and ensuing potential pitfalls as regards both scientific conclusions and socio-political decision-making. A concluding appraisal shows what could be gained through a closer cooperation of physical and human geography and a consistent search for a geomorphological turn in this latter, not least by integrating this issue in emerging ICSU/ISSC Future Earth endeavours.

Keywords Human impact • Anthropogenic geomorphology • Aggregate resources • Fluvial-coastal morphodynamics • Sand wars • Future earth

3.1 Introduction

3.1.1 Objectives and Line of Argument

The central aim of this paper is, firstly, to outline geographically relevant themes and research approaches concerning the relationships between society and geomorphology and, secondly, to discuss them critically in the context of an issue that has only recently come to attention in larger public arenas. Surprisingly enough, it

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Fig. 3.1 Illegal beach sand mining near Tangier, Morocco (© SAF-Coastal Care)

seems to be almost completely absent from the geographical discipline: the problem of aggregate extraction and scarcities resulting there from in many regions of the world (with mining methods ranging from using shovels to industrial dredging machinery, Figs. 3.1 and 3.2).

At first sight, the issue might look far less urgent than more classical socio-natural topics, such as soil erosion or hazards. However, the foreseeable effects of huge land reclamation schemes and infrastructure needs, on the one hand, and sediment starved rivers and beaches on the other, are not restricted only to local or regional scales. They clearly, and increasingly, involve highly critical international, in some respects even global, implications. In this chapter, the topic is reviewed on the basis of selected documents from the academic literature, media and civil society and it is hoped that the issues highlighted will also be addressed at a much larger scale by conceptually informed empirical geographical studies also.

The conceptual approach is as follows: firstly, typical paths and emphases in the discussion concerning both the geomorphology/society interface generally and the extraction and use of aggregates specifically are examined. In a second step, the insights hereby gained are critically compared, first, with possible links to specific geographical subdisciplines and, second, with recent conceptual suggestions from intra- und cross-disciplinary geographical approaches, such as political geography, resource geography and political ecology. Finally, the issues raised are evaluated in view of the ways in which approaches and methods of the ICSU/ISSC Future Earth research initiative may be enriched from a specifically geographical viewpoint.

Fig. 3.2 Sand dredging in the Bassac River near Cần Thơ, Vietnam (© Edward Anthony (WWF Greater Mekong, Ho Chi Min Citym Vietnam), Philippe Dussouillez et Marc Goichot (Université Aix-Marseille, CEREGE UMR CNRS 7330, 13545 Aix-en-Provence, France))

3.1.2 The Society-Geomorphology Nexus

3.1.2.1 Intra-disciplinary Perspectives

A century and a half ago, George Perkins Marsh (1864) concluded that "…human action must rank among geological influences" (cf. Sherlock 1922 who must be regarded as another pioneer as to this perspective). Such early insights were widely recognized only recently, in particular in the context of the discussion about the Anthropocene, finding a succinct wording in the title of Crutzen's (2002) article "Geology of Mankind" (and see also Crutzen and Stoermer 2000). This concept is supported by observations that current material extraction rates, together with the ensuing accumulation of urban deposits in the broadest sense, exceed the annual transport of sediment to the oceans by rivers by roughly a factor of three (Douglas and Lawson 2000).

Many of the topics that have been addressed under the heading of 'geology' since Marsh's (1864) study could just as easily be subsumed under 'geomorphology' and its sub-disciplines, as these mainly deal with forms and processes on the earth's surface. In geomorphology, certain aspects of human influence on geomorphological structures and processes, for example soil erosion in North America or problems associated with alluvial clays in Europe, were studied very intensively in the first half of the twentieth century. A specialised field of research, however, concentrating on a wider array of connections between societal influences and geomorphological forms or processes developed quite slowly only in the second half of the twentieth century (see, for example, Erdõsi 1969; Rathjens 1979).

Illuminating approaches of a very different order as to the relationships between geomorphology and society (hence the title of their contribution) characterize the recent work of Kondolf and Piégay (2011). Geomorphological structures and processes in different culturally and historically shaped contexts are placed in the foreground of their study, with an emphasis on examples from fluvial morphology. The authors also address very critically the general question about what is ‘natural’ in alleged ‘natural fluvial systems’ of geomorphological research, thus directing attention to the long and complex history of natural and societal co-production (Kondolf and Piégay 2011). More recently, their findings are embedded in a larger frame of space and time scales, highlighting the critical mismatch between natural processes and their impacts, on the one hand, and societal perceptions and institutional reactions, on the other (Kondolf and Podolak 2014). Slaymaker (2009) and Church (2010), for instance, address related issues, but adopt a view embracing the entire field of geomorphology.

The cautious approach to gradually emerging problems at the geomorphology/society interface is reflected in the decades-long search for appropriate terminology: *anthropic geomorphology* (Nir 1983), *anthropogenic geomorphology* (Erdõsi 1969; Szabó et al. 2010; Harnischmacher 2012) and *anthropogenetic geomorphology* (Stahr and Langenscheidt 2015) are all still in use. Rathjens (1979) used the latter term in its German equivalent much earlier: *anthropogenetische Geomorphologie*. Anthropogenic geomorphology, however, seems now to have gained widespread use and is used in this chapter. The concept *neogeomorphology* coined by Haff (2003) seems not to have been so widely accepted.

Following Szabó (2010) the scope of this mainly natural science-based anthropogenic geomorphology, a discipline of predominantly applied character, includes not only the study of human-made landforms. It also addresses the prediction of corollaries of disturbed natural dynamic equilibria as well as proposals as to how to preclude harmful impacts. In this way it also serves the general goals of geohazard prevention and mitigation, environmental protection and nature conservation. These approaches also include newly initiated or modified (intensified, weakened, inhibited) processes, that is what Mortensen (1954/1955) already called *quasi-natural processes*, induced by human intervention but taking place in natural ways. This term has not caught on in the international discussion.

A societal perspective on geomorphological structures and processes can also be found quite early on. Here too, soil erosion was in the foreground for a long time because of the obvious ecological and economic implications, both with regard to human intervention, potential prevention and appropriate, that is geomorphologically informed, reclamation. This perspective, however, was mainly adopted from a highly specialised geotechnical, architectural and engineering perspective. Overall, a specifically cultural geographical approach to geomorphological issues has not achieved anything like the breadth and depth that characterizes anthropogenic geomorphology today (in spite of earlier and continuing crosslinks with various approaches in landscape geography, hazard and risk approaches, cultural ecology, political ecology or resource geography).

It is obvious that the field of society's interaction with geomorphological forms and processes, be it the sense of being impacted by or exerting influences on nature, poses major research questions for geography as a whole. This is particularly true with regard to its future development and the potential for cooperation with related disciplines. This leads on to a brief look at Earth Systems' Analysis and Global Change approaches and the place of society-geomorphology issues in this global context.

3.1.2.2 The Broader Science Perspective

'Science' is used here in its broadest sense, i.e. including all academic disciplines of the natural, physical and social sciences (Cornell et al. 2013). Today, strong emphasis is placed on the integrative approaches represented by the most important global scientific organizations (as to the relatively low visibility of geographical contributions so far see Pitman's 2005 critical analysis). This is especially the case with regard to recent Global Environmental Change/GEC research (Hackman and St. Clair 2012) and the new ICSU/ISSC *Future Earth* programme, intended as a federation of projects and other initiatives in GEC research (see Future Earth 2014a, b). In these publications' programmatic statements, especially in the Future Earth subareas *Dynamic Planet*, *Global Sustainable Development* and *Transformations towards Sustainability*, the social and human sciences have advanced from a markedly peripheral position in previous global research programmes to become central partners of the natural sciences. Nevertheless, far-reaching learning processes and attitude changes will be necessary for all participants, as well as increased efforts to overcome existing institutional barriers both in the design and implementation of teaching and research. Otherwise it will be difficult to bring the degree of integration of the participating disciplines to a level that respects the complexity of the issues involved (Cornell et al. 2013; Holm et al. 2013; Palsson et al. 2013).

Clearly, however, influential actors in the most recent global research initiatives are trying to address issues and interlinkages that have so far not been adequately resolved even within geography, that is in a subject seeing itself traditionally (and in recent times once again more consciously) as an integrative cross-cutting discipline. It remains difficult to reach agreement as to which research practices should emerge from geography's position at the interface between natural and social sciences and their thematic, inter- and intra-disciplinary challenges (cf. also the insightful analysis of *bridging* vs. *tunnelling* strategies of neighbouring or partly overlapping geographical (sub)disciplines and their respective research cores, Turner 1997).

This is why a recent initiative on the part of a of number physical geographers oriented towards both the natural and the social sciences is remarkable (Lave et al. 2014). This initiative is aimed at overcoming the nature/culture dichotomy. Beginning with reflections on the co-production of socio-physical systems, an aspect that has been increasingly emphasized in recent GEC programmes, a completely new level of epistemological openness within geography is emerging here. At the same time, specific ways of cooperation are offered, documented by numerous examples of productive boundary-crossing. The initiators tie in with the (anthropogeographical) Critical Geography movement in an unprecedented manner, thereby creating a comparable Critical Physical Geography (in the sense of being inspired by critical theory and science studies). Its proponents are convinced that essential questions about the earth system are simply incomprehensible if they are addressed by natural and social sciences working in isolation from each other: “Put bluntly, to understand the Anthropocene we must attend to the co-production of socio-biophysical systems” (Lave et al. 2014: 6).

So far, specific geomorphological issues have scarcely been addressed in this transitional field. Among the exceptions are Kondolf and Piégay (2011) and Kondolf and Podolak (2014), not least with their demand for a link-up between the earth sciences and the social sciences, for a long time inconceivable from a natural science perspective. Thus, while the readiness to cooperate in some areas is clearly growing, the subject is still highly divided.

Against this backdrop the issue discussed in this chapter has been selected deliberately because of its global significance for both bio-physical and social systems and also because it illuminates the concepts of co-production and co-development (see a number of examples listed in Sect. 3.2.2). Aggregates are a resource that are indispensable not only for the bulk of the infrastructure surrounding us but also for many specialized uses (from glass and toothpaste production to fracking fluids, from sandpaper and computer chips to metallurgy). Surprisingly, however, issues connected to their extraction and (mis-)use have not yet been studied in a more consistent way within the fields either of anthropogenic geomorphology or human geography.

3.1.3 Aggregates: Current Developments and Context

There is an expression in German that translates as “like sand by the sea…”, meaning there is so much of something that it is apparently inexhaustible. Similar associations can be found in other languages. A recent UNEP (2014) study, however, entitled *Sand, rarer than one thinks*, challenges this view. Surprisingly, the suggestion to study this emerging topic critically did not come from the geomorpological community. Instead, it was triggered by the French science journalist Delestrac’s (2013) documentary film *Sand Wars*. The UNEP study explores further Delestrac’s claims: there is definitely an increasingly critical gap between the supply and consumption of aggregate resources (in particular sand and

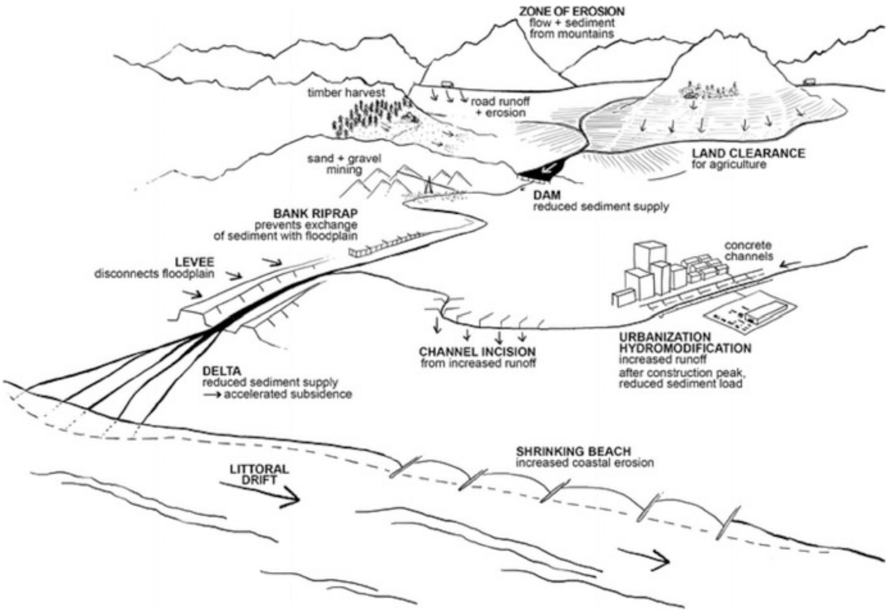

Fig. 3.3 Socio-natural process patterns leading to *starved rivers*, *sinking deltas* and *hungry beaches* (Courtesy of Kondolf and Podolak 2014, p 79. Copyright notice/disclaimer: with kind permission from Springer Science and Business Media, License Number 3645791433739)

gravel) in many regions of the world. The narrative tells us that growing quantities of fluvial sediments are trapped in a still rapidly expanding number of dammed watercourses, leading to (exacerbated by rapidly increasing riverbed mining) a situation whereby fluvial sediment loads never reach the open sea, or only with considerable delays (see Kondolf and Piégay 2011; Kondolf and Podolak 2014; Grill et al. 2015). Consequently, many coastal areas, in particular deltas and beaches, are deprived of their usual supply, thus intensifying coastline erosion and increasing these areas' vulnerability to sea-level rise. Both phenomena are succinctly characterized by the metaphors 'starved rivers', 'sinking deltas' and 'hungry beaches' (see Fig. 3.3).

In addition, accelerating processes of urbanisation in many regions of the world have led to unsustainable, and in many cases downright illegal patterns of sand and gravel extraction from rivers and on beaches (finding the expression (sand) 'mafia' in a UN publication is quite remarkable and sheds some light on aggregate extraction's implications for our societies…). Overall, these human-induced processes not only create considerably changed geomorphologies of sediment sources and sinks. They also have the potential to influence or trigger new processes and material flows with as yet unforeseeable impacts on coastal ecosystems, on urban and rural populations, and even on geopolitical and geostrategic issues (for example land reclamation on former reefs and atolls in the South China Sea allegedly pursued to legitimise sovereignty claims, see: https://en.wikipedia.org/wiki/

Territorial_disputes_in_the_South_China_Sea, accessed July 18, 2015). All of this suggests that there is hardly any sub-discipline of geography that is not actually or potentially affected by the material and immaterial effects of the structures and processes of aggregate deposits, extraction and (mis-)use addressed here.

In view of the problems and research initiatives discussed above, some fundamental questions must be asked: How has the very obvious overlap between physical and human geographical issues with regard to aggregates been discussed so far? What scope is there for improvement with a view to the desirable weakening of the nature/culture dichotomy in both intra-and cross-disciplinary terms? What kinds of conceptual approaches are appropriate and how would they improve our knowledge base, not least in order to design better response and mitigation strategies?

The following section serves the purpose, firstly of identifying some basic facts around the issue of aggregate use, followed by the main arguments of the current debate as reflected in relevant publications from various academic disciplines, civil society and the media. With regard to methodology, in this context it must be accepted that the selection of these texts can neither be systematic nor can it follow clear rules, an unavoidable circumstance in the presentation of such an initial overview.

3.2 Aggregate Extraction and (Mis-)Use

In the resource context, the term ‘natural aggregates’ is generally used for naturally sorted sediments as well as materials fragmented mechanically from solid rock (including construction waste) with particle sizes from 0.063 to 20 mm (sand) and 20–63 mm (gravel). Sand is almost automatically understood to be a sediment with a high content of quartz, but it is important to emphasise that in sedimentological terms sand defines only the grain size characteristic as such. It can be composed of all kinds of rock types or natural and artificial material, e.g. of shells, ores or glass (and their mixtures). Grain size, origin and composition define what the sand can be used for, a constraint that explains the locations and strategies of current extraction patterns as well as those of international transport and trade, even at a global level.

The following section focuses on the resource basis of unconsolidated alluvial sediments (mostly from floodplains and river courses) and beach sediments (both recent and fossil), i.e. materials resulting from fluvial, lacustrine, marine, eolian or fluvioglacial processes. Where deemed appropriate, links are made to issues related to aggregates won by processes of rock crushing, recycling and marine dredging. For the remaining sections, however, the main focus will be on societal and human geographical implications of aggregates extraction and use.

3.2.1 Overview

Compared to other global environmental issues, such as climate change or biodiversity, the threat of dwindling aggregate resources worldwide has been much less in the spotlight. Of course, the trends of recent years have been documented, both in specialised geoscientific circles (by geotechnicians, geologists and applied geomorphologists, for example Bobrowsky 1998a, b; Padmalal and Maya 2014) and by end-users (especially the construction industry). While there is generally a strong emphasis in such studies as to the consequences for the natural environment, relatively little reference is made to associated social problems and possible spatial planning solutions. Kondolf can, however, be regarded as a pioneer in this field (in particular with his brief but comprehensive syntheses 1994, 1997, 1998 and other co-authored work cited elsewhere in the chapter). Very early on, he underlined the intrinsic connection on the one hand between patterns of natural and human-influenced material transport in rivers and deltas and the development of beaches and coasts on the other (Fig. 3.1). More recent case studies time and again testify to the causal relations in the intricate patterns of socio-natural co-production in rivers and coastal systems (Bravard et al. 2013; Brunier et al. 2014). Only in very recent times have other commentaries of this issue attracted a high level of public attention, or at least have the potential to do so. Three of these works are particularly important, namely the aforementioned *Sand wars* (Delestrac 2013) and *Sand is rarer than one thinks* (UNEP 2014) as well as the book *The last beach* (Pilkey and Cooper 2014).

In spite of its brevity, the UNEP study is an informative and appropriately documented synopsis in the conventional scientific style. In contrast, Delestrac's film is remarkable for its succession of short, impressively illustrated scientific explanations, linked with case studies and interviews with both experts and persons concerned or impacted. The potential of the medium for a primarily visual approach to complex issues is exploited to the full. Pilkey and Cooper (2014) succeed in producing a vivid, comprehensive review and integration of a much broader base of specialist literature, media and civil society documentation, such as has until now not been available. In all three products an impressive array of arguments is brought together, occasionally with alarmist undertones, but they are generally well-supported by evidence.

All three works referred to above broadly overlap with the principles and aims of anthropogenic geomorphology – and provide valuable information as to number of facets of high interest for human geography subdisciplines. They also demonstrate further possibilities for human geographical research in a wide range of areas. It should be an important aim of our discipline to strengthen the role of geography here. Basic principles for such a strengthened role are outlined in the following section and in the final discussion. On the basis of brief synopses of the actors hitherto involved, thematic foci and possible conceptual approaches are suggested.

3.2.2 Actors in the Global Aggregate Industry

The aggregate debate is primarily shaped by five groups of actors: Science (often in association with international organisations such as UNEP), the media, the general public, politics and markets (especially the construction materials and the construction sectors). As in many other societally relevant fields, the framing and agenda setting by the media is crucial. They often can now relay on years of scientific research that was previously known only in closed academic circles. Many civil society actors, some with intensive contacts with scientists, have achieved similar levels of expertise. They are sometimes pioneers in diagnosing and recording the situation or suggesting possible reactive strategies. A typical example as to aggregate extraction is *The Santa Aguila Foundation* (Santa Barbara, CA) which operates and (co-)finances the important internet portal *Coastal Care*/USA (see below). It has also made possible the publication of the book *The last beach* (Pilkey and Cooper 2014). *Coastal Care* also organises one of the rare (perhaps the only) data base documenting locations of problematic beach mining (http://coastalcare.org/sections/features/sand-mining/, accessed July 18, 2015; some 200 sites are listed, but a major reconfiguration is in the works, personal communication). Other NGOs that have been highly vocal, and sometimes very influential, with regard to sand mining in rivers and on beaches or shelves include *Awaaz Foundation*/India, *Water Integrity Network*/Germany and *Global Witness*/UK. The significance of civil society groups and media is also underlined by the fact that almost half of the references in Pilkey and Cooper (2014) are based on information provided by NGOs, foundations etc., easily accessible in the internet. Transnational, interdisciplinary and cross-sectoral institutions and networks are particularly important.

The following thematic foci, intricately linked to the social, political and economic spheres shape current discourses in science, the media and civil society (often with an emphasis on manifold interconnections and interdependencies):

- Fluvial systems (e.g. Kondolf 1994, 1997; Pereira and Radnayake 2013; Grill et al. 2015)
- Marine systems (e.g. Barnard et al 2012; Pilkey and Cooper 2014)
- Biodiversity (e.g. Awaaz Foundation and Bombay National History Society 2012; Padmalal and Maya 2014; Pilkey and Cooper 2014)
- Land loss (e.g. Padmalal and Maya 2014; Delestrac 2013; UNEP 2014)
- Fresh water supply (e.g. Pereira and Radnayake 2013; Padmalal and Maya 2014)
- Natural and social vulnerability (e.g. Pereira and Radnayake)
- Infrastructures (e.g. Kondolf 1997, 1998; Pilkey and Cooper 2014)
- Land-use change (e.g. Pilkey and Cooper 2014; Padmalal and Maya 2014)
- Livelihoods (e.g. Pereira and Radnayake 2013; Global Witness 2010; UNEP 2014)
- Human rights, native titles (e.g. Quandamooka Yoolooburrabee Aboriginal Corporation/QYAC 2014)
- Health hazard (Pilkey and Cooper 2014)

- Geopolitical issues (Global Witness 2010; Franke 2014, The New York Times International 2015)

The single most important group of issues addressed in a real as well as a metaphorical sense are, however, the vast array of regulatory deficits as to aggregate (mis-)use, such as: insufficient implementation, monitoring and enforcement of both regulated and illegal extraction (even in protected areas, such as nature reserves); poor regulatory framework for rehabilitation, transport, use and trade; violations of national and international legislation; poor planning of fluvial/coastal/marine extraction activities and remedial actions; no clear rules concerning compensation when customary or property rights are disregarded or violated; inappropriate engineering responses to changes in processes and structures (rampant patronage, collusion and corruption from the local to the international level; criminal activities, e.g. attacks on law enforcement personnel, critical villagers, journalists or civil society actors; and the recurrent use of terms such as '(sand) mafia/pirates/thieves/smugglers', 'pillage', 'plunder' (e.g. Pereira and Radnayake 2013; UNEP 2014; Global Witness 2010; Pilkey and Cooper 2014, and countless media reports from both hemispheres, although with a particular focus on Africa, South and Southeast Asia).

Looking at the whole body of literature analysed for this contribution it is (not surprisingly) obvious that authors with a mainly natural science background focus mostly on the above-mentioned bio-physical environmental issues. Authors representing social sciences, media and civil society, however, predominantly address socio-economic, political and legal issues. However, many authors from both sides also connect to the other spheres. At first sight, this may appear satisfactory, since the gap between natural and social sciences is obviously less pronounced here than in many other fields. A closer look, however, shows that authors are usually quite strongly entrenched in their traditional fields of knowledge and action, clearly 'disciplined' by their usual ways of doing things – and their disciplines.

Obviously, a critical appreciation of societal perspectives proper is needed as regards aggregate issues and their potential for relevant human geography approaches. To date, there appear to be no consistent studies in this special field, although the foregoing discussion provides clear hints at a multitude of issues that deserve to be tackled from a variety of human geographical subsdisciplines. These subdisciplines include economic geography (commodity/value chains, international trade), urban geography (urbanisation, urban metabolism), the geography of (under-)development (resource transfer from the poor to the powerful), social geography (fishermen becoming sand miners), rural geography (destruction of agricultural land), tourism geography (beach mining and tourism) and, finally, applied geography (management/regulation), to mention but a few.

While all these geographical subdisciplines could also address specific political facets of aggregate issues, three specialized human geography fields stand out due to their demonstrated interest in transcending intra- and transdisciplinary boundaries: political geography proper, resource geography and political ecology. Their potential contributions with regard to aggregate issues are discussed below.

3.3 Discussion

3.3.1 Human Geography Perspectives

The current knowledge status with regard to the production and transport of aggregates from the river sources to the world's oceans and coastal areas appears to have led to rather far-reaching conclusions. This is true both for media coverage, public opinion and academic research. The widely accepted narrative is that human intervention, in particular construction of dams in most river systems on the one hand and river and beach mining against a background of widespread problematic societal (mis-)management on the other, are responsible for a wide range of problems. The main links between the underlying causes and detrimental effects are perceived to lie in the way political systems permit societal actors (politicians included) to pursue *development*. Or, following Pilkey (2005), beaches, how they form, look and develop, are "awash with politics", as indeed are all issues related to aggregate extraction in river and coastal systems and their use as an indispensable commodity for our lifestyles. The same is true for aggregates used for land reclamation, as the highly contentious disputes as to transnational trade and sovereignty issues in Southeast Asia testify. This leads not only directly to political geography proper (including geopolitics), but also to approaches in closely related fields, such as resource geography and political ecology.

Political geography stands out as some of its proponents have recently opened up novel conceptual discussions, not only contributing to new ways of addressing global issues but also directly connected to the Anthropocene at large. At the same time, they have radically changed their traditional disciplinary perspectives as two-dimensional territorial thinking is left behind and the world's materiality is consciously engaged with. Two key concepts are prominent viz. 'vertical geopolitics' (Elden 2013; Bridge 2013), meaning that the third dimension has to be added to the 'flat earth' territorial thinking by addressing volumes (including the atmosphere and subsurface underground), and 'geologic politics' (Clark 2013; Dalby 2015; Yusoff 2013), i.e. arguing for a geophysical/geological turn in political geography.

A 'geomorphological turn' in human geography perspectives, as proposed in this chapter, would fall into the logic of ensuing claims to address the three-dimensionality of the earth's processual dynamics (Clark 2013: 2826) as well as the circulation of material flows, for instance deriving from volume- and weight-based property rights over resources (commodities in storage or motion) (Bridge 2013: 56–57). But such an idea is absent from the literature. It is urgently needed, however, in order to contribute to overcoming the geological-geomorphological shortfall of human geography at large. While arguing convincingly from a novel and broad conceptual point of view, however, these recent political-geographic approaches often narrow their perspective to emerging geoengineering issues, in particular regarding strategies for coping with global climate change (as to new scientific and cultural discourses about geoengineering, but focused on infrastructure, see Brunn 2011). Therefore, in spite of their potential, they do not yet offer the multifaceted conceptual and empirical richness of the long-standing discourses in resource geography and political ecology.

Resource geography in its most recent manifestation, i.e. with a decidedly politically informed thrust, certainly is one of those interdisciplinary ways of seeing socio-natural relations in a novel way. Following the arguments of Bridge (2014) or Veltmeyer and Petras (2014), important keywords are (or could become) neoextractivism, resource and environmental security, resources and environmental justice and, above all, recent developments as to the resource-state nexus and ensuing entanglements. These latter could be characterised, for instance, by extra-territorial resource appropriation or *adventuring* (resource/land *grabs* and *scambles*, *resource races*). Obviously, these themes bear a great similarity to recent activities in aggregate extraction such as Singapore's problematic silica relationships with some of their Southeast-Asian neighbours (Global Witness 2010). The obvious links between mining companies from East Asian states proceeding with illegal black sand mining in the Philippines and state actors and corporations could be another example. While the literature addresses similar questions in a traditional framework of unequal North-South relations, there is a growing trend of seemingly comparable South-South (such as what could be called *silica imperialism*) links that poses new challenges to (not only) World System theories (see also Franke 2014).

Political ecology offers even broader overarching approaches to many of the questions mentioned earlier. Its vast body of literature(s), in particular the highly intricate and often controversial methodological discussions, cannot be developed here (comprehensive reviews are offered by Forsyth 2003; Robbins 2012). Suffice it to say that contemporary political ecology, often epitomised as *critical*, attempts to integrate political analysis with the formation and dissemination of ecological realities, which also leads to the co-production of environmental knowledge and political activism (Forsyth 2003). As Robbins (2012: 120) puts it: "'Why has the environment changed?' is a question inevitably intertwined with 'How are the terms of change defined and by whom'". Linked to this is the crucial role of *environmental narratives* or *story lines* (see Hajer 1995; Forsyth 2003; Robbins 2012). While such narratives can facilitate access to the intricacies of complex issues, they become highly problematic once they are taken for granted, almost reified, by the general public, scientists and political decisions-makers alike. Typical examples, widely documented and discussed in political ecology literature, are concepts such as *degradation* or *soil erosion*. It is not the existence of such issues that is questioned but the adequacy of their mainstream conceptualisations, leading to surprising redefinitions and insights once differing spatial and temporal scales are adopted. The complex range of issues around aggregate extraction can therefore be regarded as a recently emerged subset (and narrative) of highly important ecological and socio-political realities, although it has not yet become a focus for human geography.

The relevance of this issue is, however, obvious, and the links can be established easily by taking a seemingly simple statement from the literature as a starting point, namely: no beach is a beach like any other beach. A scientific approach to this complex ecological reality is the *littoral cell* (see Barnard et al. 2012). The interaction between marine processes, littoral cells and their hinterland watersheds (normally occupied by rural, suburban and tourism land-use mixes), creates innumerable varieties of dynamic spatio-temporal patterns and impacts along coastlines and their hinterlands – as also do the ever-changing bio-physical and human contexts along fluvial systems. But attempts at in-depth studies of what could be called *riparian cells* and their interaction with fluvial processes and patterns of risk-shifting in relation to aggregates (mis-)use caused by local or absent actors on vulnerable or disempowered populations along rivers are still to be conducted.

The conclusion, therefore, is clear: certain elements and processes of the dominant storyline as to aggregate extraction and associated issues are well proven, while some others are plausible, but as yet not convincingly documented. There is absolutely no doubt about the range of detrimental effects caused by river, beach and shelf mining, nor about widespread (mis-) use, mismanagement and illegal operations, in extremis even violent criminal acts, such as attacks on police officers, government representatives or critical journalists. A deeper understanding, however, of the interplay between bio-physical, in particular geomorphological, processes and societal conditions can only be reached by rigorous efforts of a truly geographical contextualisation in space, time, cultures and societies. “Snapshots of environmental research conducted in the present” are not enough, as Robbins (2012: 66) puts it. Nor are universalistic assertions that human interventions are solely responsible for (almost) all kinds of critical developments along our coasts and rivers. One need not be a political ecologist to ask this type of questions about society-geomorphology interaction, but adopting some of its ways of framing scientific issues and learning from its insights would enrich any (but not only) human geographic exploration of aggregate issues.

As to the geomorphological turn, some of the studies mentioned earlier point already to crucial, but underestimated facts, such as the succinct comments on seemingly ‘natural river systems’ that more often than not result from geomorphological and human co-production over centuries. The same is most certainly also true for many coasts in densely populated regions. The details of societal interventions, however, can only rarely be reconstructed (see the comprehensive overviews by Rathjens 1979; Kondolf and Piégay 2011; Kondolf and Podolak 2014). How a specific beach on, say, a Caribbean island or on the Australian Gold Coast, however, has changed over time by human interventions or how it would develop without current sand mining is difficult to predict. Human geography studies (or historical ones, for that matter) that can help to answer the question as to what kinds of societal interventions may have affected beaches and shelves over longer periods of the past are rare (but see Regnauld et al. in this volume). Such a perspective is needed to better understand today’s co-production of human intervention and geomorphological response or risk, a co-production whose impacts might be exacerbated by those mismatches between natural events and political or institutional coping strategies deplored by Kondolf and Podolak (2014).

3.3.2 The Bigger Picture: Aggregate Issues in the Sustainability Context

Time and again, critical publications and statements about current patterns of aggregates extraction hint at, or contend, that they are clearly jeopardising a host of local and regional efforts to adopt stricter policies of sustainability. And a closer look at specific cases reveals disturbing inconsistencies between highly celebrated sustainability models and their darker background facets (cf. the discussion as to Singapore's urban sustainability policies, on the one hand, and its alleged role in questionable or illegal activities of the Southeast Asian aggregates trade, on the other).

While it may seem inappropriate to view current aggregate extraction as a process threatening the stability of the planet as a whole, it can certainly be regarded as a process leading to problematic changes that are globally distributed. Even so, except for the highly generalised maps, such as presented by Young and Griffith (2009) and Pereira and Ratnayake (2013) or *Coastal Care* (http://coastalcare.org/sections/features/sand-mining/; accessed Feb. 9, 2015) there seems to be no attempt yet to present detailed regional maps of problematic extraction sites, let alone a world summary.

More detailed maps of instream mining sites or impacts exist, such as from California, Kenya or the Mekong River system (Kondolf 1998; Rowan and Kitetu 1998; Bravard et al. 2013; Brunier et al. 2014), and they give a hint at both the quantity, the pervasiveness and the problematic nature of these activities. A similar impression can be gained easily by following major river courses in Europe on Google Earth, e.g. the German sections of the rivers Rhine or Danube with their Pleistocene and Holocene floodplains, where hundreds of contemporary and former mining sites can be spotted (see for instance the highly illustrative topographical map sections at http://www.eden-niederrhein.de/). The process dynamics along ocean shores, however, do not allow for such inventories.

With regard to current patterns of international aggregates trade it would not be exaggerated to talk about global reach, even if only in relation to the documented sand transport from Australia to Dubai, from the Caribbean Islands to Hawaii or from several states in Southeast Asia to Singapore. But an overall picture is lacking, as is a better understanding of boundary-spanning, probably even trans- and intercontinental economic and political interaction, collusion and delivery, be it in the context of transparent legal frameworks or decidedly illegal or even criminal activities. Obviously, these interactions, as well as their involved actors and institutions, must be conceptualised in a multi-scale model from the local to the global level. Paths, barriers and inconsistencies of transnational patterns in a complex interweaving of objectives, substantive and functional competences should be reconstructed, based on detailed empirical work.

Gathering more hard facts regarding the trans-local reach of fluvial and marine processes or impacts on lifeworlds as triggered or modified by human interventions is clearly a more difficult task that would require more than simple snapshot studies conducted by individual researchers. The spatial scope of the littoral cells' approach could be extended, including offshore dredging activities and ensuing impacts on marine processes of erosion, long-distance transport patterns of sediments and ensuing accumulation.

Thus, many questions and issues remain to be studied in ways that transcend disciplinary boundaries, not only those between geomorphology and human geography but also between natural and social sciences at large. Against this backdrop, national and international issues of aggregate extraction and use could and should be added to the list of sustainability issues to be studied in innovative approaches such as suggested, for instance, in the context of Future Earth research agendas. Its subthemes *Dynamic Planet*, *Global Sustainable Development* and, in particular, *Transformations towards Sustainability* (Future Earth 2014a) constitute promising platforms for what is called co-design, co-production and co-dissemination, i.e. the inclusion of additional actors with their pools of expertise that traditional academic approaches only rarely have tapped into, such as offered by local entrepreneurs, media, civil society or indigenous knowledge.

While co-design, i.e. the cooperative and targeted design of research approaches in joint teams of researchers and transnational environmental NGOs, for instance, still seem to be rare as to aggregate issues, co-production and even more so co-dissemination is obviously increasing, in particular in respect of beach mining issues (Delestrac 2013; Pilkey and Cooper 2014 are excellent examples). In other words: the formation of novel knowledge arenas allowing for a deepened understanding of sustainability issues in the fields of worldwide aggregate extraction and (mis-)use is already a fact but can be extended considerably by more targeted efforts of coordination and cooperation.

3.4 Conclusion

The society-geomorphology nexus is an important but also highly challenging interface for geographical research and practice. While specifically focused approaches from either human or physical geography perspectives are and remain both important and legitimate, broader boundary-crossing perspectives offer crucial additional insights. Anthropogenic geomorphology has proved this for decades. Unfortunately, the reverse perspective, i.e. looking at geomorphological issues from a decidedly human geography vantage point, has never reached the same momentum, with the possible exception of some long-standing environmental problems such as soil erosion or specific topics in the field of geohazards. A more widespread and consistent geomorphological turn would enrich many human geography fields and make them even more valuable for both sciences and society.

The emerging detrimental impacts (proven or alleged) caused by global aggregates extraction and (mis-)use, however, has the potential to become a new and highly critical topic at the interface between society and geomorphology. Due to a growing gap between natural replenishments and rapidly increasing demand, specific types of sand and gravel are clearly becoming a scarce resource not only locally but also regionally, a situation triggering all kinds of undesired (and often unacceptable) processes and impacts both in the natural and societal spheres. A lot of disquieting facts are known already and have led to sometimes over-generalised narratives, seemingly giving clear indications about general cause-effect relations. However, cautious approaches are still advisable as the overall picture is characterised by significant knowledge gaps and over-generalisations, such as simply linking every beach retreat to inappropriate human interventions. But above all there is a lack of robust information in many mining hotspots as to natural and human-induced fluxes and budgets of aggregates in fluvial and marine systems, on the one hand, and, linked to these latter, the intricacies of interactional patterns as regards economic, political and social actors in areas and regions of concern, on the other. This problematic situation is amplified by deficits as to appropriate space-time contextualisations of observed natural and social processes and issues, not least regarding their transboundary and multiscale facets.

The implications of this development urgently require not only a broad human geography approach, complementing and extending the existing geomorphology knowledge base. New and more intense ways of cooperation with geomorphology and other facets of physical geography are of the essence and, in addition, wherever appropriate or necessary, in close contact with other disciplines. Last, but not least, a host of civil society actors who are working in and with impacted localities and communities, offer clear potential to widen the critical gaze. They address, often in more detailed and down-to-earth approaches than those adopted by academics and practitioners, the disturbing patterns of winners and losers resulting from the described resource (mis-)use.

Given this status description, it is obvious that the highly complex and challenging field of aggregate extraction and (mis-)use has the potential to become an important topic in global sustainability research endeavours as these combine already now promising approaches for the aspired to merging of relevant knowledge arenas. At the same time, it represents a conceptually challenging area of cooperation at the interface of physical and human geography.

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Chapter 4
Geomorphological Responses in a Dynamic Environment: How Landforms Interact with Human Activities in Taiwan

Jiun-Chuan Lin

Abstract This chapter attempts to assess how frequent earthquakes and seasonal typhoons that strike often and with significant consequences shape landslide, river channel change and coastal change in the dynamic environment of Taiwan, a small subtropical island. The impacts and consequences of earthquakes and typhoons, mainly manifested geomorphologically in landslides and associated features, are made even more brutally detrimental due to the dense population distribution and related human activities of Taiwan. Sediment yields from river catchments may be indicators of landslide activity, along with river channel change and several other geomorphological features. Sediment deposition in the lowlands, where there are diverse land uses and economic activities exacerbates damage caused by such processes. Sediments may accumulate at unprecedented rates (e.g. Typhoon Minudle in 2005 and Typhoon Morakot in 2009 which resulted in sediment accumulation in river channels of 30 and 60 m respectively). Seasonal dynamics and unpredictability of sediment yields manifest also in coastal geomorphology, especially because settlement and economic activities are concentrated in these regions in Taiwan resulting in both urban and rural development challenges. All these phenomena are considered as integral to the dynamics of the environmental system of Taiwan. Landslides, river channel changes, and coastal changes represent three sides of an environmental triangle that require detailed study and understanding if such challenges are to be mitigated. Remote sensing imagery, in particular aerial photos and field observation records are employed in a series of case studies to demonstrate how the dynamic Taiwan environment can better be understood in relation to the geomorphological processes and features including landslides, river channel and coastal change. Limitations to the use of marginal land and the adoption of buffer zones to mitigate geohazards are proposed.

Keywords Dynamic environment • Earthquake • Typhoon • Landslide • River catchment • Landform • Taiwan

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4.1 Introduction

4.1.1 Taiwan as a Dynamic Environment

The environment of Taiwan reflects its sub-tropical climate that is modified by the relief of young mountain ranges that are a product of plate-boundary tectonics. The most dominant features are deep gorges in the interior and multiple terraced coasts that are a result of the rapid uplift of Taiwan (island) (Peng et al. 1977; Rodriguez et al. 1999; Ota and Yamaguchi 2004).

As Taiwan is located at the colliding juncture of continental and oceanic plates, and situated in a subtropical environment, its landscape diversity is high and geohazards are many and diverse (Willett et al. 2003). With frequent earthquakes and seasonal typhoons, the slopes of Taiwan's mountainous and hilly lands are prone to landslide hazards, which in turn trigger river channel and coastal changes.

The relationship between landform and society here are intensified due to high population densities and limited available space for agriculture, industry and human settlement. The dynamic environment of Taiwan, with frequent tectonic movements, seasonal monsoons and common tropical storms invokes complex human-environment interactions. Against such a background, different types of hazards manifest in various parts of the island. In particular, river catchments with challenging and dynamic riverine conditions and dense settlement coupled with intense land use often promote vulnerability to various degrees depending on the position within the catchment.

The amount of sediment discharged from a river catchment influences the degree of geohazard, as it is related to stream energy and the potential for debris transport (Lin et al. 2006; Jen et al. 2006). Sediment volume is also related to the magnitude of earthquakes and the rate of tectonic uplifting. Taiwan thus becomes a classical laboratory to demonstrate how geomorphological processes shape landforms within a short time. In a tectonically dynamic area like Taiwan, there are many aspects that need to be considered in explaining the relationship between landscape characteristics and land use. In such a dynamic environment, the rate of erosion and deposition makes human development and settlement highly vulnerable (Dadson et al. 2003, 2004). The impacts of endogenetic and exogenentic processes affect society differentially in terms of scope, magnitude and frequency, as many geomorphological processes occur randomly in space and time. The dynamic environments of Taiwan are associated with a wide variety of geohazards, including landslides, sediment transport and deposition as well as flooding.

4.1.2 Natural Hazards

With a magnitude of 7.3 on the Richter scale, the 1999 Chi-Chi earthquake together with typhoons caused huge damage and loss. It took the earthquake-hit area 10 years to re-grow vegetation. The comparison of a series of aerial photos demonstrates vegetation changes. With field observation and aerial photos, an evolution pattern of landslides is demonstrated.

Because of tectonic movements (Konishi et al. 1968) and frequent extreme climatic processes, the landform and landscape of Taiwan is fragile and vulnerable. The elevated denudation rate due to soil erosion means it is important to understand natural processes, especially the influence of earthquakes, mass wasting, soil erosion, tropical cyclones and other hazards (Keefer 1984; Hovius et al. 2000; Murphy et al. 2002; Pearson and Watson (1986); Sepulveda et al. (2004)). Although the dynamic circumstances produce a great variety of spectacular landscapes and diverse habitats, geohazards are a natural outcome. Landslides and debris flows in the mountain areas and flooding in the coastal and lowland areas are just some examples of frequently encountered hazards (Fuller et al. 2003). Figure 4.1 lists the

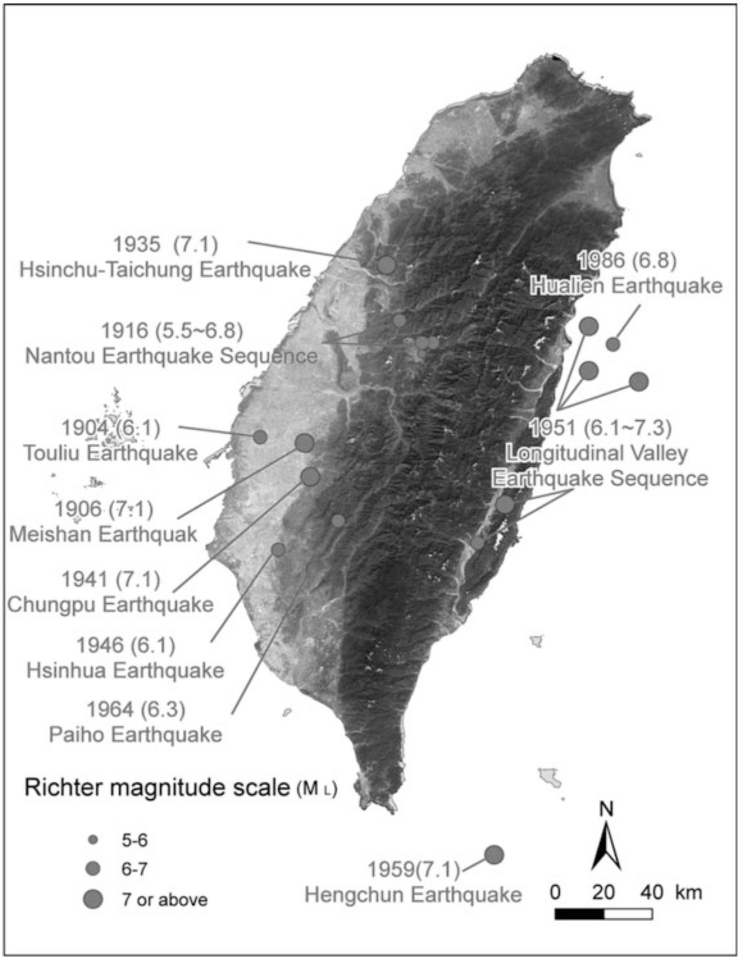


Fig. 4.1 The ten largest earthquake events in Taiwan over the last 100 years; the data demonstrate the vulnerability of the island to geohazards (Source: Central Weather Bureau (2004): www.cwb.gov.tw)

ten largest earthquake events in the last 100 years and is a clear demonstration that Taiwan is an extreme tectonic environment.

The most important influencing factors are the frequent seasonal tropical storms and typhoons. Mean annual precipitation varies across the island from 1500 mm in the west to 4000–5000 mm in the Central Range of Taiwan. In some northern parts of the island annual precipitation is augmented by winter monsoons. Figure 4.2 shows the seasonal distribution of rainfall in the country and indicates the dominance of the summer months, May to August, which represents the main typhoon season.

Since 1996, several typhoons have resulted in serious landslides and associated hazards in central Taiwan. These typhoons delivered rainfalls that exceeded 1500 mm in a single event (Fig. 4.3) and caused significant damage in different parts of the region. These episodic high-magnitude events are capable of yielding excessive rainfall during 24 h (for example more than 1749 mm of rainfall within 24 h on 31st July 1996 on Mt Alishan which approached Taiwan's world record of 1870 mm in a period of 24 h; Table 4.1). The most extreme rainfall on record is the event recorded at the Alishan weather station during which more than 2950 mm fell in 4 days from the 8th to 11th August 2009 associated with the passage of Typhoon Moroko in 2009.

4.2 Landforms and Societies Response to Geomorphological Processes

This chapter focuses on the upper, middle and lower reaches of Taiwanese rivers in order to illustrate how different types of riverine environments respond to hydrological and tectonic events that induce hazardous geomorphological events. Three typical examples are demonstrated as follows (Fig. 4.4). Figure 4.5 outlines the conceptual model of land use in different parts of Taiwanese river catchments and shows how arable land in Taiwan is limited due to the general steepness of the landscape.

4.2.1 Upper Section of Tachia River

The Tachia River catchment is situated in Central Taiwan where a series of hydroelectric power plants have been constructed and where there are now many human activities in the higher mountain areas, traditionally used for agricultural purposes, due to the improvement of transportation infrastructure since the 1960s. As the high quality of fruits and vegetable brought very high profits of economic income, many farmers tried to cultivate the fruits and vegetable on steep slopes and eventually caused a lot of landslides and debris flows. The upper part of the catchment is recognized as a major source area of sediments (Lin et al. 2006). For example many landslides caused by the Chi-Chi earthquake, magnitude 7.3, in 1999 which

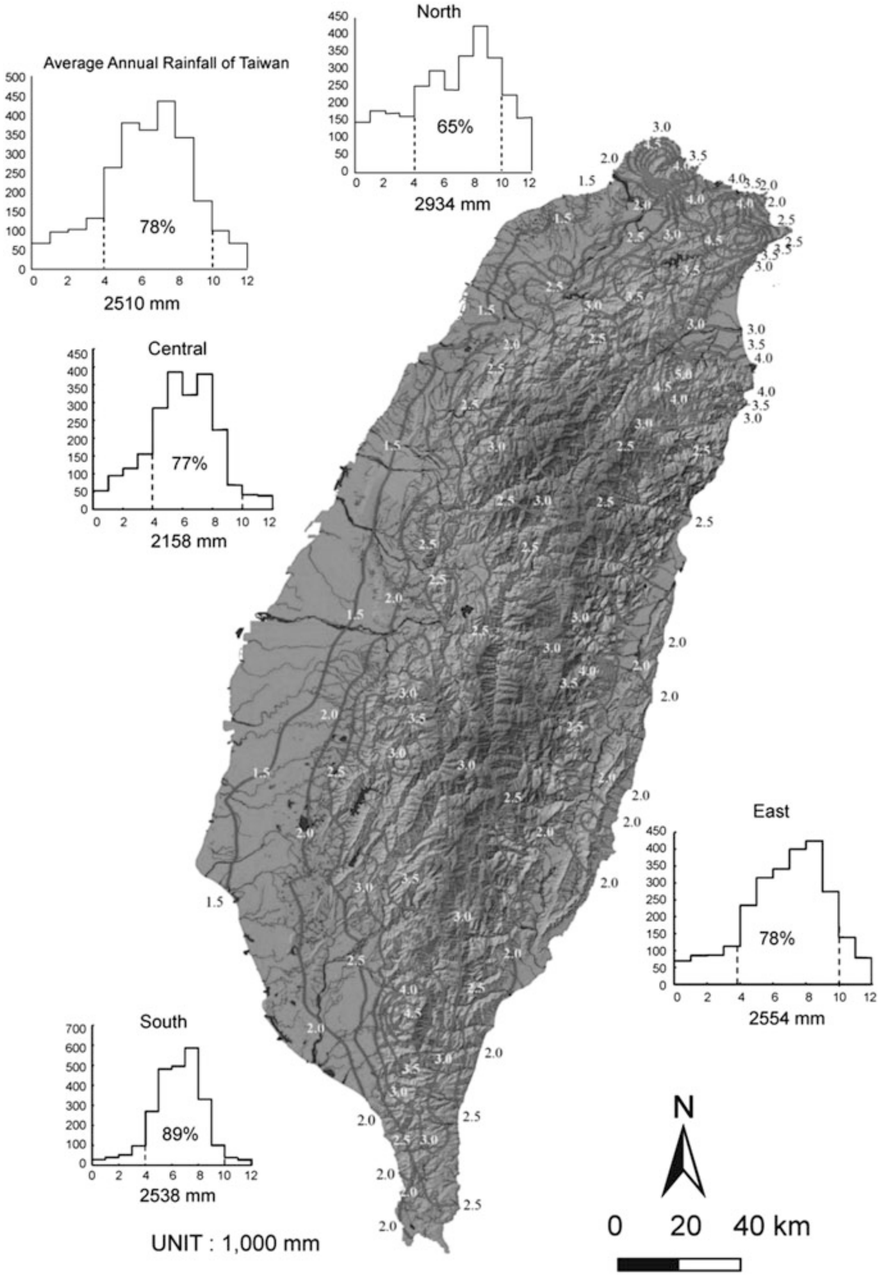


Fig. 4.2 Rainfall distribution map of Taiwan (Source: Hydrological Year book of Water Resources Agency, Ministry of Economic Affairs)

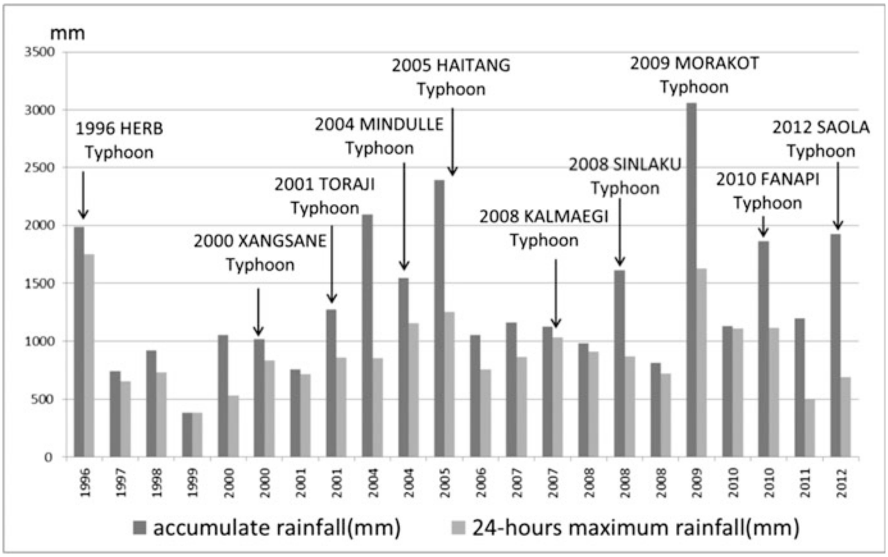


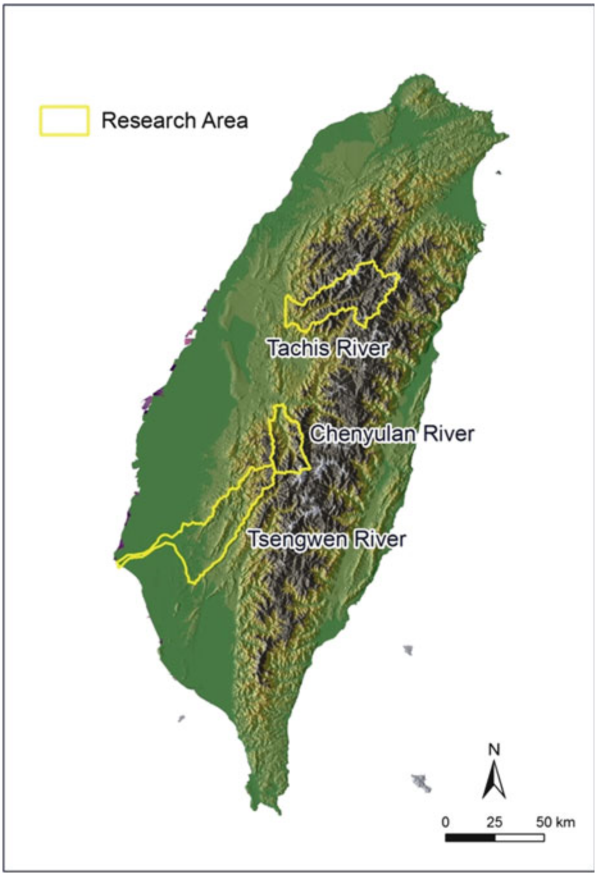
Fig. 4.3 The monthly rainfall and typhoon records for Taiwan indicating that the contribution of typhoons to total mean annual rainfall is significant, especially since the 1990s (Source: Central Weather Bureau: www.cwb.gov.tw)

Table 4.1 Comparison of maximum precipitation records of Taiwan

Duration (h)	Maximum precipitation (mm)		Precipitation from typhoon herb (mm)			
	World (time)	Taiwan area (year)	Alishan	Hoshe	Hsinyi	Hsitou
1	305 (42 min)	300 (1972)	112.5	65.5	72.0	110.0
2	483 (130 min)	560 (1972)	210.5	118.5	142.5	213.5
6		760 (1972)	616.5	337.5	386.0	538.0
12	1340	862 (1973)	1157.5	478.0	587.0	813.0
18	1689 (18.5 h)	1427 (1967)	1537.5	542.5	688.0	953.5
24	1870	1672 (1967)	1748.5	615.0	754.0	1099.0
48	2500	2260.2 (1967)	1986.5	682.5	814.5	1257.5

followed a period of heavy rainfall induced significant sediment yield (Dadson et al. 2004; Wenske et al. 2012). The heavy rainfall caused loose materials to be transported in large quantities with serious social and economic consequences. A series of aerial photos demonstrate that the landslides and vegetation cover have changed over time in the Kukuan area of Taichia River (Fig. 4.6). The main type of mass movement event in central Taiwan is rock fall, many of which are triggered by typhoons and cause massive damages (Lin et al. 2006). There were more than 22,000 landslides after the Chi-Chi earthquake in 1999 (Soil and Water Conservation Bureau 2002). More than 10 years after this earthquake, there are still huge amounts of debris and materials waiting to be transported downstream. It is estimated that central Taiwan will need at least another 10–20 years before the

Fig. 4.4 Map showing the location of catchments discussed in the text



hillslopes could be considered stable – even if there are no further typhoons. However, Taiwan normally experiences three to four typhoons annually, meaning that it is very difficult to reduce river sediment loads from the upper sections of rivers such as this.

As there are so many landslides, the influence of landslides on society is immense. It is expected that mass movements will be frequent in such a tectonically active area so that it is impossible to avoid such processes and resultant sediment fluxes from the upper part of the catchment. Sediment production as triggered by earthquakes is eventually transported downstream by fluvial processes with diverse consequences, such as bank erosion, damage to bridges and landslide dams in channels. Landslides clearly limit human occupation and economic activity and many roads, houses, bridges are damaged by these; there may also be significant deaths, injuries and loss of livelihoods following such events. If the frequency and magnitude of typhoons and earthquakes increases, this may result in further significant losses in Taiwan and it is therefore essential that more attention be paid to the impact of these geomorphological processes on society.

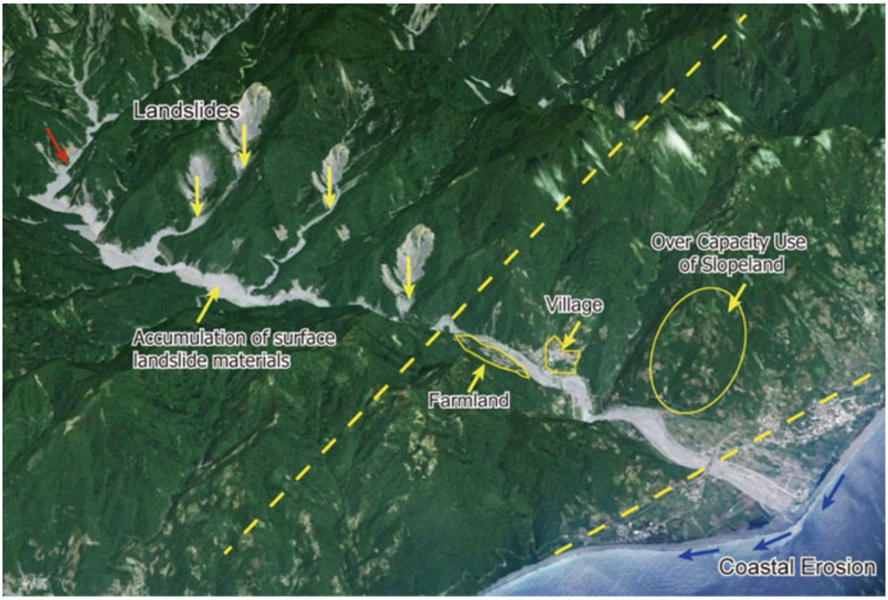


Fig. 4.5 Conceptual model of a small catchment and land use type

4.2.2 Middle Section of the Chenyulan River Channel

The Chenyulan River is a main tributary of the Juoishue River which is the largest catchment of Taiwan. In the middle section of Chenyulan River catchment, there are many human activities on river terraces as well as in the river channel. The middle sections of the catchment have both fluvial terraces and an alluvial plain as a result of a combination of tectonic uplift and sediment transport. Such areas are easier to cultivate, typically for fruit and vegetables. As indicated above, the key mechanisms triggering mass movement events processes in the country are earthquakes and heavy rainfall, especially in the central part of Taiwan. There is a clear relationship between the magnitude of these extreme events and the degree of damages experienced. These areas are clearly prone to geohazards, both directly from flooding caused by heavy rainfall and indirectly due to resultant landslides. Typhoon Herb hit the Chenyulan River catchment in 1995 and the Chi-Chi earthquake in 1999, resulting in flooding together with huge debris flows in the lower sections of the river channel. Agriculture in such localities was strongly impacted. Figure 4.7 shows that the river channel was choked with sediments and destroyed many farms.

Following typhoon events, it is possible that the channel may become a site of deposition for huge quantities of sediments or may become incised. In any case, there are clear indications that rockfalls, debris flows and flooding are frequent geohazards occurring in these areas. Careful land use planning is essential in these areas and may provide a means of adaptation to such dynamic processes.

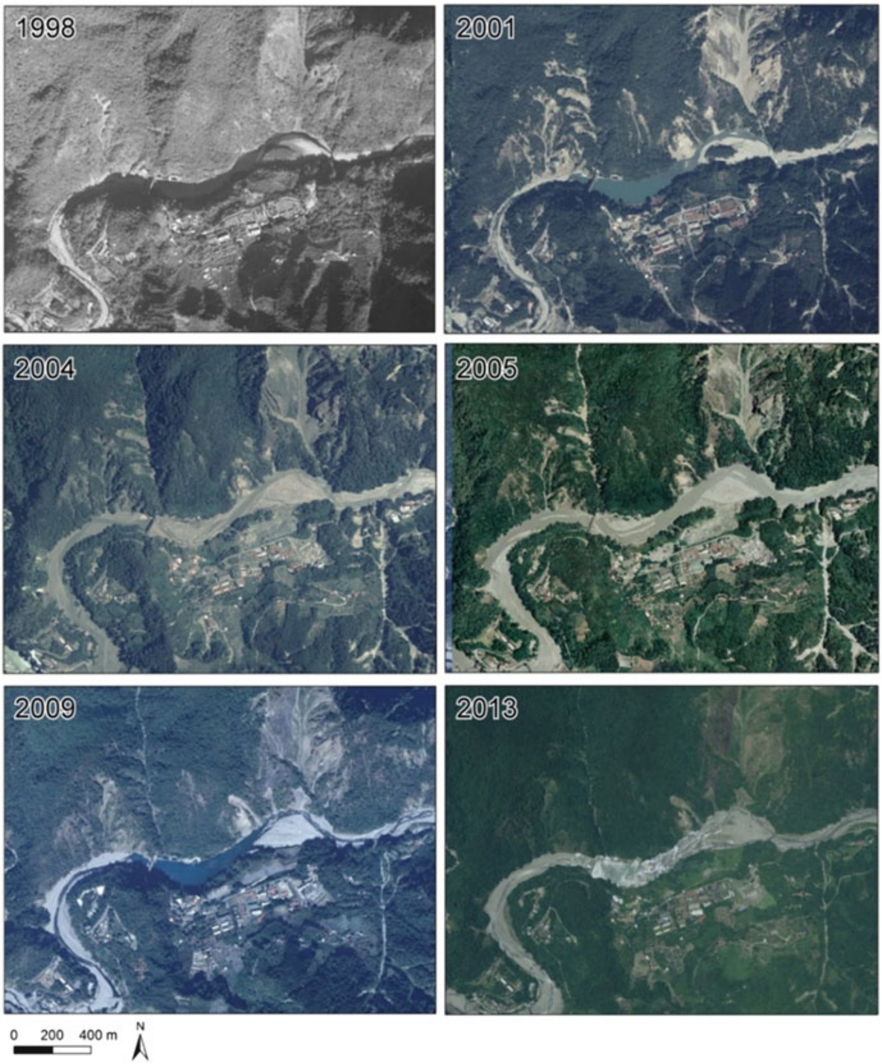


Fig. 4.6 Time series of aerial photos demonstrating slope responses associated with the Chi-Chi earthquake. These photos demonstrated the limitations of land use on hillslopes as well as rate of recovery of vegetation cover on landslide areas

4.2.3 The Estuary of the Tsengwen River

The estuary of Tsengwen River contains substantial quantities of sediment, derived especially from the upper catchment area which is dominated by highly erodible mudstones. Large areas of tidal flats and wetlands are utilised for agriculture and aquaculture. Even the coastline itself has been dramatically influenced by changes

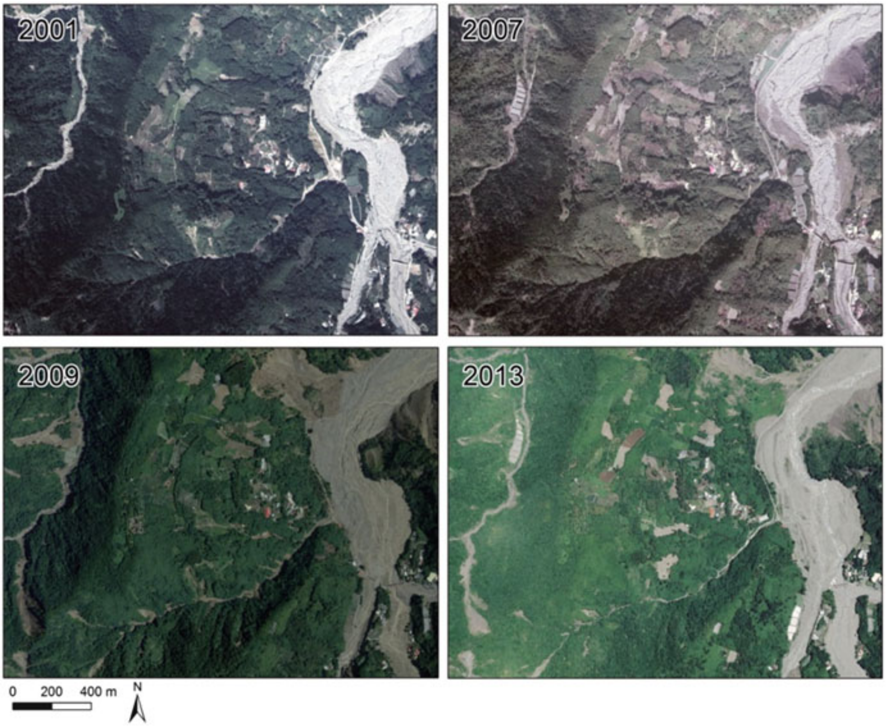


Fig. 4.7 Sequence of aerial photographs illustrating landslide evolution in the Shen-Mu village area illustrating channel erosion and land use change in mountainous areas where land use on river terraces is impacted by flooding

in sediment supply, with subsequent impacts on land use due to the deposition of enormous quantities of sediments from the upper sections of river catchments. The fan-delta of the Tsengwen River forms a substantial low-lying wetland with other coastal landforms such as a sand bar and lagoon which has been utilized for salt extraction and aquaculture over the last 100–150 years; this estuarine area has experienced extreme coastal change during that time.

Such a land use pattern is vulnerable as substantial coastal erosion occurs frequently during typhoon events. Due to the construction of the Tsengwen Dam in the upper catchment in 1973, significantly less sediment has been transported downstream to the coastal area resulting in dramatic change over the last four decades and marked impacts on the estuary. Figure 4.8 presents a time series of coastal change covering the last 100 years in this part of southwestern Taiwan. Note the erosion of the sand bar which caused considerable damage in economically productive areas and has further increased the vulnerability of this area to future damage, especially under scenarios of sea level rise.

Coastal change caused by typhoons manifests in two kinds of impacts, viz. land use change and coastal retreat. Since 1904 the coastline has changed dramatically

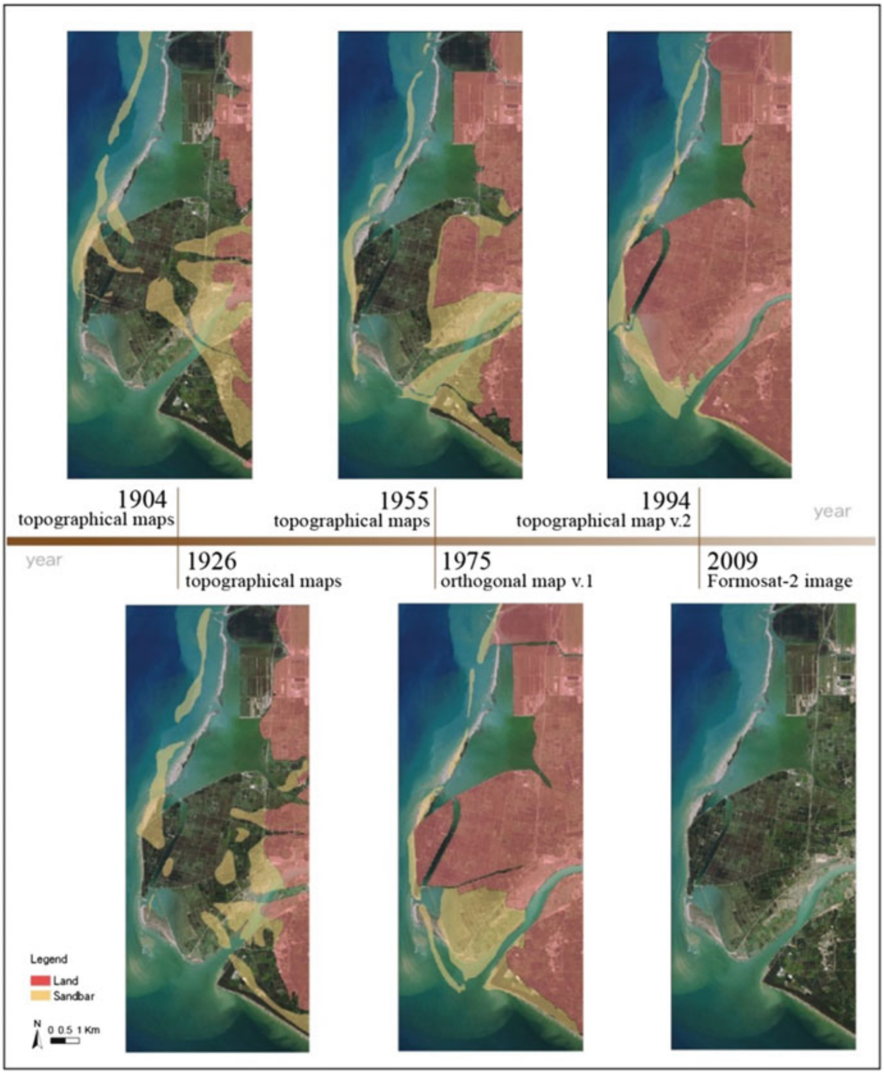


Fig. 4.8 Coastal change in the last 100 years in south-western Taiwan illustrating coastal change caused by typhoons and land use change through time

and many properties have been lost due to a combination of flooding and coastal erosion. Coastal sediments shifted by ocean currents have caused significant damage to fish farms. There is a clear need to protect the coast to prevent loss of economic value and livelihoods and also for conservation of natural resources. An understanding, therefore, of the associated geomorphological processes becomes critical in terms of continued utilization of the coastal lowlands and is a constant challenge.

4.3 Discussion

The impact of geomorphological processes on the abundant steep slopes of central Taiwan may generate enormous amounts of sediment for transport downstream to the coast. It is therefore clear that marginal land, viz. that associated with steep slopes, alluvial plain, low-lying coastal flats and wetlands endures substantial damage as a result of the combination of earthquakes and typhoons. Such areas should be afforded high priority status in order to reduce or prevent future impacts.

4.3.1 Dynamic Environments as a Challenge for Society

This study demonstrates the geomorphological influence in different parts of river catchments in Taiwan and the impact that such processes have on people. The upstream sections of the catchment are strongly influenced by mass movement processes (landslides) and are source areas for sediments. The middle parts of the catchment are easily damaged by flooding, as are the lower reaches. The estuary area is vulnerable both to flooding and bank erosion. Fluvial deposits within the floodplain are typically used for agriculture and, increasingly because of shortage of land for urbanization, there is a high demand to use these areas for development. Such constructions are at high risk of flooding, more especially due to sea level rise.

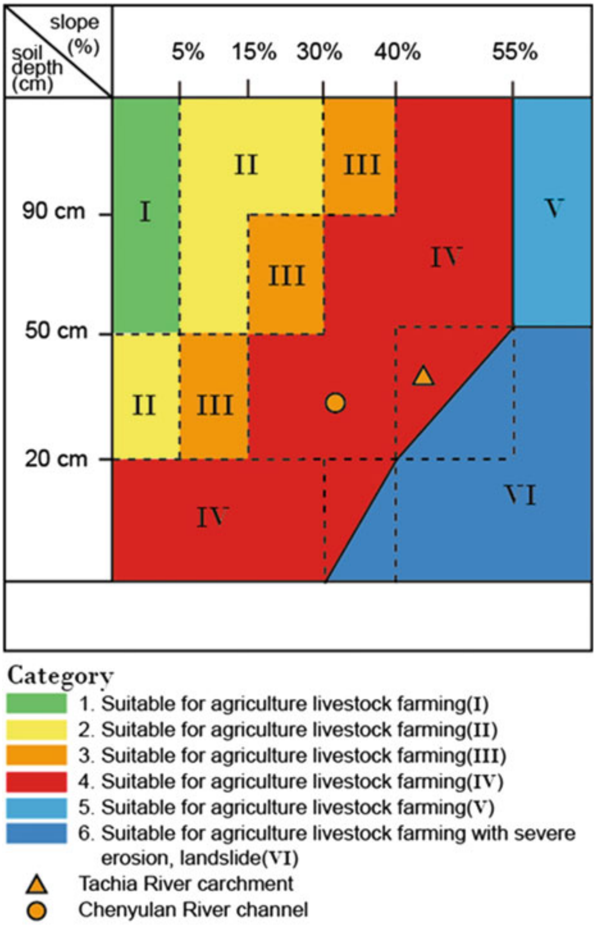
These lower reaches are always flood-prone depending on rainfall intensity and duration. A monitoring or early warming system on rainfall and hydrological conditions is therefore essential to hazard mitigation throughout the catchment.

The types of hazards in different parts of catchments in Taiwan can be considered in a sense as an evolutionary sequence of landforms and geomorphic processes interacting with human activities (Fig. 4.6). Slope retreat, bank erosion and coastal erosion are all kinds of natural processes that are unavoidable and which require deeper understanding if we are to avoid or minimize physical, infrastructural and economic losses. Therefore it is suggested that the concept of land use zoning and the incorporation of a system of buffer zones emerges as necessary interventions to mitigate damage even before land use change occurs and especially prior to any construction or engineering works.

4.3.2 Land Use Zoning

In Taiwan, marginal land such as steep slopes, flood plains and coastal land have been used for a wide range of different purposes. Clearly, as demonstrated above, these areas are strongly prone to geohazards. Therefore it is essential that careful and thorough land use mapping and zoning is carried out in order to define the nature and magnitude of potential hazards.

Fig. 4.9 Land capability category map of Taiwan (Soil and Water Conservation Law)



In the upper part of the catchment, especially on steeper slopes, there is a need for the limitation of land use type to prevent increased risk from geohazards. The land use zoning system, which is an instrument of the Soil and Water Conservation Law in Taiwan, is based on slope angle and depth of soil and has six categories (Fig. 4.9).

4.3.3 *Buffer Zones as Hazard Mitigation*

Clearly, the accurate identification and zoning of risk-prone areas is essential to the implementation of policy tools and measurements to mitigate the loss due to mass movements and related hazards. An additional intervention concerns the

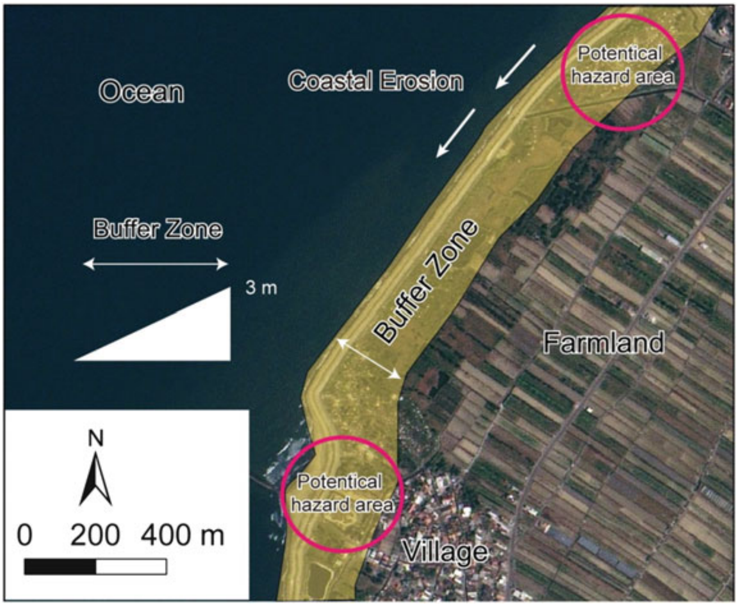


Fig. 4.10 Coastal buffer zone model. This conceptual model is based on the potential coastal hazard which may caused by sea level change in the future

establishment of buffer zones. The central part of Taiwan, at elevations from 800 to 2000 m above sea level, is the most vulnerable area because of the steep slopes and high demand on agricultural land use. Reducing land use intensity in such areas is certainly one possible solution, although the exact means whereby this is done requires careful planning. In the flood plain area, the erosion and deposition of sediments requires the establishment of a buffer zone which limits particular land use demands and prohibits particular kinds of development, such as highway construction. Reduction of the tourism demand in high mountain area is also a way to mitigate the natural processes. Figure 4.10 provides a sketch map of a typical buffer zone and indicates how this may mitigate the potential hazards. Similar buffer zones are applied in the low-lying areas of the coastal zone of south-western Taiwan. Here too, land use needs to be limited and the establishment of buffer zones can help prevent property loss.

4.4 Conclusions

Landscape sensitivity in Taiwan is influenced by its tectonic background and exposure to frequent high magnitude typhoon events. These natural conditions often coincide, such as in 1999 when the Chi-Chi earthquake was followed by torrential heavy downpours. Such exogenetic processes are clearly important for shaping the landscape of Taiwan, but also prone to very rapid change and determine the nature, distribution and magnitude of erosion, transportation and deposition. Given the constraints of such a dynamic environment, society as a whole must respond in order to ensure sustainable development. It follows that is important to keep meticulous records of earthquakes, typhoons and hydrological responses and that these records should be taken into account in future for land use management throughout the catchments. This chapter demonstrates the power of nature on Taiwan. Morphological change, well documented over the last 100 years, indicates geomorphological changes are continuously operating at different spatial and temporal scales. The concept of land use planning and buffer zone establishment is therefore essential to lower the risk from these geohazards. Such interventions are important in order to mitigate the affects of fluvial channel erosion and landslides as well as the effects of coastal flooding.

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Chapter 5
The Impact of Typhoon Morakot in 2009 on Landslides, Debris Flows and Population in the Chishan River Catchment, Taiwan

Chia Hung Jen, Hung Fei Lei, Shyh Jeng Chyi, and Min Yu Hsueh

Abstract Typhoon Morakot brought heavy rainfall in 2009 and initiated many landslides and debris flows, including in the Chishan River catchment, one of the tributaries of the Kaoping River. In this study, we report on the identification of landslides and debris flows using GIS based on the digitization of ortho-rectified aerial photos. More than 10,216 landslides and 140 debris flows were identified caused by heavy rainfall during the typhoon. Features identified as mass movement landforms were then mapped onto a 500 m grid using Getis-Ord Gi* to indicate the location of landslide concentration areas or 'hotspots'. There were significant effects on the local population due to loss of life and migration out of the affected areas. A government scheme to relocate people affected by the Typhoon Morakot landslides and debris flows was instigated in order to prevent further problems from hazards of this sort. Post-event evacuation is possible but it is recommended that the government and non-government organizations work together to ensure more effective mitigation of future typhoon hazards.

Keywords Typhoon Morakot • Landslide hotspot • Population migration

5.1 Introduction

In Taiwan, landslides in mountainous catchments are major geomorphological processes that can change the landscape dramatically. Typhoons and associated heavy rainfall destabilize hillslopes and may deliver substantial quantities of sediment to the fluvial system (Wenske et al. 2012). Subsequent fluvial processes may remove the sediment through the channel systems and subsequently trigger further responses over the whole catchment (Jen et al. 2006; Lin et al. 2006). The

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way in which landslides determine the evolution of the land surface is thus a major research topic in Taiwan (Hovius et al. 2000; Chang 2008; Shou et al. 2014). Such processes result in a high denudation rate (Li 1976; Dadson et al. 2003a, b).

On August 7th 2009, Typhoon Morakot delivered more than 2000 mm of rainfall to some localities in three days in Taiwan (Central Weather Bureau of Taiwan, CWB, 2010). It is almost 70 % of the average annual rainfall for southwestern and southeastern Taiwan (Wu et al. 2011). According to the records at the Mintzu station, the daily rainfall of August 8th 2009 reached 1114 mm/day and that is the highest daily amount since the station was established in 1977. Owing to this intensive and long duration rainfall event, the 3-day accumulative rainfall was over 1698 mm before the malfunction of the gauge on August 9th, which is more than 60 % of the annual rainfall amount (Li et al. 2011). The heavy rainfall caused many landslides and debris flows in southwestern Taiwan, especially in the Kaoping River catchment. The number of deaths reached 673 and property lost amounted to about 3.3 billion USD (Central Weather Bureau of Taiwan 2015).

Residents in this area suffered severe loss and many were forced to be evacuated and even to be permanently relocated due to the complete destruction of their properties and/or the risk of future potential hazards. By using ortho-rectified aerial photos in GIS, this study aims to map the landslides and debris flows resulting from Typhoon Morakot in the Chishan River catchment, a major sub-catchment of Kaoping River. The method adopted involves the construction of a shape file of landslides and debris flows. It is followed by mapping onto a 500 m grid network to analyze the geographical distribution of landslides and by establishing so-called hotspots of landslide activity using the Getis-Ord Gi* method. This method reveals the spatial patterns of landslides in the catchment. Short- and long-term rainfall records from the weather stations in the catchment were then examined in order to reveal trends and patterns during the rainfall events. In the final section, we examine the population statistics of 2008 and 2010 in the catchment to demonstrate the population migration induced by the Typhoon Morakot disaster. Initiatives by the government and NGOs to help local people by establishing temporary and permanent housing in locations regarded as safer are described. Such efforts, coupled with a better early-warning system should be of great help to the people in the region.

5.2 Study Area

The study area is the Chishan River catchment, a sub-catchment of the Kaoping River. It has an area of 842 km^2 and the length of the main channel in this sub-catchment is 118 km, with its source originating from the southern slopes of Mt. Yushan (also known as Mt. Morrison, 23°28′12″N 120°57′26.16″E, 3952 m a.s.l.), the highest peak in Taiwan, and its conflux with Kaoping River at 22°46′12″N 120°27′8.64″E (30 m a.s.l.).

The catchment is administrated by eight districts respectively, and they include Namasha, Jiasian, Tauyuan, Neimen, Shanlin, Meinong and Chishan of Kaohsiung

City and the Alishan Township of Chiayi County. The main channel runs from the north-northeast to the south-southwest. The eastern part of the catchment is relatively steep compared to that of the western one. The tributaries in the drainage basin also flow mostly from the northeast to the southwest (See Fig. 5.1). According

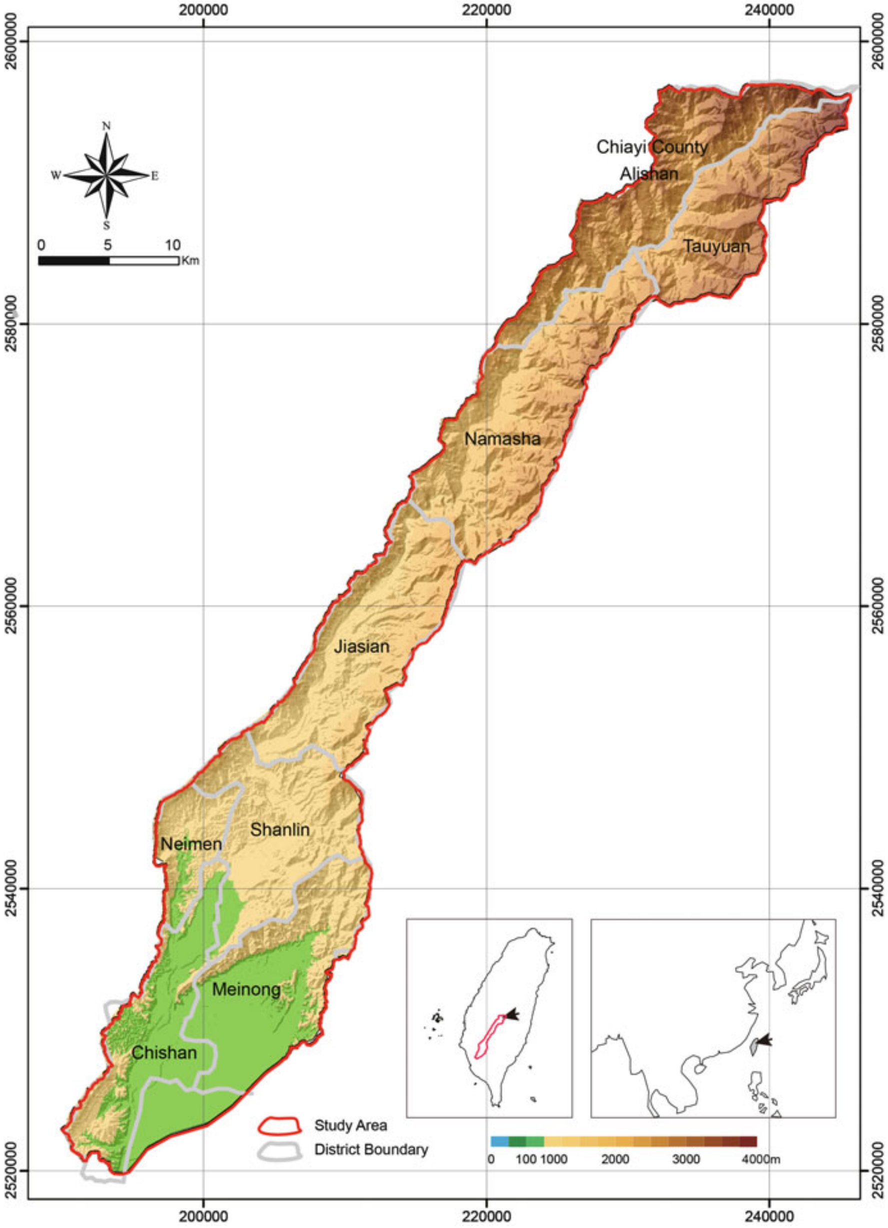


Fig. 5.1 Location of the Chishan River catchment (Coordinate system: TWD97)

to the population data of the Civil Affairs Bureau, Kaohsiung City Government (2015), the population density in 2012 was 77.85 persons per square kilometer. The average population density of Kaohsiung City and Taiwan were 483 and 722.2 persons per square kilometer respectively (Civil Affairs Bureau, Kaohsiung City Government 2015; Ministry of the Interior, Taiwan 2015b). In some districts in central Kaohsiung City, the population can be as high as 39,000 persons per square kilometer. The population density in the Chishan River catchment is relatively low.

The geological basis in the catchment is mostly composed of pre-tertiary and tertiary sedimentary rock formations, such as sandstone, shale, mudstone, interlayers of sandstone and shale, alluvial deposits, and some basalt (See Figs. 5.2, 5.3, and 5.4) (Chinese Petroleum Corporation 1982a, b). They are weak in strength and fragile (Lin et al. 2009) due to the geological regime characterised by strong tectonic movement. The regional strike is aligned mainly northeast to southwest, and it is determined by the Chishan and Jiasian faults and a series of parallel synclines and anticlines. These structures indicate that the catchment had been and still is under strong tectonic compression. This geological setting is in favor of the development of landslides and debris flows.

5.3 Materials and Methods

In this study, we use the ortho-rectified aerial photos for the mapping of landslides and debris flows in the study area. The aerial photos are provided by the Aerial Survey Office of the Forest Bureau of Taiwan. The photos were taken during August and September of 2009, shortly after Typhoon Morakot, with a Leica ADS 40 and the GDSs of the photos are 0.25 m, which can provide very detailed ground surface information. The size of each photo is about 408 MB and the depth of the pixel is 8 bit. The original aerial photos were ortho-rectified to the projection of TWD97 and can be used for survey and mapping purposes. In this study, we use 114 frames of the ortho-rectified images. The images are input into Arc GIS for the landslides and debris flow mapping (See Fig. 5.5). We also scanned and georeferenced the 1:5000 and 1:10,000 1980 maps to provide an additional data set in GIS, and use them as supplements in recognizing mass movement related features.

The first step of the landslide identification is to locate the areas with lighter tone in the digital images, which are characterized by less or no vegetation cover. These areas then were checked by the location and occurrence of further morphological features. Some areas with no vegetation near ridge-tops or near houses could be identified as bare lands, instead of landslides.

We then zoomed in to further verify by identifying morphologies, such as gullies, bedding planes and scars that are related to landslides, and checked the areas in 1:5000 or 1:10,000 maps of 1980 for contours or other physiographical features for some cases that proved to be trails, roads or even grasslands. The application of the 1980 maps can provide further information to help avoiding mistakes in identifying mass movement features. This complicated identification

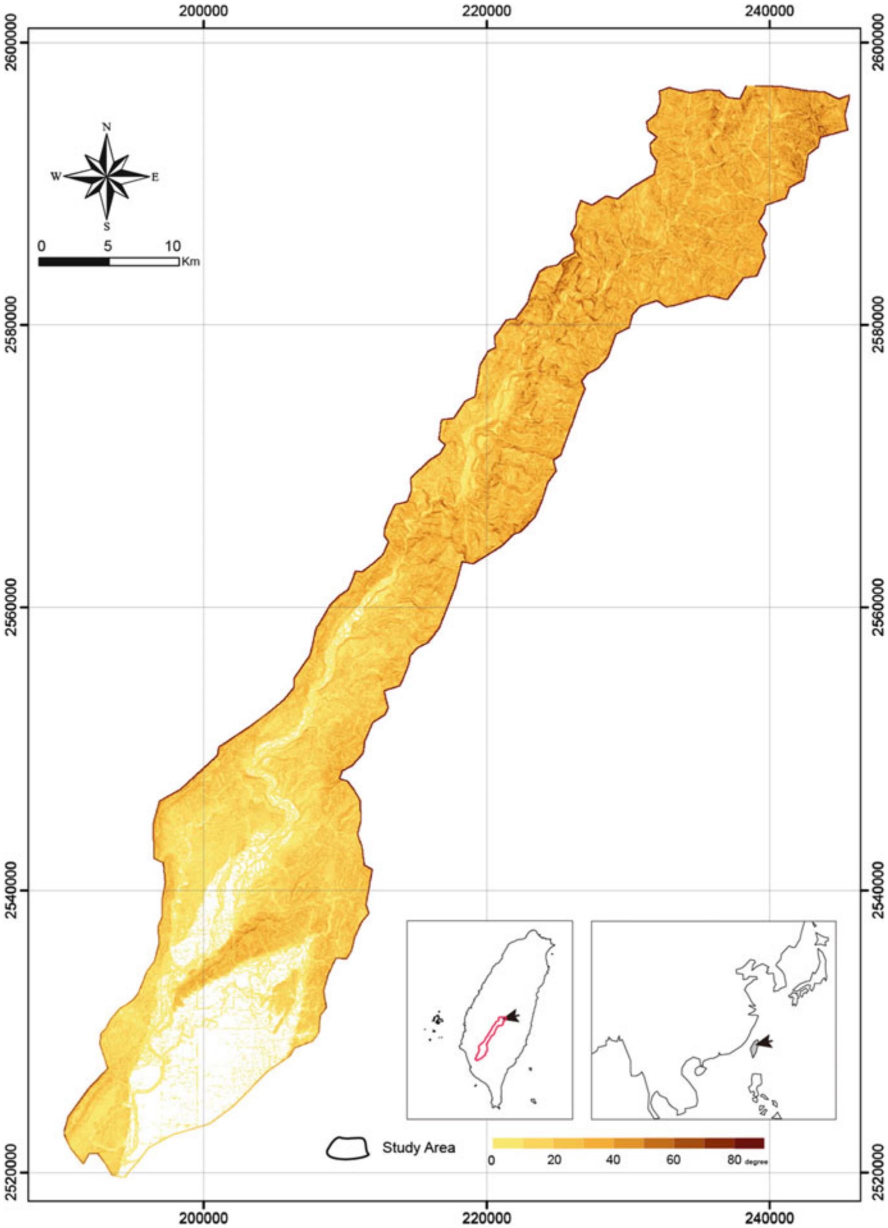


Fig. 5.2 The distribution of slope angles in the study area (Coordinate system: TWD97)

procedure cannot be replaced by using supervised or non-supervised classification automatically.

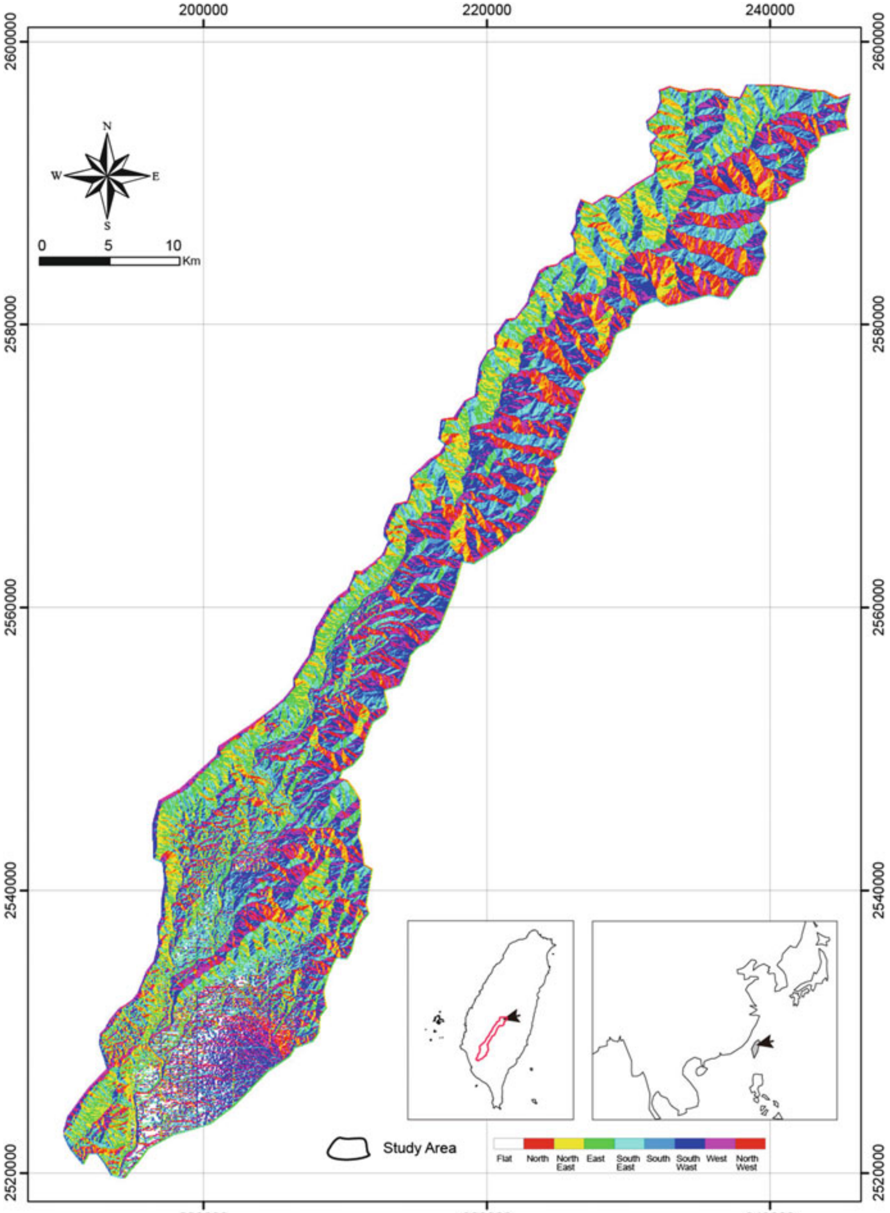


Fig. 5.3 The distribution of slope aspect in the study area (Coordinate system: TWD97)

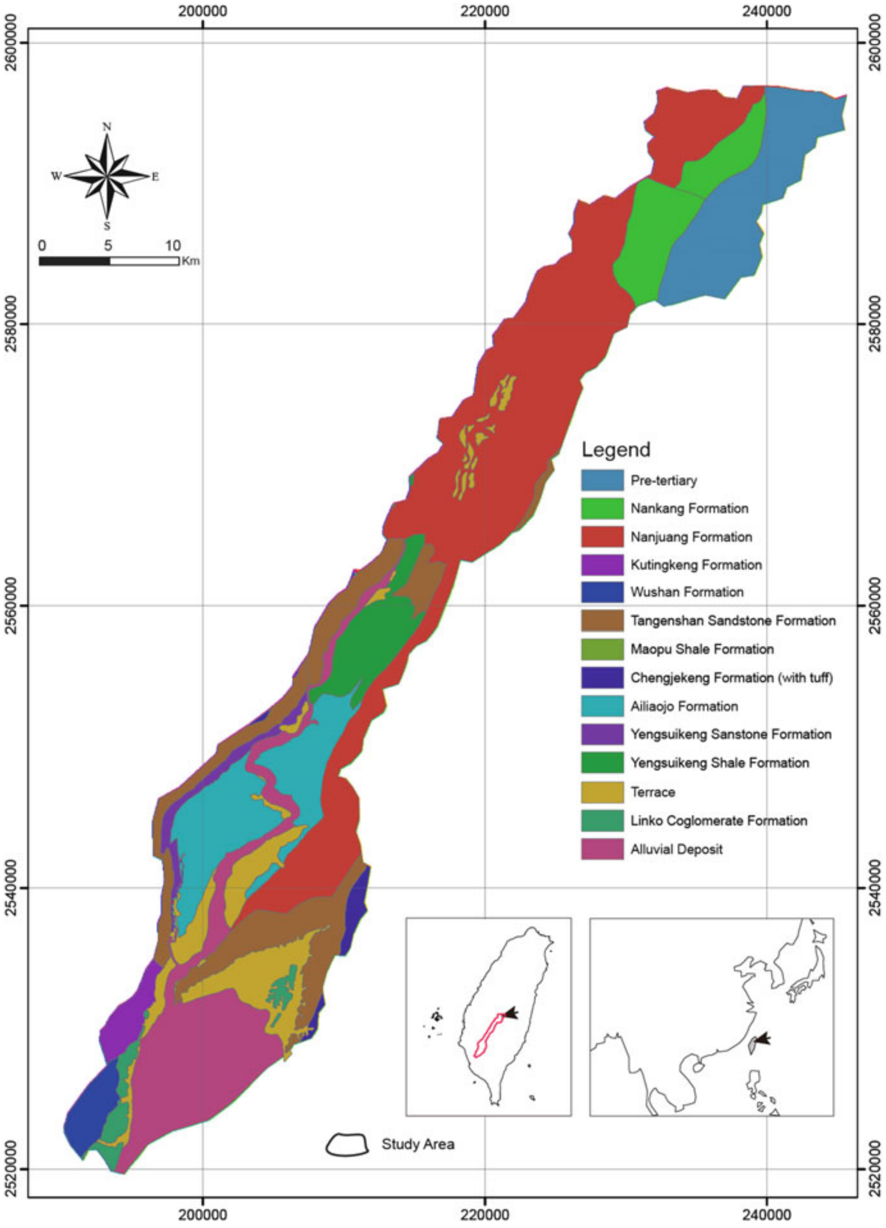


Fig. 5.4 Geological map of the study area (Source: Chinese Petroleum Corporation 1982a, b) (Coordinate system: TWD97)

The very high spatial resolution (GSDs 0.25 m) of the aerial photos makes it possible to identify even rather small size of landslides and very fine detail of any landslide features. With the quality of data used in this study, the minimum size

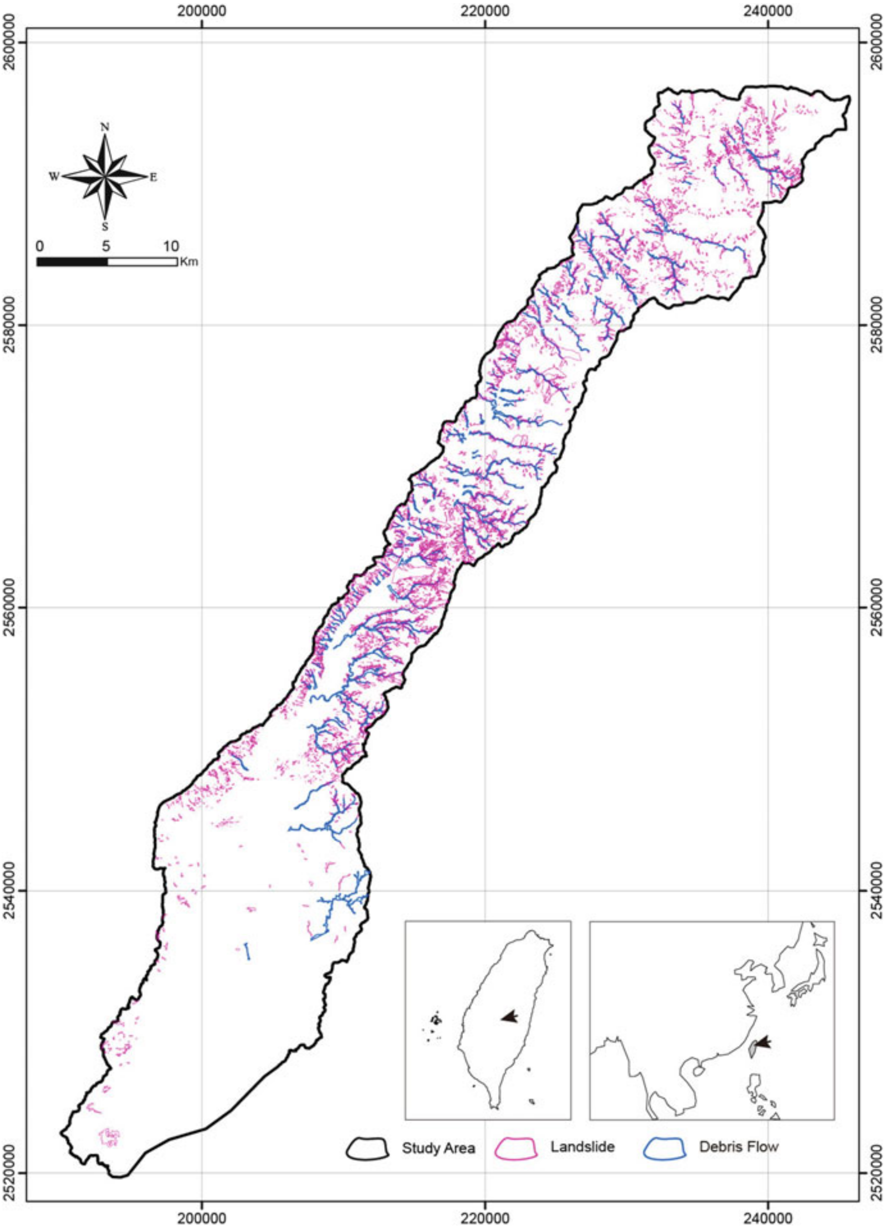


Fig. 5.5 The identification and mapping of landslides and debris flows in the Chishan River catchment (Coordinate system: TWD97)

of recognizable landslide is the equivalent of four pixels in area, which represents approximately a projected area of 0.25 m^2. In our mapping of landslides, there are only about 306 landslides with areas less than 10 m^2, which is 3.31 % of total landslides in the catchment. If these small landslides were all mis-identified, that small portion of landslides would not bring any significant influence upon the analytical result of the whole. As we can see later from the result, the very fine spatial-resolution ortho-rectified aerial photography can facilitate landslide mapping with accuracy that may offer a new insight into the magnitude and frequency of landslides and other mass movements during extreme events, such as Typhoon Morakot.

Mass wasting of soil and rock is a major process in the development of hillslopes and especially in steep mountainous regions (Selby 1993). In identifying the type of mass movement, Varnes (1958) proposed the classification of ‘Falls’, ‘Slides’, ‘Flows’ and ‘Complex’. Hutchinson (1988) proposed the classification by the morphology with consideration of mechanism, material, and rate of movement. In the classification, he adds more sub types, including ‘Translational landslides’ in the ‘Landslides’ category and ‘Debris flow’ in the ‘Flow’. Translational landslides are defined as the mass movement of slope material due to plane failure and transport downslope owing to gravity. Debris flows, containing a poorly sorted mixture of rock clasts and silt-mud matrix, generally run down pre-existing channels. Their tongue- or lobe-shaped deposits are thin compared to their downslope length. On land they commonly transform from landslides (Allen 1997).

In this study, mass movements are classified as ‘translational landslide’, ‘road-related landslide’, ‘other landslide’ and ‘debris flow’. Translational landslides are important features in the study area, and many were identified in the study. To identify translational landslides, firstly the bedding plain in ortho-rectified aerial photo images is located. They are then checked with the contour maps of 1:5000 or 1:10,000 and the geological maps with notes on dips and strikes of rock formations for further verification (Fig. 5.6). If the strike is parallel to the contour line and the dip points to the downward channels or roads, a landslide with a clear association with the bedding plain is identified as being of the translational landslide type.

Road-related landslides are those that occur on hillslopes adjacent to a road or track and are classified separately from translational landslides in this study because the high resolution aerial photo images made it possible to do so. Roads emerge as a major factor leading to slope instability at times of heavy rainfall or earth tremors. It is demonstrated below that differentiating the road-related landslide from translational landslides and other mass movement proved to be useful in looking at the characteristics of landslides in this study area. Landslides, not including either translational landslide or road-related landslide, are categorized as ‘other landslide’ in this study.

Once a channel is occupied by large quantities of colluvium with recognizable granular particles in the ortho-rectified aerial photos and the outlet of that channel forms a tongue- or lobe-shaped depositional area, it is mapped as a debris flow site in this study.

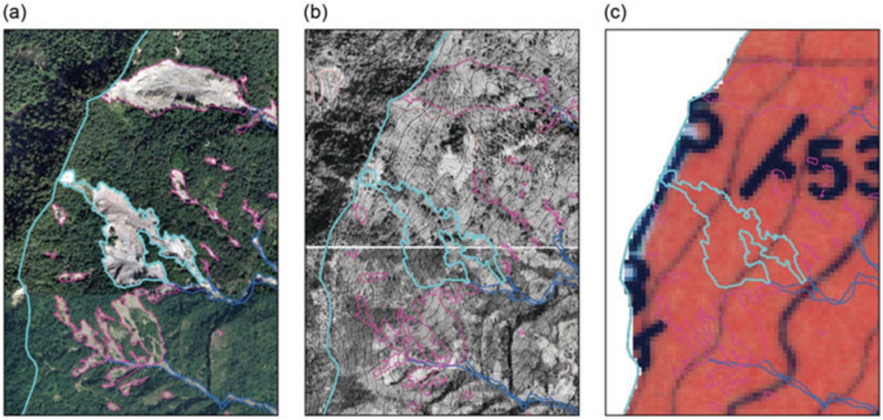


Fig. 5.6 Large translational landslide (demarcated by *light blue line*) in (**a**) ortho-rectified aerial photo, with clear bedding plain in the landslide, (**b**) 1:5000 map with contour lines, with slope aspect facing southeast, (**c**) geological map, showing the formation dipping to the southeast (Source of geological map: Chinese Petroleum Corporation 1982a, b)

The following step involves mapping the landslide distribution pattern – including statistically significant ‘hotspots’ – localities with exceptionally high frequencies, using the Getis-Ord Gi* method in Arc GIS 10. The process converts the landslide data from vector to raster format and, in this case, using a 500 × 500 m grid network. The equation used for calculating Gi* is as follows:

$$Gi^{*} = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \overline{X} \sum_{j=1}^{n} w_{i,j}}{S \sqrt{\frac{\left[n \sum_{j=1}^{n} w_{i,j}^{2} - \left(\sum_{j=1}^{n} w_{i,j} \right)^{2} \right]}{n-1}}}$$

$$\overline{X} = \frac{\sum_{j=1}^{n} x_j}{\mathrm{n}}$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j^{2}}{n} - \left(\overline{X}\right)^{2}}$$

Wang and Lin (2007) used the Getis-Ord Gi* method to identify hotspots of built-up areas in the Keelung River catchment in the Taipei Basin employing the same size grid and were able to map both spatial and temporal patterns of construction. Liao (2013) also used the Getis-Ord Gi* method to identify the spatial accessibility to pediatric services in Taiwan.

We used the facility ‘fixed distance band’, with parameters ‘distances band’ or ‘threshold distance’ to identify the hotspots and form the conceptualized spatial relationships of the mass movement features. In this study, we use 1500 m, or three grids of 500 m for the threshold distance, just as Wang and Lin (2007).

The population data of the study area were analyzed in order to explore the societal effects of the landslides and debris flows caused by Typhoon Morakot of 2009. The population data used in this study is at ‘Li’ and village level, which is a tier lower than the district (Kaohsiung City) and township (Chiayi County). We collected the population data for the end of 2008 and again for 2010 across the catchment, i.e. one year before and after Typhoon Morakot in 2009. The difference in the population can be used to indicate the migration of people affected by the event.

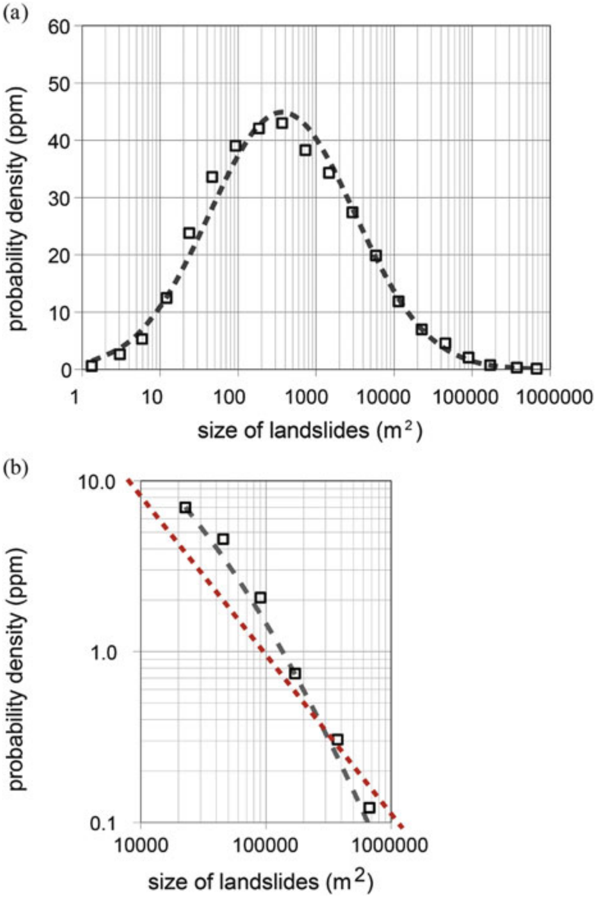
5.4 Results

The total number of recognized landslides is 10,216, including translational landslides, road-related landslides, and other landslides, and that of debris flows is 140 (Fig. 5.5). In all landslides occupy an area of 4207 ha, covering 5 per cent of the catchment as a whole. The largest landslide exceeds 206 ha in area. Transforming the magnitude and frequency (by area) of these landslides into a probability density distribution by a user-defined classification, we obtain Fig. 5.8a showing that the data fit to a lognormal distribution. The basic attributions of the lognormal distribution are correct in its assumption of a stochastic process which, in the set of landslides of a given rainfall event, includes that (1) every landslide is independent to each other, (2) there exists an optimum size of landslides that is defined by the configuration of materials and processes for the given place, and (3) the change rate at any given size of landslide is not constant but a linear relative difference being proportional to the size of landslide itself.

Fujii (1969) proposed a cumulative frequency-area distribution that correlated well with a power law relation of the type $N \propto A^{-\alpha}$, where N is the cumulative number of landslides, A is the landslide area, and $\alpha = 0.96$. However, the power law can operate well only for landslides over a certain magnitude (see, for example, Pelletier et al. 1997; Harp and Jibson 1995, 1996; Malamud and Turcotte 1999). Using air-photo- and ground-derived data, Brardinoni and Church (2004) suggested that both small and much larger magnitude of landslides may not be adequately represented by the power-law distribution. In the study of landslides after the rainstorm of 18 November 2001 in a 370 km^2 catchment in British Columbia, Guthrie and Evans (2004) show that the magnitude-cumulative frequency data plotted well on a power law curve for landslides only greater than 1 ha.

Stark and Hovius (2001) introduced a five parameter double-Pareto distribution to fit the entire range of landslide magnitudes, and obtained estimates for the slope of the power law tail of the distribution of $\alpha + 1 = 2.11$ for large landslides for the Taiwan inventory. In our case, for landslides larger than 1 ha, the probability density function may be approximated by a simpler power law as shown in Fig. 5.7b. In other words, for any given catchment with a total landslide area of around 1 ha, there will be one landslide of 0.1 ha in area; where total landslide area

Fig. 5.7 (**a**) The probability density distribution of landslides in this study area can be fitted precisely by a lognormal distribution. (**b**) The probability density distribution of landslide having an area over 1 ha



is 10 ha, there will be one landslide of about 1 ha, and so on. Since the total landslide area in the studied catchment is 4027 ha, the largest landslide could have an area as large as 402.7 ha, although in fact it is only 206.6 ha. For the lognormal distribution we propose here, there is also a slight systematic error at landslide size lower than 0.2 ha which may indicate some inappropriate settings in the assumptions of the stochastic processes underlying the lognormal distribution.

Translational landslides, landslides associated with roads and the remaining landslides are compared in Fig. 5.8. Of the 10,216 landslides mapped in this study, 318 landslides are associated with road construction and 276 landslides are translational. Although the number is not high, the magnitude of these two groups of landslides is relatively large. The reason for this is that Typhoon Morakot brought extremely heavy rainfall and caused extensive slope failures on the catchment scale.

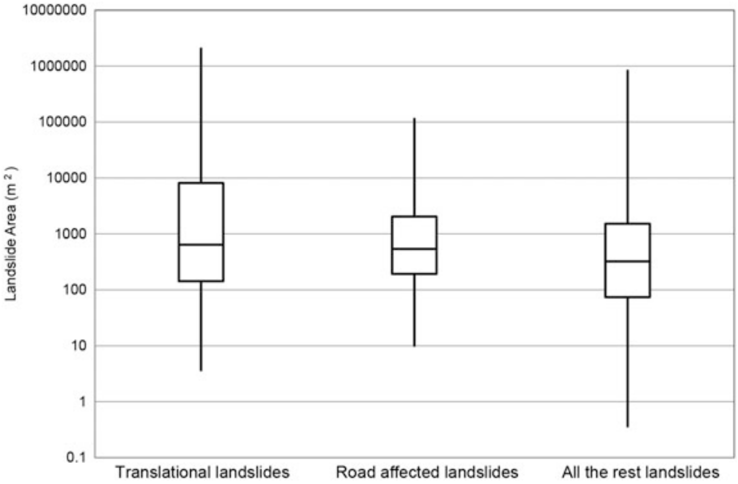


Fig. 5.8 *Box* and *whisker plot* of translational landslides, landslides affected by road and other landslides

The median size of translational landslides is 632.0 m^2, and that of landslides associated with roads and other landslides is 331.6 m^2. The translational landslides represent the movement of relatively large tilted rock segments. A typical example is the massive translational landslide that buried Xiaolin village and killed almost 490 persons. It was the biggest landslide of this typhoon event; its relief from the crown to the toe is 1000 m, and its width is about 3000 m. In Fig. 5.9, five indicative figures of the translational type, including five segments of exposed bedding plain of rock formation can be found in this landslide site. This landslide not only buried the entire village, but also blocked the main channel of the Chishan River (Fig. 5.9).

Figure 5.10 illustrates the result of Getis-Ord Gi* analysis of the identified landslides. Red coloured parts indicate areas with a high concentration of landslides while the blue ones indicate the area of relative few landslides; the yellow shaded areas are intermediate. Clear spatial patterns are evident, with three big hotspots in the middle parts of the catchment, including the area between Jiasian and Namasha, the area between Jiasian and Alishan, and the area between Namasha, Tauyuan and Alishan. The 'coldspots' (blue coloured) are situated either in the lower part of the catchment, which is between Neimen, Shanlin, Chishan and Meinong, or at the northern part of Tauyuan, which lies within a smaller area of lower concentrations in the northeast corner of the catchment.

The analysis clearly reveals that the distribution of mass movement events in response to the typhoon was spatially uneven. Most landslides locate in 26.7 % of

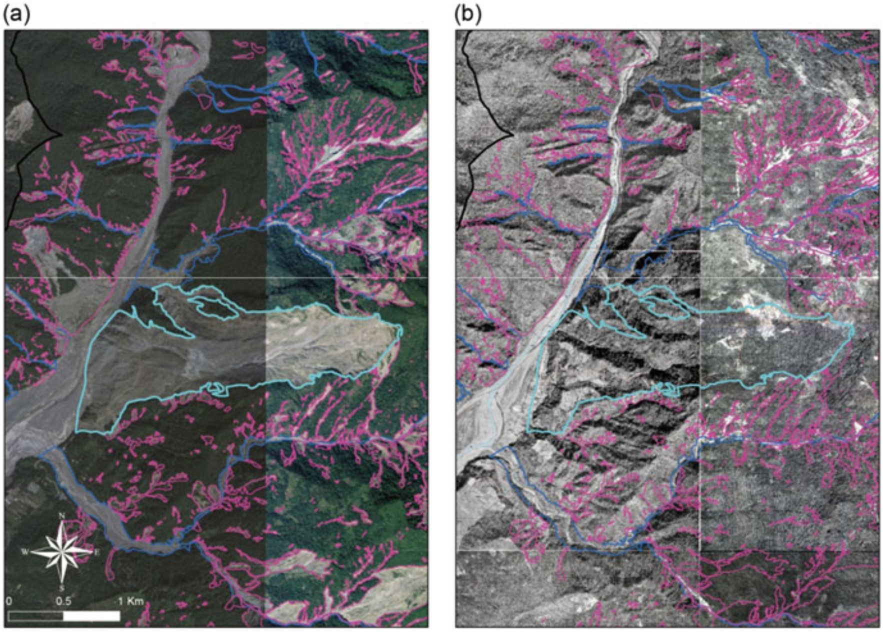


Fig. 5.9 The translational landslide that buried Xiaolin village in (**a**) ortho-rectified aerial photo and (**b**) 1:10,000 map

the total catchment area (hotspots) (Fig. 5.11, Table 5.1). Moreover, the debris flows were also mostly located in the landslide hotspot areas indicating that the event initiated several mass movement types.

The spatial patterns of mass movement features caused by Morakot indicate that some parts of the catchment with a particular combination of slope and underlying geology proved to be less susceptible.

In Taiwan, the Soil and Water Conservation Bureau (SWCB) set up a warning system, which is based on the continuous rainfall data being recorded by the nearest local rainfall station nearby each potential debris flow site. The information on possible debris flow hazard are issued on the website (http://246eng.swcb.gov.tw/) and broadcast in TV news or radio programs. In addition, a network of real-time monitoring stations has been introduced to facilitate the collation and distribution of vital debris flow information (see for example, in the case of Jilai: http://210.69.127.168/debrisFinal/ViewStationEn.asp?StationID=19).

Before the Typhoon Morakot event, SWCB (2009) identified 22 potential debris flow sites in the Chishan catchment that were considered to be at risk of activation in the case of total rainfall exceeding 500 mm. After Typhoon Morakot, 140 debris flows resulting from the heavy rain could be delineated from aerial photo images and verified through field checks. The extensive landslides delivered a substantial amount of sediment to the fluvial system which contributes to the formation of many new debris flows in the study area with consequent risk to the people who live in the area.

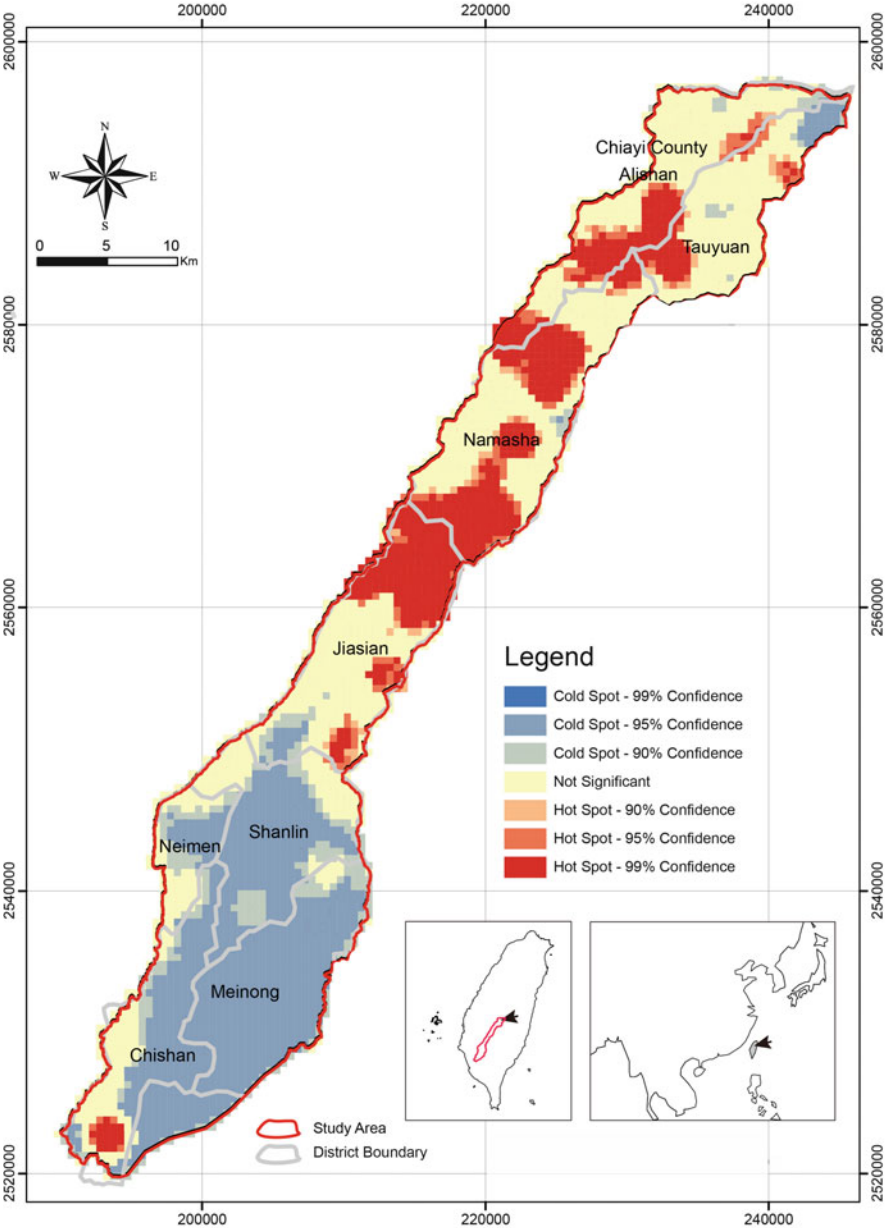


Fig. 5.10 The Getis-Ord Gi* analysis of landslides caused by Typhoon Morako (Coordinate system: TWD97)

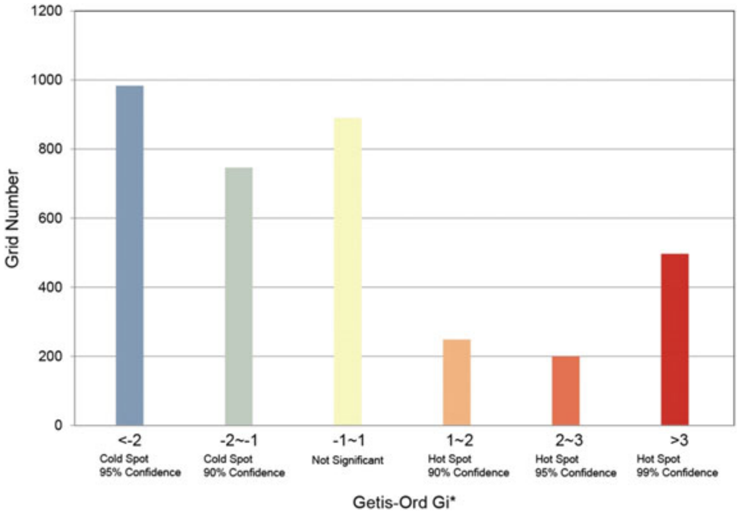


Fig. 5.11 The Getis-Ord Gi* statistics of landslides caused by Typhoon Morakot

Table 5.1 Getis-Ord Gi* Z scores in the analysis

Getis-Ord Gi* Z score			No. of grids	%
<−2	Cold spot	95 % confidence	989	27.5
−2 ~ −1	Cold spot	90 % confidence	757	21.1
−1 ~ 1	Not significant		890	24.7
1 ~ 2	Hot spot	90 % confidence	258	7.2
2 ~ 3	Hot spot	95 % confidence	205	5.7
>3	Hot spot	99 % confidence	497	13.8

Therefore, SWCB revises the threshold of the potential rainfall causing disaster, from 500 mm to between 350 and 450 mm, to address the issue (See the example of Jilai mentioned above).

The population distribution for each Li and Village of the study area in 2008 is shown in Fig. 5.12. Population densities are generally higher in the lower parts of the catchment. The difference in population numbers between 2010 and 2008 is depicted in Fig. 5.13a and as a percentage is in Fig. 5.13b. There is clearly population change between 2010 and 2008, which is associated with the landslide and debris flow events that occurred in the catchment as a result of the typhoon. The village with most population change is indicated in red in Fig. 5.13. This is Xiaolin Village, which was totally destroyed by a huge translational landslide; the population reduction in this area was −34.6 % between 2010 and 2008. The landslide caused the deaths of 397 people, the disappearance of 53 others, and buried over 100 houses (Lin et al. 2011). The green–shaded area indicates the site set aside for those surviving and represents a population change rate of +48.3 % over the same

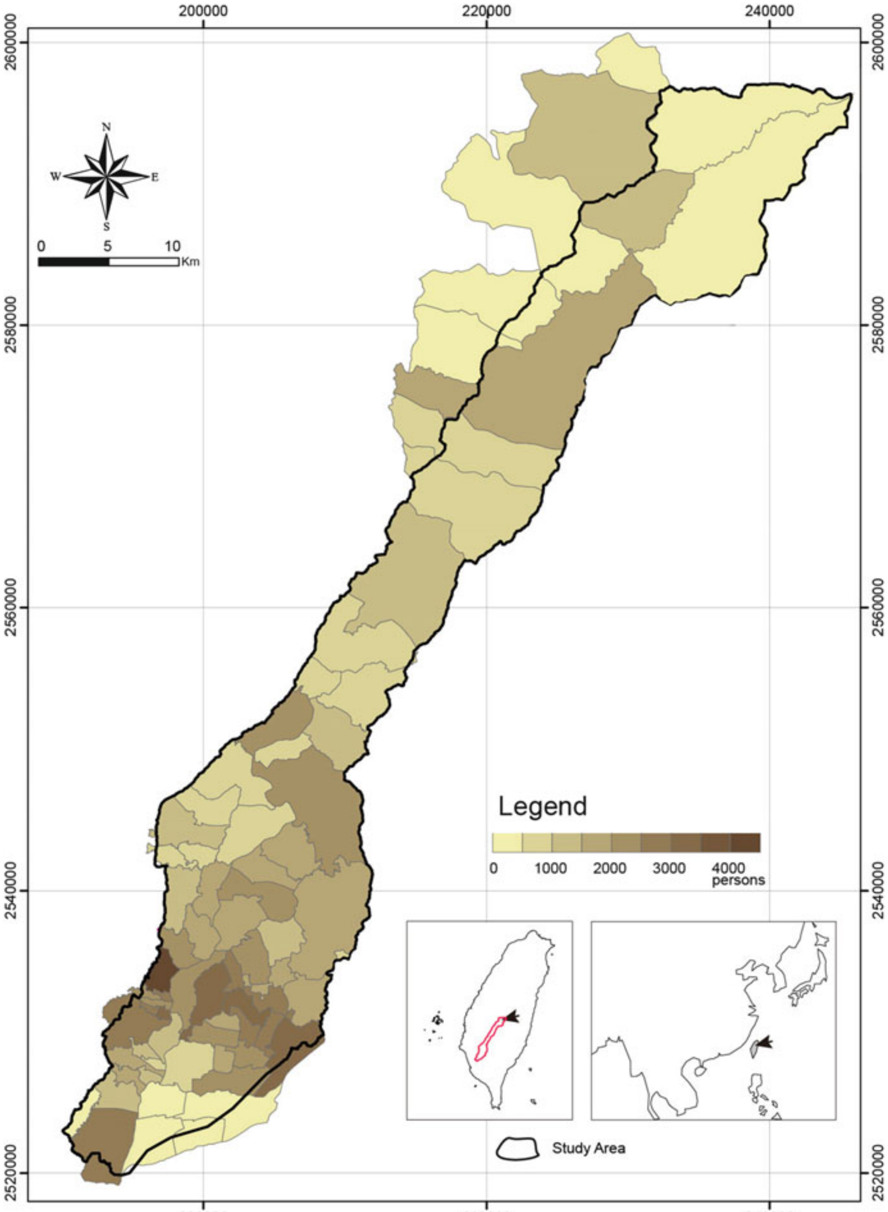


Fig. 5.12 The population in 2008 in each Li and Village in study area (Coordinate system: TWD97)

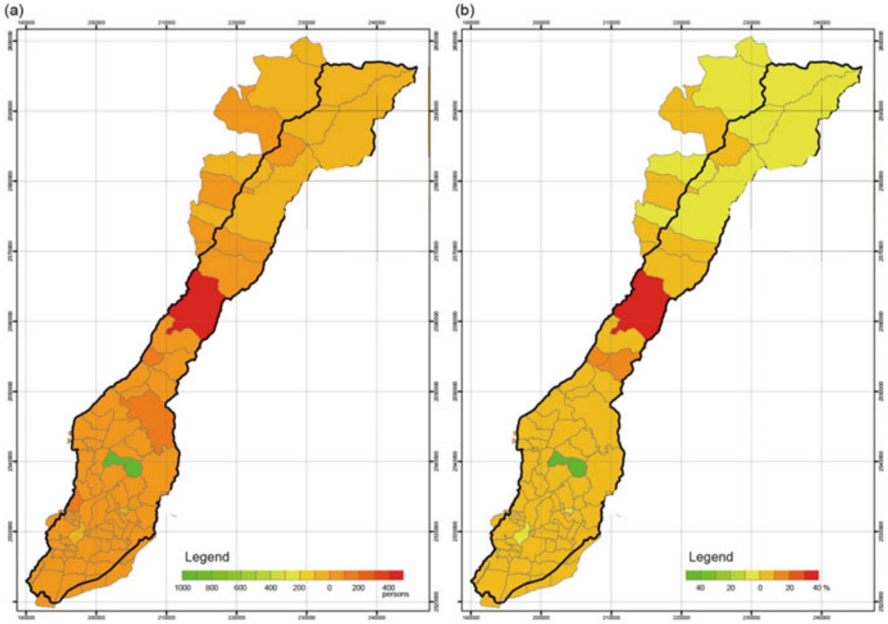


Fig. 5.13 (**a**) The population difference and (**b**) population percentage difference between 2010 and 2008 in each Li and Village in study area (Coordinate system: TWD97)

period. Some 982 persons were moved into this particular area after Typhoon Morakot.

In this study, the population difference between 2012 and 2008 is plotted onto the 500 m grid network (Fig. 5.14) to demonstration the spatial pattern between the landslide hotspots and population change. The result shows that the areas with most population change between 2012 and 2008 are in Chishan and Meinong, and both in the landslide 'coldspot'. It also shows that many people moved away from places not even affected by landslides. The area in the northern part of Jiasian is both landslide 'hotspot' and an out-migration area. The residents were affected by the landslides, and they left the area to prevent further hazards. The landslide hotspots in Namasha and Tauyuan are relatively low population density.

Population census data indicate that more than 1952 persons left the study area after Typhoon Morakot, and were relocated to the unaffected part of the catchment. The severe conditions caused by the effects of Typhoon Morakot and the perception of the hazard contributed to population migration, a trend which is continuing according to the 2013 population record of Civil Affairs Bureau of Kaohsiung City Government (2015).

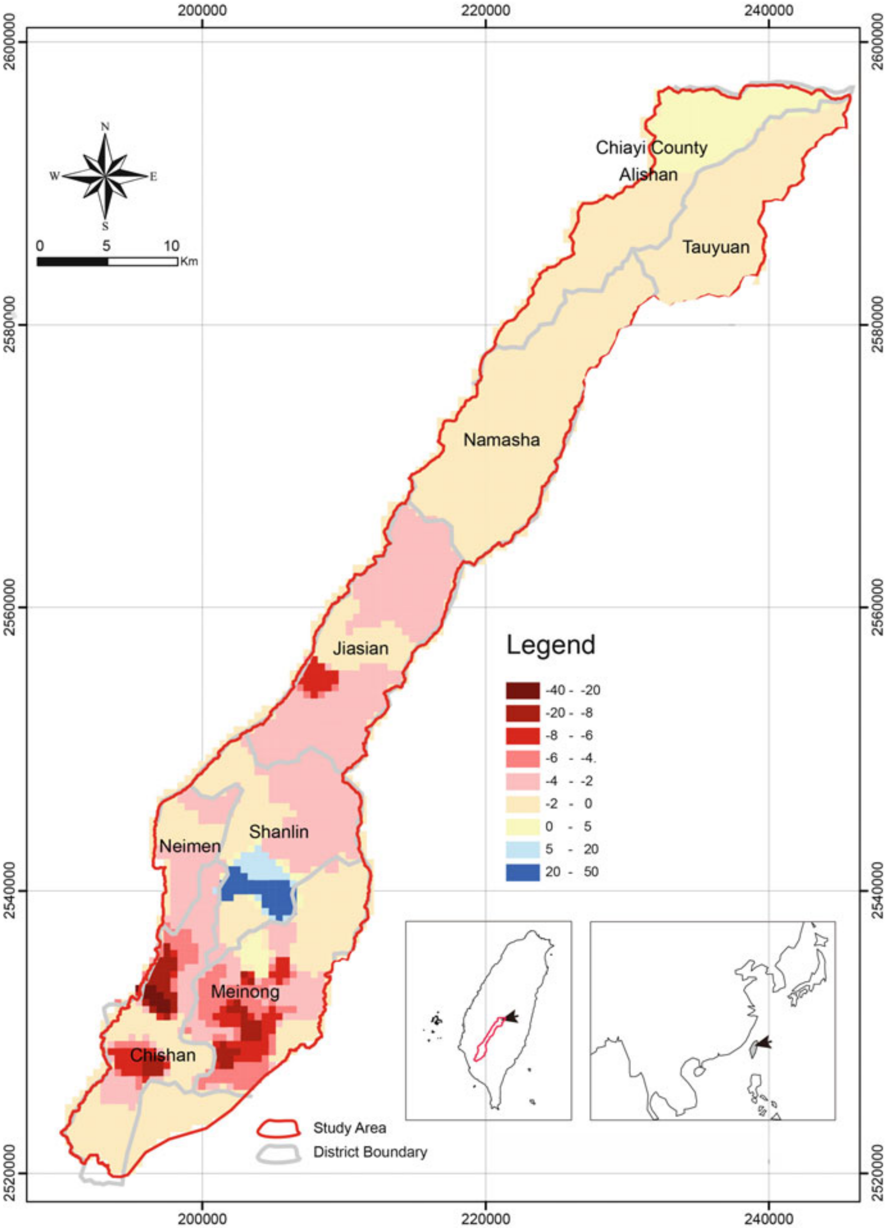


Fig. 5.14 The population difference between 2012 and 2008 in 500 grid network in study area (Coordinate system: TWD97)

5.5 Discussion and Conclusions

The landslides and debris flows caused by Typhoon Morakot were extensive in the Chishan River catchment of Taiwan. There were 10,216 landslides and 140 debris flows delineated from ortho-rectified aerial photos which occurred during the event compared to just 22 potential debris flow sites in this catchment previously identified by SWCB. The destruction by Typhoon Morakot was, therefore, quite overwhelming. The magnitude and frequency of these features approximates a lognormal distribution with a systematic error when the landslides are below 0.2 ha in area.

Translational landslides mapped in this study are relatively large features with a median size of 632 m^2, which is almost double the median size of the other landslides. The example of the largest translational landslide, at Xiaolin village – which is 3 km wide and extends over almost 1 km of relief – demonstrates the markedly destructive nature of such features. The sediment created by the landslide not only buried the entire village but also formed a huge talus that blocked the main channel of the Chishan River and created a dammed lake. The result was significant reduction in population due, in part, directly to loss of lige caused by the landslide and partly due to subsequent relocation and migration. The situation is clearly shown as the red shaded hotspot in Fig. 5.13a, b.

Landslides related to roads in the catchment are relatively similar to other (non-translational) landslides but resulted in terms of the infrastructural damage to transport routes that they caused. Indeed, several important national routes pass through this catchment, including the southern trans-island highway connecting the eastern and western parts of southern Taiwan. These infrastructural problems hampered initial rescue efforts and also provided additional factors inducing migration. To date, the road system has not been fully restored, and problems for transport of agricultural products, which are the main source of income in this area, are still being experienced. In this sense, the local economy has been seriously impacted with implications for the remaining population. According to data from the Kaohsiung City and Chiayi County governments, 1951 persons left the area immediately following the disaster and a further 2384 more left between 2010 and 2012. National and local governments joined with non-governmental organizations including the Buddhist Tzu-Chi Foundation as well as Catholic and other Christian church charity groups to provide funding for free new safe housing to exchange with the old potentially hazardous ones. A locality was identified on which to construct temporary and permanent dwellings for the local residents to avoid their exposure to similar hazards in the future. The site of increasing population density is indicated by the area shaded in Fig. 5.13a and b. Some 982 persons moved into this area in the immediate aftermath and a further 1010 persons settled there up to 2012.

The pattern of landslide hotspots produced in the Getis-Ord Gi* analysis is similar to the pattern of population migration after Typhoon Morakot in that areas with high density of mass movement features are those from which people migrated. This results from the combined effects of hazard perception, economic pressure and inconvenience caused by the damaged road system. There has been a clear institutional response to this in Taiwan. The central government amended the 'Disaster Prevention and Protection Act' in August 2010 in order to mitigate the effects of future natural hazards (Ministry of the Interior, Taiwan 2015). Articles 24 and 27 of the revised law allows compulsory evacuation by the police and army from areas prone to the effects of typhoons as soon as the typhoon warning issued by the Central Weather Bureau. Those evacuated are accommodated in temporary shelters. The government can also shut down the road system to prevent movement of people into or through areas at risk. While the new legislation is aimed to reduce the risk from such typhoon-related hazards, it does nonetheless cause potential inconvenience to local people. Given that the potential for future hazards remains, together with uncertainty regarding future economic conditions and ongoing transport infrastructural problems, it is perhaps not surprising that population migration is continuing. The magnitude of the typhoon and its impacts has disrupted the entire socio-economic system and it will therefore take considerable time before a new equilibrium is established.

In this study, we have mapped the landslides and debris flows caused by Typhoon Morakot of 2009 in the Chishan River catchment. The Getis-Ord Gi* analysis of landslide hotspots has revealed areas with higher concentration of landslides as well as the spatial patterns of population movements. There are 10,216 landslides and 140 debris flows identified and mapped from the ortho-rectified aerial photos. The substantial number and size of these landslides caused widespread significant damage and loss of life in the study area. There are three major mass movement hotspots in the middle and upper catchment, which indicate that the environmental factors are complex and involve more than just underlying geology. Due to the direct effects of such events on population and their socio-economic conditions, it is essential that both government and non-governmental organizations work together to mitigate the impact of any future typhoons.

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Chapter 6

Delineation of Historical Fluvial Territories and the Implications for Flood Mitigation, with Reference to Four Selected Reaches in Taiwan

Su-Min Shen

Abstract Levee construction in support of land reclamation policies has been implemented on almost all well-developed braided channels in Taiwan during the twentieth century. Increasing record-breaking high-intensity rainfall events and consequent severe flood disasters since the mid-1990s, however, have raised great concerns about reclaimed active floodplains. In light of the non-hard engineering flood mitigation approach being adopted, a geomorphic perspective of land management seems to be absent in Taiwan. Thus, with reference to four braided channel reaches, this chapter aims to demonstrate the delineation of the reclaimed active floodplains, so-called historical fluvial territories (HFTs), and to examine the landcover/landuse type change in the HFTs over the twentieth century. The reason why a geomorphologically-informed active floodplain is essential and an urgent need on flood disaster mitigation in Taiwan is also justified. A historical approach, employing sequential historical map overlays, aerial photographs and orthogonal maps with GIS analysis, was adopted. Various official archives were also consulted. It is established that HFTs identified from historical maps and aerial photographs published in the first half of the twentieth century can be regarded as active floodplains in the near-natural condition. Although most lands in the HFTs remain in agricultural use, as originally planned, land use intensity has been gradually increased especially in those close to the economic cores. It is argued strongly that land development should be strictly monitored, not only in those areas at present officially defined as flood-prone but across the entire active floodplain in near-natural conditions, such as the HFT proposed by the current work.

Keywords Braided channel changes • Floodplain • Historical fluvial territory • Historical archives • Taiwan

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6.1 Introduction

Ongoing and widespread major flood disasters have resulted in huge life and property losses around the world. Flooding alone caused more than 154,000 deaths and more than 53 billion dollars worth of total damage worldwide during last 20 years, based on the EM-DAT database (maintained by Centre for Research on the Epidemiology of Disasters, http://www.emdat.be/). One of the major factors exacerbating flood risk is the reclamation of formerly active floodplains. Thus, it is being increasingly recognised that 'working with nature' is a key consideration in the design and implementation of sustainable and cost-effective river rehabilitation measures. Floodplain restoration, under the aegis of the Water Framework Directive of EU (2000/60/EU) and, later, the Floods Directive (2007/60/EU), has been implemented or at least highly promoted in EU countries (e.g., Ollero 2010; Piégay et al. 2006; Ureña and Ollero 2001) and also in the USA (e.g., Rapp and Abbe 2003).

In Taiwan, most rivers have been heavily engineered and channelised along the middle to lower channels. Engineers have played the lead role in the management of rivers for utilitarian objectives and these will clearly remain key foci for river management, as described by Brizga and Finlayson (2000) for rivers in Australia and New Zealand. Levee-confined channels, however, are much narrower than the territories that the rivers once occupied. Continuous natural disasters since mid-1990s, especially the catastrophic impact of Typhoon Morakot in 2009 have raised great concerns around flooding issues on the formerly reclaimed active floodplains. The seemingly ideal solution of 'working with nature' for flood mitigation has been advocated by activists, e.g., Liao (2006) and Lyu (2015) (http://eem.pcc.gov.tw/node/31062), engineers, e.g. Chen (2012), and individual officers from the land management and river authority, e.g. Chen (2010) and Yang (2010). However, questions such as: 'to what extent have the formerly active floodplains been reclaimed?', 'what are current land uses on the reclaimed land?' and 'how and why have the areas been transformed?' remain largely unanswered.

Thus, this chapter aims to demonstrate the delineation of the reclaimed active floodplains, labeled here as 'historical fluvial territories' (HFTs), to examine the landcover/landuse type change in the HFTs over the twentieth century, and to justify why geomorphologically-informed active floodplain management is an essential and urgent need for flood disaster mitigation in Taiwan. The lower reaches of the Sanchan Stream (*SC Str*), Taimali Stream (*TML Str*), Chishan Stream (*CS Str*) and Wu River (*Wu R*), which represent various environmental settings, are selected as study areas.

6.2 Study Area

Natural channel patterns reflect the interaction of controlling factors across various spatial and temporal scales in particular environmental settings. Located at the tectonic collision boundary of the Eurasia Plate and Philippine Sea Plate and lying in the path of frequent typhoons in the NW Pacific Ocean, the geologically young island of Taiwan (Fig. 6.1a) has very high relief (~3952 m), highly fractured geological substrates and is characterised by steep gradients and high drainage density. Due to the limited island area (36.5×10^3 km^2) and the spatial arrangement of the NE-SW major divides, the drainage basins are small and the rivers are short and steep. Taiwan's climate is tropical to sub-tropical and influenced by typhoons and the annual monsoon cycle (Fig. 6.1b). Mean annual rainfall for the island as a whole is around 2500 mm, and seasonality of rainfall is significant, especially in southern Taiwan.

Such geological and climatic conditions are underlying causes of natural disasters in Taiwan (Fig. 6.1e). Fluvial processes which result in major geomorphic

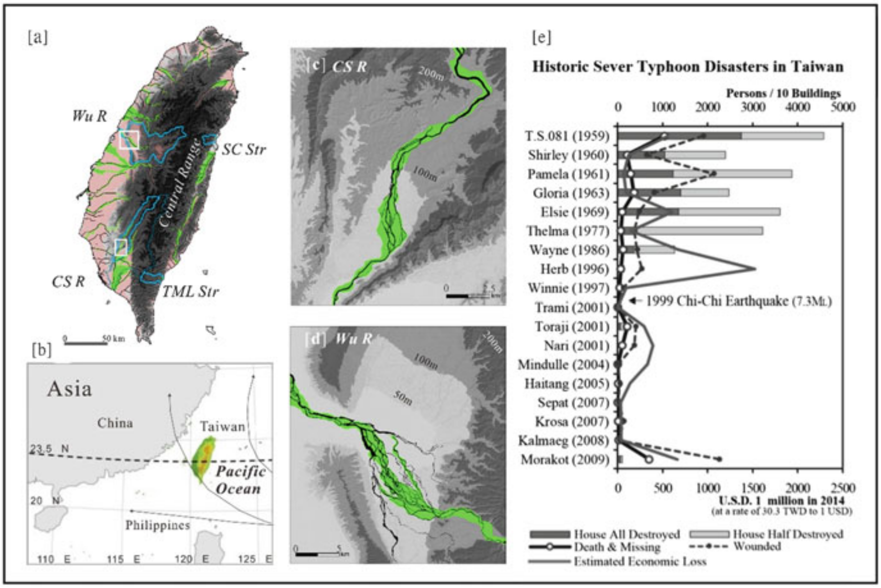


Fig. 6.1 Natural environmental settings of Taiwan island and the location of selected catchments (**a**) Major ranges (in *grey* tone) and Holocene alluvial deposits (*white*) shows Taiwan a characteristic mountainous island. River territories (channel migrating zone) of major rivers identified from historical maps in early twentieth century (*dark grey*) (Shen 2013)
Drainage basins of four selected rivers are indicated with *black line*. (**b**) Located off southeastern Asia, the island lies in the path of frequent typhoons in the NW Pacific Ocean, with major typhoon tracks indicated by *arrows*. (**c**) The lower valley floodplain of the Chishan River (*CS R*). (**d**) The multi-channel system on the Wu River (*Wu R*) alluvial fan. (**e**) Historical records of the most disastrous typhoon events after WWII in Taiwan

dynamics such as overbank deposition, meander migration and avulsion are always related to major typhoon-triggered flash floods (Chang and Chen 1999) since peak discharges are very closely linked with the occurrence of typhoons (Huh et al. 2009). The most recent example is Typhoon Morakot in 2009. The extraordinary heavy rainfall, which exceeded the 150–200 year return period event, caused widespread landslides, debris flows, dammed lakes and flooding in southern Taiwan (NCDR 2010). The record-breaking accumulative rainfall of up to 2319 mm in southern Taiwan occurred within three days and the maximum 24-h and 48-h accumulative rainfall (1623.5 and 2361 mm) were close to world record levels (1825 and 2467 mm, NCDR 2010). The event also awakened concerns of over development on the marginal lands, most especially on the floodplains.

Braided channels tend to develop where river stretches are characterised by steep slopes and/or large sediment loads (Schumm and Kahn 1972) and so are well-developed in Taiwan, where the rivers are characterised by highly contrasting seasonal discharge, high sediment concentrations with a significant proportion of coarser materials and also high slope-channel coupling. Thus, not surprisingly, braided channels are very well developed in Taiwan (Lin 1957; Hwang 1980). Chang (1983) identified 56 braided channel reaches along 30 rivers, based on the 1:50,000 topographic maps published in 1971. Four types of braided streams were classified but neither the change of channel width or the extent of channel migration were mentioned in Chang's analysis. Based on comparison of four sets of medium-scale historical maps of 1900s, 1920s, 1960s, 1980s and recent satellite images taken in 2013, Shen (2013) re-examined and summarised the spatial distribution of braided channels. They are particularly well-developed on alluvial fans in the lower reaches, in relatively wide (semi-) confined valley floodplains along the midstream reaches, and also dominant on the alluvial fans which develop at the river mouths of most small streams, where main ridges are immediately adjacent to the sea around the eastern and southern coast. Four stretches of the braided channel were thus chosen as study areas and were briefly introduced below.

The *Sanchan Stream* (*SC Str*) and the *Taimali Stream* (*TML Str*) both originate from the eastern flank of the Central Range and drain steeply into the Pacific Ocean (Fig. 6.1a and Table 6.1). The *TML Str* valley broadens at around 4 km before the stream reaches the Pacific Ocean and at which point the alluvial fan develops. The *Chishan River* (*CS R*) is one of the major branches of the Kaoping River located in southern Taiwan (Fig. 6.1a and Table 6.1). It originates in the metamorphic-rich Yushan Range but flows largely through very fractured sedimentary rocks of the Western Foot Hills. The catchment is steep and elongated and only in the lowest 10-km valley segment does the valley floodplain widen up to 3 km (Fig. 6.1c). The *Wu River* (*Wu R*) is one of the major rivers of central Taiwan (Fig. 6.1a and Table 6.1). It originates from the predominantly metamorphic Hsueshan Range and flows through the Western Foot Hills and Taichung Basin that comprise mainly sedimentary rocks. The Wu alluvial fan forms when the river flows out of the Western Foot Hills and occupies the southern part of the Taichung Basin (Fig. 6.1d). Confined by the adjacent alluvial fans of the Dali Stream and the Maolou Stream, the fan has an oval configuration.

Table 6.1 Basic data of four selected river channels

	Sanchan stream	Taimali stream	Cishan river	Wu river
Area (km^2)	123.3	221.5	842.0	2025.6
Max. height (m)	3101	3092	3952	2596
River length (km)	24.5	36.2	118.0	119.1
Channel gradient	1:8	1:86	1:142	1:92
Rock types	Highly metamorphic rocks	Highly metamorphic rocks	Shale, sandstone and alternations of sandstone with a few metamorphic rocks	Slate, argillite, quartzite, sandstone, shale, alternations of sandstone
Annual rainfall (mm year^{-1})	2339	3002	2376	2087
Annual river discharge (MCS)	267	544	1318	3727
Max. event	No gauge station	Gauge station failure (Typhoon Morakot in 2009)	1040 mm/day, 1915 mm/3 days (Typhoon Morakot in 2009)	722 mm/3 days (Typhoon Mindulle in 2004)

Sources: Chen et al. (2012), Hsu et al. (2008), Hsieh et al. (2013); Hydrological Year Book of Taiwan (Republic of China) in 2013

The natural channels have been gradually modified since the late sixteenth century when the population of Taiwan started to increase dramatically (Knapp 2007). Extensive cultivation in the major coastal plains and basins in the western Taiwan were conducted by Han Chinese immigrants from the southeastern China. By the late nineteenth century, before the Japanese occupation, all suitable lowlands, including the *CS R* (Tsai 2006) and *Wu R* (Wurih Township Office 2004), were transformed into paddy fields. It is probable that only those under the threat from flooding or invasion by indigenous tribes were not reclaimed.

Modern flood control technology was initially introduced into Taiwan during the Japanese colonial period (1895–1945). Large-scale flood defence projects were implemented along nine major rivers in the 1930s, including *Wu R* and the Kaoping Stream (of which the *CS R* is a major tributary) (Ku and Liao 2012). These projects were established not only to mitigate flood hazards but also for reclaiming new lands from the active floodplains (Ma 2005). A similar strategy of levee construction in response to flood hazards was adopted by the Taiwan government after WWII and applied to the major rivers in eastern Taiwan from 1960, and later to the midstream valley floodplains of major rivers in western Taiwan, e.g., *CS R*, and also to the alluvial fans at the river mouth of smaller streams from around 1980, e.g., *TML Str* and *SC Str* (Shen 2013).

6.3 Materials and Methods

This study aims to identify the near-natural (original) conditions and to depict the landcover/landuse change on formerly active floodplains of the selected streams. A historical approach is adopted by overlaying sequential historical maps, aerial photographs and orthogonal maps (ortho maps) with GIS analysis. The procedure is similar to the common practice that describes river mobility in recent history by overlaying historical positions of channels, e.g., Marston et al. (1995). The term ‘historical fluvial territory’ (HFT) is used in this study to indicate the formerly active floodplain delineated from the historical maps and aerial photographs, i.e., the area which is subject to flooding.

The length of time represented by ‘recent history’ very much depends on the availability of the reliable archival materials. Modern surveying and cartographic techniques were not widely applied in Taiwan until 1895 by the Taiwan Governor Office (TGO) under Japanese rule. A medium-scale topographic map series, at scales of 1:25,000 and 1:50,000, for the whole island have been published, although with different projection, coordinate system, cartographic standards and specifications. The earliest available aerial photographs with wide coverage were not taken until the late 1930s (by the US Air Force, Shen and Chang 2003). Various sets of larger-scale ortho maps (at a scale of 1:5000) with background images of aerial photo- or satellite-origin have been produced since the mid-1970s by the Taiwan Government. Considering the research aim in this study, four major sets of maps

Table 6.2 Geo-archives used in the current study

I. Channel morphology, historical fluvial territory and major landcover types
Major sets
[1] Topographic maps at scale 1:25,000 and 1:50,000 – 1920s
[2] Aerial photographs at scale around 1:20,000 (black and white) – late 1940s
[3] Ortho maps at scale 1:5000 with background image and contour interval 5 m (black and white) – late 1970s
[4] Ortho maps at scale 1:5000 without contours (color image) – early 2000s
Complementary sets
[5] Topographic maps at scale 1:50,000–1910s
[6] Topographic maps at scale 1:25,000–1960s
[7] Ortho maps at scale 1:5000 with contour interval 5 m (black and white) – around 2000
[8] Satellite images of Formosa II – since 2000
II. Recent landuse change
[9] GIS layers and attribute tables of the 1st National Landuse Databank, 1995
[10] GIS layers and attribute tables of the 2nd National Landuse Databank, 2006–2008
III. Archives and official documents related to the study area, to flood hazard or to levee construction

and images, including several complementary sets, were used as appropriate (Table 6.2).

Features of interest in this study include those indicating former channel traces, i.e., main channels, smaller braided channels, dry channels, abandoned channels, distributaries, fluvial-origin scarps, and other major landcover types, e.g., levees and farmlands, in the HFTs. They were interpreted either by stereo pairs of the aerial photographs or based on the tone, color, form, texture on the rectified background images of the ortho maps. Ortho maps at a scale of 1:5000 produced in the early 2000s were used as the base maps and all other scanned historical maps and aerial photographs were rectified to the base maps using an ArcGIS platform before overlapping and digitizing. Similar procedures have successfully been practised by the current authors (Weng et al. 2010; Hsu 2013; Shen 2013).

Geomorphic features such as dry channels, barren/vegetated bars and scarps are exclusively noted with dedicated map keys in the medium-scale historical maps published by the TGO and are very helpful, although only qualitatively, in revealing channel morphology in the early twentieth century. The aerial photographs and large-scale ortho maps preserve the “ground truth” at the moment when the images were taken. Identification of the active floodplain on these images is also straight forward, even on the black/white version, with the characteristic combination of high reflectance of un-vegetated bars and dry channels and low reflectance of river flow, etc. In short, the formerly active floodplain was interpreted mainly based on the earliest available version of aerial photographs taken in late 1940s in this study, then corresponded to the geomorphic features shown on the historical maps. Fieldwork was then conducted to check the existence and location of scarps and also the current landuse types. When the image of the aerial photo proved less satisfactory, the outer margin of the farmland based on map interpretation was used as the operational definition of a dynamic zone boundary, by assuming the farmers only cultivated paddy fields in non-flooded areas, at least based on their life experience. In addition, archives and official documents related to the flood disaster investigation and levee construction of the study area were also consulted to clarify the process of landcover change over the course of a century.

To depict the recent land use change in the HFTs, GIS layers and the attribute tables of the first and the second National Land Use Survey completed during 1995 and 2006–2008 (NLSC 2006–2008), respectively, were compared. The national land use investigation was conducted by the National Land Surveying and Mapping Center, Ministry of the Interior, and based on aerial photogrammetry, field investigation and GIS (http://www.nlsc.gov.tw). The land use classification scheme of the databanks consists of nine first-level divisions, which are in turn divided into 41 second-level classes and further 103 third-level sub-classes. The first-level division includes agricultural land (01), forestry land (02), transportation land (03), hydrological land (04), construction land (05), public land (06), recreational land (07), mine and salt industry land (08) and others (09). Very roughly, construction land may be considered as high landuse intensity, transportation, public and recreational land with medium intensity, while the rest as the low intensity.

6.4 Results: Channel and Landcover/Landuse Change Within Historical Fluvial Territories

Based on the historical analysis approach, the results of the channel and landcover/landuse change analysis within the historical fluvial territories (HFTs) of each selected stream are presented, firstly the channel morphological change, then the delineation of the HFTs, and finally the landcover and landuse change over a decadal time period (1995–2006).

6.4.1 Channel Morphology and Landcover Change in the Historical Fluvial Territories (HFTs)

6.4.1.1 Sanchan Stream

Interpreted from the sequential maps and imageries in the first half of the twentieth century (Source maps, see Table 6.2 – [1], [2], [6]), the lower reach of the Sanchan Stream (*SC Str*) was characterised by a single main channel, possibly bifurcated, on the active floodplains (map key: gravel ground, barren land and bush land), and a few scarps were noted on the historical map in 1920s and in 1960s (Fig. 6.2a, b). The northern scarp is seen to be coincident with the outer margin of the northern distributing channel on the aerial photo in the 1940s (Fig. 6.2b) and also with the 15-m contour line shown on the large-scale ortho maps in the 1970s. The scarp

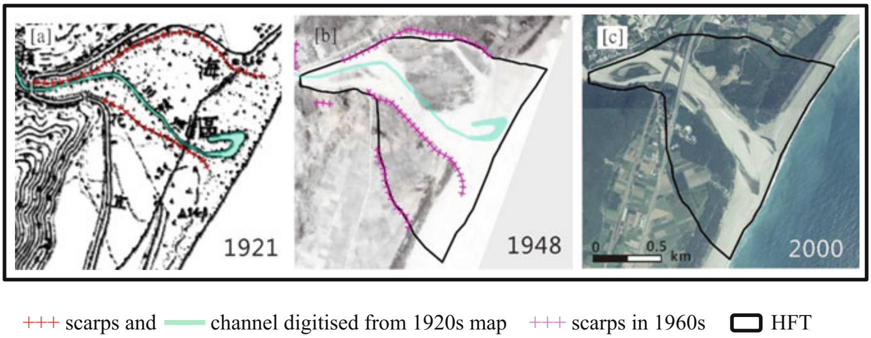


Fig. 6.2 Channel and landcover change shown by sequential maps and images of the lowest reach of the Sanchan Stream. Scarps noted on the historical map (**a**) coincide with the features shown on the aerial photo (**b**) and are preserved in tha landscape at present. The landcover change occurred mainly around mid-twentieth century and the delineated HFT is much wider than the current channel (**c**). The year that the background map/image was published or taken is indicated in the lower right of each figure

farther to the south of the main channel is coincident with the contour line of 15-m and is considered as the southern boundary of the HFT of this stream. Both are major scarps and can be traced in the field at present. As a result, the delineated HFT (Fig. 6.2c) is 150.84 ha in area with maximum width around 2 km. Landcover change within the *SC Str* HFT had begun by mid-1960s, as indicated by the upland fields shown on the source map (Table 6.2 – [6]), and gradually extended either side of the main channel (Table 6.2 – [3]). It is now protected by the levee system situated according to the 50-year return period, the regular design standard for county-administered streams in Taiwan.

6.4.1.2 Taimali Stream

The lower reach of the Taimali Stream (*TML Str*), which is located on an alluvial fan, was characterised by a multiple braided channel in the early twentieth century (Fig. 6.3a). The active channel zone occupied the entire valley floor although most of the time the stream discharge was probably low (Table 6.2 – [1], [2]). Based on the similar procedures as described in the method section and demonstrated for the *SC Str* above, the HFT of the *TML Str* is delineated along the major scarps, which are still preserved in the landscape (Fig. 6.3a). Its HFT is 523.65 ha in size with maximum width around 3 km (Fig. 6.3b). Cultivation may have started in early 1960s and almost all reclaimed lands have become paddy fields by mid 1970s along with levee construction (Table 6.2 – [6], [3]). At the same time, the channelised reach was transformed into a single braided channel, with significant narrowing of channel width to less than 0.5 km.

The levee system along the lower reaches of *TML Str* was constructed initially in accordance with a 25-year return period and has been reconstructed and lengthened with even higher standards in response to the severe typhoon disasters. It was built

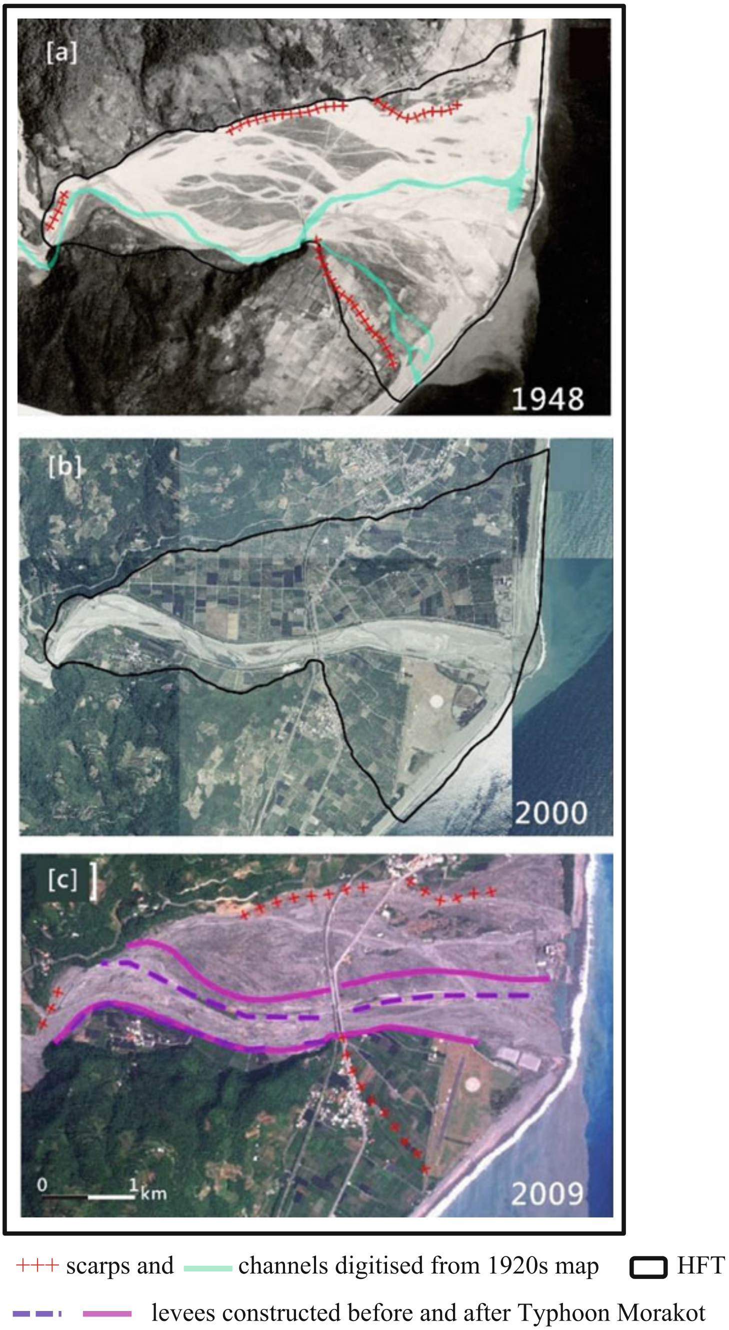
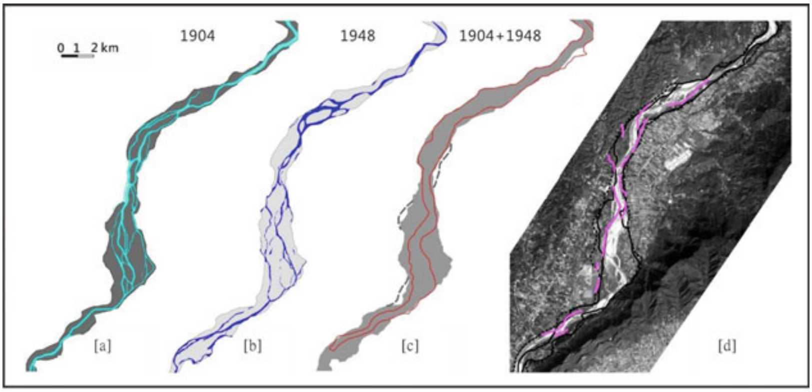


Fig. 6.3 Channel and landcover change shown by sequential maps and images of the lowest reach of the Taimali Stream. As shown in (**b**) and (**c**), significant landcover change, from channels and



■ □ ▨ ☐ HFT interpreted from different sources (the year indicated in the figures)

━ ━ channel systems identified from historical maps in 1904 and aerial photos in 1948, respectively.

━ inundated area of Typhoon Morakot-induced flood in 2009, identified from satellite image immediate after the event

╍ small scarps digitised from the topographical map in 1960s

━ levee system (pink line) constructed before Typhoon Morakot.

Fig. 6.4 Inundated area along the lower reach of the Chishan River during Typhoon Morakot in 2009 was found almost located within its histoical fluvial territory (HFT) (**c**), which were identified from historical maps in 1904 (**a**) and aerial photos in 1948 (**b**).
FORMOSAT-II satellite images in 2013 (*light grey* – constructed area, *dark grey* – vegetated area) show the major landcover type- farmland at present (**d**). It is also obvious that the confined channel system is much narrower than its HFT. The year that the delineation of the HFT based on is indicated

with a revised design standard according to a 50-year return period (Chang 2011), a requirement which is usually only applied to major rivers in Taiwan, after Typhoon Haitung in 2005 (dashed line in Fig. 6.3c). The levee, however, collapsed in 2009 due to the extremely high sediment-laden flash flood during Typhoon Morakot (NSTCDR 2010). The *TML Str* reclaimed the entire valley floor (c.a. 1.2 km) (Fig. 6.3c) as it existed half a century ago (Fig. 6.3a). The levee system was rebuilt again with the 50-year return period plus an additional 2.5 m allowance (WRA 2011) after Typhoon Morakot in 2009 (solid line in Fig. 6.3c).

6.4.1.3 Chishan River

Along the lowest 10 km segment of the valley, where the Chishan floodplain widens (Fig. 6.1c), well-developed braided channels can be easily identified (Fig. 6.4a).

◄

Fig. 6.3 (continued) bars into farmlands, occurred around mid-twentieth century. The delineated HFT is much wider than the current channel (**b**). The stream re-claimed the entire valley floor during the high sediment-laden flash flood induced by Typhoon Morakot and a new levee system with even higher standard has been constructed (**c**). The year that the background map/image was published or taken is indicated in the lower right of each figure

The *CS R* HFT (Fig. 6.4d) of approximately 1111.27 ha, is delineated based on the active channel zone shown on the historical map of 1904, the aerial photograph of 1948 (Fig. 6.4a, b) and the location of scarps shown on the historical maps of 1960 (Fig. 6.4c) (Table 6.2 – [2], [6]). Major landcover change in the HFT occurred between 1948 and 1985; around 63 % of the HFT area has been reclaimed (Weng et al. 2010). Along with the channelisation, the width of the active channel zone decreased but the braided pattern still remains (Fig. 6.4d).

The first stretch of levee along the *CS R* was constructed in 1932 (Chishan Township Office (2006)) and the levee system has been gradually upgraded, with a design standard of the 100-year return period (Fig. 6.4d). This levee system also failed during Typhoon Morakot in response to the 200-year flood peak triggered by its record-breaking rainfall (1856 mm during 72 h) and large quantity of sediment (16.15×10^9 m^3) output from widespread landslides and debris flows (NSTCDR 2010). The inundated area was confined to the HFT (Fig. 6.4c) (Weng et al. 2010).

6.4.1.4 Wu River

The multi-channel system with numerous distributaries, located on the *Wu* alluvial fan (Fig. 6.1d), is clearly shown on the historical maps (Table 6.2 – [1]) and those published in 1904 and 1916 (Fig. 6.5a–c). The *Wu R* HFT is defined mainly by the outer perimeter of the farmlands shown on the maps published in the early twentieth century, assuming that the active floodplain, which was subject to more frequent flooding events, would not be reclaimed when there was no flood defence structure. The delineated *Wu R* HFT (6231.29 ha) covers almost the entire fan (Fig. 6.5d) and more than half of the area was repeatedly inundated in the major flood events of 1912 and 1959 (Hsu 2013) (Fig. 6.5a, b).

The *Wu R* flood control project was carried out between 1931 and 1939 (Ku and Liao 2012), mainly for the alluvial fan reach, with a 50-year flood protection standard. As a result, this channel reach has been gradually transformed into a single braided channel. Its levee system has been maintained, lengthened and strengthened up to the 100-year standard after WWII by the Taiwan government. Because of its location close to the third largest city in the country (Taichung), both the diversity and intensity of landuse are much greater than in the other three HFTs under consideration.

In summary, land reclamation in the four selected active floodplains has directly resulted in landcover and channel morphology change over the twentieth century. Landcover change within the HFTs has seen a shift from fluvial-related units such as channels and bars, to cultivated land. The area of current channels, confined by artificial levees, is much smaller than the HFTs, delineated based on the fluvial-origin features interpreted from historical maps and aerial photos. Braided channels have adjusted predominantly through channel narrowing, as recorded elsewhere (e.g. in Italy, see Surian and Rinaldi 2003). Although heavily modified, most channels have retained the braided pattern because of the characteristic natural environments in Taiwan – steep relief, seasonally contrasting river discharge and abundant supply of coarse sediments.

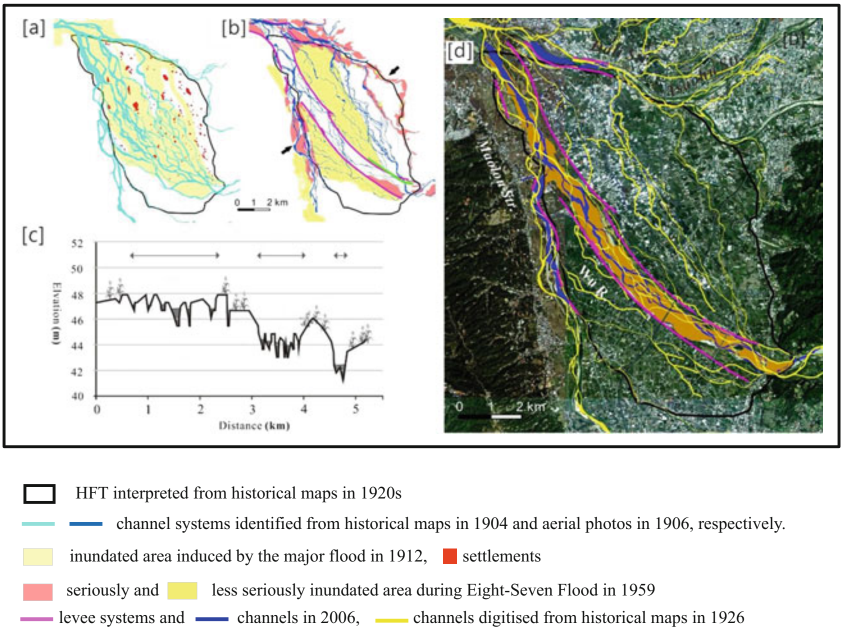


Fig. 6.5 Former distributary channel system and inundated area in the early twentieth century and current landcover on the Wu River fan
This fan reach suffered frequently from major floods before the levee was completed, e.g., in 1912 (**a**) and in 1959 (**b**). Cross section of the *Wu R* fan shows that the reach was characterised by three main channels in 1916 (**c**); the bottom of western channel was higher than the eastern ones and were subject to avulsion. Location of the cross section is noted with *arrows* in (**b**). The inundated areas by these major floods, however, occurred almost within the delineated HFT (*grey dashed line*). Diverse landcover types are shown by FORMOSAT-II satellite images in 2013 (*light grey* – constructed area, *dark green* – farmland, *darkest green* forestry area) (**d**). The contrast of current levee-confined channel and multi-braided pattern digitised from 1926 maps is significant.
Source: Figures (**a**), (**b**) and (**c**) is revised from Hsu 2013 Figs. 4.9, 4.10 and 2.13, respectively

6.4.2 *Recent Land Use Change*

Land reclaimed from active floodplains has always been dedicated to agricultural use and also classified as such in the land management system. Comparison of the first and the second National Land Use Surveys (NLUS), which were conducted in 1995 and from 2006 to 2008 respectively (NLSC 1995 and 2006), shows that agricultural land (Division-01) usually has the highest percentage of HFTs area with a slight decrease between the two surveys, except in the case of *SC Str* HFT (Table 6.3). Major change occurred varies between the two NLUSs in the four HFTs. In the *SC Str,* it is from agricultural land (D-01) to forestry (D-02) HFT, while in the HFT of *TML Str* the shift is from forestry (D-02) to ‘other’ (D-09). During this period land use in the *CS Str* HFT changed from agriculture (D-01) to hydrological land (D-04) and other (D-09) while in the HFT of *Wu R* the changes

Table 6.3 Percentage of land use division in 1995 and in 2006 in four selected streams

Division	01	02	03	04	05	06	07	08	09
SC-1995	34.76	11.54	3.00	28.25	0.85	0.00	0.00	6.15	15.45
SC-2006	6.74	36.58	3.63	31.07	1.45	0.00	2.59	1.75	16.19
TML-1995	50.42	14.18	3.10	22.22	1.06	0.00	0.00	0.20	8.80
TML-2006	48.07	2.77	2.67	24.64	1.51	2.08	0.00	1.29	16.99
CS-1995	63.81	3.69	1.07	25.21	0.74	0.00	0.00	0.26	5.22
CS-2006	48.72	2.57	1.52	36.13	0.76	0.00	0.00	0.33	9.97
Wu-1995	63.01	0.06	3.94	23.25	7.46	0.70	0.00	0.56	1.02
Wu-2006	56.00	1.24	7.98	13.57	12.76	2.96	0.13	0.34	5.02

01 agricultural land, *02* forestry land, *03* transportation land, *04* hydrological land, *05* construction land, *06* public land, *07* recreational land, *08* mine and salt industry land, and *09* others (0901-07: barren/grass/bush/beach land; 0908: vacant land and developing land)

involved hydrological land (D-04) and agricultural land (D-01) being converted to construction land (D-05), transportation (D-03) and other (D-09). The overall trend is an increase in landuse intensity (Table 6.3) in the HFTs. Examples from *SC Str* and *Wu* R HFT show how the landuse type can be transformed.

A patch of privately-owned industrial land in the northern part of the *SC Str* HFT has been transformed from agricultural land since 1970s (Figs. 6.2 and 6.6) via the ongoing policies of promoting industrial development, implemented by the Industrial Development Bureau of the Ministry of Economic Affairs, i.e., *Statute for the Encouragement of Investment* (1960–1991), *Statute for Upgrading Industries* (1990–2010) and *Statute for Industrial Innovation* (2010-) (Regional Planning Committee 2014). The original development permit was approved for the cement industry. Later, part of the land was developed for a marine biotechnology factory, and the developer is now applying for a permit to develop a tourist hotel for the other portion of the land (Eastlife Biotech 2014), which is located around 100 m from the levee with a design standard of 25-year return period.

Sometimes landuse change may occur in advance of the issuing of the required permit, or even without a permit at all. In the *Wu R* HFT, such change has occurred to the north of the current *Wu R* channel, where two-thirds of the area is the Special Agricultural District (SAD) between the *Wu R* and the *Dali Str* (Figs. 6.5d, 6D). The SAD is designated particularly to preserve the fertile arable lands and non-agricultural landuse can only be applied with special permit. According to Lin's (2013) field investigation, however, the area under agriculture decreased from 922.8 ha in 1991 to 727.7 ha in 2012, while the area of industrial use increased from 19.5 to 160.9 ha in the same period in this area.

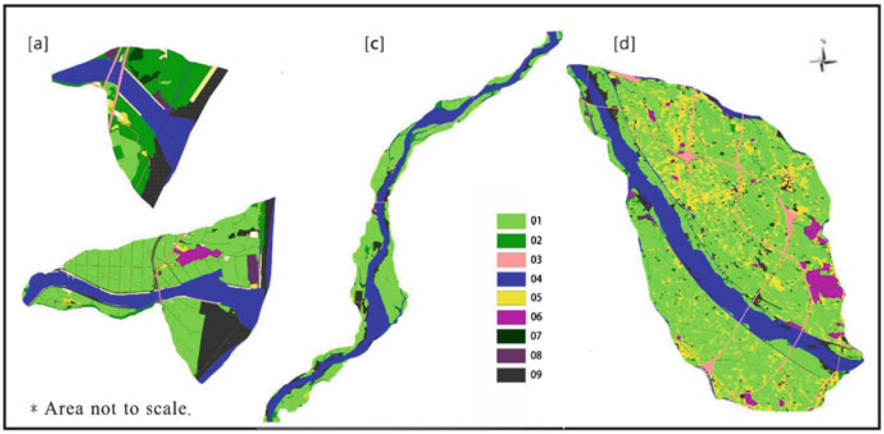


Fig. 6.6 Recent landuse condition in the HFT of four selected river reaches. (**a**) The lowest reach of the Sanchan Stream; (**b**) Taimali Stream; (**c**) the lowest reach of the Chishan River valley; (**d**) alluvial fan reach of the Wu River
Note: Land use classification scheme consists of nine first level divisions, which are in turn divided into 41 second-level classes and further 103 third-level sub-classes. The maps demonstrate the landuse in 103 sub-classes, however, the representing colors of nine first-level divisions in the legend are deliberately designated by the current authors to give an overall impression of the land use pattern in the study areas
1 Agricultural land. *2* Forestry land. *3* Transportation land. *4* Hydrological land. *5* Construction land. *6* Public land. *7* Recreational land. *8* Mine and salt industry land, and *9* Others (0901-07: barren/grass/bush/beach land; 0908: vacant land and developing land)
Source: The second National Land Use Investigation of Taiwan by National Land Surveying and Mapping Center, Ministry of the Interior. The project was executed from 2006 to 2008 based on aerial photogrammetry, field investigation and GIS. http://www.nlsc.gov.tw

6.5 Discussion

Reclaiming new land from the marginal lands, such as floodplains, has been practised around the world. In Taiwan, land reclamation along braided river channels has occurred during the twentieth century implemented by the authorities. The middle and lower segments of most river channels have been heavily engineered and channelised. Most of the land is still in agricultural use as it was originally dedicated. The tendency of increasing landuse intensity in HFTs in recent years, as shown in the *Wu R* and *SC Str* cases, has raised the flood hazard risk and should be carefully monitored. The extent of the flood-prone zone, from the geomorphic perspective, however, is usually invisible and ignored in the land suitability analysis in the application procedure of land development plan in Taiwan.

For ecological restoration purposes, Kondolf (2011, p. 36) argued ‘Given the advantages of the erodible corridor concept, why has the concept not been more widely applied?’ This question is also applicable to the flood mitigation issue in

Taiwan. Having suffered from severe natural disasters since 1990s and especially after the devastating impacts of Typhoon Morakot in 2009, the idea of 'working with nature' has been promoted in the national spatial development strategies (National Development Council 2010). Reinforcement of land use control and integrated flood management is now especially emphasized by the central government (e.g., WRPI 2012; Executive Yuen 2014). The role of land-use planning in flood management (as advocated by many international agencies, e.g., WMO 2007) seems nowadays to be well accepted at least by the government in Taiwan. However, Benito and Hudson's (2010, p.123) comments remain pertinent in that integrated flood management '…represents a paradigm shift in thinking, and is difficult for the river authority to abruptly change philosophical approaches, or expend the financial resources to replace existing flood control infrastructure.'

Land is one of the most valuable resources and commodities in Taiwan. Setting infrastructure back from the former active channel to give the river a zone in which to freely erode and deposit remains an immense challenge in the country. Even the implementation of land expropriated for public interest seems to have become more difficult. For example, front-line engineers encountered great difficulty to convince some farmers to give up their seriously damaged houses and high-risk lands which lay immediately along the current *TML Str* channel (Fig. 6.3c) (Chang 2011, WRA 2011 News release) when planning to rebuild the levees with a higher design standard (50-year return period plus an additional 2.5 m allowance) after Typhoon Morakot (WRA 2011). Such management actions are expensive and complex to implement, as indeed elsewhere in the world (e.g., Hudson and Middelkoop 2015).

The term '(fluvial-origin) reclaimed land' does indeed exist in the official sense in Taiwan, since most of the land reclamation projects have been conducted by the authorities. The term is defined, however, in a very narrow sense from the geomorphic viewpoint. 'Reclaimed land' defined by the land management agency refers to land created by the government's investment in hydrological engineering and has to be officially registered. According to current statistics, the area classified as such is only some 13,000 ha (WRA website). Land reclaimed during the Japanese occupation period and that which was reclaimed after WWII (but not yet registered) is probably excluded, such as the HFT of *Wu R*, which alone would represent half of this amount.

Under current laws and regulations, there has been strict control on land development in the flood-prone zones. However, they are defined in such a way that the areas referred to are much narrower than the zone that active floodplains once occupied in the early twentieth century. According to the Water Act and related legislation in Taiwan, land development is restricted in the 'river reservation zone' and in the 'first-class flood plain control zone', and is conditional in the 'second-class flood plain control zone'. The former mainly indicates the current narrow channel confined by levees; the latter has been only implemented for one river – the Tanshui River which crosses Metropolitan Taipei, the capital city. Lack of understanding of fluvial systems by the general public and decision makers is probably the first step that needs to be taken in addressing this inconsistency.

Geomorphic expression of the originally well-developed braided channels and wide active floodplains within this highly dynamic environmental setting is self-evident in Taiwan, as exemplified by the four selected streams in this study. Information conveyed in the abundant historical archives can be very useful with careful interpretation from a geomorphic viewpoint. Examples from *Wu R*, *CS R* and *TML Str* clearly demonstrate that inundated areas were almost all located within the HFTs, delineated in this work, during the most extreme flood events in the southern half of Taiwan over the course of a century, for example in the severe flooding in 1959 and during Typhoon Morakot in 2009 (Figs. 6.5b, 6.3c and 6.4c respectively). HFTs, based on the delineating procedure proposed here, can be regarded as the near-natural active floodplains when modern flood control technology was just introduced in Taiwan in the early twentieth century. It is strongly argued that proper land development should be strictly monitored not just in the officially defined ‘flood plain control zone’ or ‘reclaimed land’ but in the geomorphologically-sound delineated HFTs (historical fluvial territory) proposed by the current research.

6.6 Conclusion

In Taiwan, ongoing severe flood disasters caused by record-breaking high-intensity rainfall events since the mid-1990s have raised increasing concern over flooding issues on reclaimed active floodplains. With reference to four braided channel reaches, this chapter interpreted historical fluvial territories (HFTs) using a historical approach, verified by examples from *Wu R*, *CS R* and *TML Str*, and demonstrates that inundated areas were almost all located within the HFTs during the most extreme flood events over a century time span. In other words, the HFTs can be regarded as the near-natural active floodplains. The progress of channelisation and land reclamation has been closely related to land reclamation enterprises led by the authorities. It is also concluded that land use intensity has been increasing in the HFTs although most land is still in agricultural use as originally dedicated. Thus, for flood mitigation, it is strongly argued that a strategy of low impact development should be applied to the HFT, the former active floodplains, rather than the much more restricted area of ‘second-class flood plain control zone’ or ‘reclaimed land’ as defined by the current laws and regulations.

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Chapter 7
The Political Ecology of Land Subsidence: A Case Study of the Solar Energy-Farming Scheme, Pingtung County, Taiwan

Shew-Jiuan Su

Abstract Land subsidence in southwestern Taiwan has long been in focus as a result of its environmental and political implications. Much research has been conducted with a view to better understanding its causes and effects, but a political ecology perspective has thus far been lacking. Various policy and technological solutions are being pursued for preventing land subsidence but often the policy tools to prevent land subsidence are unable to be implemented as the interests of stakeholders vary. The solar energy-farming scheme, initiated by the Pingtung County government in 2009 following the devastation caused by Typhoon Morakot, is an illuminating case study in this regard. The scheme was established to convert low-lying land used for aquaculture into solar energy plants. The plan was not only expected to provide economic opportunities for the locals but also to prevent land subsidence. This study adopts a structural approach to analyze both natural and human elements in order to explore the problems of land subsidence. Utilizing findings from qualitative interviews, policies and documents, this paper offers a structural consideration of the political ecology of converting aquaculture to solar energy-farming in Pingtung County. The land subsidence of Pingtung may be considered a result of a convoluted system of political ecology and political economy. The solar energy plan case study casts light on how society in coastal areas of Taiwan can reverse land subsidence. Through the analysis of national policies and local actions in facing land subsidence, this chapter examines the political ecology of how the solar energy-farming scheme was established, and what this solution implies for socio-cultural, economic and environmental development.

Keywords Land subsidence • Environmental adaptation • Hazard mitigation • Political ecology • Solar energy-farming • Taiwan

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7.1 Introduction

Land subsidence is considered a form of environmental degradation induced by both natural causes and various human economic activities. Most studies concerning land subsidence tackle its causes, rate of development, measurement techniques, modeling, ecological consequences and possible remedies (e.g., Amelung et al. 1999; Fielding et al. 1998; Galloway et al. 1998; Hu et al. 2004; Massonnet et al. 1997). This type of scientific and utility-oriented research reinforces the study of land subsidence in a positivist and utilitarian way. However, in terms of making sense of social behaviours and how the social conceptualization of human-environment relations may contribute to, or counter, land subsidence, a deeper form of analysis is needed. The main aim of this study is to examine how an understanding of the socio-economic, cultural and political reality factors interact with physical environmental conditions and may contribute to a more comprehensive picture of land subsidence development. The chapter employs a case study of a solar energy-farming scheme in Pingtung County in order to understand the political ecology of land subsidence in the context of Taiwan. Subsidence of low-lying coastal land in southwest Taiwan has long been characterized by environmental politics that involve complex interactions between coastal land use, water resource allocation, the local economy and national economic policy. The stakeholders include landowners, land users, economic entities and enterprises, local and central government politicians and various government agencies. While the stakeholders are of central importance to an understanding of land subsidence, their motives may be facilitated or constrained by laws and policies and their implementation. Thus, policies and politics related to the coastal environment are also important considerations if land subsidence and its associated problems are to be addressed.

While land subsidence is a physical phenomenon, it is never exclusively natural, since it is an environmental process generated by gravity but influenced and even exacerbated by human activities (Galloway et al. 1999; Holzer et al. 1984; Niebling et al. 2014). Typhoon Morakot,[1] in August 2009, was a catastrophic event that subsequently led to a change in policy in the case of the Pingtung County. Morakot devastated the area's coastal regions to such an extent that the county government formulated a strategy to benefit the local socio-economy and to safeguard the coastal land, viz. the solar energy-farming scheme. The present study focuses on the response of Pingtung County to cope with land subsidence, a case study that yields a complex but revealing example of political ecology. This case study further demonstrates the integration of nature, historical water use, national economic policies, and even local interests in land resources. Land subsidence in Pingtung

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[1] Morakot is a Thai word meaning 'green jewel' and, in the context of this study, the event could be considered as the stimulus for Pingtung County to promulgate its solar energy-farming scheme to utilize abundant solar energy to change the fate of its low lying land.

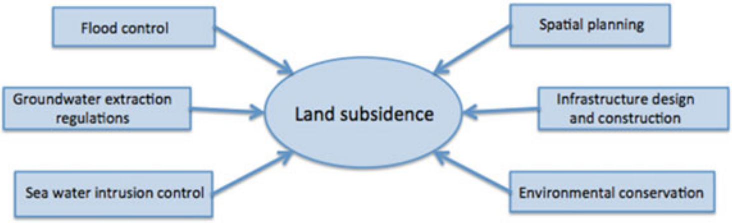

Fig. 7.1 Land subsidence information is related to various fields (Adapted from Abidin et al. 2010)

County may be considered a result of a convoluted and intertwined system of political ecology and political economy.

In order to effectively analyse the political ecology of land subsidence, various sources of information are required (Fig. 7.1, after Abidin et al. 2010). Various physical environmental factors related to geomorphology, groundwater and precipitation are important for understanding land subsidence. In relation to the socio-political and economic aspects of land subsidence, several other factors, including aquaculture development, water pumping and national and county policies are of significance. As the physical and societal elements may interact in complex ways, revealing the political ecology of land subsidence is difficult. The aim of this chapter is to clarify the relationship between land subsidence and society in order to develop a deeper understanding of the political ecology of the solar energy-farming scheme.

The issue of land subsidence in Taiwan has previously been approached mainly from a natural scientific and positivist perspective. The implications of the problem and its relevance for socio-cultural and political life are rarely discussed in academic studies. When technological modernization and economic growth are considered more important than any other human elements, ignorance of sustainable human-environment relations seems to become the norm. Dismissing how ordinary people and their lives are related to nature, how people contribute to the functioning or malfunctioning of environmental systems and even how the legal and political system may influence social perceptions of nature are worthy of examination. Taiwan society underwent a critical change in the late 1980s and 1990s following the lifting of national Martial Law in 1987. Martial Law controlled society's freedom of speech, press, rights to assembly, etc., meaning that progressive ideas and opinions were stifled. With the lifting of these constraints, many kinds of organizations mushroomed and some emerged with an interest in investigating environmental problems. Concerns relating to poor environmental management were expressed and focused on the lack of appropriate regulations and on existing regulations that were either piecemeal or not implemented adequately (Lin 1993). Many public and academic forums advocated the importance of both physical environmental and human elements to be dealt with simultaneously. For example, Hsu (1995) highlighted the groundwater problems that arose in relation to political and legislative issues caused by a combination of various factors, including the low status of the national Water Bureau, the paucity of appropriate scientific information about groundwater, the lack of conservation knowledge and the shortage of both funds and manpower (Fig. 7.2). Land subsidence can be viewed simplistically as a consequence of the over-extraction of groundwater, but other factors including policy actions and economic activities need to be taken into consideration and this makes it a much more complicated issue. The disconnect between physical scientists and social scientists in relation to their approaches to land subsidence is obvious and there appears to be no common platform to bring these different perspectives together. This chapter argues that solutions to land subsidence problems lie in holistic or trans-disciplinary endeavours. To conceptualize a more complete understanding of land subsidence, there needs to be an approach that is context-dependent. Space, time, society and nature all have to be accommodated to demonstrate how the physical environment and society are intertwined.

In this time of global change, the "Anthropocene" concept has been introduced to define the most recent period of earth history when human activities have seemingly overwhelmed nature (Eckart and Krafft 2006; Steffen et al. 2007; Meadows, Chap. 2, this volume). The concept reflects the fact that human activities have significantly altered the earth system. Political ecology may well be an alternative approach to investigate the interaction of society and nature that has brought about the unsustainable environmental situation we face today. Swyngedouw (2007) has questioned whether real sustainability is possible without politicization of the environment. This means that the environment must be context-oriented, as regions, nations and even communities have varied politics. Blaikie (2008) went as far as to argue that environmental justice is impossible without political justice. Incorporating these various factors is a significant challenge, not least because trans-disciplinary research is often costly to researchers, so that a sound political ecology approach for understanding Taiwan's land subsidence has yet to be achieved. Exploring the political ecology of the solar energy-farming scheme of Pingtung County is therefore a demanding task for which the present study is a first step.

Several methods are employed in this chapter to achieve its aim. Through field observation of coastal land subsidence and interviews with local residents, the author attempts to conceptualize how land subsidence and the local population are interrelated. This concept frames the author's understanding of land subsidence and makes the political ecology approach essential for resolving its consequent problems. The field observation and field interviews were conducted during April–August 2014. In addition to an extensive literature review, Taiwan's national policies in relation to land subsidence, in particular water rights and economic policy, were also investigated. As land subsidence manifests as an environmental issue, trends in physical parameters such as rainfall and sunlight hours were also examined.

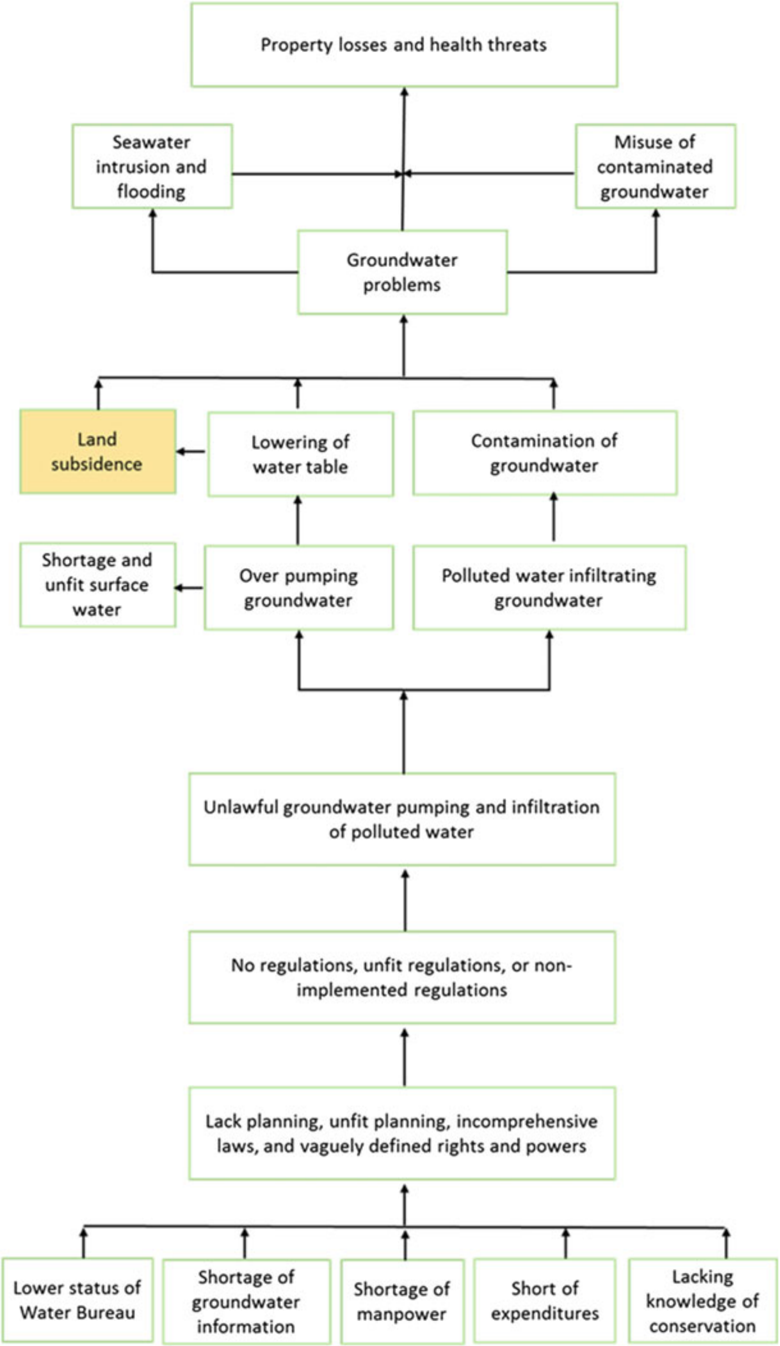

Fig. 7.2 A Taiwanese perspective on groundwater problems (After Hsu 1995)

7.2 A Political Ecology Perspective on Land Subsidence

7.2.1 Land Subsidence and Society

Land subsidence is a gradual or sudden sinking of the ground surface with respect to adjacent terrain or sea level (Galloway et al. 1999; Hu et al. 2004). Its causes may be natural, such as tectonic movement and sea level rise, or may be human-induced, such as through excessive pumping of groundwater, oil or gas, coal or ore extraction and underground tunnel excavation. Land subsidence may have costly or even disastrous consequences for society. Examples include seawater intrusion, salinization, ecological degradation and damage to transport infrastructure and buildings. Land subsidence occurs globally, but its impacts are most significant in densely populated and coastal areas. More than 150 major cities in the world face significant land subsidence (Hu et al. 2004). As excessive water pumping may often be the main cause, its consequences relate not only to the physical environment but also to society, including the economy, quality of life etc. The health of aquatic systems and terrestrial ecosystems is fundamental to the sound development of human settlements. Conserving and managing the fresh water supply is also important and land subsidence presents a significant challenge in this respect too. For example, more than 80 % of US land subsidence is a result of over-extraction of underground water and there is increasing human dependence on land and water resources that threatens to worsen existing land subsidence problems and initiate new ones (Galloway et al. 1999).

The mitigation of land subsidence has major economic and political implications (Phien-wej et al. 2006; Liao and Lin 2013). Groundwater management, expanding piping infrastructure, and enforcing pumping regulations may be costly in financial, ecological and political senses. In Taiwan's rural and agricultural areas, such effects have been evident and politics-ridden because of the historical context of water pumping and the political economy of water use in the country. Both political economy and political ecology are crucial for understanding water pumping and land subsidence. For example, in the late 1960s when the capital city of Taipei encountered land subsidence, investigations pointed to over-extraction of groundwater as the major cause. Discouraging water pumping and providing piped water thus became a priority during the 1970s–1980s. Only after 1987, when the Fei-tsui Dam was established to serve the Taipei metropolis, was groundwater pumping greatly reduced. The success in preventing Taipei land subsidence was partly due to abundant precipitation and the fact that regional geology and geomorphology facilitate the efficient infiltration of meteoric water into rock fissures. In retrospect, it was easy to solve the "illegal" water pumping, because the city was closely monitored by a strong authoritarian state. Even so, the complex issue of water rights was not adequately accounted for.

Fig. 7.3 A traditional house which has been consumed by land subsidence (Source: taken by author, Jia-tung Township, Pingtung County, July 2014)

7.2.2 A Brief Introduction to Taiwan's Land Subsidence

The southwest of Taiwan has been a hotspot for land subsidence and its impact on the environment for the past four decades has been substantial. The problem contributes to substandard housing and living quality (Fig. 7.3). While effective management interventions in the case of Taipei arguably led to the adoption of an over-simplistic approach, the issues of environmental justice, national economic policy, local interest, social risk and resilience etc. are all different in southwestern Taiwan and suggest a much more complex situation in comparison with the capital city.

Figure 7.4 shows the distribution of land subsidence as of 2005 highlighting that three counties are of particular concern, namely Changhua, Yunlin, and Pingtung; the situation remains broadly representative of the contemporary pattern. Hsu et al. (2014) highlighted how the coastal areas are especially impacted, notably Yunlin County, which witnessed the most severe subsidence over the last two decades as a consequence of groundwater extraction for aquaculture and agriculture. Over the past three decades, subsidence of almost 3 m has been recorded for several coastal counties (Liu et al. 2014).

In 2011 when serious subsidence on the Taiwan high-speed rail was identified, Yunlin County was again placed under the spotlight. Research has indicated that pumping of deep underground water (defined as water more than 200 m below the surface) is the major reason for this (Liu et al. 2014). The safety of the high-speed rail network is considered to be a strategic national concern so that the eradication of land subsidence in central Taiwan has become a priority. As a result, measures have already been taken to eradicate the problem in Yunlin. However, without high-speed rail tracks in Pingtung County, land subsidence in the Jia-tung and Lin-bian areas had to be addressed through other initiatives. In essence this explains why the solar energy development was funded by the county government in response to the devastation caused by typhoon Morakot. Clearly, there are various means by which land subsidence in Taiwan is dealt with, which may be an outcome of local, regional or national politics depending on circumstances.

The low-lying coastal areas of Pingtung County (Fig. 7.4) were overwhelmed during Typhoon Morakot in 2009. Traditionally, these areas were used for aquaculture, but households in Lien-bian and Jia-tung townships were also significantly damaged. The decision was taken to resolve the problem of land subsidence in the long term and Pingtung County proposed a solar energy-farming scheme to replace aquaculture as the main form of land use. The plan was made feasible due to favourable natural conditions and timing, since not only does the area receive long sunlight hours but the international price of solar cells was low at the time. The development seemed timely but there was also controversy around environmental justice in the area. The solar energy-farming scheme, which is locally known as 養水種電 "Yang-shui-chong-dian", meaning "cultivating water to produce electricity", is the first case nationally and internationally of deploying solar panels on subsiding and previously aqua-cultural land. Although solar energy has been promoted in Taiwan for more than two decades, the particular set of circumstances and combination of factors may be regarded as experimental and presents a case that is suitable to the analytical approach of political ecology.

7.2.3 Water Rights and Land Subsidence

The issue of water rights is complex and is approached from different perspectives of culture and power in different parts of the world (Bulloch and Darwish 1993; Donahue and Johnston 1998) but it is universally a manifestation of environmental

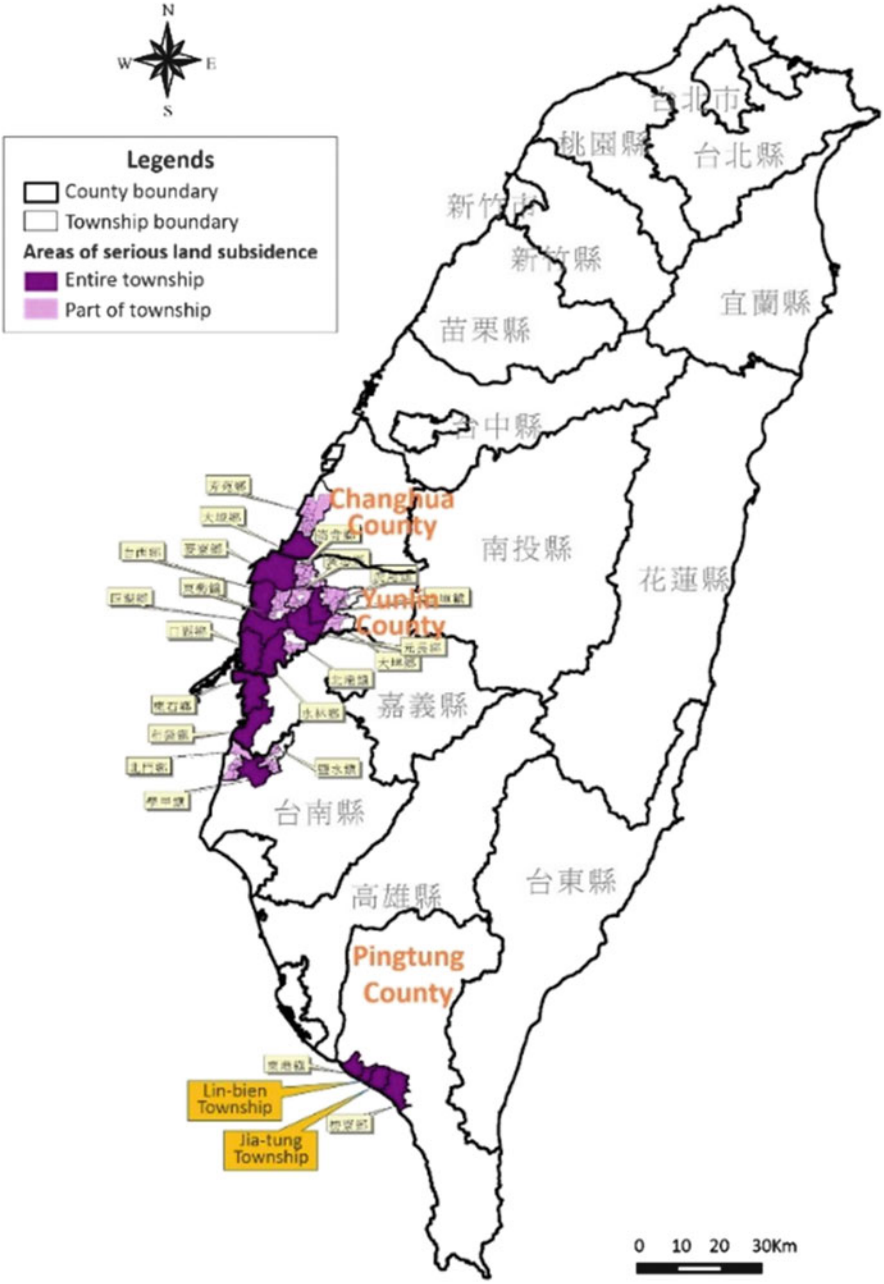

Fig. 7.4 Areas of land subsidence as defined by Council of Economic Affairs (2005)

politics and justice. Prior to the modern era of Taiwan, the Japanese colonial government[2] exploited the country for its agricultural produce, in particular rice and sugar cane. Access to water at this time was strictly controlled by a highly organized and efficient bureaucracy (Tu 1993; Higashi 1944). The Society of Water Utility for Agricultural Fields, as it was then known, was the principal authority in this respect. Following the establishment of the republic in 1949, the bureaucratic system was retained, although the responsible authority was renamed as the Department of Irrigation and Engineering. The Department assumed all the water rights established by the colonial government and, because agriculture was the most important economic activity, the Department was very powerful and even influenced election outcomes. Even today, provision of water rights in most rural areas are controlled by this authority (Lin 1998).

Taiwan's Water Act of 1963 was inherited from an earlier version established by the republican government in China. The Department of Irrigation and Engineering emerged as a massive state apparatus to implement the Water Act and became a highly influential political machine. Although the revised Water Act was promulgated to facilitate agriculture, water rights were not re-defined or delineated to suit the needs of Taiwan's changing society. Taiwanese society had gradually changed from the Japanese era and agricultural practice had evolved, but the enforcement mentality in relation to water rights was still in effect. Under Martial Law, with Taiwan's authoritarian state, water rights issues were never legally or economically re-considered to meet the demands of a changing society.

Due to the changing economy and national policy, the Water Act underwent several amendments but the fundamental nature of water rights has not really changed; national policies and priorities have continued to determine the approach. The economic policies of the state were given priority and water rights allocation followed accordingly. Civil society therefore developed a reactive attitude by which groundwater was extracted without permission, especially in places where the resource was abundant. Self-facilitated pumping stations were commonly seen in southwestern Taiwan. Even with the relaxation of Martial Law in 1987, water supply was "…subject to the approval of the central authority-in-charge" (Article 18, Water Act). This conditional statement clearly leaves room for political manipulation, although the order of priority is listed as: (1) domestic household use and public good use; (2) agricultural use; (3) hydro-power; (4) industrial use; (5) navigation; and (6) others. However, with the state's industrialist and capitalist mentality, industry has really been the top priority for water usage. The centralization of

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[2] Taiwan was colonized by the Japanese between 1895 and 1945. When World War II ended, Taiwan was taken over by the Republic of China under the supervision of the Allies of the World War II command (UN). Before that, the Japanese established a tightly controlled irrigation system for agriculture with a holistic bureaucratic management. The Society of Water Utilization for Agricultural Fields established local branches to police water use and agricultural order. This policing and practising of water rights was then assumed by the Taiwan Department of Irrigation and Engineering.

water rights underlies the reasons why coastal agricultural and aquacultural activities continue pumping groundwater without permits.[3]

Taiwan's legal framework and implementation of water rights has been inadequate for the past five decades (Lin 1998). With the government manipulation of water rights to favour industry, the Water Act is only partially implemented and is found wanting in relation to environmental justice. The general public, in this case the aquaculture farmers, choose to bypass water laws while cases of water disputes between county and central governments are also common. Examples include the pumping of groundwater and distribution of reservoir water for industrial development in Kaohsiung from the river catchments of Pingtung and Tainan Counties. Since this deprives landowners and land users of Pingtung and Tainan of water rights, it is not surprising that disputes between various actors across Kaohsiung, Tainan and Pingtung are ongoing (Chen 2001; Lam 2002; Lin 1998).

Taiwan's industries have been prioritized in respect of water rights in times of shortage (Chen 2001; Lam 2002). Nevertheless, when land subsidence was diagnosed as a consequence of groundwater pumping in the 1970s, it was politically conceptualized to be the result of pumping by agriculture and individual households. The misconception that agriculture is responsible for the heavy utilization of valuable water remains apparent today. Agriculture and aquaculture have effectively been made the scapegoats for land subsidence. The authorities (and the public) seem to forget that the development of agriculture and aquaculture along the coast was an important national policy from the late 1960s to 1980s in order to accelerate economic growth. Subsequently, in the late 1980s to early 1990s, many industrial parks were established along this marginal coastal land and aquaculture was also encouraged. However, the state's policy for developing coastal areas was essentially profit oriented and industry was more strongly supported and subsidized than agriculture. Rapid industrial investment by the state, county and even by individuals drove the economic boom of Taiwan. Many coastal areas were converted to industrial use. However, since land subsidence became prevalent and negative consequences became apparent, it was the farmers who became regarded as the culprits. As the prevalence of such perceptions took root, agriculture and aquaculture came under pressure, especially at times of water shortage and at locations of land subsidence. This has placed tremendous political pressure on counties such as Pingtung and Yunlin, where a high proportion of the population engages in agricultural and aquaculture. A thorough and critical review of water rights and land subsidence is clearly overdue (Lin 1993).

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[3] Electricity is required to enable groundwater to be pumped from these individual wells. Thus the well owners have to apply for a utility permit and the installation needs to be done by the utility company on site. However, the utility company has no cause to investigate what the electricity is used for and whether or not the applicant has the right to extract groundwater. So-called "illegal pumping" has thus becomes prevalent, while well owners claim they are acting within the law because they pay the electricity bills.

7.2.4 A Political Ecology Perspective on Land Subsidence

The allocation of water resources is critical to the political economy and ecological politics in Pingtung. The water issue is compounded by the fact that the industrial city of Kaohsiung is nearby as this spatial proximity aggravates the competition for water. As national policies led to the promotion of industry over agriculture, water rights conflicts between Kaohsiung and Pingtung became intense, especially during periods of water shortage. A case in point is the newly developed Great Tsao-jou Reservoir project (in Pingtung), which was established ostensibly to reduce the flood in hazard in coastal areas and to conserve the integrity of alluvial terraces. However, it is widely accepted that it was constructed mainly to support industry in Kaohsiung. Logically, the reservoir will reduce water supply to the alluvial plain and exacerbate land subsidence in the coastal areas of Pingtung. Land subsidence in coastal Pingtung county is clearly a complex and manifestly political issue.

The scapegoat status of agriculture and aquaculture in the southwestern counties did not really change until 2010 when the Taiwan High-speed Railway Company realized its predicament with respect to land subsidence in central Taiwan. The sinking ground in Changhua and Yunlin counties was seen to be jeopardizing the safety of high-speed trains. A comprehensive investigation was conducted by a national team of researchers and members of the Control Authority. Results indicated that land subsidence was migrating towards the high-speed rail tracks (Tu 2011) and that the rate of subsidence was far greater than expected. Land subsidence here is perhaps surprising because agricultural activities and water pumping in this area had in fact been reduced (Lin 2004). Further investigation indicated that pumping of shallow wells, mainly for agriculture and aquaculture, has minimal impact because groundwater recharge prevents subsidence. Deep wells, however, developed by the industrial sector are more likely the source of the problem, as rainwater does not easily reach such depths. This perspective on well depth and water infiltration casts new light on the land subsidence problem. Water extraction by industry and schools[4] are bought into the picture as processes that will need to be considered if land subsidence is to be addressed comprehensively.

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[4] Findings have indicated that primary and middle schools along the high-speed rail track may be held partially responsible for land subsidence. This points to the Ministry of Education's policy that encourages schools to obtain water via wells, rather than tap water, in order to become 'green campuses'. Unfortunately most schools dug deep wells that inadvertantly contributed to the problem of land subsidence.

7.3 Solar Energy-Farming as a Strategy to Mitigate Typhoon Hazards

7.3.1 Natural Environmental and Social Background to Land Subsidence in Pingtung County

Land subsidence in the coastal area of Pingtung became apparent in the early 1970s, when freshwater clams and eels were in high demand in the international market. Pingtung is highly suitable for aquaculture due to the abundance of groundwater in the Lin-bian River catchment (Yang 1997). Many households established artesian wells in backyards and pumped water for both agricultural and aquacultural activities, although this was driven to some degree by water rights inequity as argued above. In the 1980s, when land subsidence emerged as a significant environmental problem that required national policy changes, the method of semi-salt water aquaculture was introduced to reduce pumping (Lin 2004) and even international market conditions appear to have contributed to this adjustment. Water pipelines were constructed linking the aquaculture fields with sea water pipes (Fig. 7.5). The policy to encourage the use of seawater was based on two unverified assumptions. Firstly, it was argued that groundwater extraction by aquacultural farmers was the

Fig. 7.5 Water pipes conveying seawater into aqua farms (Source: taken by author, Jia-tung Township, Pingtung County, July 2014)

major reason for land subsidence in the area. Secondly, it was assumed that replacing underground freshwater extraction with seawater would slow down and even stop land subsidence. However, for the farmers themselves this meant adopting a new technology, with requirements to invest more, to learn new skills etc; the farmers appear to have endured these costs silently.

As a result of the high water table, abundant underground water and artesian wells, the percentage of tap water provision has always been relatively low in Pingtung County. Less than 50 % of households in Pingtung are connected to a direct tap water supply provided by the utility company (Table 7.1). This again points to the lack of properly implemented water rights here, since the national average is 92 %. The low rate of water provision in Pingtung County has historical, economic, political and even ecological roots. First of all, the once state-owned utility company neglected to provide the necessary pipe infrastructure for Pingtung and so the county people developed their own water pumping system. Even to this day, the elected county government would debate whether direct water provision should be regarded as a priority and much of the population prefers to use spring water or groundwater that they consider to be of better quality than purified tap water. Consequently, the county government has remained indecisive regarding the direct provision of water (Su 2008).

Aquaculture in Pingtung is favoured by its regional climate. Hung-chun, the nearest weather station to the study area, is estimated to have 2234 h of sunlight annually (Table 7.2), compared to the national average of 1729 sunlight hours. This climate is an obvious boost to solar energy but also reduces aquaculture costs because cold fronts and low temperature conditions are rare here, thus facilitating greater productivity. Such a situation is clearly favourable also in terms of generating solar power. Extreme events such as typhoons have a strong influence on society's perception of nature in Taiwan. The most severe example of this in recent times, Typhoon Morakot (August 2009), in due course generated a politically and environmentally controversial initiative to change landuse in the low-lying land of

Table 7.1 Water-served population, selected cities and counties of Taiwan: 2013

County	Total population	Population covered by tap water provision	Population utilizing tap water provision	% of water-served population
National	**23,373,517**	**22,742,956**	**21,721,711**	**92.93** %
New Taipei City	3,954,929	3,937,515	3,855,380	97.48 %
Taipei City	2,686,516	2,686,516	2,679,598	99.74 %
Taichung City	2,701,661	2,631,447	2,525,924	93.50 %
Tainan City	1,883,208	1,883,208	1,863,482	98.95 %
Kaohsiung City	2,779,877	2,735,130	2,654,361	95.48 %
Changhua County	1,296,013	1,278,767	1,203,715	92.88 %
Yunlin County	707,792	707,307	665,701	94.05 %
Pingtung County	**852,286**	**574,482**	**399,596**	**46.89** %

Source: The Water Bureau, Affairs of Economic Council, the Executive Yuan of Taiwan 2015

Table 7.2 Sunlight hours of selected areas, Taiwan 1981–2010

Site	National average	Taipei	Taichung	Kaohsiung	Mountain Jade	Sun Moon Lake	Hung-chun
Hour	1729	1405	2043	2212	2008	1646	2234

Source of Data: Central Weather Bureau, Taiwan 2015
Unit: hour

Table 7.3 Highest recorded rainfall during Typhoon Morakot, August 6–10, 2009

National ranking	Precipitation (mm)	Station name	Station code	Township site
1	3004.5	Mt. Ali	46753	A-li-san Township, Chia-yi County
2	2908.5	Mt. Wei-liao	C0R10	San-di-men Township, Pingtung County

Source: Central Weather Bureau, Taiwan 2010

Jia-tung and Lin-bian. Rainfall exceeding 3000 mm (Table 7.3) fell over three days in the upper catchment of the Lin-bian River. The extreme discharge and debris flows significantly impacted these lower lying lands and persuaded the county magistrate to initiate a scheme to attempt to resolve problems related to land subsidence in such areas (see below).

While the natural characteristics of the region are crucial to socio-economic development and the evolution of the land subsidence problem of Lin-bian and Jia-tung, the issue is very complex and, indeed, contested. It is too simplistic to be dealt with effectively by any single authority. The lack of discussion and debate in the public arena is perhaps a symbol of the lack of political will and managerial skill to address this cryptic problem.

7.3.2 *The Solar Energy Plan as a Land Use for the Lowlands of Lin-Bian and Jia-tung*

The county government of Pingtung, in responding to Morakot, called upon an expert team to promulgate a solution to land subsidence. The team suggested a solar energy-farming development as a "...green alternative to support the local economy and to improve the quality of life"[5] (Liberty Time Net, 20 Feb 2011). This plan was aimed at promoting sustainable development of the area but was also politically astute because central government was promoting the reduction of carbon emissions and the development of green energy alternatives to fossil fuel. Thus, the

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[5] According to the Taiwan national policy hazards relief, alternatives for better use of impacted land are: (1) urban forestry, (2) artificial reservoirs (i.e., impoundments or lakes), (3) refilling with soil and debris, (4) land leased out to those willing to develop other environmentally sound options, and (5) solar energy.

solar energy plan gained the support of the Council for Economic Affairs, which is the central agency for developing green energy. Although a plan of this magnitude required a formal environmental impact assessment (EIA), the central official bureaucracy pushed this through even though the participating energy companies were not thoroughly scrutinized as to their technical and managerial skills in relation to the solar energy scheme. By the end of 2013, Lin-bian and Jia-tung townships had 70 ha of solar energy-farming sites established on the low-lying coastal land and were already producing 25 MW of power (Figs. 7.6 and 7.7; Table 7.4).

A county platform to facilitate the negotiation between the energy companies and the victims of the Morakot flooding (i.e., the aquaculture farmers) was established (Fig. 7.8). The procedure was thought likely to be complex and slow but was in fact very hastily implemented; zoning codes were changed summarily and a comprehensive EIA was avoided. This example is an illustration of Taiwan's hazard politics since, in the case of an extreme event such as Morakot, political pressure from both national and local sources produces linear but possibly over-simplistic or 'knee-jerk' responses, albeit well-intended. Inconsistent governance and decisions, which are partial or not based on a full consideration of the facts, or which are unlawful, may ultimately have detrimental effects and herald further problems in the future.

Since the solar energy-farming scheme was put forward by a decision-maker, the Pingtung County Magistrate, who happens to be both a native son of the county and

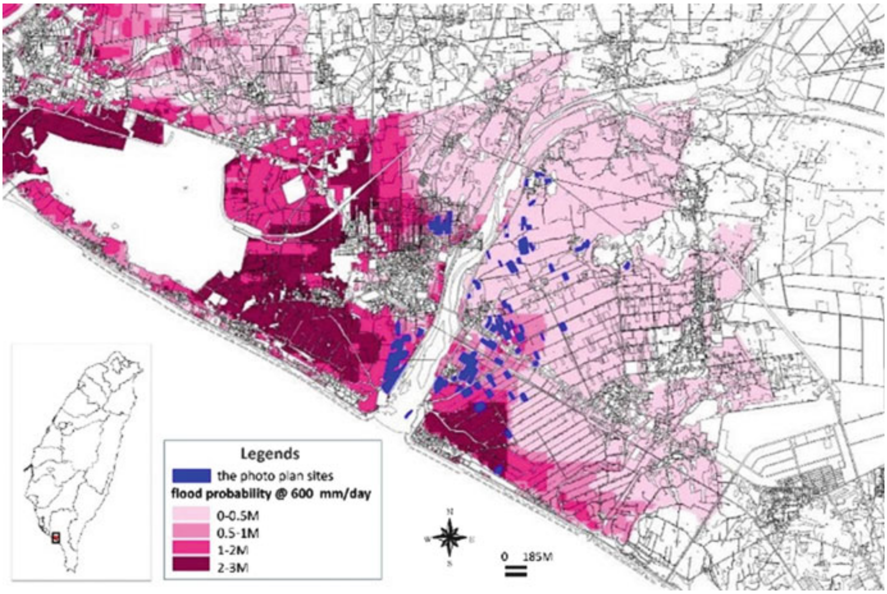

Fig. 7.6 Solar energy farming sites and flood probability of Lin-bian and Jia-lung Townships (Source: Redrawn from the map of the Water Bureau and Pingtung County Government)

Fig. 7.7 A view of the solar energy farming plant in Jia-tung township (Source: taken by the author July 2014)

Table 7.4 Characteristics of solar energy farming sites in Pingtung, 2013

Area for solar energy-production	Max. capacity (MW)[a]	Area (hectare)
Lin-bian township	**13**	**24.2**
Wen-an	5	10.4
Kuang-lin	5	8.7
Cheng-lin	3	5.1
Jia-tung township	**12**	**20.4**
Hsin-pu	5	8.1
Jia-her	5	9
Wen-fong	2	3.3
Total	**25**	**44.6**

Source: Pingtung County Government 2013

[a] Maximum capacity denotes million watts produced

a strong green energy advocate, (and whose party is in opposition to the majority party in central government) it can be seen that hazard politics deploy on both sides. However, as the solar energy-farming scheme is designed both for green energy and coastal security, factors which are concordant with national policy, the central government offered its support. The national policy to reduce carbon emissions

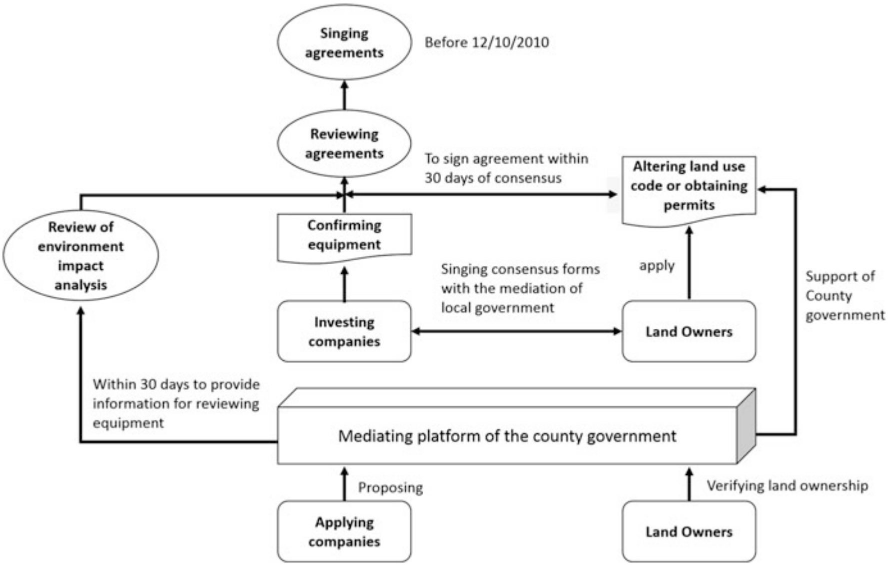

Fig. 7.8 Procedures to match energy companies and landowners (aqua-farmers) (Source: Drawn by author, based on graphs of Pingtung County Government 2010)

acted in concert with the perceived need to reinforce the hazard politics. These coincidences of a political nature contributed to the rapid approval and development of the solar energy-farming scheme without any comprehensive or careful evaluation of its possible long-term socio-economic and ecological impacts. While the wider effects of the plan remain to be seen, an environmental triumph for the area, temporarily at least, seems at face value to have been achieved.

7.3.3 The Solar Energy Plan in Perspective: Costs and Benefits

Water rights, land subsidence, seawater intrusion, salinization, environmental degradation, water resource allocation, land use and private wells all influence costs and benefits in a solar energy scheme of this sort. The problems associated with these issues need to be determined by examining the various advantages and disadvantages. In the case of the Pingtung solar energy-farming scheme, an additional important financial consideration relates to the advancement in solar cell technology and its changing costs. The evolving political climate certainly influenced the situation too. In 2000, when the leader of the opposition party was elected President of the country, President Chen in his inaugural speech defined a new era for sustainable development in Taiwan with the slogan ‘Green Silicon

Island State' and in which the island was envisaged to have a knowledge economy, sustainable environment and a just society. He emphasized the significance of balancing ecological conservation and economic development. Consequently, the development of energy efficient technology and the mitigation of environmental problems were considered national priorities. Accordingly, because of this policy support, environmental technology advancements were pursued and the use of solar energy started to take roots in society.

The utilization of solar energy has a global context as well. After the 2008 global financial crisis, many countries tried to revitalize their economy with green energy and Taiwan was among the pursuers. Green energy was aimed at bringing environmental benefits by reducing carbon emissions and in assisting the national economy by reducing the country's reliance on imported petroleum and increasing employment opportunities. Due to various factors, including the overproduction of solar cells, changes in the European economy debt and the mining of US shale gas, the prices of solar cells and related equipment declined from 2010 until well into 2014 (Shih 2012; Chen 2013a, b). By the end of 2007, the Taiwan Energy Bureau recorded that 410,000 households nationally were equipped with solar energy technology amounting to some 1.68 million square meters of solar panels and the southern counties were leading the way. By 2011, the adoption of solar energy exceeded 500,000 households and solar panels increased to 2.04 million square meters, amounting to 6.63 % of Taiwan's households (Taiwan Energy Bureau 2012). With the Renewable Energy Act, more southern counties put forward incentives to encourage using solar energy.

The solar energy-farming scheme proposed by Pingtung County was provided with significant levels of support from the Energy Bureau, the Council for Economic Affairs, and Taiwan Power Company (hereafter TaiPower). In addition to highly favourable feed-in tariffs, the construction of the solar panels was subsidized by the Council, the rationale being that the subsidies could relieve local distress and in turn mitigate land subsidence. Four private energy companies were solicited and completed the bidding procedure to implement the solar energy-farming scheme on site. There were certainly advantages for the private energy companies. According to Shih (2012), the regular net return of producing solar energy to feed in TaiPower could be as high as 7–10 % yearly. With the clearance of land made available by the county and landowners coupled with additional subsidy provided by central government, the net returns from this initiative are expected to grow further. Other advantages have ensued, for example, the landowners lease out their low-lying land to the energy companies and are also employed to maintain the solar panels at a minimum wage.

However, the situation poses a number of political economy questions, in particular: Why do landowners provide the land at such a low price to energy companies? What are the reasons underlying the provision of cheap labour for the energy company on site? What factors determine the proportion of land that each farmer leases out and what happens to the remainder? Will there be hazardous materials left on the land? Given the county government role in mediating the relationship between the energy companies and farmers, whose interests does it serve? All these are legitimate questions in respect of sustainable development of the area in the longer term. However, because no comprehensive EIA was conducted for the solar energy-farming scheme, they remain unanswered. Nevertheless, without a legitimate EIA, without proper consideration of the landowners' rights, without evaluating the technology used for the low-lying land, the solar energy plan remains a risk factor for the local community. Also remaining to be seen is the socio-economic resilience of the solar farming landowners and the local community.

All major role players including central and local governments, private energy companies and landowners may well regard the Pingtung County solar scheme as economically and ecologically beneficial for the time being. In promoting the plan, the county magistrate sought at once to safeguard low-lying land, to relieve the locals of an economic bottleneck, and to advance renewable energy industry (Liberty Times 2011.1.28, A 14). While these aims may well be far-sighted and noble, the scheme is still in an experimental stage. Government incentives have important implications and possibly unintended consequences that need to be explored. Environmental and social justice has to be demonstrated. In order to effectively develop synergy between the mitigation of flood hazard and environmental and socio-economic sustainability, the political ecology of land subsidence and its solution will have to be more comprehensively considered.

7.4 Concluding Remarks: The Political Ecology of Land Subsidence

Land subsidence is a geohazard with its roots in geomorphology and hydrology and with huge social, economic, political and even cultural implications. This complex cocktail of issues comprises three key elements, i.e., space, time and society operating at a range of scales. Considering the linkages between all three elements and their interactions is necessary to shed light on the political ecology of land subsidence. In the case of Pingtung County, there was convergence of timing that resulted in particular actions by the authorities. For example, the timing of the typhoon, the development of a national renewable energy policy, and even the timing of solar cell price reductions all interacted to play a role in decision making (Yang 2014).

Finally, in relation to the social-political aspects of land subsidence, various contextual issues are important, including the relationship between small and larger landowners, the local economy especially in relation to aquaculture, and national coastal land policy. In incorporating all of these elements in the analysis, it is argued that a political ecology approach opens up the possibility to better understand the relationship between nature and society (Neumann 2005; Robbins 2004; Watts 2000), although it is of course specific to each case (Swyngedouw 2007). It is clear that political ecology deals with power relations, structural elements and agency perspectives in order to develop a complete picture of land subsidence. In this case the attitudes and values of stakeholders have yet to be fully explored and this will be essential if a more comprehensive picture of the situation is to be revealed and for environmental justice to be achieved.

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Chapter 8
Towards Long-Lasting Disaster Mitigation Following a Mega-landslide: High-Definition Topographic Measurements of Sediment Production by Debris Flows in a Steep Headwater Channel

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Abstract Mega-landslides usually cause long-lasting subsequent sediment production, and long-term strategies for disaster mitigation are necessary in the case of such extreme events. The Ohya-kuzure landslide in central Japan is typical of sites where hillslope erosion and sediment yield have been continuously active since its formation in 1707. Sediment production is particularly active by debris flows in the headwater channels formed within the landslide. However, the dynamics of such debris flows in steep headwater channels have not been fully examined compared to those in gentler downstream reaches. To investigate the changes in headwater channel bed sediments remobilized mainly by frequent debris flows, repeated high-resolution measurements were carried out using terrestrial laser scanning. Freeze-thaw weathering in the surrounding slopes, which are composed of deformed shale and sandstone layers, delivers quantities of small particles onto the valley floor. Measurements in spring, summer, and autumn conducted over two years provided high-definition (0.1 m resolution) topographic datasets, revealing the seasonal amount of erosion and deposition to be on the order of 1000–5000 m^3. Erosion and deposition along the reach also showed contrasting spatial patterns according to the sections bounded by knickpoints and valley narrows. These basic estimates of sediment production in headwater channels can be utilized for further mitigation of possible sediment-related disasters in downstream areas.

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8.1 Introduction

Compared to small- to medium-sized mass movement features, mega-landslides ($>10^7$ m^3) caused by episodic triggers, such as extreme rainfall events and earthquakes, are relatively rare in human history (Keefer 1999; Korup et al. 2007; Korup 2012). Clearly such events are extremely hazardous at the time of their occurrence. Moreover, mega-landslides are potentially hazardous for a long time subsequent to their initial formation, due to continuous sediment yield that produces significant ongoing hazards downstream, impacting settlements and infrastructure along the river over distances far beyond the original slope failure location. Long-term strategies for disaster mitigation are therefore necessary in the case of such extreme events. However, the nature of sediment delivery by debris flows in unstable steep terrains after mega-landslides has not been fully examined. Lake sediments can record such historical sediment yields from upstream landslides over hundreds to thousands of years (Trustrum et al. 1999), although such an ideal situation is not always available particularly in urbanized areas.

The Ohya-kuzure landslide in central Japan is typical of landslide sites; in this case, erosion of hillslopes and sediment yield have been continuously active since its formation, about three centuries ago (Fig. 8.1). The earthquake-induced landslide is located in the uppermost region of a tributary of the Abe-kawa River, and the main channel was filled with abundant sediment immediately after the occurrence of the landslide. This caused significant hazards in the area, whereby channel avulsion caused a new course of the main stream to form a waterfall, and dammed lakes were reportedly formed (Fig. 8.1). After some time, incision into this sediment resulted in fill terraces along the main stream at heights of tens of meters above the channel bed. Even after centuries, sediment transportation remains active due to debris flows in headwater channels in the landslide (Tsuchiya and Imaizumi 2010). Very considerable erosion control efforts, known as “sabo” work (Ministry of Construction 1988), have been applied to the landslide area to stabilize the slopes and to prevent damage by debris flows (Fig. 8.2).

However, the physical dynamics of such debris flows in steep headwater channels have not fully been examined compared to those in gentler downstream reaches, partly due to limited access to such remote areas. Acquiring detailed data of topographic changes is one of the challenging issues for the study of debris flows in steep headwater channels. Even basic estimates of sediment production volumes, which are crucial for mitigation of possible sediment-induced disasters in the downstream areas, are difficult to obtain. Remote sensing approaches, such as aerial photography and laser scanning, are more efficient methods of performing such measurements (Imaizumi et al. 2005, 2006; Higuchi et al. 2012). However, both spatial and temporal resolutions are often insufficient to precisely capture the

Fig. 8.1 An old pictorial map showing the Ohya-kuzure landslide triggered by the Hoei earthquake in 1707. This map was drawn in 1863, and the changes in the location of villages and roads, as well as newer landslides after the Ohya-kuzure landslide are shown

frequent changes in topography by recurring debris flows. Terrestrial laser scanning (TLS) is one of the most efficient approaches to measuring topographic changes in steep channels and landslides (e.g., Rowlands et al. 2003; Teza et al. 2007). In this study, TLS was utilized for repeated measurements of valley-bottom deposits to investigate the changes in headwater channel bed sediments remobilized mainly by frequent debris flows. The measurements revealed basic estimates of sediment production and detailed spatial and temporal patterns of the valley bottom sediment in the headwater channel.

Fig. 8.2 Artificial check dams in the Ohya-kuzure landslide along a tributary of the upper Abe-kawa River. Quite many dams have been constructed for “sabo” erosion control work in this area. The entire photograph shows a part of the area of the Ohya-kuzure landslide terrain, and the study site, the Ichino-sawa catchment, is shown in the central left of the photograph

8.2 The Ohya-Kuzure Landslide Site

The Ohya-kuzure landslide is located in the upstream part of the Abe-kawa River watershed (Fig. 8.3). The landslide is one of the largest non-volcanic landslides in Japan, having an area of 1.8 km^2 and an estimated volume of 1.2×10^8 m^3 (Imaizumi et al. 2006). The landslide was triggered by an intense earthquake in 1707, the Hoei Earthquake, which had an estimated magnitude of M8–9 (Ishikawa 2011). Subsequently, the unstable landslide terrain has been one of the most active debris flow areas in Japan (Imaizumi et al. 2005, 2006).

The specific area selected for the TLS measurement is a midstream portion of a small headwater catchment named Ichinosawa (area: 0.22 km^2, channel length: 650 m) located in the north-central part of the Ohya-kuzure landslide (Figs. 8.2 and 8.3). This headwater catchment typically has a slope angle of 40–50°, which is greater than the angle of repose of the sediments. Hence, rock fragments from the hillslope bedrock, composed of a well-deformed accretionary complex including shale and sandstone of early Eocene to early Miocene age (Sugiyama and AIST 2010), readily reach the valley bottom forming talus deposits. Together with large quantities of gravel, boulders over several meters in diameter often accumulate in the steep – mostly over 30° – channel bed. Some surface water runoff regularly occurs but most of the water passes through the thick sediments as underground

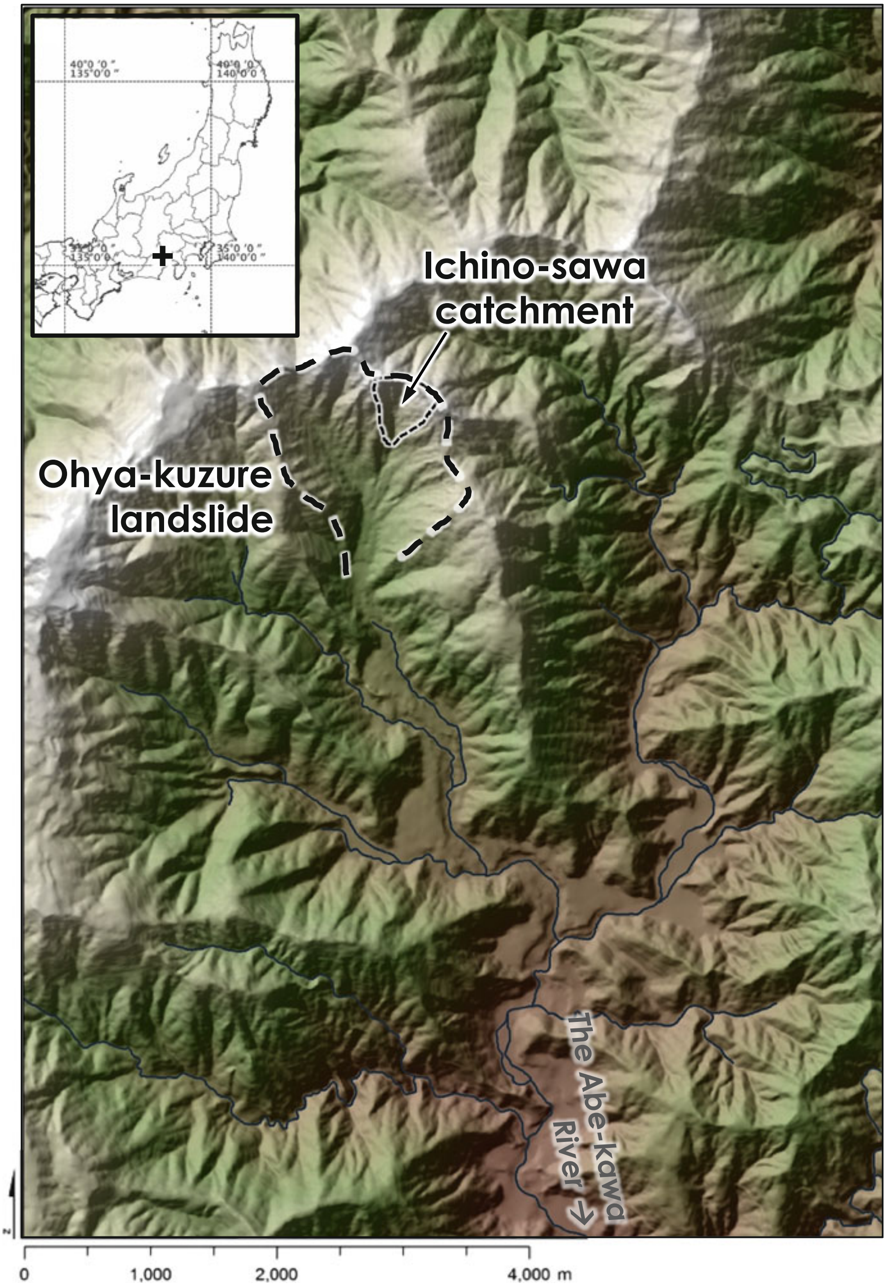


Fig. 8.3 Topography around the Ohya-kuzure landslide, the background hillshade image is derived from a 10-m DEM provided by Hokkaido-Chizu Co.

flow. Due to the frequent disturbance of the steep bedrock slopes, vegetation cover is limited and the slopes are bare rock surfaces.

The annual precipitation in the study area is ca. 3400 mm. Rainfall is seasonal and occurs mainly in the wet season from June to October, when the effects of cold fronts and typhoons are active; precipitation from December to February accounts for just 10 % of annual totals (Imaizumi et al. 2006). The catchment was significantly scoured during the summer of 2011 and the amount of valley-bottom sediment was observed to be the smallest in the last decade. November 2011 was therefore the appropriate time for the commencement of continuous field measurement.

8.3 Methods

A GLS-1500 terrestrial laser scanner by Topcon Co., Japan (Fig. 8.4) was used for the measurements of the valley floor. The maximum measurable range of the scanner is 500 m (for target objects with a 90 % reflectance), with accuracies of 4 mm in distance (at 150 m range) and 6″ of angle. The minimum point spacing is 1 mm at 20 m distance; the spot diameter of the laser is approximately 16 mm at a distance of 100 m. Because an infrared laser with a wavelength of 1535 nm was used in the device, the laser scanning was inapplicable to water and wet materials. Atmospheric conditions, particularly moisture and fog, also strongly affect the capability of laser scanning. Measurement speed is up to 30,000 points per second, while the time for one scanning operation at a given position, including setup, object scanning, target marker measurement and photograph (RGB colour) capture, was approximately 40–80 min. The body weight of the device is 16 kg (without batteries), and the total weight including other necessary items (battery, tripod, operation computer, targets etc.) is 40–50 kg.

Beginning in November 2011, field measurements were carried out in spring (May), summer (August), and autumn (November) for 2 years (Table 8.1). The time series of TLS data obtained during a total of seven seasons were labelled as: 1111, 1205, 1208, 1211, 1305, 1308, and 1311, where each number shows the year in two digit form followed by the month.

For each measurement, the scanner was set at two positions, on the downstream and upstream sides of the target area (Fig. 8.5). The scan position on the downstream side was located on a bedrock slope, where the land has been relatively stable for many years. Some other monitoring equipment including a rain gauge and video cameras were also installed around this point. Because the stable area for placing the scanner is limited, the locational variation in the downstream scan position was relatively low each time (several meters of differences). In contrast, the location of the upstream-side scan position varied more, because it was set in the valley bottom where the surface morphology is very dynamic. There was therefore no fixed stable location for the scan position on the upstream side.

Fig. 8.4 Terrestrial laser scanner used in this study, GLS-1500 by Topcon Co.

Table 8.1 Conditions of the study site for each time of scanning

Number	Name	Date of survey	Sediment situation	Debris flow
1	1111	Nov-22-2011	Poor	–
2	1205	May-14-2012	Rich	–
3	1208	Aug-23-2012	Poor	Occurred
4	1211	Nov-21-2012	Very poor	Occurred
5	1305	May-10-2013	Rich	–
6	1308	Aug-16-2013	Still remains	–
7	1311	Nov-19-2013	Poor	Occurred

In order to perform registration of the point clouds, measured from different scan positions, at least five reference targets (markers with a special reflectance pattern for GLS-1500) were placed in the study area. The two point clouds obtained from the upstream and downstream scan positions were registered by the target matching (tie-point) method using these multiple reference targets. In addition, two further targets were set for georeferencing, i.e., registration onto geographic coordinates. Because the scanner was set with strict horizontal constraints, only XY transformation is necessary for the georeferencing, and hence two targets were considered to be enough. The positions of the georeference targets were measured with GNSS (global navigation satellite system) receivers (Topcon GRS-1 or Trimble GeoXH 6000) which are capable of obtaining geographic coordinates with horizontal and vertical accuracies of <10 cm by post-processing corrections. The baseline solution was obtained using the public data of nearby GNSS base stations provided by

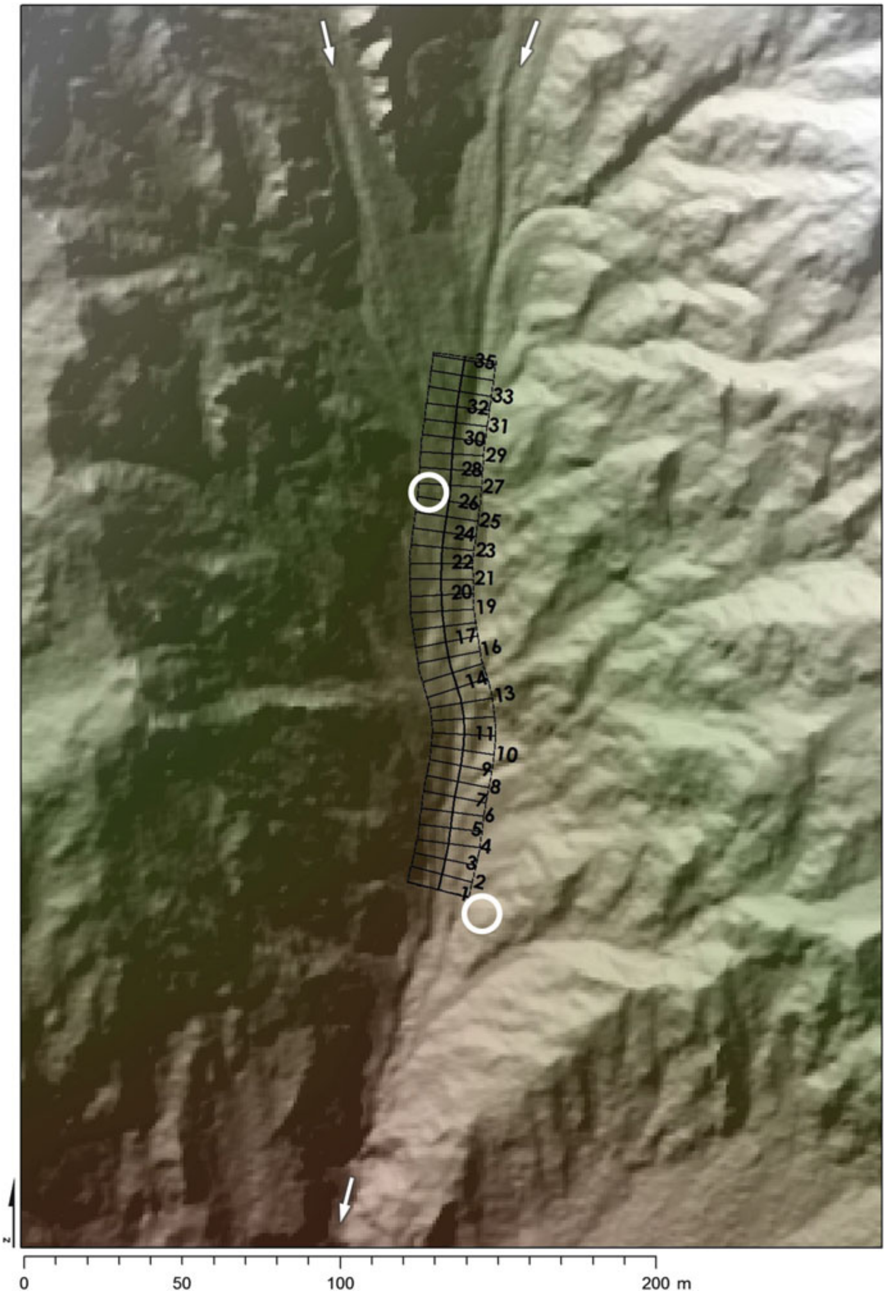


Fig. 8.5 Target area for terrestrial laser scanning. The background hillshade image is derived from an airborne-laser derived DEM with a resolution of 1 m provided by MLIT. Transverse cross section lines (20 m long) are set along the longitudinal section of the valley centre (170 m) at a spacing of 5 m. Two *white circles* indicate the approximate scan positions of the TLS. *Arrows* show the flow directions of major channels

GEONET, the Japanese GNSS network operated by the Geospatial Authority of Japan.

Point cloud data were obtained and managed using Topcon ScanMaster software. The point cloud data were first georeferenced onto geographic coordinates (Japan Plane Rectangular CS VIII with JGD2000 datum, EPSG:2450) by distance resections using the two georeference targets coupled with the GNSS coordinates. After manually eliminating unnecessary points or noises, the point clouds were exported as a LAS file and imported into ESRI ArcGIS software. The point clouds were then converted into DEMs by using simple triangulated irregular network (TIN) interpolation, because minimal vegetation cover was present. The resolution of the DEMs was set, according to the average point density of the point clouds.

Differences of the DEMs between closest time periods were then computed (labelling rule: e.g., 1205–1111). A DEM with a resolution of 1 m obtained by airborne laser scanning (ALS) in 2010, provided by a local office of the Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT), was also used to represent the initial condition of the study area. Sections for longitudinal and transverse profiles were set for the valley bottom sediment, covering areas 170 m long and 20 m wide (Fig. 8.5). The spacing of the transverse cross-sections was 5 m. Elevation along the profiles was then extracted, and the temporal changes in the profile elevation compared. Channel slope gradients were also calculated along the longitudinal profiles, using a measurement scale of 6 m which averages the very local variations in slope gradient caused by individual boulders. Although the elevation of bedrock beneath the sediment is difficult to establish in many parts of the study reach due to the thickness of coarse sediment, the approximate amount of sediments therein was quantified by subtracting the minimum elevation of DEMs throughout the time periods from each DEM. This is referred to as the depth raster of the valley bottom sediment. From the depth raster, the volumes of sediment within the study reach can then be calculated. The method is summarized as a workflow chart in Fig. 8.6.

8.4 Results

After field measurement and data processing, point clouds of the target area were obtained (Fig. 8.7). The registration errors, i.e. errors related to the target-based matching of two point clouds for each day of scan, were typically of the order of millimeters, while georeferencing errors which relate to the coordinates measured with GNSS receivers were of the order of centimeters (estimated accuracies of the post-processed GNSS data were <10 cm). In addition, the measurement error by TLS is of the order of millimeters (4 mm at 150 m distance, as noted before). The overall accuracies of the point clouds obtained are therefore considered to be of the order of centimeters to a decimeter.

Table 8.2 shows the properties of all point clouds obtained. Depending on the measurement conditions at the field site (mostly a factor of atmospheric condition,

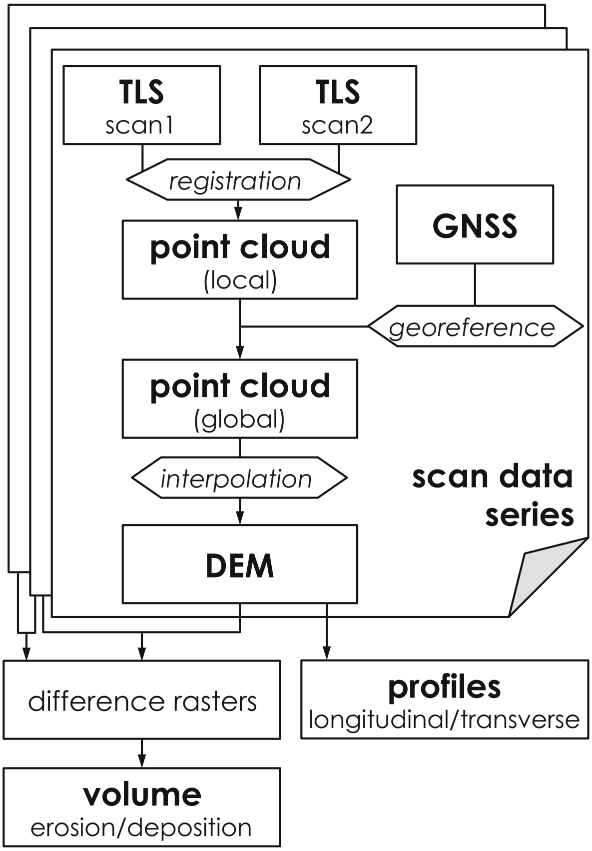


Fig. 8.6 Data processing workflow in this study

for example in some cases the sudden occurrence of fog disabled the laser measurement), the total returned number of laser scans varies from 2,349,712 to 16,107,191 points. The density of point clouds, i.e. the number of points normalized by scan area, ranges from 62.0 to 306.0 points/m^2. These values equate to a mean spacing between points of between 0.062 and 0.127 m. The resolution of DEM converted from the point cloud was therefore determined to be 0.1 m for all the scan data.

At the beginning of the TLS surveys in November 2011, the sediment present in the study site was much less compared with that in the previous years, according to visual observations in the field. Although resolutions are different, the difference between the 10-cm DEM of the TLS data (1111) and the 1-m DEM of ALS taken in 2010 clearly shows there was sediment missing in 2011 (Fig. 8.8a). In many areas, changes in bed elevation of more than 5 m were observed. Figure 8.9a illustrates the estimated changes in the bed elevation in the study reach.

In some periods, particularly 1211–1305 (Fig. 8.8e), the trend of positive and negative changes in elevation (slightly over ±40 cm) is different for each side of

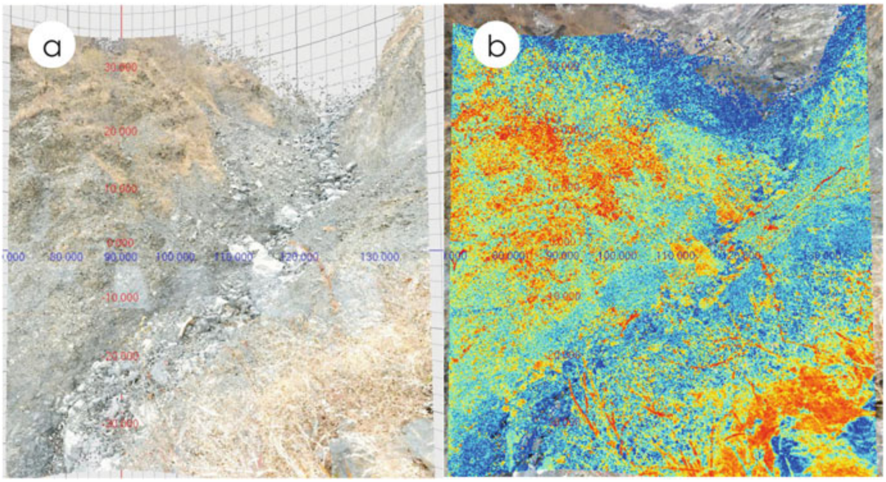


Fig. 8.7 Point cloud data obtained by TLS measurement (1111). (**a**) RGB-colour coded points, reproducing three-dimensional structure of visible scenery. (**b**) Point cloud coloured by intensity values of laser returns (*red*: high, *blue*: low). The intensity values are mostly high in surrounding steep slopes where intense laser returns are expected due to the angle of surface to the laser emission

Table 8.2 Point cloud properties of each scan

Name	Date (YY/MM/DD)	Total returns (pts)	Area of point cloud (m^2)	Shot density (pts/m^2)	Equivalent resolution (m)
1122	11/11/22	2,349,712	26,223	89.6	0.106
1205	12/05/14	3,541,973	40,891	86.6	0.107
1208	12/08/23	6,802,080	37,337	182.2	0.074
1211	12/11/21	16,107,191	52,641	306	0.057
1305	13/05/10	3,547,361	57,200	62	0.127
1308	13/08/16	12,303,233	47,000	261.8	0.062
1311	13/11/19	8,008,954	40,100	199.7	0.071

the valley-side slopes: positive elevation change dominates on the left-side slope while negative change dominates on the right-side slope (Fig. 8.8e). Because the slope gradients of the valley sides are quite steep (typically 30–80°), unexpected slight lateral shifts of the data (horizontal error) can easily affect the vertical changes for such steep slopes. These systematic variations in elevation difference, for the entire side slopes, are likely to be due to such lateral shifts of the data caused by errors in georeferencing, and these particular trends have been disregarded. Distinct local changes in elevation can be observed despite such overall trends. Hereafter these localized changes in elevation between each scan are described.

Following the winter season of 2011–2012, the amount of sediment in the study reach generally increased, and the difference between 1111 and 1205 in the TLS data indicates a marked deposition in upstream and downstream portions of the

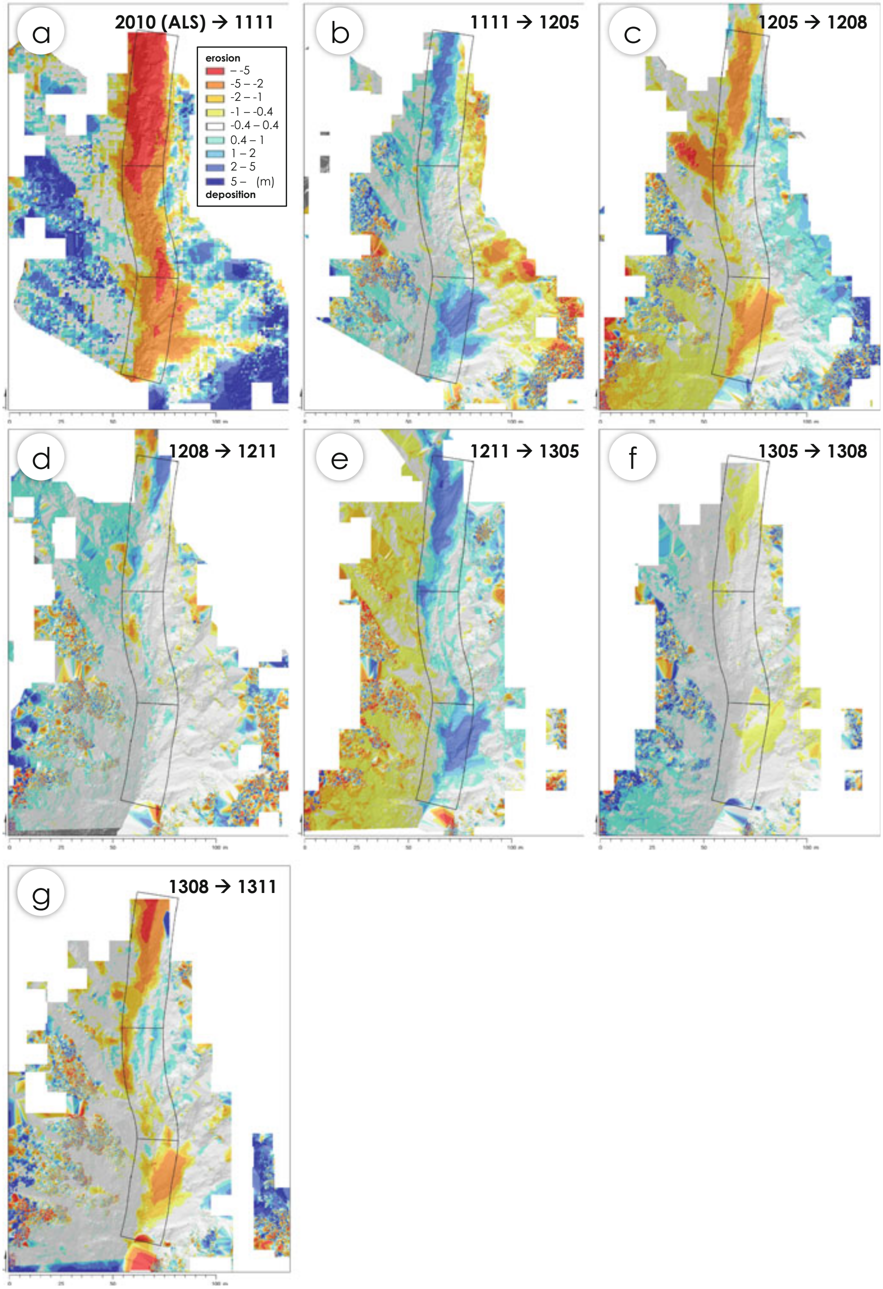


Fig. 8.8 Differences of elevation for each season. Areas with insufficient point data are masked by white cells. (**a**) 1111 compared to ALS data (1 m resolution) in 2010. A large amount of erosion of the valley bottom sediment is clearly observed. (**b**) 1205 compared to 1111. Deposition is observed in the upstream reach and the downstream talus cones. (**c**) 1208 compared to 1205. Erosion is occurring. Slope collapse has occurred in the right side slope at the mid-upper position. (**d**) 1211 compared to 1208. Relatively less changes are observed, while some patchy erosion is

study reach of more than 2 m depth (Fig. 8.8b). The depositional areas are mostly due to the development of talus cones, the sediment of which is supplied from side slopes (Fig. 8.9b).

During the rainy season, from 1205 to 1208, several debris flows occurred, and the erosion of the deposits appears to have taken place in the study reach (Fig. 8.8c). The right bank in the mid-section of the study reach showed a typical negative change in elevation, which corresponds to the collapse of bedrock on the valley-side slope (white dashed line in Fig. 8.9c).

During the transition from the summer to autumn season (1208–1211), the overall changes in elevation appear to have been less than those of the previous seasons, where almost no change was observed for the lower portion of the study reach. However, in the mid to upper sections, patchy erosion was observed (mostly on the right-side bank), while deposition occurred in the uppermost section of the study reach (Figs. 8.8d and 8.9d).

Through the following winter (1211–1305), deposition occurred again mainly in the upper and lower parts of the study reach (Fig. 8.8e). The area of deposition appears to have been slightly larger than that in the previous year (Fig. 8.8b). However, despite the dominance of deposition, two linear depressions along the flow direction were observed on the surface of the deposits in the mid reach (Fig. 8.9e), indicating some surface erosion.

During the period 1305–1308, no heavy rainfall events were recorded and changes in the sediment elevation were minor except for slight erosion in the upper portion and lower talus cone in the study reach (Fig. 8.8f). The surface sediment appeared to be somewhat coarser than in the spring season (Fig. 8.9f).

In the summer of 2013, heavy rainfall occurred several times during typhoon events and multiple debris flows were observed in the study reach. The amount of erosion was accordingly large during this time period (1308–1311) (Fig. 8.8g). In some portions in the upper part of the valley, bottom sediment was subject to more than 5 m of erosion, whereas linear areas of deposition along the flow direction were observed on the left side of the mid reach (Figs. 8.8g and 8.9g).

As noted above, the surface elevation of the valley bottom sediment is generally at a minimum in summer and at a maximum in spring. However, the changes differ locally within the study reach. The longitudinal profiles along the study reach, whose average slope is as steep as 54 %, clearly show contrasting trends of erosion and deposition (Fig. 8.10a). The upper and lower sections have large changes in elevation, while the middle section shows much smaller changes. Compared to the summer data (1208) when the bed elevation was nearly at its minimum (Fig. 8.8c), the deposition through winter was much more, 2–3 m in the lower section and up to

Fig. 8.8 (continued) observed at the right side in mid to upper portions. Clear deposition is shown in the uppermost position. (**e**) 1305 compared to 1211. Deposition is clearly observed. (**f**) 1308 compared to 1305. Less changes are observed, except some erosion in upstream and downstream portions. (**g**) 1311 compared to 1308. A high amount of erosion is observed in the upstream reach, while some deposition is also shown in the mid reach

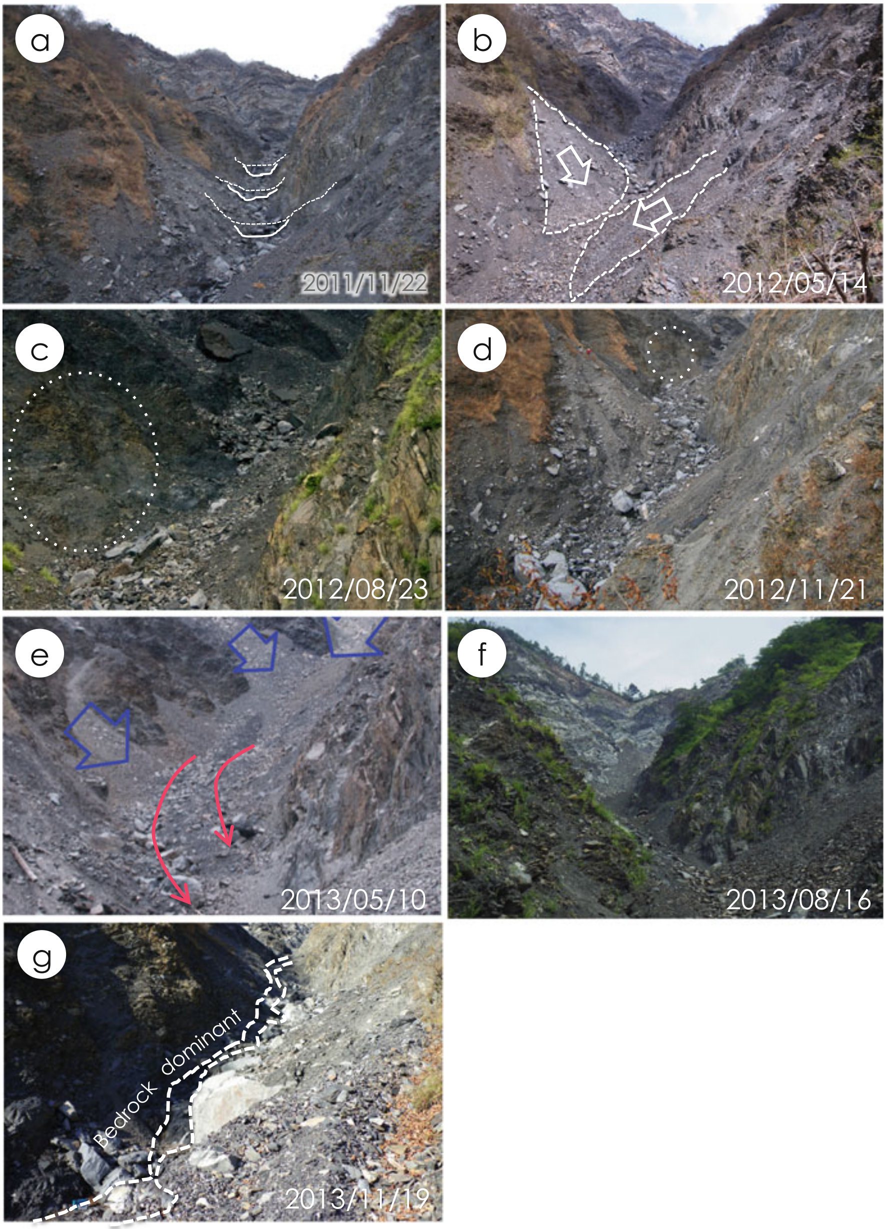


Fig. 8.9 Pictures of the scan target area for each survey. (**a**) 1111. Approximate cross-sections in 2010 are shown in white dashed lines. (**b**) 1205. Talus cones are clearly observed in the downstream part of the study reach. (**c**) 1208, zoom-in view of the mid to upper portions. *White dashed circle* indicates the location of slope collapse on the right side slope (see Fig. 8.8c). (**d**) 1211. The *dashed circle* corresponds to that in (**c**). (**e**) 1305. Sediments supplied from side slopes (*wide blue arrows*) are abundant, whereas erosional lineaments are also observed (*thin red arrows*). (**f**) 1308. The situation is similar to 1305. (**g**) 1311. The sediments have been well eroded, and bedrock surfaces are well observed

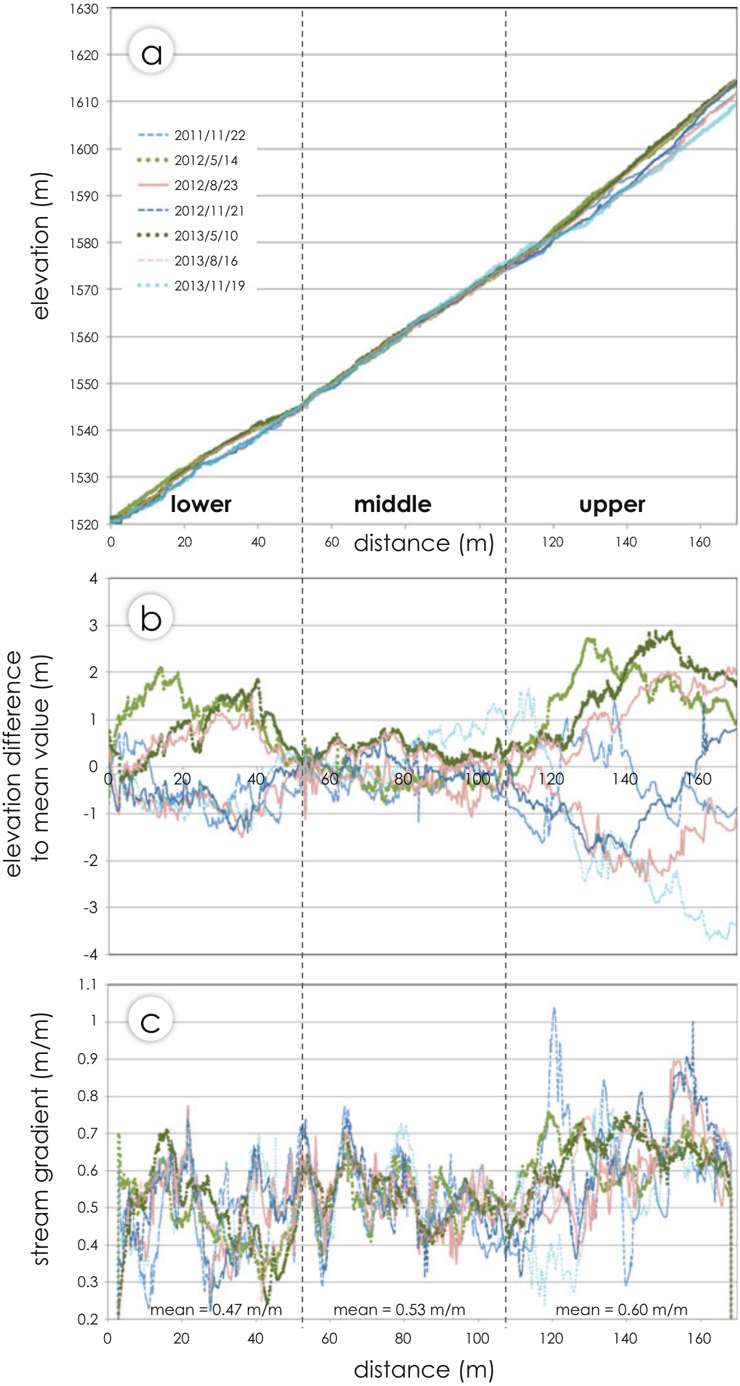


Fig. 8.10 (**a**) Longitudinal profile of the study reach for each season. (**b**) Seasonal differences in elevation, normalized by the mean elevation value for the entire datasets. (**c**) Stream gradient

5 m in the upper section, while the changes in the middle section only show ±1 m differences (Fig. 8.10b). The upper section also showed greater deposition (1–3 m) before winter. These three subsections, i.e., the lower, middle and upper sections, can then clearly be separated according to these observations. Hereafter these domains are referred to as the upper, middle and lower sections, respectively. By extracting the watershed boundaries from the 1-m DEM by ALS, the source area above the uppermost point in the study reach appears to be 80,353 m^2, and the catchment areas feeding from side slopes into each section are 51,678 m^2 for the upper, 17,268 m^2 for the middle, and 27,487 m^2 for the lower one.

The 6-m scale stream gradients show cyclic patterns along the valley (Fig. 8.10c), which is more distinct in summer to autumn. These peaks in stream gradient represent both coarse sediment (boulders) and bedrock knickpoints. The cyclic pattern of the gradient, which changes seasonally, indicates step-pool-like features in the valley bottom sediment, presumably related to the pulses of debris flows and/or hydraulic forces by surface flows over the deposits. The boundaries of the subsections, in contrast, correspond to the locus of bedrock knickpoints with the fixed locations of the high peaks of stream gradient.

Transverse cross profiles also show the contrasting differences in bed elevation along the study reach (Fig. 8.11). The upper section shows clear deposition through winter, as well as slight deposition before winter (Fig. 8.11a, b). Some parts of the middle section show large changes (~2 m) (Fig. 8.11c) but typically less (<1 m) (Fig. 8.11d). The lower section shows 2–3 m of deposition through winter, but is less dynamic in other seasons (Fig. 8.11e, f).

By subtracting the minimum elevation raster from each DEM, the temporal changes of the sediment storage were obtained, and found to be 1000–5000 m^3 (Fig. 8.12). As noted above, sediment storage is generally high in spring and low in summer, but local variations indicate that the storage in the middle section is relatively stable throughout the seasons.

8.5 Discussion and Conclusions

The order-of-magnitude estimate of sediment storage within this reach corresponds well with the sediment volume of 2000–19,000 m^3 in a longer reach, including that of this study, roughly estimated by photographs for an older time period (2001–2004) (Imaizumi et al. 2006). This indicates that, with some variations, the sediment yield in the study area has been consistently high (in the order of 10^3–10^4 m^3) for years to decades. However, even along the short reach of the scan area, the three subsections exhibit different patterns of erosion and deposition of sediment. Such local variations can be related to those variations occurring in debris flow

Fig. 8.10 (continued) (horizontal scale: 6 m) for each season. Mean values of stream gradient for each subsection are also shown

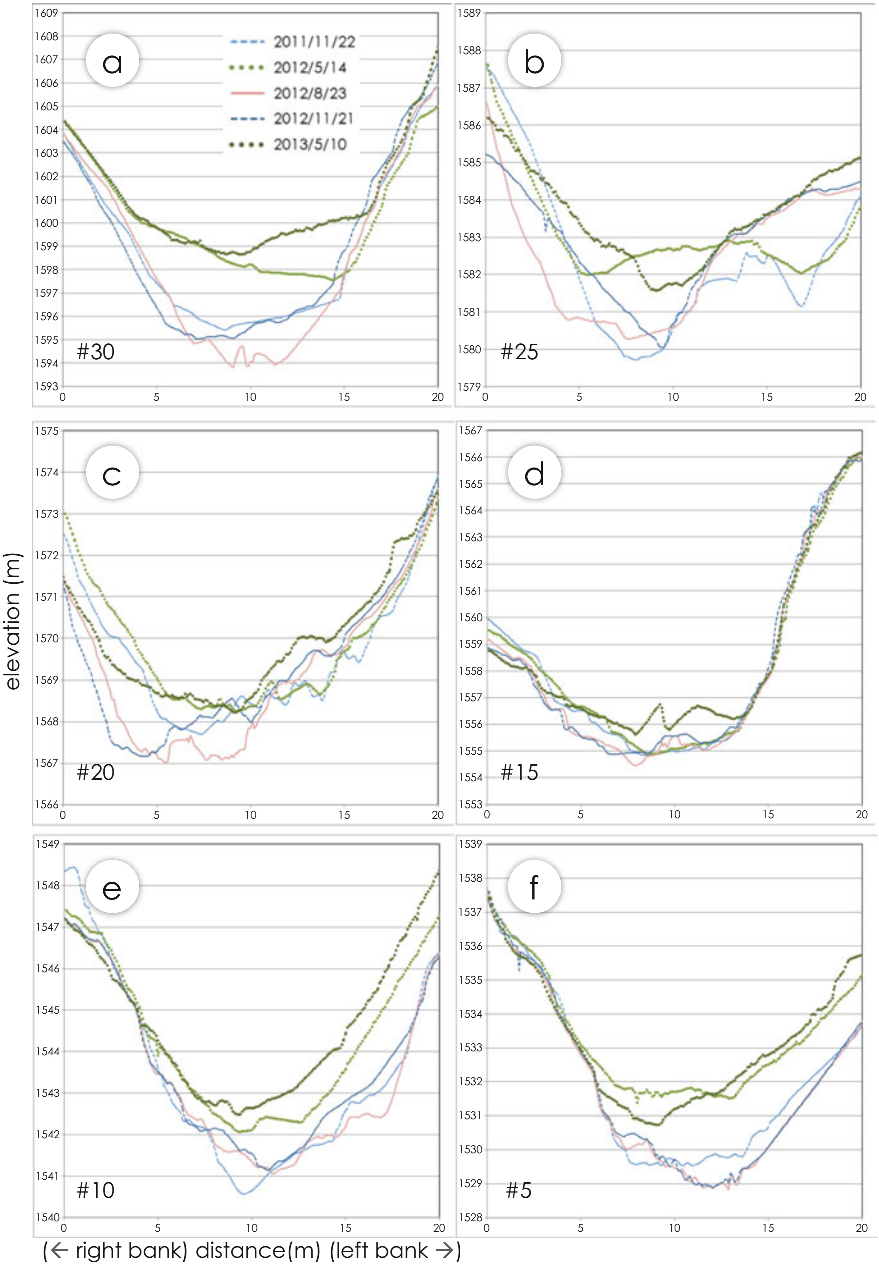


Fig. 8.11 Examples of transverse cross profiles along the study reach. Number of section lines is shown in Fig. 8.5

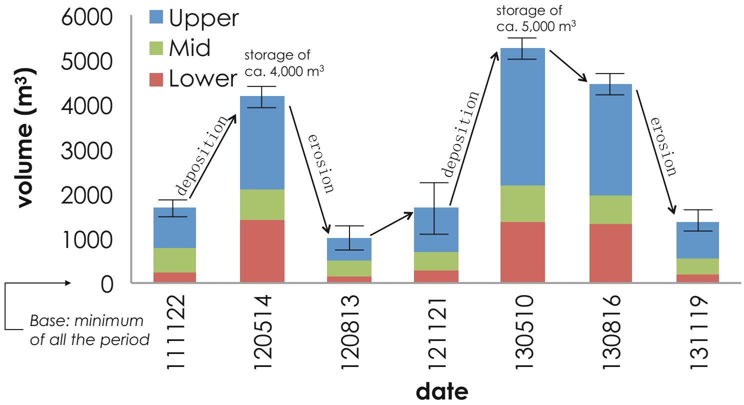


Fig. 8.12 Seasonal changes in sediment storage in the target area

dynamics and surrounding topographic conditions. The boundaries between the subsections (Fig. 8.10) seem to correspond to the narrowing portions of the valley where distinct bedrock exposure on the valley bottom occurs as knickpoints. The bedrock topography of the valley bottom and valley-side slopes can therefore be important in determining the kinematics of debris flows therein. Also, the bedrock in the valley bottom itself can change by erosion when exposed to the debris flowing over it. The bedrock of the valley-side slopes actually changed due to a collapse event (Figs. 8.8c and 8.9c), which acted to widen the valley. The interactions between debris flows and bedrock will change the location and characteristics of the subsections on a decadal time scale.

The upper section appears to have experienced the largest changes and variability in topography. Here, the slope gradient is steepest and the sediments could have a higher mobility than those of the lower sections. Transportation of both fine and coarse sediments may occur by recurring debris flows in this section. However, monitoring of the debris flows in this section is limited because of the fact that video recordings for this section were not possible. Judging from the predominantly coarse sediments in this section, relatively infrequent, intense debris flows are likely to be responsible for the higher mobility of valley bottom sediments here.

The middle section exhibits considerably less change in surface elevation compared to the upper and lower sections. The downstream end of this section, which corresponds to the point where the valley narrows and bedrock exposed as a knickpoint, may have a higher water depth during flooding. Increased shear stress, induced by surface flows, could lead to a greater mobility of finer-grained sediments (small gravels), whereas this is not sufficient to mobilize larger boulders lying beneath the finer material.

In the lower section, the supply of relatively fine-grained sediments from the valley side slopes is abundant, and is observed as large talus cones on both sides of the channel. In this reach, remobilization of fine sediments by debris flows was captured by video monitoring (Imaizumi et al. 2013). Imaizumi et al. (2013)

observed that the prominent surface flow causes partial fluidification and mass movements of channel bed deposits. Following the migration of the portion that was fluidized, the compaction of the finer sediments leads to frequent saturation and finally causes debris flows. By this mechanism, the majority of mobile particles during debris flows are fine-grained sediments rather than large boulders. As shown in the longitudinal profiles (Fig. 8.10), the changes in sediment elevation are moderate in this section, and field observation shows that the changes are mostly due to the accumulation and removal of relatively fine-grained sediments, while large boulders seem to be immobile and only excavated following debris flows (Fig. 8.9). Relatively low stream gradients in this section (0.47 m/m) may account for the fact that debris flow energies are insufficient to initiate the movement of larger sediment blocks.

The source of the sediment in each subsection can be divided into two types: (1) small to large sediment particles transported from the upstream area by debris flows, and (2) small particles supplied from the side slopes. The latter is mostly derived from freeze-thaw weathering of the surrounding slopes composed of deformed shale and sandstone layers, which provide small rock particles into the valley bottom, particularly in the late autumn to early spring season.

The uppermost catchment above the study reach has an area of 80,353 m^2, and this seems sufficient for the accumulation of enough surface water to generate debris flows when intense rainfall events occur; large boulders can then be transported by such debris flows along the valley bottom. The side slopes along the upper section also have relatively large catchment areas (51,678 m^2 in total), and such areas are, even though clear channels are not apparent, favourable for the abundant supply of sediment by mass movements onto the valley bottom. This source of sediment supply is responsible for the high amount of deposition and erosion in the upper section throughout the year.

On the contrary, the side slope source areas for the middle section are relatively small (17,268 m^2), and the sediment supply into this section relies mainly on debris flows coming from the upper section. Due to the narrowing of the valley and associated knickpoint at the downstream end of the middle section, sediments coming from upstream can be trapped at this point and maintain a valley bottom surface that is smoother than the underlying bedrock. This sediment cover may be the cause of the small range of fluctuations in valley-bottom elevations in this section: the transported sediments can pass over the relatively smooth surface, and neither erosion nor deposition occurs within this reach to any significant degree. In addition, the narrowness of the valley may cause a significant increase in water depth during flooding, and the consequent higher shear stresses developed would be expected to make sediment mobilization easier.

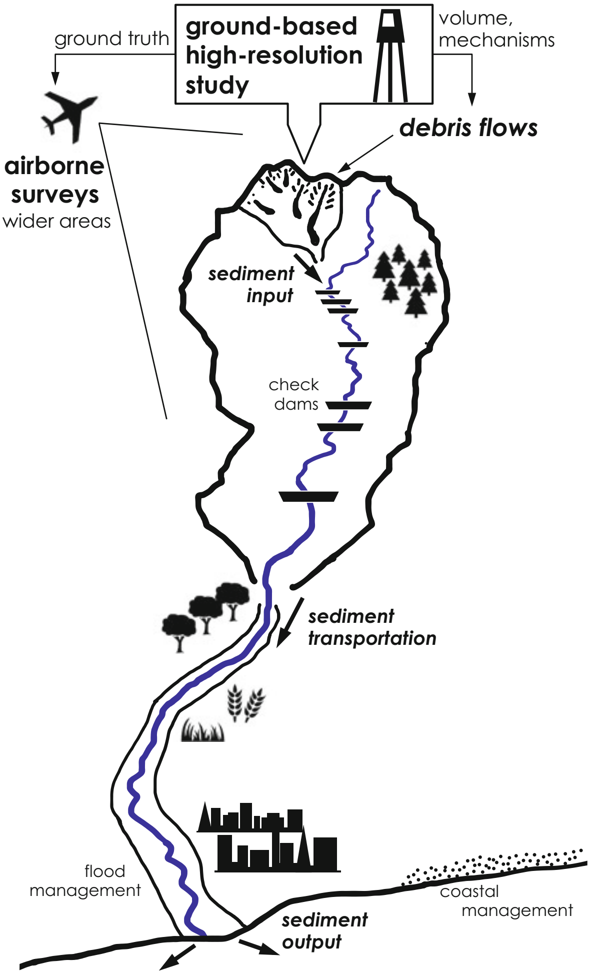
Sediment input from the side slopes is again large in the lower section, with a total source area of 27,487 m^2, where obvious talus cones are observed. In addition, due to the increased volume of water in this downstream reach, sediment delivered by debris flows can readily travel further downstream once initiated. Accordingly, the amount of deposition and erosion in this section is moderate compared to that of the upper section.

In summary, the TLS measurements of the debris-flow deposits in the valley bottom of the steep headwater channel in spring, summer and autumn over 2 years provide multi-temporal high-definition (0.1 m resolution) topographic datasets, revealing seasonal variations in the amount of valley-bottom sediment of the order of 1000–5000 m^3. Erosion and deposition along the reach also shows contrasting spatial patterns according to the sections bounded by knickpoints and valley narrows. The upper section exhibits steepest channel slopes with the largest changes in valley-bottom elevation, indicating the more frequent transportation of coarse sediments. In the middle section, bed elevation is relatively constant, where transportation seems dominant due to smooth sediment coverage and deeper water flows within the narrow valley. In the lower section, immobile coarse boulders are present, while deposition and erosion of relatively fine sediments seem dominant.

It should be noted that even three centuries after the formation of the mega-landslide, such disturbance regularly continues in the steep headwater catchment. The time period of this study is, however, relatively short (two years) compared to the entire history of this landslide terrain. Therefore, further monitoring and measurements should be, on one hand, continued to reveal longer-term, annual to decadal trends in sediment dynamics in the study site. On the other hand, linking such a high-resolution but short-term analysis on sediment production in the steep headwater channel to longer-term studies of sediment transport in broader areas is essential for comprehensive understandings of intense sediment transport from headwater to downstream (e.g., Korup et al. 2004).

Such long-term studies in downstream gentler reaches may include different approaches. Figure 8.13 shows a schematic illustration of sediment production and delivery in a watershed-scale area for the Abe-kawa River. The high-resolution ground-based survey, which provides detailed insights into volume, timing and mechanisms of sediment production by debris flows therein, can be used as a ground truth for aerial surveys, including aerial photogrammetry and ALS. The aerial survey has been carried out every year recently for a wider area of the Abe-kawa River catchment. Although the resolution by such aerial surveys is relatively low (1 m), compared to those by TLS (0.1 m), spatial analysis of the sediment transport by debris flows can be performed for broader areas in the catchment with a longer time span (e.g., Imaizumi et al. 2015), where TLS data may be used for assessment and enhancement of accuracies of the airborne data. Furthermore, the amount and local-scale characteristics of sediment deposition and erosion by debris flows in such a headwater steep channel should be related to the sediment yields in downstream areas. Although each debris flow in the study area mostly remains in the valley bottom of the landslide terrain and coarse sediment does not reach further downstream at annual scales (Imaizumi et al. in press), decadal transport rates of fine-grained and suspended sediments are constantly high in the downstream reach of the study area (Nishikawa et al. 2006; Kondo et al. 2008). Links between the timing and amount of mobile sediment production by upstream debris flows and sediment transport in the downstream reaches should therefore be further assessed. For instance, intense sediment yields, initially mobilized by debris flows and subsequently by fluvial transport, toward downstream

Fig. 8.13 Schematic illustration of issues on sediment dynamics in a watershed



reaches may be reduced by construction of numerous check dams along the reach. However, the decrease in sediment transport in the midstream of the river would result in bank erosion and damages in bridge piers. In contrast, downstream reaches of the Abe-kawa River shows a trend of increasing riverbed height even decades after prohibiting the operation of gravel and sand mining (Ito et al. 1999), potentially increasing the flood risks therein. Even flood risk may increase when land subsidence occurs due to earthquakes in such channelized lowlands (e.g., Hughes et al. 2014), where the study area is prone to frequent earthquakes and tsunamis. Long-term changes in the amount of sediment output from river to coastal areas on the order of 10^5 m^3/year (Uda et al. 1994) can also cause changes in the amount of sand storage at the coast, which may result in uneven changes of the coastlines including significant coastal erosion. Like those, long-term, comprehensive mitigation strategies for sediment-related disasters should be applied to a whole watershed from headwater to river mouth. Therefore, for the watershed-scale balancing of sediment budget, high-resolution and high-frequency monitoring of sediment production in headwater areas would strongly contribute to optimize the distribution of facilities for sediment controls along the mid to downstream reaches.

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Chapter 9

Landslide Typology Using a Morphological Approach and Establishment of an Inventory Map Based on Aerial Photo Interpretation in Central Vietnam

Hong Luong Le, Toyohiko Miyagi, Abe Shinro, and Eisaku Hamasaki

Abstract Landslides are destructive and annually recurring phenomena which cause substantial property damage, disruption of traffic and fatalities along transport arteries in the central provinces of Vietnam. The production of a landslide inventory map is a very important preliminary step to determine landslide susceptibility, hazard, and risk assessment. There are a number of methods for producing landslide inventory maps, such as geomorphological field mapping and visual interpretation of stereoscopic aerial photographs. The exact choice of method depends on the quality of collected data, type of data, purpose of the map, map scale and availability of aerial photographs etc. In this paper, visual interpretation of stereoscopic aerial photography is used to prepare an inventory map because of the type of data collected on landslide occurrence. These features are clearly discernible in terms of morphological features that manifest as changes in the form, shape and appearance of the topographic surface. Most of these features can be recognized and appropriately classified through the interpretation of aerial photographs. 523 landslides are identified and based on these features were classified into five categories as follows: (i) rotational slide, (ii) translational slide, (iii) compound slide, (iv) debris slide and, (v) debris flow.

Keywords Landslide typology • Morphology • Inventory map • Vietnam

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9.1 Introduction

Landslides in mountainous area are significant geohazards; they seriously affect living conditions, resulting in loss of human life, substantial property damages and possible disruption of vital transport and communication links. In the central provinces of Vietnam, landslides occur frequently and most of them result from reactivation of old landslides. Therefore, identifying existing landslides and producing a landslide inventory map is important as a basic source of data on the spatial location of landslides and the prediction of future landslides.

In this chapter, we discuss the identification of the existing landslide topography in central Vietnam based on the interpretation of aerial photography. The methodology used for landslide identification is based on the post-event results of landslides which have left discernible morphological evidence in the form of topography that is characteristic and distinct from any other landform unit. In this way the relationship between topography and surface drainage can be viewed and evaluated. Through a series of investigative tools, including air photo interpretation, we identified topographic features (consisting of the main scar, body and micro features among others) of a landslide unit and recorded the shape, size, direction and style of dissection and other associated autonomous processes. We were able to establish the typology of the landslide action and identified the type or types of movement associated with it. The inventory map was produced using the same data and method. In this case, the landslides were classified into five categories: (i) rotational slide, (ii) translational slide, (iii) compound slide, (iv) debris slide, (v) debris flow. We used aerial photographs at a scale of 1:33,500 that were taken in 1999 for identification and mapping, since at the time of this study, this was the only appropriately scaled imagery available. Since it probably takes several hundred years or more to erode all discernible features left by landslide occurrence, these photographs are deemed adequate to establish the inventory and typology.

9.2 Study Area

The study area (Fig. 9.1) is located in the west central part of Vietnam and lies between 16°00′ and 15°20′ N and 107°37′30″ and 107°52′30″ E. It was chosen because the topography of the region is characterised by the Truong Son mountain range stretching from north to south, and is one of the most challenging terrains in Vietnam in terms of human activity. The area has a tropical monsoon climate with two hydrometeorological seasons: a typhoon and high rainfall season lasting from September through March and a dry season lasting from April through August. The mean annual temperature is 23.5 °C and average rainfall around 2500–3000 mm (Nguyen Khanh et al. 2000). The peak rainfall season is between October and November.

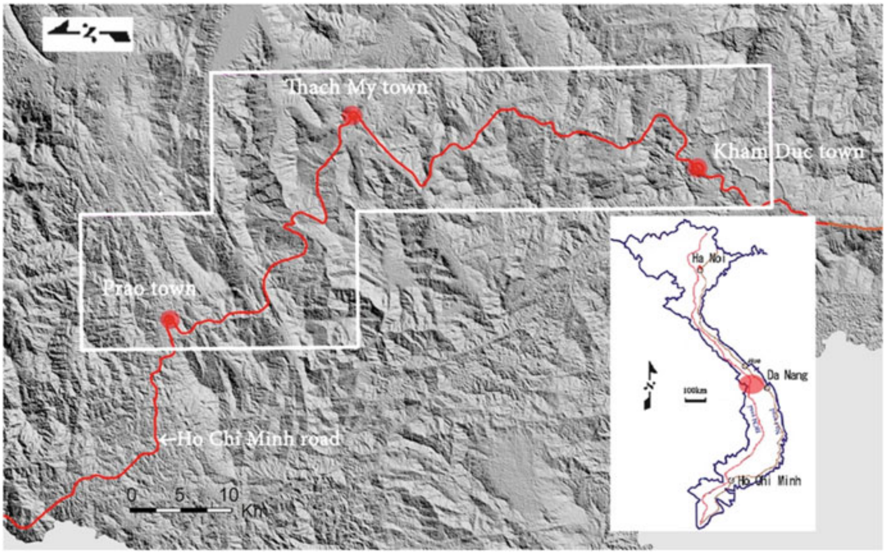


Fig. 9.1 Location of the study area

Geologically, the study area forms part of the Truong Son structural block, in which strata date from the Pre-Cambrian to the Mesozoic. The Cambrian to Ordovician zone occurs some 20 km to the north of the town of Prao. The lithology consists mainly of sericite schist, rich in organics (coal) with lenses of altered felsic effusives, conglomerates and silty sandstone. The Mesozoic zone lies between Prao and the town of Thach My where the lithology is dominated by reddish sandstone, mudstone and conglomerate of Triassic to Jurassic age. A number of thin coal or organic rich layers are also inter-bedded among the sedimentary rocks. The zone is also characterized by a cuesta landform. Most of the landslides here have occurred as translational forms where the bedding planes are associated with a weak layer. The Pre-Cambrian zone lies between Thach My and Kham Duc town and the geology here consists mainly of Pre-Cambrian schist and gneiss. The rocks are strongly and deeply weathered. Additionally, there is a Quaternary terrace deposit. The occurrence of landslides in the study area is strongly related to geology and weathering features.

9.3 Landslide Identification

9.3.1 Background to Identification of Landslide Types

The term ‘landslide’ can be defined as a movement of a mass of rock, debris or earth down a slope under the influence of gravity (Cruden and Varnes 1996). When landslides occur, they alter the local topography of the land surface and leave discernible signs in comparison to the surrounding areas. Most of these indicators are morphological and involve changes in the shape or appearance of the topographic surface. It is possible that they can be recognized, classified and mapped through the interpretation of (stereoscopic) aerial photographs (Rib and Liang 1978; Hansen 1984a, b; Hutchinson 1988; Baum et al. 1999; Guzzetti et al. 2012). The morphological characteristics of each landslide depend on the type of movement (fall, flow, slide, or combination thereof), velocity of movement and characteristics of the material being moved. Geomorphologists cannot retrospectively compute exact mass movement velocity, but it is possible to interpret the morphological signature left by a landslide to determine the extent of slope failure and to infer type of movement (Guzzetti et al. 2012).

Additionally, other aspects such as vegetation characteristics and drainage condition of slopes need to be considered as factors to aid classification. In regard to morphological characteristics, various features are recorded, such as the nature of concave-convex slopes, the occurrence of semi-circular niches, step-like morphology, back tilting of slope faces, hummocky relief, crack formation and steepening of slopes. Vegetation characteristics include the identification of disrupted or partially dead vegetation across the slope, especially if coinciding with morphological steps. Less dense vegetated areas are recognized through lighter tones; there may be differences in vegetation appearance inside and outside of the landslide feature or noticeable changes in vegetation in relation to drainage conditions. Drainage characteristics include disturbed or anomalous drainage patterns and zones of stagnated water or exceptionally well-drained areas.

9.3.2 Suggested Typology of Landslide Topography

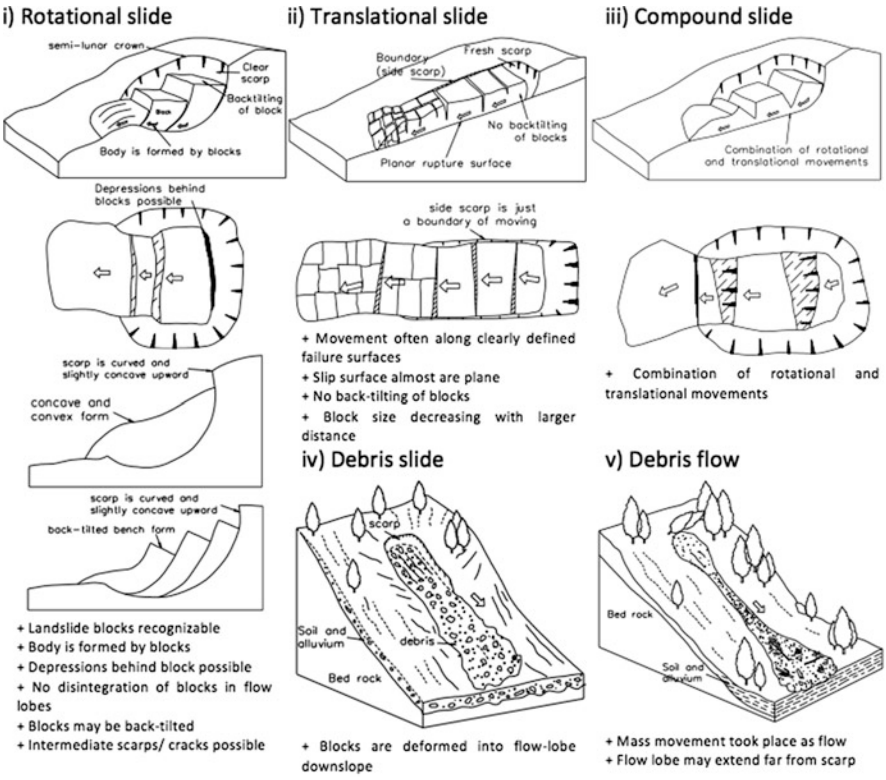
According to the widely used Cruden and Varnes (1996) classification (Table 9.1), there are 16 types of landslide classified based on type of movement and type of material. In this classification, there are many kinds of material involved and modes of movement. In this study it was difficult to determine material type using aerial photographs so the categorization of slope movements is less detailed than the Cruden and Varnes classification scheme.

In this study area, we recognized and classified the flowing five types of mass movements: (i) rotational slide (RS), (ii) translational slide (TS), (iii) complex/compound slide (CS), (iv) debris slide (DS), (v) debris flow (DF). Among these types, there are three types (rotational slide, translational slide, compound slide) that can be classified by their characteristic topographic features, i.e. main scarp, lateral scarp, landslide body. The other two types (debris slide, debris flow) can only be identified by the topographic features of the body of the feature in question (Fig. 9.2).

In order to identify and classify each type of landslide, the precise definition and morphological characteristics of each type need to be understood. We here

Table 9.1 Summary of Cruden and Varnes 1996 classification system

	Type of material		
		Engineering soils	
Type of movement	Bedrock	Predominantly coarse	Predominantly fine
Falls	Rock fall	Debris fall	Earth fall
Topples	Rock topple	Debris topple	Earth topple
Slide (rotational and translational)	Rock slide	Debris slide	Earth slide
Lateral spreads	Rock spread	Debris spread	Earth spread
Flows	Rock flow	Debris flow	Earth flow
Complex	Combination of two or more principal types of movement		



i) Rotational slide

- + Landslide blocks recognizable
- + Body is formed by blocks
- + Depressions behind block possible
- + No disintegration of blocks in flow lobes
- + Blocks may be back-tilted
- + Intermediate scarps/ cracks possible

ii) Translational slide

- + Movement often along clearly defined failure surfaces
- + Slip surface almost are plane
- + No back-tilting of blocks
- + Block size decreasing with larger distance

iii) Compound slide

- + Combination of rotational and translational movements

iv) Debris slide

- + Blocks are deformed into flow-lobe downslope

v) Debris flow

- + Mass movement took place as flow
- + Flow lobe may extend far from scarp

Fig. 9.2 Features used for landslide typology in the study area (modified from referenced data)

described the five types of geomorphological features that have allowed us to classify the different types of mass movements in the study area:

Rotational Slide A rotational slide is defined as a sliding mass of weak rock and/or soil situated on a cylindrical or other rotational rupture surface (Hungr et al. 2014). The slide movement is more or less rotational about an axis that is

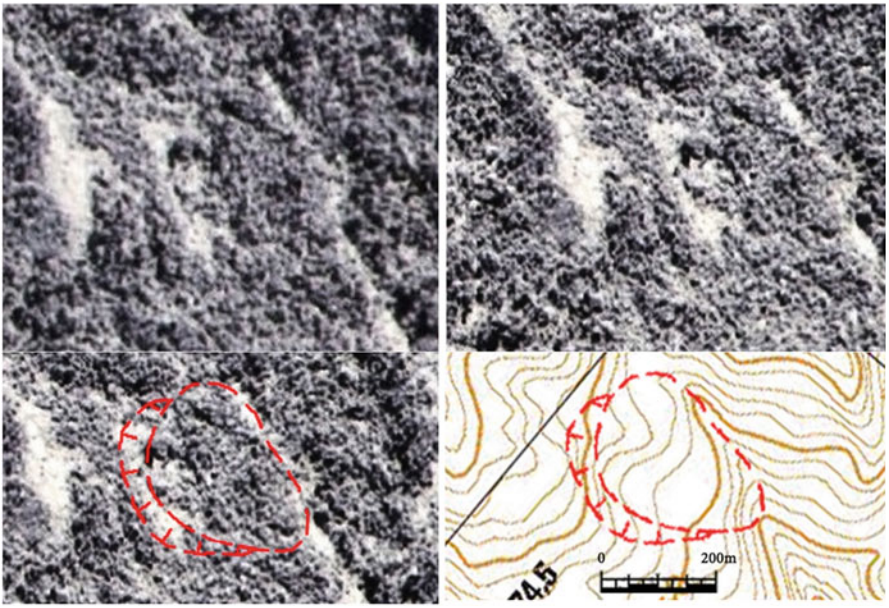


Fig. 9.3 Stereo aerial photo pair (D2-99-05-168 and 169) showing a typical rotational slide

parallel to the contour of the slope. The body is formed by blocks and is generally easily recognizable. There is no disintegration of blocks in the flow lobes and they include spoon-shaped irregular landforms. The morphology is characterised by a prominent main scarp and a distinctive back-tilted bench formed at the head of the slide. In the stereo-pair image from the aerial photographs (shown in Fig. 9.3), the block is very clear as it constricts the stream. There are depressions behind the block and ponding occurs in the back-tilted area.

Of course, not all landslides exhibit these features due to post-event weathering, erosion processes and the type of landslide material. In the case of landslide #95 (Fig. 9.4), this has a semi-lunar crown and lobate frontal part, the scarp is curved and slightly concave upward and the slope is characterized by concave (niche) – convex (run-out lobe) forms. These morphological features are specific characteristics of a rotational slide.

Translational Slide A translational slide is a sliding mass of rock and/or block of cohesive soil that moves across one or more inclined planar rupture surfaces (Hungr et al. 2014). In the case of rock, planar slides usually involve dip slopes that have been undercut by erosion or excavation. The slide head may be separating from stable rock along a deep vertical tension crack. In the case of a soil planar slide, it is likely controlled by a weak layer, inclined at an angle exceeding the angle of repose. Before total failure, tension cracks often form during initial disturbance. During and after the failure event, the sliding mass separates from stable soil along these tension cracks and leaves a fresh scarp, forming a graben. The main scarp is

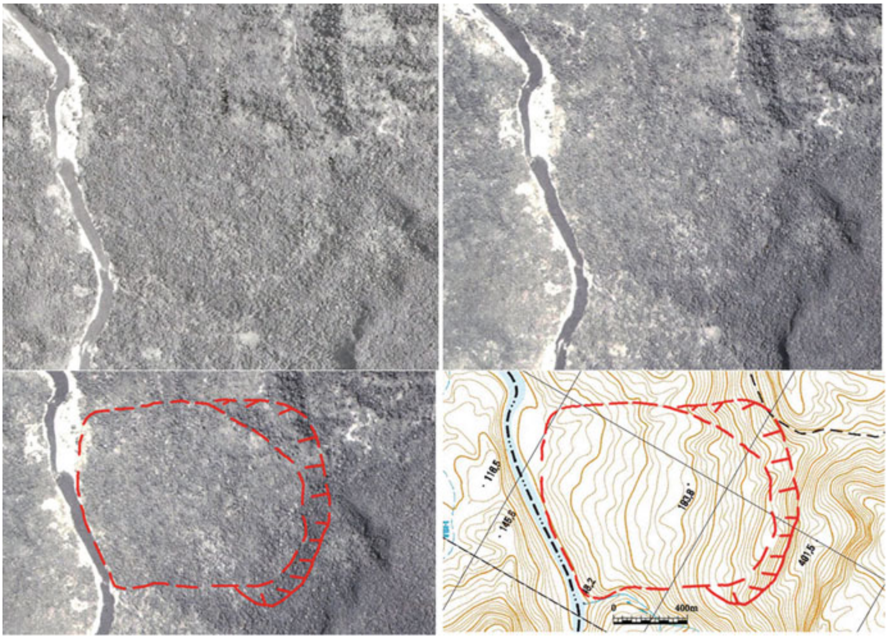


Fig. 9.4 Stereo aerial photo pair (D2-99-05-168 and 169) showing a typical rotational slide

not a slip surface, and the side scarp represents the movement boundary between the detached and the stable zone (Fig. 9.2ii). The slip surface is relatively shallow and the run-out characterised by hummocky, even chaotic relief and decreasing block size with distance. In the source area and along the movement pathway the vegetation is denuded, often with lineation in the direction of movement. In comparison with a rotational slide, there is no ponding below the crown, and surface drainage is either disordered or absent on the body (Soeters and van Westen 1996); the scarp is clear and often elongated with no back tilting of blocks. Figure 9.5 shows a typical translational slide in which a weak layer overlays a planar rock structure. At the head of slide, the separate stable soil and sliding area can easily be recognized. The slip surface is almost planar and the debris accumulates at the bottom of slope, in the process deflecting the river.

Compound Slide A compound slide is a sliding mass of rock and/or soil on a rupture surface consisting of several planes or an irregular rupture surface consisting of a number of randomly oriented joints. When a landslide occurs as a compound slide, it creates a concave-convex slope morphology. The concavity is often associated with a linear, graben-like depression. There is no clear run-out but there is a gentle convex/bulging frontal lobe. Back-tilting facets are associated with (small) antithetic faults (Soeters and Van Westen 1996). Figure 9.6 illustrates typical features of this type of slide.

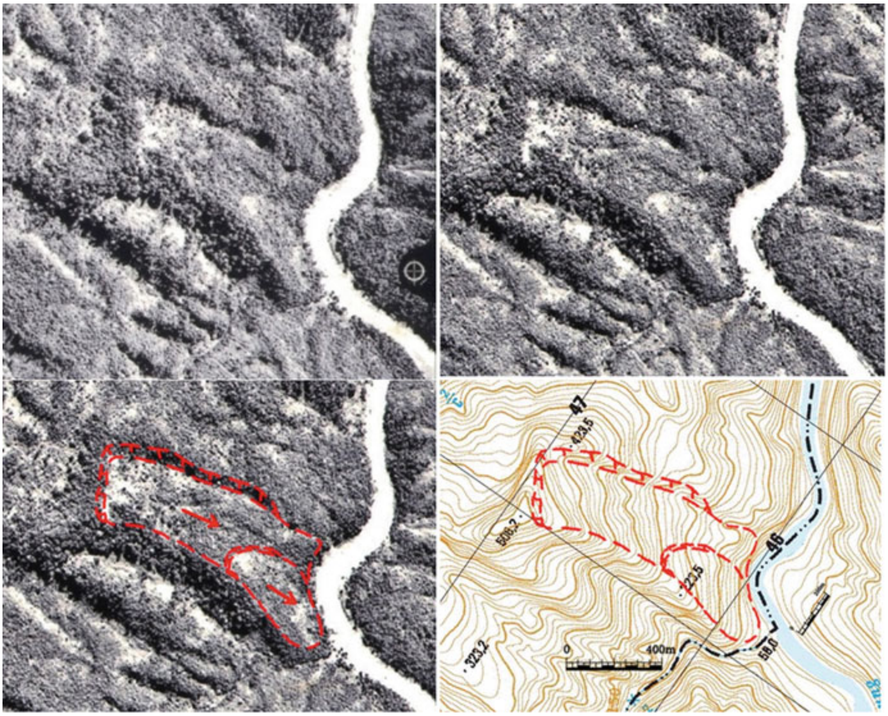


Fig. 9.5 Stereo aerial photo pair (D2-99-06-415 and 416) showing a typical translational slide

Debris Slide A debris slide involves the movement of a mass of unconsolidated material along a steeply-sloping, planar surface parallel to the ground. Usually, the sliding mass is a veneer of colluvium, weathered soil or pyroclastic deposits sliding over a stronger substrate. Many debris slides become flow-like after moving from tens to hundreds of meters and may transform into extremely rapid debris avalanches (Hungr et al. 2014) and accumulate downslope. Based on this definition, we can deduce morphological characteristics belonging to this type; blocks (the landslide body) are deformed by flow structures fluid motion downslope and display clear flow-structures with a lobate convex frontal section. The flow-lobe is usually larger than the initial blocks (landslide body). Vegetation on the scar and body is highly disturbed and clearly distinguishable from the surroundings. Figure 9.7 shows these features. Drainage conditions include ponding or disturbed drainage towards the rear and deflected or blocked drainage at the frontal lobe.

Debris Flow A debris flow involves movement of loose soil or highly weathered unconsolidated rock on a steep slope. It often occurs simultaneously with heavy rainfall and can be initiated by a slide, debris avalanche or rock fall from a steep slope above or as a result of spontaneous instability in a steeply sloping stream bed (Hungr et al. 2014). Under such conditions, these materials can liquefy or be subject to a significant increase in pore-pressure and therefore flow downslope rapidly

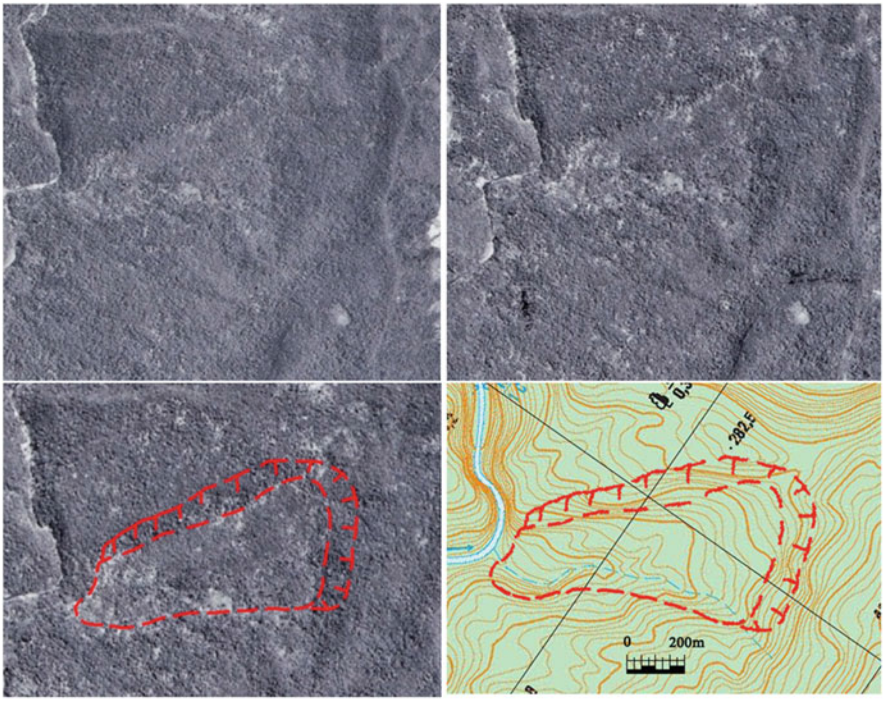


Fig. 9.6 Stereo pair aerial photo (D2-99-04-226 and 227) showing a typical compound slide

under the influence of gravity. Morphological features associated with this type of landslide typically include large numbers of small concavities or one major scar associated with the source area. There is almost complete destruction along the movement pathway, sometimes marked by depositional levees. Figure 9.8 shows a typical debris flow feature in the study area.

9.4 Landslide Inventory Mapping

A landslide inventory map is defined as a terrain map showing the distribution of landslide features in the existing landscape. They can contain diverse data on past landslide occurrence, such as location, date of occurrence, activity and physical properties of landslides in a region (Fell et al. 2008; Pasek 1975). Such maps play a key role in risk assessment for disaster management and they may provide scientific data for applied landslide research. In this study, a landslide inventory map was prepared through interpretation of aerial photographs. Using this method, all the unstable locations were mapped at a scale of 1:25,000 onto topographical maps. The photographs were taken in 1999 at scale of 1:33.500 so this means that it was

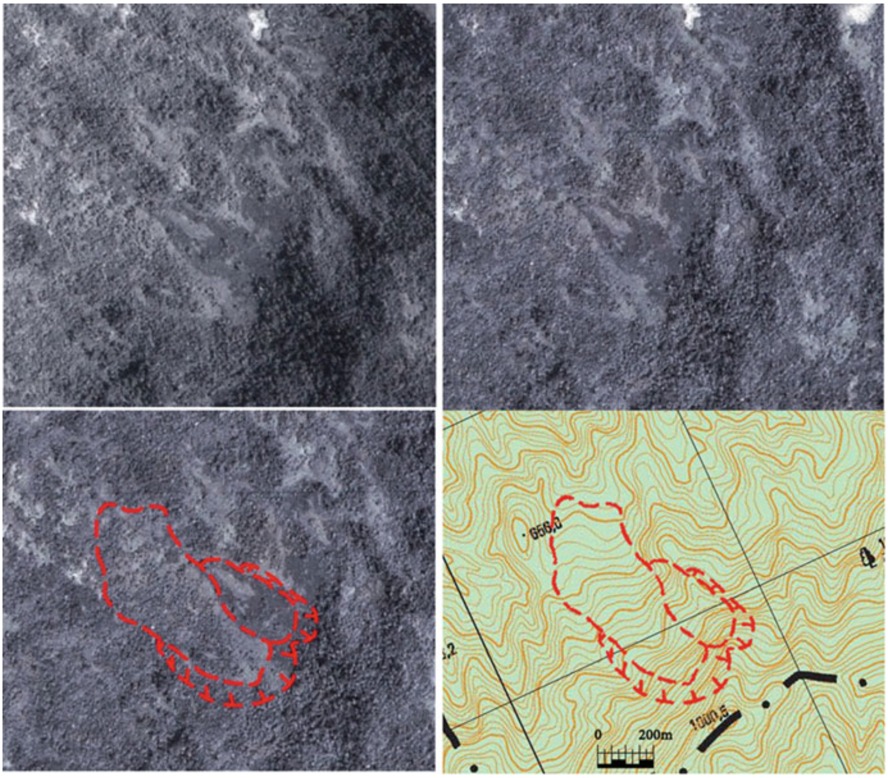


Fig. 9.7 Stereo pair aerial photo (D2-99-03-244 and 245) showing a typical debris slide

possible to interpret large scale landslides (over 150 m in width). Landslides to the south west of Prao town are examples of this (Fig. 9.9). We recognized the presence of a number of small ravines, gullies and bare land, although these are more difficult to differentiate from real scars due to their small size. These features suggest that many small landslides have taken place in the past. We were able to identify these as debris slides or debris flows that occurred in weathered soils and tend to follow existing stream channels or ravines. The landslides are too small to be included on the topographical map.

Figure 9.10 presents another typical characteristic of landslide distributions which were identified in the Thon A So area. The zone is located in the northern part of the homoclinal slope in the southern section of the major Mesozoic syncline. A large number of landslides are observed here and the scars are clearly identified on the northward dip slope. Many other types of landslide topographic features are also located here. It emerges that landslide distribution is very strongly reflective of geological structure. In the front slope regions, landslides are mainly translational and occur along bedding planes whereby the slip surface tends to be parallel to the

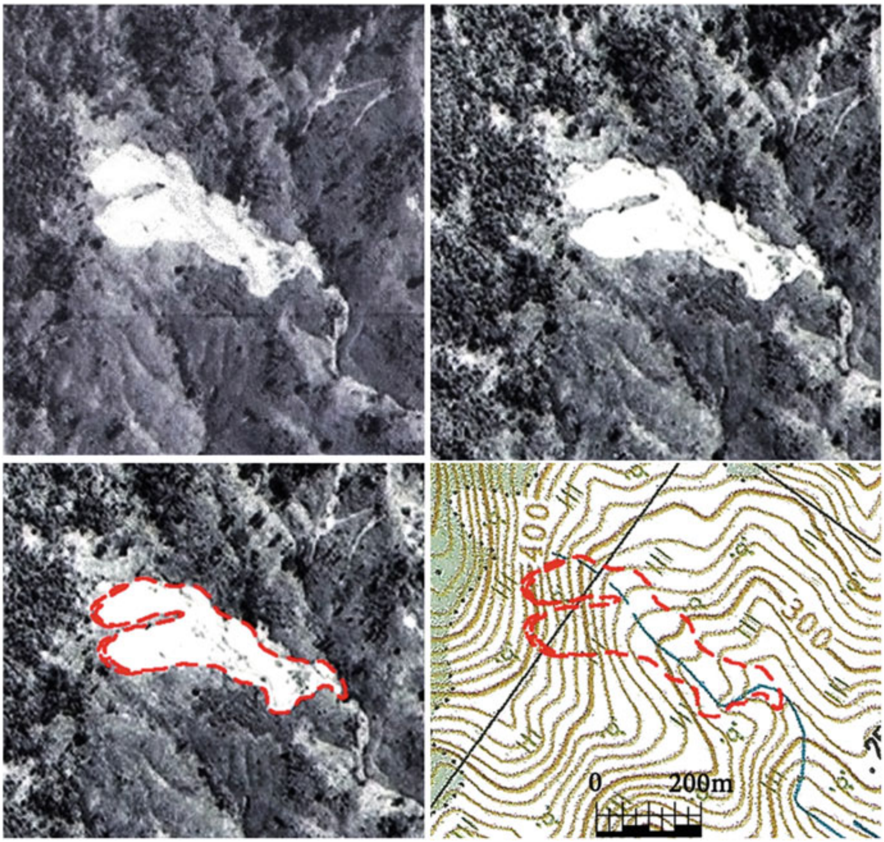


Fig. 9.8 Stereo pair aerial photo (D2-99-06-127 and 128) showing a typical debris flow

slope. In the back slope areas, fracture controlled rock falls, slip ruptures along vertical joints and fractures predominate. Unfortunately, given the scale of the photographs it proved impossible to identify rockfalls.

Figure 9.11 presents an example of a landslide inventory map, which is one of five that have been produced covering 1000 km^2 of the study area and recording a total of 523 landslides. Most of these were medium to large-scale features. The largest landslide identified on the study area, with an area of some 5 km^2, occurs in the Kham Duc area, while the smallest occupied an area of just 0.02 km^2. The features were classified into five categories: most (283) are rotational slides, 56 are translational, 5 landslides were classified as compound slides, 163 as debris slides and 16 as debris flows.

Maps depict the distribution and type of landslide, but do not record information on activity and physical properties which would require further work, although in this study we used the inspection sheet (Fig. 9.12) which was developed by the

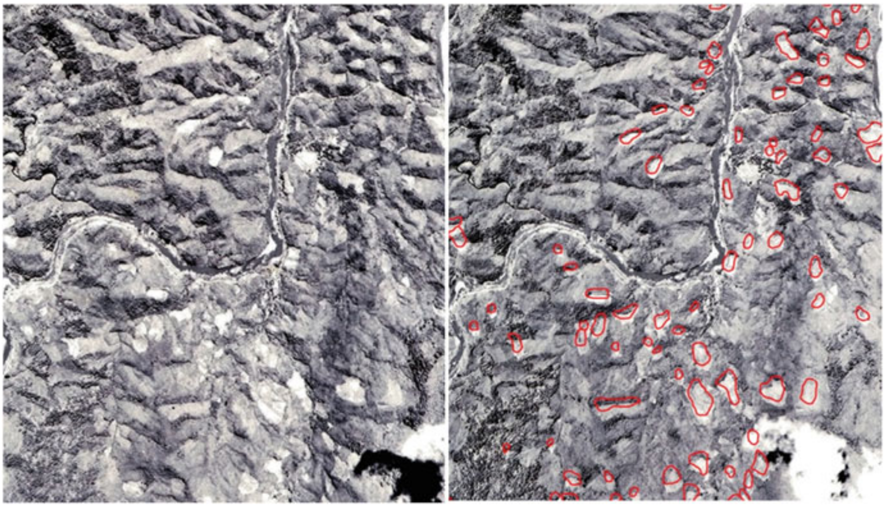


Fig. 9.9 Aerial photo stereo pair (D2-99-05-434 and 435), southwest of the Prao area

Japanese Landslide Society to evaluate the probability of landslide reactivation using the AHP (Analytic Hierarchy Process) approach, which incorporates geomorphic factors within and beyond landslides. To illustrate the potential of this method, we chose to evaluate landslide #18, with the resultant score of 70 suggesting that this landslide has a high probability of reactivation (Le et al. 2014).

9.5 Conclusions

In this study, mass movement features have been classified and mapped on the basis of the morphological signatures left by the features. These signatures are unique to the type of movement observed. Landslide inventory maps of the study area have been produced using aerial photograph interpretation. These maps are very useful for people to define the spatial location of landslide sites and provide a basic data source for applied landslide research and authorities to improve their strategies for industrial and infrastructure risk management. Detection and mapping of landslides using satellite images remains a challenging task. Formal standards for identification as yet do not exist, and the interpreter classifies landslide morphological features based on experience, and on the analysis of a set of characteristics (signatures) that can be identified on the images.

In this study, we attempted to evaluate the probability of landslide reactivation employing a methodology which involves the recognition of geomorphic features

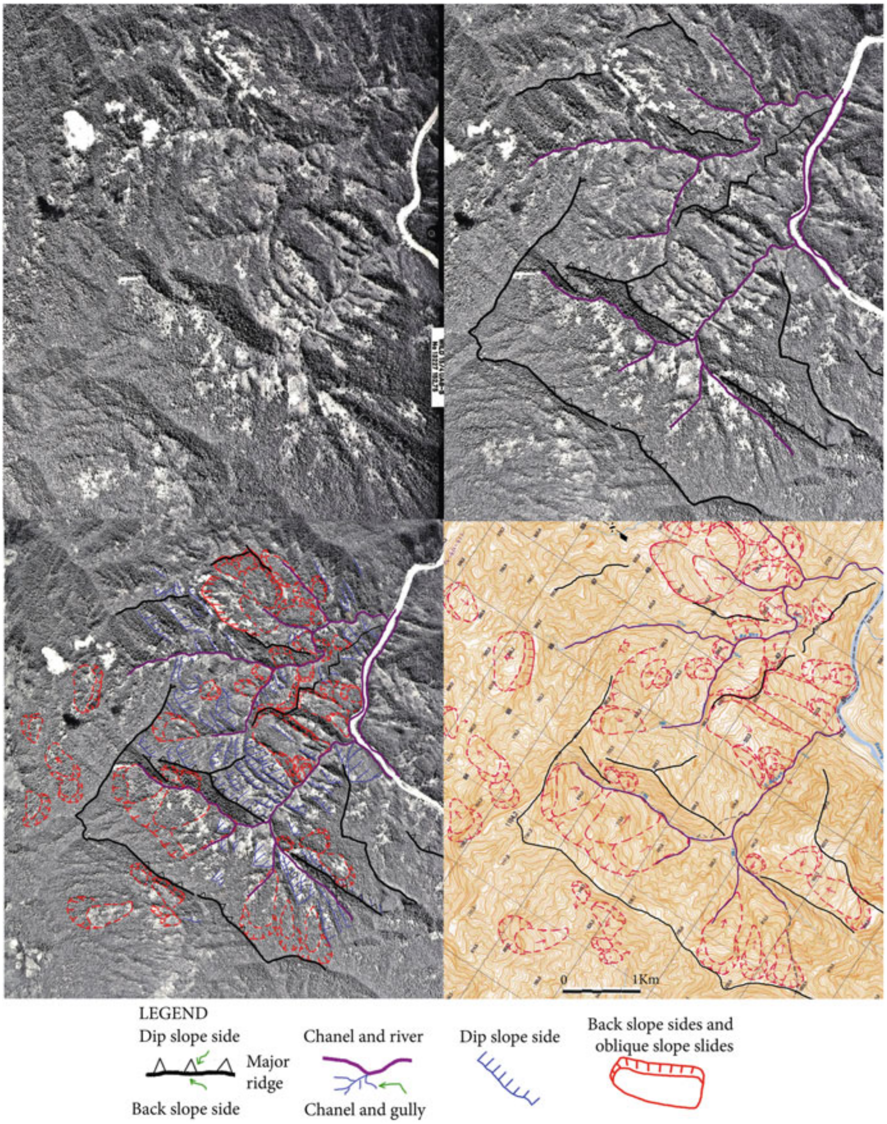


Fig. 9.10 Air photo stereo (D2-99-06-415 and 416) showing the main joint plane and bedding plane trending parallel to or dipping with slope

within and outside of the landslides. Some of the smaller features remain difficult to identify due to limitations of photography. Future modifications of the method and improvements in the quality of imagery will improve the value of this kind of work in landslide prediction and mitigation.

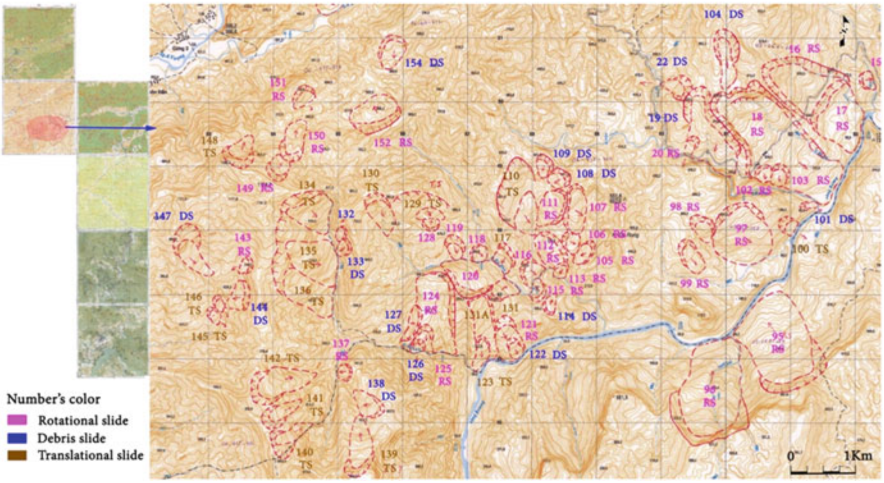
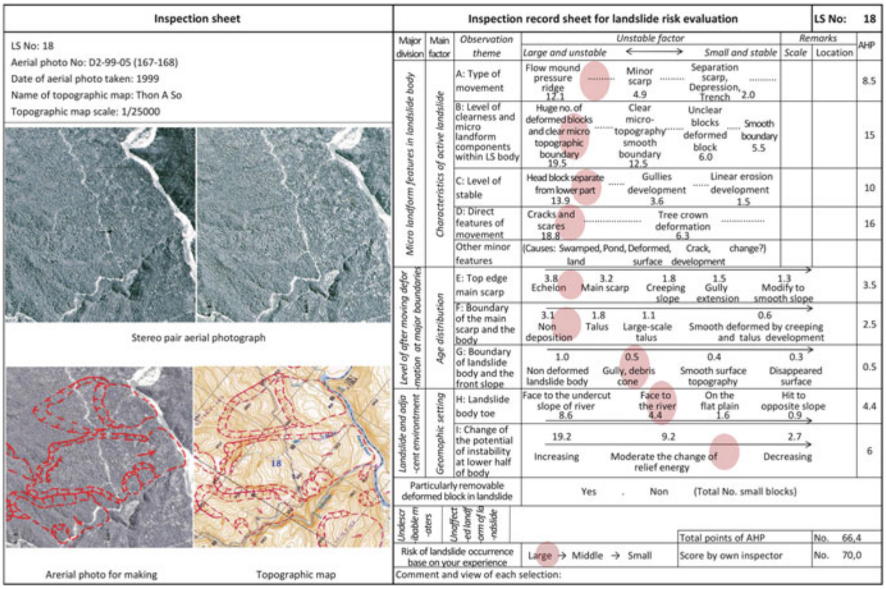


Fig. 9.11 Example of landslide inventory map of a small part of the study area



Inspection sheet

LS No: 18
Aerial photo No: D2-99-05 (167-168)
Date of aerial photo taken: 1999
Name of topographic map: Thon A So
Topographic map scale: 1/25000

Inspection record sheet for landslide risk evaluation LS No: 18

Major division	Main factor	Observation theme	Unstable factor: Large and unstable ⟷ Small and stable	Remarks: Scale	Remarks: Location	AHP
Micro landform features in landslide body	Characteristics of active landslide	A: Type of movement	Flow mound pressure ridge 12.1 ⋯ Minor scarp 4.9 ⋯ Separation scarp, Depression, Trench 2.0 ⋯			8.5
		B: Level of clearness and micro landform components within LS body	Huge no. of deformed blocks and clear micro topographic boundary 19.5 ⋯ Clear micro-topography smooth boundary 12.5 ⋯ Unclear blocks deformed block 6.0 ⋯ Smooth boundary 5.5			15
		C: Level of stable	Head block separate from lower part 13.9 ⋯ Gullies development 3.6 ⋯ Linear erosion development 1.5			10
		D: Direct features of movement	Cracks and scares 18.8 ⋯ Tree crown deformation 6.3 ⋯			16
		Other minor features	(Causes: Swamped, Pond, Deformed, land surface Crack, development change?)			
Level of after moving defor-mation at major boundaries	Age distribution	E: Top edge main scarp	3.8 Echelon → 3.2 Main scarp → 1.8 Creeping slope → 1.5 Gully extension → 1.3 Modify to smooth slope			3.5
		F: Boundary of the main scarp and the body	3.1 Non deposition → 1.8 Talus → 1.1 Large-scale talus → 0.6 Smooth deformed by creeping and talus development			2.5
		G: Boundary of landslide body and the front slope	1.0 Non deformed landslide body → 0.5 Gully, debris cone → 0.4 Smooth surface topography → 0.3 Disappeared surface			0.5
Landslide and adja-cent environment	Geomophic setting	H: Landslide body toe	Face to the undercut slope of river 8.6 → Face to the river 4.4 → On the flat plain 1.6 → Hit to opposite slope 0.9			4.4
		I: Change of the potential of instability at lower half of body	19.2 Increasing → 9.2 Moderate the change of relief energy → 2.7 Decreasing			6
Particularly removable deformed block in landslide			Yes . Non (Total No. small blocks)			
Undescr-ibable m-atters	Unaffect-ed landf-orm of la-ndslide					
				Total points of AHP	No.	66,4
Risk of landslide occurrence base on your experience			Large → Middle → Small	Score by own inspector	No.	70,0
Comment and view of each selection:						

Fig. 9.12 Example of inspection sheet of risk evaluation based on a the AHP approach to landslides

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Chapter 10
Vulnerability and Exposure to Geomorphic Hazards: Some Insights from the European Alps

Margreth Keiler and Sven Fuchs

Abstract Geomorphological processes and society are connected through a diverse set of relationships and feedbacks. One of the main connections concerns the impact of hazardous geomorphic processes on society that lead to economic and life losses. Due to the extent of geomorphological activity in mountain regions, and the considerable proportion of these that are occupied and used by people, mountains are a particular focus in geohazard and interdisciplinary risk research. Taking the European Alps as an example, a short overview indicates the fundamentals of mountain hazard processes and highlights trends in the number of different hazard types in Austria. Climate and environmental change as well as their influence on mountain hazard processes are discussed with a focus on the cryosphere and hydrosphere. Key issues in developing a more thorough understanding of increasing losses and future risk are exposure and vulnerability. Initial insights on exposure are provided by an analysis of the past evolution and current situation in the context of spatial and temporal distribution of values at risk; this is illustrated with reference to Austria. The importance of vulnerability for risk reduction is internationally acknowledged but somewhat less studied and, indeed, seems to be hidden between the different foci of disciplines. Innovative methods for vulnerability analysis (documentation, vulnerability curves) are presented contributing to close this gap. Overall, mountain hazard research highlights the importance of connecting geomorphology and the socio-economy in order to contribute to the most challenging questions of more sustainable societies.

Keywords Mountain hazards • Environmental change • Vulnerability • Exposure • Risk dynamics

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10.1 Geomorphology and Society in Mountain Regions

Mountain areas are typically characterised by steep gradients which result in highly-dynamic geomorphic processes such as landslides and other gravitational mass movements, sometimes also in combination with cascading processes, leading to multi-hazard situations (Kappes et al. 2012a). At the same time, significant proportions of mountain regions are used for human settlements, with associated economic and transport infrastructure, which results in risk. The main challenge of risk reduction is rooted in the inherently connected dynamic systems driven by both geophysical and social forces, hence the call for an integrative management approach based on multi-disciplinary concepts that take into account different theories, methods and conceptualisations (Fuchs and Keiler 2013).

Mountain areas cover around 40 % of the total land area of Europe, within which almost 20 % of the total population lives (Nordregio 2004). European mountain regions therefore provide for a significant proportion of human settlements and areas used for economic purposes and recreation. Mountain regions are particularly prone to changing environmental conditions, and they show a greater range of susceptibility to disturbance than many other landscapes (Slaymaker and Embleton-Hamann 2009). Probably the most important reason to focus on hazards, vulnerability and risk in mountain regions is the recognition that global changes of important magnitude, in particular climate and land-use change, are already underway (Slaymaker et al. 2009; Seneviratne et al. 2012).

Alternations of the spatial and temporal pattern of exposure and vulnerability are dependent on the spatial extent of hazardous processes threatening societies, in particular their magnitude and frequency, as well as on the socio-economic changes within society (Keiler et al. 2010; Field et al. 2012). While hazard assessment has a long tradition, the assessment of exposure and the quantification of vulnerability are more recent concerns in hazard and risk research (van Westen et al. 2006). Some aspects of research on geomorphic hazards, such as the impact of highly destructive processes on buildings, infrastructure and agriculture and questions regarding multi-hazard risks (Kappes et al. 2012a, b), help to close the gap between disciplinary approaches in science and humanities. Nevertheless, mitigation and adaptation may remain fragmentary with respect to the optimal level of protection of exposed societies or vulnerable elements at risk. Moreover, most analysis has thus far been based on a static approach and neglects long-term as well as short-term dynamics in hazard, exposure and vulnerability.

In this chapter, a brief overview on mountain hazards is given reflecting on some recent insights on the influence of environmental change with a focus on the European Alps. We then highlight key research challenges and provide examples of enhanced vulnerability and exposure analyses in the context of mountain hazards.

10.2 Hazard Processes and Environmental Change

Following Varnes (1984) and Fell et al. (2008), a hazard is in general a condition with the potential to produce an undesirable consequence. A natural hazard in the geomorphological context is rooted in gravitational forces endangering any exposed elements at risk. A natural hazard, therefore, represents the potential interaction between humans and their environment. With respect to natural processes, the description of hazard should include the location, volume (or area), classification, and velocity (or pressure), hence, information on its probability of occurrence within a given period of time for a specific location, referred to as frequency, and of a given magnitude. Frequency is conceptualised as the number of occurrences within a given time period, and magnitude refers to scientifically based measures of the strength of physical processes involved. Where measures of magnitude concern impacts of an event on the anthroposphere (such as elements at risk exposed to natural hazards), the term intensity is used instead (Giles 2013). With respect to mountain hazards, assessments are repeatedly based on intensity estimates that incorporate human variables as indices of destruction since direct measurements of process magnitude are not regularly available (van Westen et al. 2006).

Landslides are common natural hazards in mountain regions and can be defined as the downslope movement of soil, rock or debris due to gravitational forces (Crozier 1999) and are triggered by processes such as heavy rainfall, rapid snow melting, earth tremors, slope undercutting, etc. Their impact on society ranges from low (small and shallow landslides in remote regions and less used areas) to high (collapse or burial of buildings and infrastructure, loss of life and loss of agricultural land). Although large magnitude landslides have a low probability, these events result in significant loss of human life throughout European mountain regions (Kilburn and Pasuto 2003). Society contributes to the occurrence of landslides (e.g. through land-use change, road construction) as well as influencing the impact of the events by construction of properties on steep slopes. People are then vulnerable even to small magnitude landslide events (Blöchl and Braun 2005).

In mountain regions, hydrological processes (such as river floods with high transport capacity, flash floods or torrential floods) a further prominent geohazard types. They are triggered by heavy or prolonged rainfall and rapid snowmelt, ice jams or ice break-up, damming of river valleys by landslides or snow avalanches, and failure of natural or man-made dams (WMO 1999). According to United Nations (UN 2002) floods are among the most common, most costly and most deadly hazards. In hazard management in the European Alps two types of river flooding are distinguished: static and dynamic. Static flooding occurs in areas with relatively flat topography. Water levels rise slowly and flow velocity is very slow if the water is moving at all. The damage caused by static flooding is attributed to the influence of the water on the building structure. In dynamic floods, the water movement is much more rapid and affects the elements at risk due to erosion or direct impact.

Snow avalanches are fast moving mass movements that can contain, in addition to snow, rocks, soil and vegetation on ice (Bründl et al. 2010). Avalanches occur due to terrain (inclination, aspect and roughness of ground surface), meteorological (temperature, precipitation, wind speed and direction) and snowpack factors (snowpack structure, depth and water content). Avalanches are classified into two main groups: loose snow avalanches and slab avalanches (the latter are in general most frequently disastrous, see Fuchs et al. 2015). The elements at risk are affected by the air pressure plume in front of the avalanche and/or by the high impact pressure of the snow in motion.

The spatial and temporal overlap of areas used by people and areas impacted by geomorphic hazards has repeatedly led to significant economic losses and fatalities globally. Comprehensive databases on disasters due to natural hazards present world-wide trends which can point to an increasing number of reported events, people affected and economic losses, although there has been a decrease in the number of reported fatalities in the last few decades (e.g., Keiler 2013; CRED 2014; Munich Re 2014). At the regional level, such as the European Alps, data on hazardous events and associated losses are relatively well documented (Fuchs et al. 2013). The overall damages related to hydro-meteorological phenomena (storms, floods and landslides) are shown to have increased significantly in recent decades (EEA 2012). Unfortunately, given duplication of research efforts and administrative responsibilities, several bibliographies and databases concerning hazard inventories exist, which makes comparison challenging. Despite the resulting inconsistency and incompleteness of individual inventories with respect to mountain regions (Eisbacher and Clague 1984; Alger and Brabb 2001), the general event dynamics can be consistently resolved. In Fig. 10.1, the number of hydrological hazards that occurred in the mountain regions of Austria is shown for the period 1900–2014, including the 10-year moving average and the linear trend. While in the early decades of the twentieth century, the 10-year moving average increased from around 50 to 100, the linear trend is higher. A considerable shift in the data trends can is found during the 1960s and early 1970s where the 10-year moving average exceeds the linear trend. Although since 1975 the number of events decreased marginally, and the 10-year moving average falls under the linear trend, there is an increase again from 2000. An average of 163 events (floods, fluvial sediment transport and debris flows) occurs every year, however, some years exhibit a strongly above-average hazard occurrence. Across the European Alps, particularly high economic losses were experienced due to severe floods, landslides and torrent processes in August 2005 and June 2013 (Hilker et al. 2009; Keiler et al. 2010).

Most hazard processes show cyclic or episodic activity, which is influenced by different factors. Climate and environmental changes are increasingly being recorded in the European Alps across several different parameters. Temperature changes in this region have increased at twice the rate of the global average since the late nineteenth century (Auer et al. 2007). Furthermore, precipitation has also increased non-linearly, with significant regional and seasonal differences as well as differences by elevation and aspect within the European Alps (Auer et al. 2007;

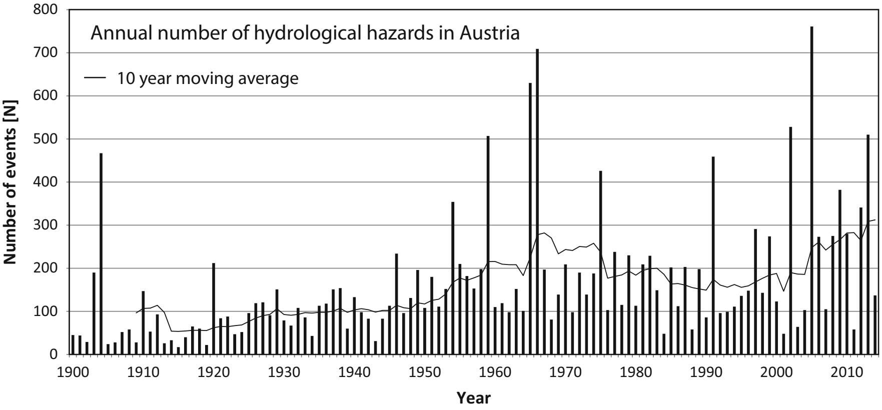

Fig. 10.1 Number of hydrological hazards in Austria for the period 1900–2014 (Data source: Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management 12/2014)

Brunetti et al. 2009; Austrian Panel on Climate Change 2014). Snow and ice are key components of the hydrological cycle since the duration, and depth of seasonal snow cover play an important role within the alpine ecosystem (Beniston 2003) in addition to having an economic influence, for example on tourism, hydro-power and agriculture (Callaghan et al. 2011). Snow cover is also a determinant of potential snow avalanches; indeed, water in general is an important factor influencing geohazards in mountain areas. Permafrost monitoring sites throughout the Alps also show changes in alpine permafrost distribution, temperature profiles, and active layer thickness (Haeberli 2013). While the direct effects of the changing hydro-climate on these systems have now been monitored for several decades, the indirect effects on geomorphological processes and on sedimentary systems are less well known (Sattler et al. 2011). Furthermore, geomorphological processes in high-relief areas are strongly influenced by various interacting factors e.g., slope angle and aspect, weathering, sediment availability, slope moisture supply, and land cover. These processes evolve in a downslope direction, leading to high spatial and temporal variability in the process domain and thus in hazard probabilities. Moreover, changes in cryospheric systems can give rise to ‘downstream’ interconnected geomorphological impacts such as hazard events that represent periods of decreased land surface stability.

Modelling suggests that the nature and magnitude of potential impacts of climate change could be dramatic (Schröter et al. 2005). Improving knowledge of geomorphic processes has led scientists to conclude that the environmental conditions of the past may not be adequately representative of the conditions that may be experienced in the near future (Gibbs 2012). The projected global rise in temperature will have impacts on both the hydrosphere and the cryosphere (e.g., Huggel et al. 2012; Haeberli 2013). Resulting changes in snow and rainfall have implications for snow cover thickness and duration (which also affect subsurface temperatures), and catchment runoff (Stocker et al. 2013). Furthermore, temperature and precipitation changes can also be linked to changes in glacier mass balance and terminus position, in particular at high elevations (Steiner et al. 2008; Diffenbaugh et al. 2013). However changes in temperature, precipitation and, accordingly, in snow parameters, will result in a retreat of glaciers and in permafrost degradation following a time lag. In relation to such effects, the amount of unconsolidated material prone to erosion and remobilisation will likely increase, even if a precise prediction seems to be challenging (Korup et al. 2012). Moreover, the generation of runoff in the high mountains is primarily determined by snowmelt and thus by spring temperature (Stewart 2009) and during summer also by ice melt of the glaciated areas. A fast and early-season onset of snowmelt in the high and mid-elevations may lead to snowmelt-generated floods in the mountains and the lowlands (Diffenbaugh et al. 2013; Meng et al. 2013).

The rise in temperature is accompanied by an increased content of moisture in the lower atmosphere, which results in intensified dynamics with respect to precipitation events (e.g., Foelsche 2005). Due to the expected accentuated precipitation regime, the frequency and magnitude of geomorphic processes such as landslides, torrent processes and floods may be altered and lead to increasingly destructive events (Keiler et al. 2010), although this has so far remained unproven with respect to snow avalanche activity based on documented events (Laternser and Schneebeli 2002). A recent study indicates that changing climate conditions may affect wet snow avalanche activity in respect of timing and elevation of occurrence (Baggi and Schweizer 2009). However, only few papers provide insight into the climatic control of snow avalanches (Eckert et al. 2010) and these do not address recent changes in avalanche activity. Corresponding to the high variability of snow depth and snow cover in mountain areas, possible effects on snow avalanche activity may be expected to cover a wide range from decreasing or increasing occurrence to a shift from dry to wet snow avalanches.

Growing losses are experienced also as a result of increasing population, economic wealth and human activities in general in hazard-prone mountain areas (Keiler 2013). Following the current discussions on changing environmental conditions, vulnerability and exposure are the key terms in reducing disaster losses (Field et al. 2012).

10.3 Exposure

The importance of mountains in the global ecosystem, as well as their provision of livelihood for considerable parts of the world population, has been assessed at the scientific but also political level (Messerli 2012), such as by the United Nations International Decade for Natural Disaster Reduction (UN General Assembly 1989) and the International Year of the Mountains in 2002 (UN General Assembly 1998). Socioeconomic developments have led to an asset concentration over time and a shift in urban and suburban population in the many mountain regions (Slaymaker and Embleton-Hamann 2009). Population density and land use are direct drivers of socioeconomic change in mountain regions. Apart from the overall population number, it is also the population distribution and composition, such as the level of urbanisation and household size, as well as the increasing effects of counter-urbanisation (Löffler and Steinicke 2006) which explains the level of exposure to mountain hazards. Examples include land-use changes, such as deforestation and urban development, but also population growth, migration and the development of traffic infrastructure and tourism facilities (Fuchs et al. 2015). Thus, the assessment of exposure of elements at risk is an important key variable in natural hazard risk management.

Recently, studies related to an assessment of elements exposed to mountain hazards have been carried out in the European Alps, with respect both to long-term and short-term dynamics (Fuchs and Bründl 2005; Keiler et al. 2006). Long-term dynamics are rooted in the significant increase in numbers and values of buildings endangered by natural hazard processes, and can be observed in many mountain regions. Short-term fluctuations in values at risk supplemented the underlying long-term trend, in particular with respect to temporary variations of persons and of vehicles on the road network (Keiler et al. 2005; Zischg et al. 2005). By quantifying a fluctuation model it was shown that strong variations could be observed during the winter season for mountain resorts as well as over daytime (Fuchs et al. 2013).

To provide an example, in Fig. 10.2 the long-term variability of buildings exposed to mountain hazards (hydrological hazards and snow avalanches) is provided for the Republic of Austria. A significant increase in the number of elements at risk of being exposed can be seen for many communities, such as the Federal States of Salzburg, Tyrol and Vorarlberg. In both, urban and rural communities, the total number of buildings exposed to mountain hazards had more than tripled since the 1920s, and the total value rose by a factor of almost 4. From the total of approximately 2.4 million buildings in Austria, around 120,000 are exposed (exposure was defined as located within the respective hazard zones[1]) which is around 5 % of the total real estate with a total value of € 66 billion (hydrological hazards € 60 billion, snow avalanches € 6 billion). Altogether around 430,000 people inhabit these exposed buildings (hydrological hazards 400,000, snow avalanches 30,000) which is around 5 % of the total population in Austria.

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[1] To identify hazard zones, defined design events are used to estimate the spatial range and pressure distribution of the hazard processes. The methodologies applied therefore differ slightly between the Alpine countries, but the principle for drawing up hazard maps is similar; as described below for snow avalanche hazards in Austria (Republik Österreich 1975, 1976). In Austria, red colour on avalanche hazard maps indicates areas where the expected pressure from avalanches with recurrence intervals $T = 150$ years exceeds a limit >10 kPa/m^2. Yellow colour indicates areas where pressure from avalanches with recurrence intervals $T = 150$ years is >1 kPa/m^2 and <10 kPa/m^2. Inside red areas, the construction of new buildings is usually hindered, in some Federal States also legally forbidden. In yellow areas, particular regulations have to be considered with regard to the expected avalanche pressure, such as the reinforcement of walls on the hill side of a building (see also Holub and Fuchs (2009) as well as Keiler and Fuchs (2010) for a related in-depth discussion).

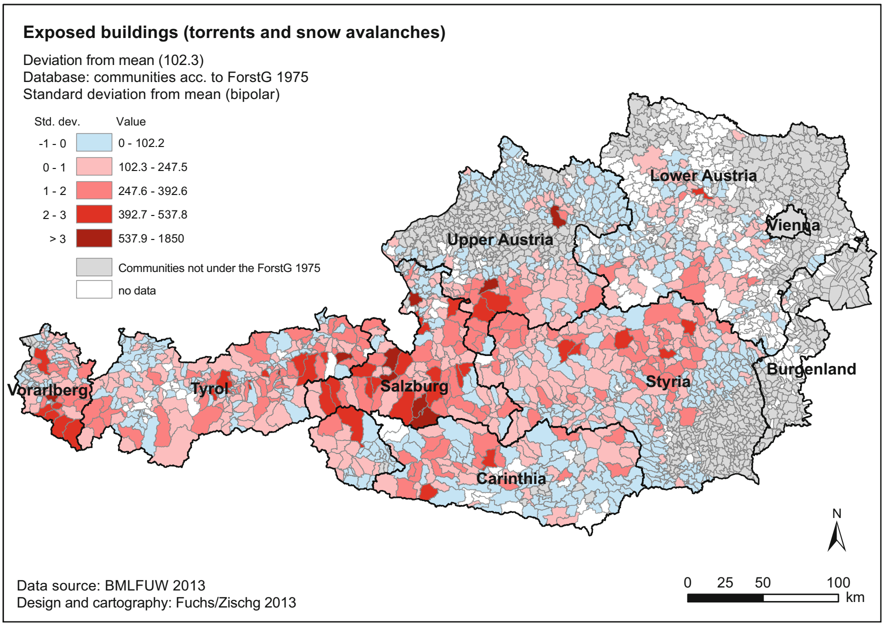

Fig. 10.2 Number of exposed buildings (torrents and snow avalanche), shown as deviation from the mean (102.3 buildings per municipality) (Source: Fuchs et al. (2015))

Both long-term and short-term temporal changes in various elements contribute considerably to the risk level, and should therefore be included in operational risk analyses.

10.4 Vulnerability

As stated by the IPCC (Field et al. 2012) vulnerability is a key factor but also a main source of uncertainty in risk reduction. Only recently has vulnerability assessment of natural hazards emerged as an important research field (e.g. projects within the EU FP 7 such as MOVE, ENSURE, CONHAZ). The consequences of natural hazards are generally measured in terms of losses, either on a metric scale (e.g. in monetary units), or on an ordinal scale based on social values or perceptions and evaluations. Birkmann et al. (2013) present different thematic dimensions of vulnerability in a holistic framework: the social, economic, physical, cultural, environmental and institutional dimension. These dimensions have in common that it is challenging to translate the facets of vulnerability into assessable criteria and indicators (Kappes et al. 2012b). However, the better understanding of contributing factors to vulnerability is an essential need for improving risk reduction.

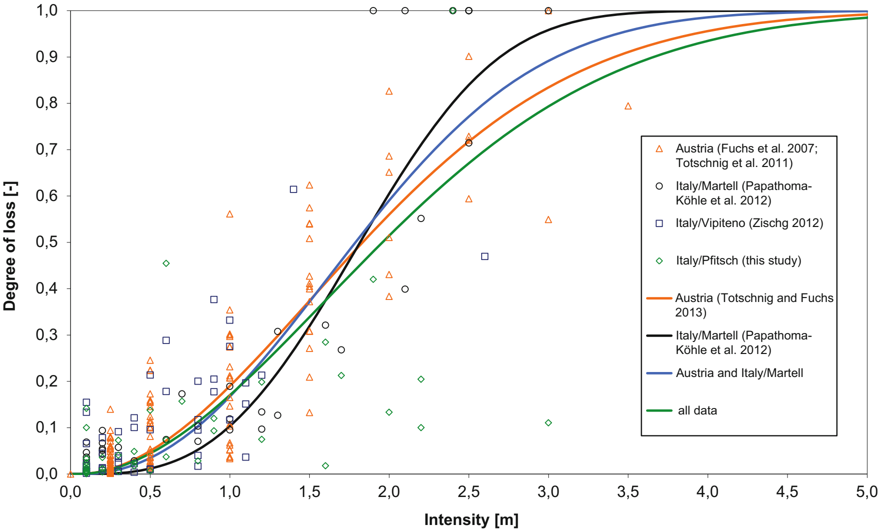

Fig. 10.3 Different vulnerability curves for test sites in the European Alps (Source: Papathoma-Köhle et al. (2015))

In studies related to geomorphology, and as far as physical vulnerability is concerned, vulnerability was defined by UNDRO (1982) as the "degree of loss to a given element, or set of elements, within the area affected by a hazard. It is expressed on a scale of 0 (no loss) to 1 (total loss)". There is no universal method for assessing vulnerability, different assessment methods can be classified in qualitative, semi-quantitative, or quantitative approaches (Fuchs et al. 2011). There are three dominant methods used: vulnerability matrices (Papathoma-Köhle et al. 2012), vulnerability indicators (Birkmann et al. 2013), and vulnerability functions or curves (Fuchs et al. 2007a; Apel et al. 2009; Totschnig et al. 2011, see Fig. 10.3). Additionally, fragility curves have been developed recently (e.g., Merz 2006; Tsao et al. 2010), which express in contrast to vulnerability curves a relation between the intensity of the process and the probability of exceeding certain damage states.

Papathoma-Köhle et al. (2011) provide an overview of different methods and approaches for physical vulnerability assessment developed and applied for different mountain hazard types (floods, landslides, debris flow and torrential processes, rock falls and snow avalanches). Almost all the approaches are based on estimation and general assumptions with few validation data. The general lack of data considering vulnerability (also repeatedly claimed in other studies) and the related uncertainty in the vulnerability quantification may be illustrated by an example. In Switzerland and Austria, events with high losses are followed by detailed event analyses with different foci such as (1) triggering and boundary conditions of the damaging process as well as processes sequences (Bezzola and Hegg 2007) and (2) economic direct losses for payments by insurance companies, national organisations or the administration (Fuchs 2009). Damage patterns and related aspects of processes, buildings and surrounding geomorphological characteristics, however, are to date not necessarily in the focus, and thus these features are not sufficiently documented. Consequently, the development of vulnerability studies is limited to a small number of available damage data (Uzielli et al. 2008; Totschnig and Fuchs 2013). Further challenges exist in assessing or reconstructing the intensity of the geomorphological process on individual buildings (Quan Luna et al. 2011; Jakob et al. 2012) as well as in understanding the interaction between the process and the affected buildings and infrastructure and their spatial distribution (Fuchs et al. 2012).

Vulnerability curves are an essential step within quantitative risk assessment (Bründl et al. 2009) in order to assess the impact of alternative risk reduction strategies and in land use planning (Greiving et al. 2006; Holub and Fuchs 2009) as well as estimating the economic costs of future events under different scenarios, but also in cost-benefit analyses for protection measures (e.g., Fuchs et al. 2007b; Markantonis et al. 2012). Thus, vulnerability assessment plays an essential role in connecting the impact of geomorphological processes and decision processes in society. However, the existing online risk assessment calculation tool, EconoMe (Switzerland), which is used for cost-benefit analysis of mitigation measures (Bründl et al. 2009), only uses a few defined vulnerability parameters for the different hazard types according to defined building functions. The values applied are based mostly on estimation and consequently are a main source of uncertainty. Papathoma-Köhle et al. (2015) focus on the constraints of available data for vulnerability assessment to mountain hazards and developed a toolbox including three functions: (1) enhancement of the post-event damage data collection process, (2) assessment of monetary loss of future events and (3) continuous updating and improvement of an existing vulnerability curve by adding data of recent events.

Additionally, geomorphologists contribute to improved insights on vulnerability to hazardous processes by testing and improving process runout modelling approaches. Based on the study of Akbas et al. (2009) and Quan Luna et al. (2011) three vulnerability curves for debris flows expressing intensity not only as deposition depth but also an impact pressure and kinematic viscosity were developed for each individual building. They derived intensity information of the considered event by numerical modelling using the model FLO-2D. Quan Luna et al. (2011) concluded that the main shortcomings of this study are insufficient data points regarding the affected elements at risk and the variation in values due to the differences in building quality, state, and structural characteristics. Further studies considering vulnerability functions were conducted by Calvo and Savi (2009), testing the integration of different concepts regarding impact forces from processes (e.g. flood waves, avalanches impact pressure, hydrostatic and hydrodynamic forces). Additionally, the uncertainty and constraints of applied hazard models for calculating velocity, processes height/depth and impact forces have to considered in a detailed vulnerability assessment. Recent efforts in the field of vulnerability research include physical-based calculations of vulnerability for buildings according to their individual structural properties and hazard scenarios (Mavrouli et al. 2014; Mazzorana et al. 2014). A drawback of these approaches is the lack of necessary detailed information on buildings and thus they can only be used in limited cases.

The contribution of geomorphology to vulnerability assessment rests on improving physical vulnerability approaches and thus also to a narrowly-defined part of the direct economic vulnerability dimension (Birkmann et al. 2013). Nevertheless, these dimensions of vulnerability are strongly connected to the other dimensions such as social or institutional vulnerability. Physical vulnerability can be viewed as a starting point, which propagate with different effects through the other dimension depending on conditions of the society (Fuchs 2009). Thus, physical vulnerability and the interdisciplinary contributions by geomorphologists to this topic are crucial aspects of vulnerability assessment that are needed to narrow the gap between disciplinary approaches of the sciences and humanities.

10.5 Conclusions

A diverse range of natural hazards has always threatened populations in the European Alps but these natural processes, as well as society itself, have changed over time. Currently, societies in the European Alps are in transformation from a strategic focus on hazard management to a perspective of a risk culture challenged by dealing with increasing losses. Therefore, including exposure and vulnerability in understanding increasing losses as well as for management strategies has become essential, especially considering future environmental changes and socio-economic developments.

Monitoring of hazard processes (events) and analyzing subsequent consequences is crucial to improving an understanding of processes as well as event predisposing and trigger factors. The documentation of hazard events in the European Alps reveals a range of parameters over time. Moreover, an increasing trend in hydrological hazards can be identified, although for snow avalanches thus far no trend is detectable. The current situation regarding hazard processes is strongly connected to the cryosphere and hydrosphere and, in the European Alps a future increase in process activity for most mountain hazard types is assumed.

Strong changes of exposure are evident for the European Alps as indicated by the example of Austria, a situation that will continue to be highly dynamic in the future. Methods for analyzing vulnerability are less developed and complicated by several uncertainties. Monitoring in the context of vulnerability remains to be developed, as does an awareness of this factor as a key element of decreasing losses and risk reduction. However, some recently developed approaches show promise as a means of closing this gap for mountain hazard risk management.

Estimation of the evolution of risk and potential losses induced by mountain hazards in the European Alps remains challenging due to temporal and spatial variability of climatic parameters, the limited knowledge of long-term effects of climate change on hazard processes as well as the dynamics of societal influences on the exposure pattern and changes in vulnerability. Aiming at the application of integrated risk management strategies, links between the different disciplinary perspectives need to be established. Space and time, as well as vulnerability, are appropriate connecting points for such an integrated approach between natural and social sciences (Fuchs and Keiler 2013; Birkmann et al. 2013).

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Chapter 11
Reclamation and Land Consolidation Effects on Organic Matter Sedimentation in Lake Kiba-Gata, Japan

Seiya Nagao, Hong Tuoi Bui, Yuriko Kawano, Tomoyo Suzuki, Shinya Ochiai, Koyo Yonebayashi, Masanori Okazaki, Akiko Goto, Takashi Hasegawa, and Masayoshi Yamamoto

Abstract The effects of reclamation and land consolidation on organic matter sedimentation were studied in a small lagoon, Kiba-gata, which is one of the three Kaga lagoons (Shibayama-gata, Imae-gata, and Kiba-gata) located in central Japan. Reclamation work was conducted during 1954–1969 to increase the paddy field area and to improve the drainage system. Lake Kiba-gata was affected by changes in the drainage system and land consolidation around the lagoon. A sediment core was obtained in the central part of Lake Kiba-gata in June 2012. The organic matter flux recorded in the sediment core increased from 1.1 to 2.3 and from 3.9 to 7.5 g cm^{-2} $year^{-1}$, respectively, during 1903–1974 and 1989–2012, although it was similar to the flux recorded for 1974–1989 following reclamation. The C/N ratio, $\delta^{13}C$, and $\delta^{15}N$ values also changed during these time intervals. These results indicate that the primary productivity in the lagoon is increasing with time and that the recent contribution of phytoplankton to productivity has exceeded the level of past contributions because of changes in drainage and increase in human activity around the lake due to the reclamation and land consolidation.

Keywords Human impact • Carbon isotopes • Nitrogen isotopes • C/N ratio • Sedimentary organic matter • Sedimentation rate

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11.1 Introduction

Lakes are globally important water resources for human uses such as drinking water, agricultural irrigation, industry and hydroelectric power generation. Reclamation work, the process of creating new land from lakes, rivers, and coastal marine environments, is an important mode of human impact on aquatic environments. Land reclamation in and around lakes was prevalent in many parts of Japan during the 1950s–1970s (e.g., Hachiro-gata, Lake Nakaumi, Kahoku-gata) in order to facilitate increased food production, but there were negative consequences, including lake shrinkage, water quality deterioration and dramatic changes to lakeshore ecosystems (Saito 1964). Closed and semi-closed lakes, which have no substantial surface or subsurface outflow, are particularly sensitive to human activities such as agricultural and industrial activities and reclamation projects. In order to better understand the effects of reclamation on the aquatic environment, it is important to study changes in organic sedimentation processes because the quantity and quality of organic matter in sediments reflects the dynamics of production and accumulation rates in lakes.

The three Kaga lagoons (Shibayama-gata, Imae-gata, and Kiba-gata) are located in the central part of Japan (Fig. 11.1) and surrounded by lowlands. The lagoons

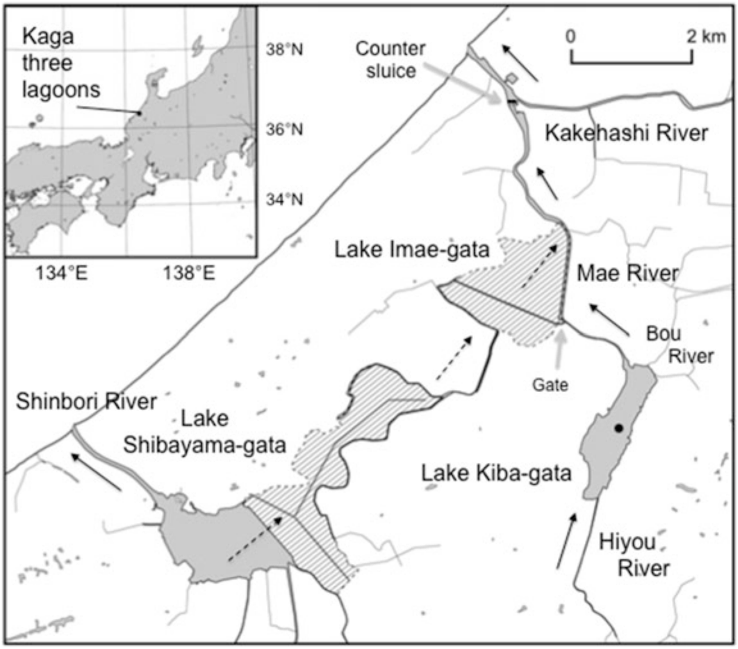

Fig. 11.1 Sampling locations around Lagoon Kiba-gata, central Japan. Reclaimed land is shown as *shaded areas*. The *black spot* in the centre of Lake Kiba-gata shows the sampling location of the sediment core used in this study. *Dashed arrows* indicate the water flow direction prior to reclamation. Numerical map data are based on Fundamental Geospatial Data provided by the Geospatial Information Authority of Japan, and National Land Numerical Information provided by the Ministry of Land, Infrastructure, Transport and Tourism, Japan

were previously subject to frequent floods from counter-currents of the Kakehashi River, which was the only outlet for water from these three lagoons. The drainage capacity in these lowland areas is generally rather poor and most of the farmland was flooded frequently (Ishikawa Prefectural Government 1986). Water in the lagoons flowed from Shibayama-gata and Kiba-gata into Imae-gata through the Mae River to the Kakehashi River. Imae-gata, a brackish lake, had chloride concentrations of 1–10 g l^{-1} (Mashiko 1976) because of backflow from the Sea of Japan through the Kakehashi River. The frequent floods occurred especially following the subsidence of farmland caused by the Fukui earthquake in 1948. The local residents and communities have been making strong claims for the consolidation and improvement of drainage around their farmland (Hokuriku Regional Agricultural Administration Office 1970).

A reclamation project, “Kaga three lagoons reclamation project” was planned in the early 1950s to improve drainage in the lowlands and to increase the productivity of surrounding farmland. The reclamation work was undertaken to open a new channel (Shinbori River, Fig. 11.1) to divert floodwaters from the related basins into the sea and the reclamation of Imae-gata and two-thirds of Shibayama-gata over the period 1954–1969 (Shigemi et al. 1966; Hokuriku Regional Agricultural Administration Office 1970). Lake Kiba-gata was left untouched by reclamation because it plays an important role in irrigation and flood attenuation around the lowland area. Nevertheless, reclamation work was carried out in the wetlands around Lake Kiba-gata and farmland consolidation and the construction of flow channels were also conducted. The drainage system was therefore changed substantially as a consequence of this reclamation and the Shibayama-gata water system was separated from the Imae-gata and Kiba-gata systems. The present water flow direction is presented in Fig. 11.1.

This study was conducted to assess the diverse effects of reclamation, including the impacts of drainage adjustment on the environment of a small and semi-closed lagoon, Lake Kiba-gata. The sedimentation of organic matter in the lagoon was investigated using a sediment core sample collected from the central part of Kiba-gata in June 2012. Organic matter preserved in lake sediments can provide key information related to lacustrine nutrient dynamics as a function of the historical watershed scale land use change and input of nutrients from the watershed (Meyers 1994; Meyers and Teranes 2001). The total organic carbon/ total nitrogen (TOC/TN) ratio, δ^{13}C, and δ^{15}N are parameters that are useful in ascertaining organic matter sources in lakes and lagoons (e.g., Yoshioka et al. 1988; Brenner et al. 1999; Lawson et al. 2004; Das et al. 2008). We measured these parameters to investigate the sources of sedimentary organic matter and to assess its dynamics over time in Lake Kiba-gata.

Therefore, the objectives of this study are to assess earth surface processes, especially erosion and transport of geomaterials and their effects on the aquatic environment as a consequence of reclamation and consolidation work in relation to Lake Kiba-gata. The changes in organic matter deposition are highly sensitive to catchment and lake dynamics and continuous records for the changes in aquatic environment are recorded in the sediment (Meyers 1994; Meyers and Teranes 2001).

11.2 Materials and Methods

11.2.1 Sampling Location

Lake Kiba-gata is located in the Kaga area of Ishikawa Prefecture in Japan (Fig. 11.1). Lake Kiba-gata has a mean water depth of 1.7 m, area of 1.14 km^2, and water volume of 1.7×10^4 m^3. The watershed area is 38 km^2. The chemical oxygen demand (COD) concentration was at a maximum, 11 mg l^{-1} in 1990, and has remained about double the national standard of this lake class (3 mg l^{-1}) over the last decade (Komatsu City Government 2014). Suspended solid concentrations were 12–21 mg l^{-1}, and total nitrogen and phosphorous were 0.92–1.3 mg l^{-1} and 0.066–0.11 mg l^{-1}, respectively in 2000–2011 (Komatsu City Government 2014). Bottom sediments consist mainly of silt, although the inflow area of the Hiyou and Bou Rivers is characterized by sandy sediment (Sekito et al. 2006).

11.2.2 Sampling and Pretreatment

Using a gravity core sampler (HR-type, Rigo Co., Japan), a sediment core of 27 cm was obtained in 2012 from the central part of the lagoon in order to avoid the influence of direct fluvial input (Fig. 11.1). The sediment core was sliced into subsamples at 1 cm intervals. To study the sources of lake sedimentary organic matter, in 2013 we collected suspended solids in the surface waters in the central part of Lake Kiba-gata using a plankton net sampler (NXX17, mean mesh size of 0.072 mm). We also collected the suspended solids using continuous flow centrifugation (Nagao et al. 2005) on 23 July and 2 October 2014. All sediment and suspended solid samples were freeze-dried and ground in an agate mortar.

11.2.3 Analytical Methods

The water content of the sediment samples was estimated from weight loss following freeze-drying. Grain size distribution was measured using a laser diffraction particle size analyzer (SALD-2200; Shimadzu Corp., Japan). The freeze-dried and ground samples were treated with 1M HCl to remove inorganic carbon for analyses of total organic carbon (TOC), total nitrogen (TN), and stable carbon and nitrogen isotope ratios. The TOC and TN contents were measured using the elemental analyzer (2400 Series II; PerkinElmer Inc., USA). The precision of TOC and TN analyses was, respectively, ±0.009 % and ±0.003 %. The stable carbon and nitrogen isotope ratios were analyzed with mass spectrometers of three types (IsoPrime EA, GV Instruments Ltd., UK; DLTA plus and DELTA V Advantage, Thermo Fisher Scientific Inc., USA). Stable carbon and nitrogen isotope ratios are shown as $\delta^{13}C$ values relative to VPDB and $\delta^{15}N$ relative to atmospheric N_2 as:

$$\delta^{13}C, \delta^{15}N = (R_{sample}/R_{standard} - 1) \times 1000$$

whereby: R_{sample} and R_{standard} denote the $^{13}C/^{12}C$ or $^{15}N/^{14}N$ atomic ratios of sample and international standard respectively. The reference materials USGS40 ($\delta^{13}C_{VPDB} = -26.39$ ‰, $\delta^{15}N_{air} = -4.52$ ‰), L-Alanine ($\delta^{13}C_{VPDB} = -19.6$ ‰, $\delta^{15}N_{air} = 1.6$‰), ANU-sucrose ($\delta^{13}C_{VPDB} = -10.80$ ‰), IAEA-N1 ($\delta^{15}N_{air} = 0.4$ ‰), and IAEA-N2 ($\delta^{15}N_{air} = 20.3$ ‰) were used to calibrate the measurement results. The precision of $\delta^{13}C$ and $\delta^{15}N$ analyses was, respectively, ±0.18 ‰ and ±0.31 ‰.

The ^{210}Pb and ^{137}Cs radioactive concentrations were measured in order to establish a chronology with a view to estimating the sedimentation rate of the core. First, 10 g of powdered samples was pressed into discs (0.5 cm thickness, 5.0 cm diameter) using a hydraulic press and sealed in a plastic bag. After establishing the radioactive equilibrium between ^{222}Rn and ^{214}Pb (about one month), the activity concentrations of ^{210}Pb (46.5 keV), ^{214}Pb (352 keV), and ^{137}Cs (661.6 keV) were determined using gamma-ray spectrometry with a Ge detector (LO-AX-51370-20; Ortec, USA). The activity of excess ^{210}Pb ($^{210}Pb_{ex}$) was estimated by subtracting the activity of ^{214}Pb from that of ^{210}Pb. The sedimentation rate of the cores was then estimated based on the $^{210}Pb_{ex}$ as a function of mass depth (Krishnaswamy et al. 1971; Appleby and Oldfield 1978) and obtained by fitting results of the constant rate of supply (CRS) model (Kanai et al. 1995). The sediment layer dating were interpolated from the estimated sedimentation rate.

11.3 Sediment Physical Properties, Organic Matter and Age Model

Profiles of basic parameters are presented in Fig. 11.2. The water content decreases from 79 to 51 % with depth in the core. Mean grain size increases with core depth from 11.5 to 24.5 μm, although four minor peaks are apparent. ^{137}Cs activity reaches a maximum at depth of 11–12 cm, but the radioactivity is almost constant with depth in the surface layer. This vertical profile is not a consistent trend and is affected by changes in inflow flux of ^{137}Cs from the watershed. Therefore, we do not use ^{137}Cs profile to estimate the sedimentation rate. $^{210}Pb_{ex}$ activity decreases with increasing depth from 0 to 9 cm, remains constant between 9 and 12 cm depth and again decreases with depth from 12 to 22 cm. The basal sediments of the core are estimated on the basis of $^{210}Pb_{ex}$ activity and is estimated to be shortly before

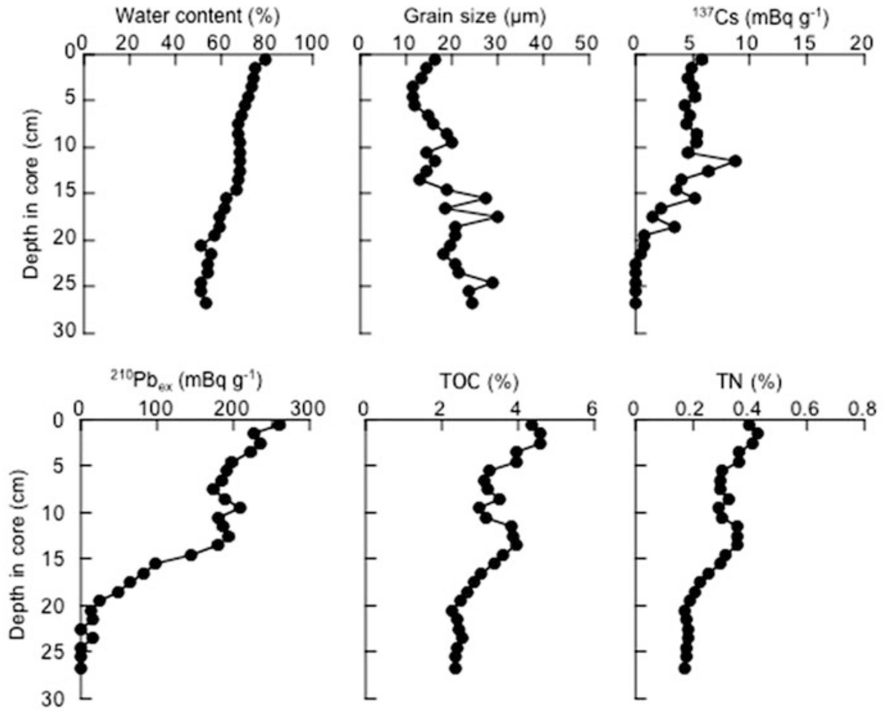

Fig. 11.2 Water content, grain size, ^{137}Cs and excess ^{210}Pb radioactivity, total organic carbon (*TOC*) and total nitrogen (*TN*) contents of the sediment core sample from Lake Kiba-gata

1890. The sedimentation rate changes between the three depth intervals and is estimated as 0.11–0.16 g cm^{-2} year^{-1} (average 0.14 ± 0.02 g cm^{-2} year^{-1}) at depths of 0–9 cm, 0.07–0.09 g cm^{-2} year^{-1} (average 0.08 ± 0.01 g cm^{-2} year^{-1}) at 9–12 cm and 0.04–0.06 g cm^{-2} year^{-1} (average 0.05 ± 0.01 g cm^{-2} year^{-1}) at depths of 12–22 cm by the CRC model. Total organic carbon (TOC) contents were 2.34–2.36 % at a depth of 25–27.4 cm and 4.37–4.59 % in the surface layer of 0–3 cm. The profile of TOC content varies with depth and shows a similar variation pattern to that exhibited by ^{210}Pb$_{ex}$ and total nitrogen (TN) content.

11.4 Accumulation of Organic Matter and Its Characteristics

The parameters of sedimentary organic matter are depicted in Fig. 11.3. The organic matter flux was estimated using the sedimentation rate and organic carbon content in the sediment core. The flux increased from 1.13 to 2.26 mg C cm^{-2} year^{-1} and from 2.66 to 7.46 mg C cm^{-2} year^{-1} in two sedimentation steps during 1978–1989 and

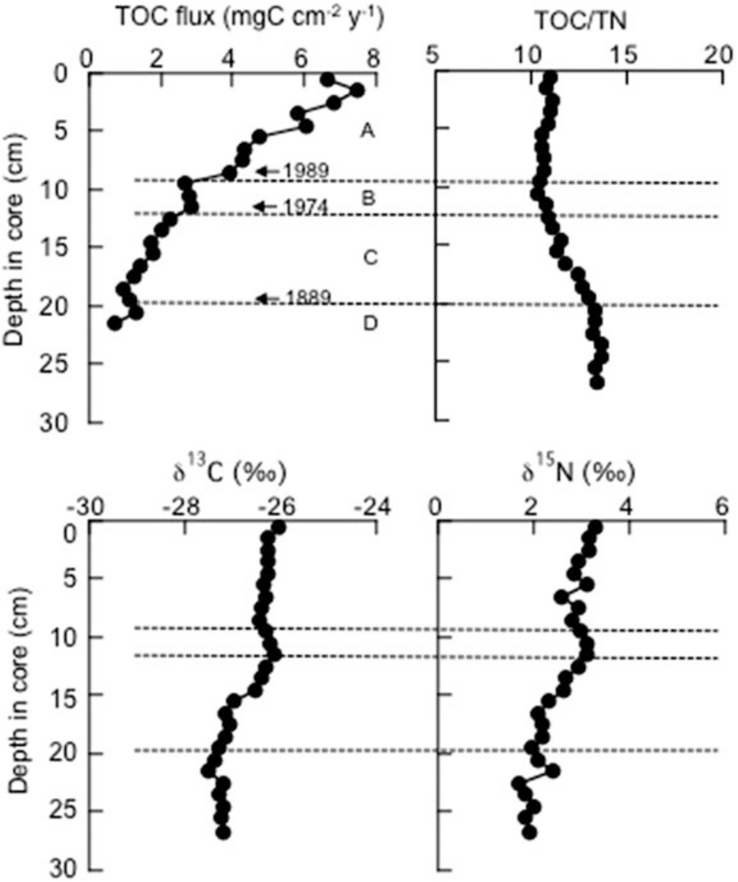

Fig. 11.3 Total organic carbon (*TOC*) flux, TOC/total nitrogen (*TN*) ratio, δ^{13}C of organic mater and δ^{15}N of total nitrogen as a function of core depth for the sediment core sample from Lake Kiba-gata

1989–2012 respectively. The rate of increase during the most recent interval is three times higher than in the past. These results suggest that eutrophication and organic sedimentation occurred following reclamation. From the variation trend, the TOC flux is divisible into four time intervals identifiable, from the base of the core upwards as A: almost constant until around 1900; B: increasing from 1903 to 1968; C: constant during 1974–1984; D increasing from 1989 to present (i.e. 2012).

The C/N ratio, δ^{13}C, and δ^{15}N values also vary among these sediment layer intervals. The C/N ratio remains almost constant (10.7–11.0) with depth during period D, but decreased from 12.7 to 10.9 during period B. The C/N ratio was almost constant, around 10.5 ± 0.2 during period C, and 13.4 ± 0.2 in period A. This range of C/N ratios corresponds to the mid-range of values between those of algae and terrestrial plants (Meyers 1994). The mixture of both sources varies with each time interval due to the changes in primary production of phytoplankton and the supply of terrestrial plants from the lake watershed.

Sedimentary organic matter in Lake Kiba-gata exhibited $\delta^{13}C$ values of −27.5 to −26.0 ‰. The $\delta^{13}C$ value increases slightly in magnitude from −26.4 ‰ to −26.0 ‰ and from −27.2 ‰ to −26.3 ‰ in periods D and B respectively. In periods C and A, the $\delta^{13}C$ value is almost constant, -26.3 ± 0.09 ‰ and -27.2 ± 0.1 ‰ respectively. The $\delta^{13}C$ value was −27.5 ‰ for the TOC collected by the plankton net (7.65 % of TOC and 9.1 of C/N ratio) on 6 June, 2013 and was −22.8 ‰ to −23.5 ‰ for the TOC including phytoplankton (21.6–27.0 % of TOC and 5.1–5.9 of C/N ratio) on 23 July and 2 October 2014, respectively, in Lake Kiba-gata. These values are more enriched than those generally reported (−30 to −25 ‰) for other lakes (Yoshioka et al. 1988; Meyers 1994; Meyers and Lallier-Vergès 1999; Vuorio et al. 2006). The $\delta^{13}C$ values of TOC shifted from −27.5 ‰ in June to −22.8 ‰ at the end of July in Lake Kiba-gata. Eutrophic lakes generally have great potential to exhibit large spatial and temporal variations in $\delta^{13}C$ of phytoplankton because of dense algae blooms (Mizutani and Wada 1982; Goericke et al. 1994). The pH of Lake Kiba-gata surface water was 6.7–9.5 during the year and was maximal during spring–summer (Sawada et al. 1988). The vertical distribution of pH exhibits decreasing values with depth (Sawada et al. 1988). A similar trend was observed at the monitoring station in the center of Lake Kiba-gata in 2013 (Nagao, unpublished data). This fact reflects that the phytoplankton growth increases in the surface depth layer during spring–summer. Therefore, the shift of $\delta^{13}C$ values of POC in surface lake waters during spring–summer is considered to be the effect of growth of phytoplankton in the small lake, Kiba-gata. The upper Kakehashi River exhibited a $\delta^{13}C$ value of −27.5 ‰ on 30 September 2014. Results indicate that the current organic matter characteristics in the Kiba-gata sediment shifted due to phytoplankton properties.

The $\delta^{15}N$ value of total nitrogen across the entire Kiba-gata sediment core ranges from 1.82 to 3.30 ‰. The $\delta^{15}N$ value slightly increased from 2.81 ‰ to 3.30 ‰ and from 2.17 ‰ to 2.92 ‰, respectively, during periods D and B. In periods C and A, the $\delta^{13}C$ value remains almost constant (3.06 ± 0.07 ‰ and 1.97 ± 0.23 ‰ respectively). The $\delta^{15}N$ value was 6.64 ‰ for the suspended solids collected using a plankton net on 6 June, 2013 and was 2.33 ‰ on 23 July 2014 and 5.43 ‰ on 23 July and 2 October 2014 for the suspended solids including phytoplankton. The trend resembles that of the $\delta^{13}C$ value of sedimentary organic matter. Despite the very real potential for diagenetic biasing of the initial source character of organic matter, several parameters (C/N ratio, $\delta^{13}C$, and $\delta^{15}N$ values) that describe composition of bulk organic matter provide reliable evidence of its sources (Meyers 1994; Meyers and Lallier-Vergès 1999).

11.5 Effects of Reclamation and Land Consolidation

The marked and rapid changes may be related to the reclamation and land consolidation that occurred in Lake Imae-gata and Shibayama-gata during 1954–1969. Hydrological conditions were changed due to land reclamation of Shibayama-gata and Imae-gata, the establishment of paddy fields around Lake Kiba-gata and the construction of the Mae River gate (Fig. 11.1). The Cl concentration in surface waters was 27–30 mg l^{-1} for Kiba-gata and 30 mg l^{-1} for Shibayama-gata in 1960 (Kanetsu 1973). However, in 1987, slightly lower values of 12–22 mg l^{-1} were recorded (Sawada et al. 1988) and 12–13 mg l^{-1} in July–December 2014 as measured in this study. Rainfall values remain similar over time, being 2548 mm in 1960 and 2635 mm in 2014 (Japan Meteorological Agency 2014). Therefore, different levels of dilution of the lake waters by rainfall appears unlikely. The results reflect decreased inflow of brackish water from the Kakehashi River due to the reclamation and the establishment of a counter sluice at the junction of the Kakehashi River (Fig. 11.1). Increased organic carbon contents in recent sediments commonly derive from human and industrial activities, reflecting the eutrophic status of a system (e.g. Meyers 1994).

Changes in the aquatic system were also observed for other water properties. The level of transparency fell from 4.8 m on average in October and November 1910 (Ishikawa Prefectural Fisheries Experimental Station 1912), 1.3–2.4 m in 1930 (Kawa 1969) to 0.5 m in 1987 (Sawada et al. 1988). Aquatic plants such as water caltrop and water snowflake in Lake Kiba-gata disappeared in 1980 (Editorial Committee of Kiba Town History 2009). Also, the COD concentration reached a maximum value in 1990 (Komatsu City Government 2014). The surface lagoon water pH was 6.6–7.8 in June 1974 and September 1976 (Sumita and Watanabe 1979), but 6.7–9.5 on average 8.5 during 1987. The suspended solids in the upper of Kakehashi River water exhibited 12.8 for the C/N ratio, −27.5 ‰ for δ^{13}C of organic matter, and 3.38 ‰ for δ^{15}N. However, the suspended solids in the surface lake waters from Kiba-gata were 5.1–9.1 for the C/N ratio, −27.5 to −22.8 ‰ for δ^{13}C of organic matter, and 2.33–6.64‰ for δ^{15}N value. The C/N ratio, δ^{13}C, and δ^{15}N of the recent sediment samples have shifted to those of lake suspended solids including phytoplankton rather than those of terrestrial plants in the upper part of river. The results indicate that primary productivity in the lake is increasing over time and that the contribution of organic matter has shifted to phytoplankton. This inference is consistent with the variation of TOC flux and characteristics of organic matter recorded in the sediment core after "the Kaga three lagoon reclamation project" and the land consolidation work around Lake Kiba-gata during 1954–1969.

11.6 Conclusions

Impacts of human activity on water quality and on the transport and deposition of sediments in aquatic environments are particularly strong in small, semi-closed, and closed lakes. This study examined organic matter sedimentation in a lake over the last hundred years and explored the impact of a reclamation project conducted during 1954–1969. Organic matter content and quality analysis provide information of the changes in erosion, deposition and water quality by reclamation and land consolidation. A sediment core was collected at the central part of Lake Kiba-gata, a semi-closed and small lake in June 2012. The organic matter flux increased during 1978–2012 in two sedimentation steps during 1978–1989 and 1989–2012. The flux in the later period increased to twice that of the former period. The C/N ratio, $\delta^{13}C$, and $\delta^{15}N$ values show similar variation. The parameters in 1989–2012 are lower in C/N ratio and higher in $\delta^{13}C$ and $\delta^{15}N$ than those in 1978–1989. The inflexion point is related to the reclamation and land consolidation of Lake Imae-gata and Shibayama-gata during 1954–1969, as indicted by changes in hydrological conditions. These results indicate that deposition of organic matter supplied from forest and paddy filed increases by the increase in erosion. The primary productivity in the Lake Kiba-gata is also increasing and the organic matter contribution to the sediment has shifted to phytoplankton because of the increased residence time of water as a result of reclamation and land consolidation, although organic matter supplied from forest and paddy fields increases with increasing erosion. The organic matter fluxes recorded in the sediment core reveal a continuous loading record from the catchment and can be used as a benchmark against which to assess the impacts of reclamation and consolidation. Such studies are useful to assess the changes in the catchment and their possible effects on local communities and their activities including agriculture and forestry.

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Chapter 12
Impact of Short-Term Flooding on Livelihoods in the Kenya Rift Valley Lakes

Joy A. Obando, Simon Onywere, Chris Shisanya, Anthony Ndubi, Dan Masiga, Zephania Irura, Nicholas Mariita, and Haron Maragia

Abstract Short term flooding episodes can have devastating impacts on both the natural processes and community livelihoods. The Lakes Baringo, Bogoria, Nakuru and Naivasha lie within the arid and semi-arid northern part of the central rift valley in Kenya and are vulnerable to climatic variability with particular challenges related to water resources. This chapter presents the extent of flooding of four lakes in the central rift valley in Kenya over the period from January 2010 to December 2014. Documentation of the changing spatial extent of the water levels in the four lakes was conducted using Geographic Information Systems (GIS) digital

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techniques and information extraction and representation from selected Landsat satellite image data for the years 2010, 2013 and 2014. Results show an increase in the lake levels over the study period and the extent of flooded areas that is highly influenced by the geomorphology of the environs of the lakes. The rising lake levels have affected the ecology of the riparian areas of the lakes thus impacting on the biodiversity, wildlife, tourism infrastructure and the settlements around the lakes. The communities settled especially around Lake Baringo have been displaced and their livelihoods affected.

Keywords Central rift valley lakes • Geomorphology • Lake level rise • Flooding impacts • Livelihoods

12.1 Introduction

The changing global environment continues to have an impact on both natural processes and community livelihoods. Increasing population and pressure on the environment, together with a variable climate, have resulted in numerous livelihood challenges. In Kenya, more than 80 % of the land area is classified as arid and semi-arid land (ASAL) (Sombroek et al. 1982; Jaetzold et al. 2010). These ASALs have low fertility, fragile soils with low nutrient content, low organic matter content and poor physical properties for water infiltration and storage. Increases in human population and livestock numbers over the years in the ASALs have caused pressure on available natural land resources, including vegetation, soils and water. This has resulted in past as well as current land degradation processes of varying types and magnitude. The dynamics of population and livestock pressure, when considered in the light of changing land tenure, arising from changing lifestyle of the inhabitants from pastoralism to sedentarization or accommodation of agro-pastoralism practices, are likely to accelerate the processes of land degradation. Lakes Baringo and Bogoria located in Baringo County, and Lakes Naivasha and Nakuru situated in Nakuru County, are within the ASAL area of the Central Rift Valley in Kenya. Baringo County has a projected population of 700,628 in 2017, up from 555,561 recorded in the 2009 population census (Baringo County CIDP 2014; Kenya National Bureau of Statistics 2013); the Nakuru County population is projected to increase to 1,925,296 in 2017, increasing from 1,603,325 in the 2009 population census (Nakuru County 2013; Kenya National Bureau of Statistics 2013). There is accordingly more pressure on the land and the natural resources than ever before. Baringo County's economy is largely livestock related, accounting for 70 % of the county's income and providing employment to 90 % of the population (Government of Kenya 2010). The rest of Baringo's economy is supported by the tourism industry.

All four lakes under consideration lie within the ASAL of the Central Rift Valley of Kenya, which is part of the Greater Eastern African Rift Valley System. These lakes are internationally recognized as Ramsar sites (www.Ramsar.org) due to their significant biodiversity. Three of the lakes, Bogoria, Naivasha and Nakuru, are incorporated within national parks and are well known tourist destinations in Kenya. Lake Baringo also attracts a significant number of tourists despite it not being a reserve. The lake is situated within an area of marginal farming, with communities mainly engaged in pastoral and agro-pastoral farming around the riparian area of the lake, with some irrigation activities at Perkerra Irrigation Scheme.

Lakes Bogoria and Nakuru are alkaline and are confined within grabens bordered by steep escarpments bordering them to their east and west. Lakes Naivasha and Baringo are freshwater lakes and are more open lake systems surrounded by substantial plains. All the lakes are endorheic and have no modern surface outlets. The area of the lakes is in general characterized by low and very erratic annual rainfall totals (Jaetzold et al. 2010). Sustainable management of these fluctuating tropical lake ecosystems remains a pressing priority on account of their catchments being degraded catchment due to intensive cultivation, subsistence farming and ever expanding urban settlements (Onywere et al. 2012). These activities influence the quantity of surface runoff and discharge feeding the lakes and subsequently faunal and floral community in the lakes. Key characteristics of the four lakes are summarized in Table 12.1.

Studies by Johansson and Svensson (2002) indicate that anthropogenic changes have had significant effects on the lake levels and their ecological quality has continued to decline. Awange et al. (2013) have, for example, shown the probable impact of anthropogenic activities leading to a decline in Lake Naivasha levels over the period 2002–2010. The effects of invasive water hyacinth in Lake Naivasha and the high nutrient loading impacting on the physicochemical characteristic and phytoplankton productivity have also been documented (Mironga et al. 2012). Aloo (2002) reports that the depth of Lake Baringo decreased from a maximum of 9 m and a mean of 5.6 m in 1972 to a maximum of 4 m and mean of 2.5 m (in 2002) due to increased magnitude of siltation, evaporation, damming and diversion of the inflowing rivers. Ochieng et al. (2007) found that some parts of the central rift valley lakes are more polluted, with Lake Nakuru having relatively higher concentrations of heavy metals that point to anthropogenic addition from industries in Nakuru town.

Harper et al. (2003) document the ecology of Lake Bogoria, and Vareschi (1982) for Lake Nakuru. The Bogoria and Baringo wetlands have been subjected to increasing human impacts through irrigation and tourism (Owen et al. 2004). The negative effects of the invasive shrub *Prosopis juliflora* on the local ecosystem in the Lake Baringo area have been an issue of concern (Mwangi and Swallow 2005; Gichua 2013). The chemical, physical and biological properties of the lakes are influenced by catchment hydrology, which influences the conductivity and alkalinity of the water with significant knock-on effects on phytoplankton population (Oduor and Schagerl 2007).

Previously unpublished records of the Eastern African Rift Valley lakes levels in Kenya show a significant rise in the levels and flooding of the mudflats and ring of acacia forest around the lakes in 1901 and 1963. The current flooding being

Table 12.1 Key characteristics of the Lakes under average conditions

Characteristics	Lake Baringo	Lake Bogoria	Lake Naivasha	Lake Nakuru
Latitude, Longitude	0°38′N, 36°05′E	14°25′N, 36°6′E	0°45′S, 36°20′E	0°18′S, 36°4′E
Altitude (amsl)	1000	990	1890	1759
Surface area (km^2)	207	34	160	40
Mean depth (m)	2.5	5.4	3–6	0.5–3.5
Volume km3	930	0.231	5.0	0.159
Catchment area (km^2)	6820	700	3200	1800
Mean annual temperature (°C)	30	28	23	24
Conductivity (μScm^{-1})	894.4	31046.4	374.3	49,000
Turbidity	69.24	45.66	48.1	111.3
Inflow rivers	Molo, Ol Arabel, Mukutan, Ndau	Sandai, Loboi, Emsos	Malewa, Gilgil	Makalia, Nderit, Naishi, Njoro, Larmudiak
Annual pptn mean (mm)	675	500–1000	1000	750
Nature of water	Freshwater pH 8.26	Alkaline pH 9.07	Freshwater pH 8.1	Alkaline pH 9.85
County of location	Baringo	Baringo	Nakuru	Nakuru

Sources: Water Resources Management Authority (2013), Odada et al. (2006), Kiage and Liu (2009), Bhandari (2005), Bergner et al. (2003), Hickley et al. (2003)

witnessed suggests a return of a 50-year cyclic climatic event. Conway et al. (2005) provide analysis of the impacts of rainfall extremes in 1961 and 1997 and the flooding of Lake Victoria and other Eastern African lakes. The four lakes were reported in September 2011 to have rising floodwaters (Onywere et al. 2012, 2013). The diverse range of environmental problems in the lakes are problematic for several reasons: Ochieng et al. (2007) conclude that all the four lakes are ecologically significant because they provide habitats for bird wildlife and are important economically for the fishing industry (Naivasha and Baringo), drinking and irrigation water and as major tourist attractions. This chapter aims to examine the nature of lake level changes during the recent past and to explore the potential impacts of these changes.

12.2 The Study Area

The Lakes Baringo, Bogoria, Nakuru and Naivasha (Fig. 12.1) lie within the arid and semi-arid Central Rift Valley of Kenya. The lake ecosystems have received attention as environmental hotspots (UNEP 2009). Lake Baringo, Kenya's third largest freshwater lake, has a catchment that is characteristic of semi-arid environments and faces many challenges among which soil erosion and water pollution rank highest and which have direct implications for human health (Johansson and Svensson 2002; WRMA 2013). The drainage into Lake Baringo through the Molo River, which collects water from the Mau Escarpment as far south as Elburgon forest, is structurally controlled and follows the troughs between the fault scarps or the base of fault scarps. The river drains through the Loboi plain into the lake. The Ndoloita hot springs are also controlled by Ndoloita fault scarp and this input drains into Loboi Swamp just to the north of Lake Bogoria; the swamp forms part of the drainage of Lake Baringo.

Lake Naivasha is also a freshwater lake, and has been well studied due to its importance and high economic value as a centre of Kenya's floricultural industry – a top foreign exchange earner for the country (Harper et al. 2011). The lake also supports fishing and water supply to settlements around the lake as well as the geothermal plant at Olkaria. It is also a valuable fresh water resource and habitat to a diverse population of water birds and large mammals, including hippopotamus (UNEP 2009). Lake Naivasha has continued to be over-exploited for various reasons, including water abstraction for horticultural irrigation, geothermal power exploration (Mariita 1995) and domestic water supplies. A prolonged drought in Kenya in 2009–2010, together with ongoing resource exploitation, caused the lake to recede to its lowest level since the late 1940s (Harper et al. 2011; Onywere et al. 2013). Water abstraction for agriculture, deforestation in the catchment, diversion of inflow, nutrient, sediment and chemical runoff into the lake and invasive species are all major concerns for the Lake Naivasha's future (UNEP 2009).

Lake Bogoria is a narrow N-S elongated soda lake lying in a trough formed between a fault-fragmented eastward sloping Kipngatip plateau of phonolite lava to

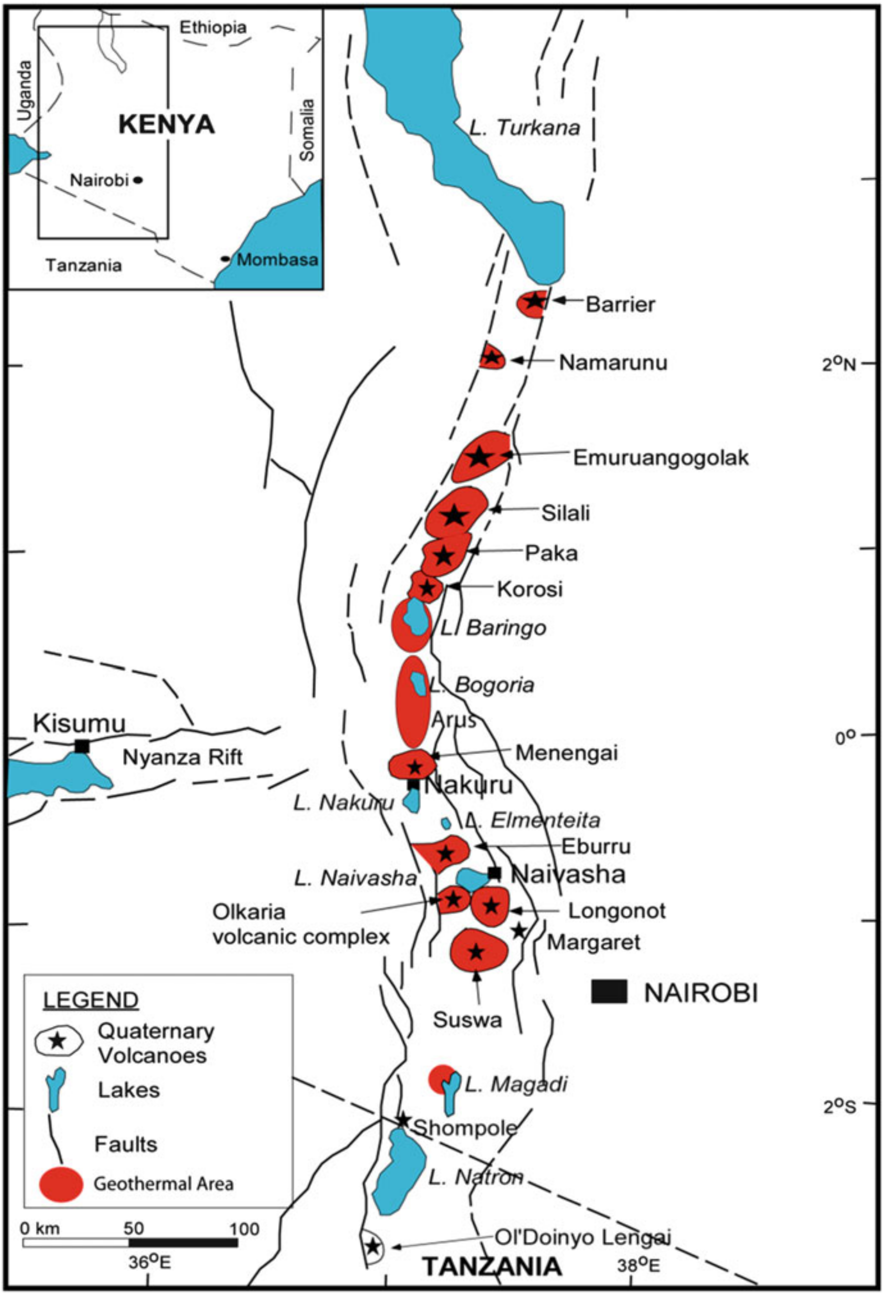

Fig. 12.1 The Rift Valley Lakes in Kenya

its west, and the Bogoria fault scarp immediately to its east. The lake is replenished and sustained by a number of springs, most of which emerge along the N-S fissures at the shores of the lake (Onywere 2005). Some of the springs are hot and even boiling. The Emsoss warm spring water flows in from the south through fissures on Emsoss escarpment. The lake waters are highly saline and contain sodium carbonate, chloride and fluoride. There is a supply of low saline waters from the hot springs due to decomposition (solution) of alkaline igneous rocks and recirculation of groundwater by the hot springs. Mahon (1972) suggests the possibility of an influx from deep geothermal waters underlying an extensive area of the Rift Valley, which could be a source of water contamination in the area. Heavy siltation has considerably degraded water quality in Lake Baringo with a detrimental effect on the quality of drinking water and on its fisheries (MEMR 2012).

Lake Nakuru is a shallow soda lake, lying in a graben between the Lion Hill fracture zone in the east and a series of east downthrown step-fault scarps leading to the Mau Escarpment to the west. The lake is elongated in the N-S direction in line with the trend of the axial rift faults and dammed to its north by Menengai caldera. It is rich in algae and attracts millions of flamingos, for which the lake is famous. The flamingos often migrate to other lakes because of its frequent fluctuations and sometimes desiccation in response to climate variability. The drying up of streams feeding into the lake coupled with high evaporation during drought periods greatly reduces the levels and sewage water from Nakuru Municipality at such times may be the only surface input to the lake, although there is also a perennial supply from small springs off Lion Hill. There has been high sediment influx into the area due to increased cultivation on the poorly structured soils, leading to increased soil erosion and accelerated surface runoff during the rains. Loss of natural vegetation particularly in the Mau Forest catchment area and the Bahati Forest threatens the Lake's water quality and water balance. Between 1986 and 2003, roughly one-fifth of the forested area in the upper reaches of the River Njoro catchment was lost (UNEP 2009).

12.3 Methods

The extent of flooding in four lakes was evaluated using Landsat satellite imagery and ground truth survey. The spatial resolution and scale of data provided a synoptic view and facilitated analysis of local and regional drainage patterns and relationships. Processing of remote sensing data formed part of the interpretation. The theory behind the interpretation is well documented (Lillesand et al. 2008; Köhl et al. 2006; Pratt 1977; Harris 1987). Image enhancement and digital image analysis were performed using Earth Resources Data Analysis System (ERDAS) software applied to Landsat Thematic Mapper images. Digital image enhancement, directional edge enhancement (derivative) and convolution filtering were performed on the image data. These methods of image processing were particularly suitable in identifying linear features and land cover patterns which were digitized to design the GIS data on the ArcGIS platform and that also facilitated computation of the area under water.

Full image scenes of Landsat TM data path 169 and row 060 were downloaded from the United States Geological Survey website for the study. Images of the same month (December 2010, December 2013 and December 2014) were identified and downloaded for processing and interpretation. Analysis of water levels was made by delineating the spatial extent of the area covered by water on the images and overlaying the results to see the difference between them. Computation of area in km^2 was carried out so as to obtain the difference in the area covered by water in December 2010, December 2013 and December 2014, with other images being analyzed to map the trend. Various band combinations were used to derive false colour composite products from where visual interpretation and delineation of the lake boundaries was made. Road infrastructure and village location vector products from archived data were then overlaid on the image products to determine the impact of the flooding on infrastructure. Onywere et al. (2013) documented the lowest extent of the lakes using the image of January 2010 at the peak of the dry spell of 2009–2010. The fieldwork involved visits to the Lake Baringo and Bogoria area at the beginning of September 2013 and to Lake Nakuru and Naivasha at the end of September 2013. The ground truthing survey was used to support observations and data gathering and involved documenting the areas and infrastructure affected by the flooding.

12.4 Results and Discussion

12.4.1 Extent of Flooding from Raised Levels of the Lakes

Remote sensing images for January 2010, December 2010, December 2013 and December 2014 show a drastic but consistent increase in water volume (Table 12.2) which flooded the lakes' riparian areas and that affected the infrastructure and the biodiversity. However, in the period between December 2013 and 2014, Lakes Bogoria and Naivasha recorded a slight decline in levels of 0.74 % and 2.31 %, respectively.

The Lake Baringo area that was flooded increased from 143.6 km^2 in January 2010 to a high of 219.8 km^2 in December 2014, an increase of 76.2 km^2 (53.1 % increase by area) (Fig. 12.2). Among the four lakes, Lake Baringo has villages and other community settlement activities within the floodplain that were significantly affected. All areas below the 980 m contour line were submerged by floodwaters and indeed remained so for some time afterwards. Previous analysis shows a decrease of Lake Baringo from 148 to 124 km^2 between 1973 and 2000 representing a decrease of 16 % (Johansson and Svensson 2002). The decrease mainly affected the southern and eastern part of the lake where the topography of

Table 12.2 Extent of flooding of the four Lakes; Baringo, Bogoria, Naivasha and Nakuru

Lake area (km^2)	Baringo	Bogoria	Naivasha	Nakuru
January 2010	143.57	32.56	107.66	31.80
December 2010	172.37	36.68	134.30	43.14
December 2013	215.05	40.68	165.15	55.67
December 2014	219.75	40.38	161.34	56.28
Change in lake area (km^2)				
January 2010 – December 2010	28.8	4.12	26.64	11.34
December 2010 – December 2013	42.68	4.00	30.85	12.53
December 2013 – December 2014	4.70	−0.30	−3.81	0.61
Total change in area (km^2)	76.18	7.82	53.68	24.48
% change in area				
January 2010 – December 2010	20.06	12.65	24.74	35.66
December 2010 – December 2013	24.76	10.91	22.97	29.04
December 2013 – December 2014	2.19	−0.74	−2.31	1.10
Total % change in area	53.06	24.02	49.86	76.98

the area is much flatter and with a higher loading of silt from the rivers feeding the lake. The topography of the lake's riparian area to the north is much steeper.

Lake Bogoria lies in a deep depression and the volume of the water increase flooded only a small area compared to the other lakes. The Lake Bogoria flooded area rose from 32.56 km^2 in January 2010 to 40.38 km^2 in December 2014, an increase of 7.82 km^2 (24.02 %) by area over the 4-year period (Fig. 12.3).

The flooded area of Lake Naivasha rose from a low of 107.7 km^2 in January 2010 to a high of 161.3 km^2 in December 2014, an increase in area of 53.68 km^2 (49.86 %) as indicated in Fig. 12.4. Indeed, this was the first of the rift valley lakes to overtop its banks. Lake Nakuru increased its flood area from a low of 31.8 km^2 in January 2010 to a high of 56.28 km^2 in December 2014, representing an expansion of 24.48 km^2 (76.98 % increase by area) (Fig. 12.5).

12.4.2 Impacts of Flooding on Community Livelihoods

The increase in lake levels led to flooding in the catchments of all four lakes. Notably, there was destruction of infrastructure, loss of biodiversity and elevated risk from water-related and waterborne diseases as well as general loss of livelihoods for the local communities. Of the four lakes studied, the most affected over the period was Lake Baringo, both from the point of view of the size of the human population affected and the loss of infrastructure such as schools, settlements, dispensaries and the size of the area under water. In Baringo, the spread of the floodwaters submerged entire villages, displacing the communities and their livestock. At least eight schools in the villages, along with health care centres, were submerged. It is estimated that more than 1250 pupils were affected by the engulfment of classrooms (Nyakeyo and Njeru 2013). Figures 12.6 and 12.7

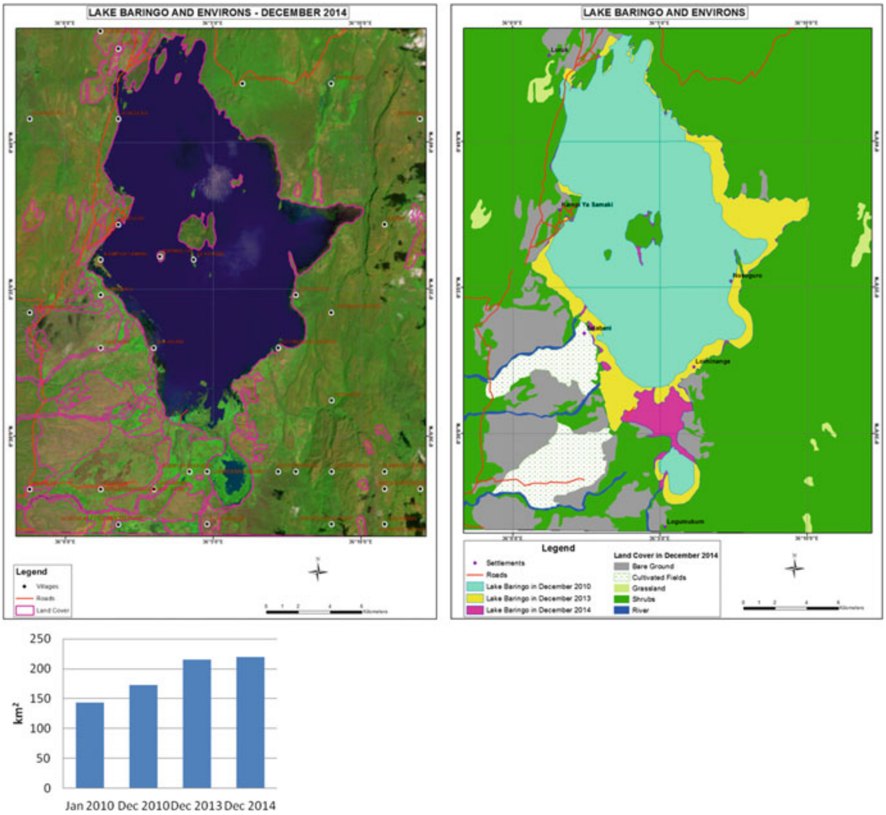

Fig. 12.2 Changes in spatial extent of Lake Baringo – 2010–2014 Lake Bogoria lies in a deep depression and the volume of the water increase flooded only a small area compared to the other lakes. Lake Bogoria flood area increased from 32.56 km^2 in January 2010 to 40.38 km^2 in December 2014 an increase of 7.82 km^2 (24.02 %) increase by area over the 4 year period (Fig. 12.3)

show submerged classroom and flooded grazing land respectively. Furthermore, the flooding induced additional pressure on the surrounding land, which is likely to generate human-wildlife conflicts, and at the same time threatens the community socio-economic activities that support livelihoods.

The flood assessment report for August 2013 (Nyakeyo and Njeru 2013), estimated that 61,740 ha of pasture and browsing lands, with the capacity to support up to 38,588 livestock units, were submerged by the floods. Furthermore, livestock was lost to predators that inhabit the lake. In addition, the continued presence of the floodwaters has led to restructuring of the vegetation community. It is likely that the soils in the area were affected in their microclimate and moisture content in turn impacting micro-organisms and nutrient availability.

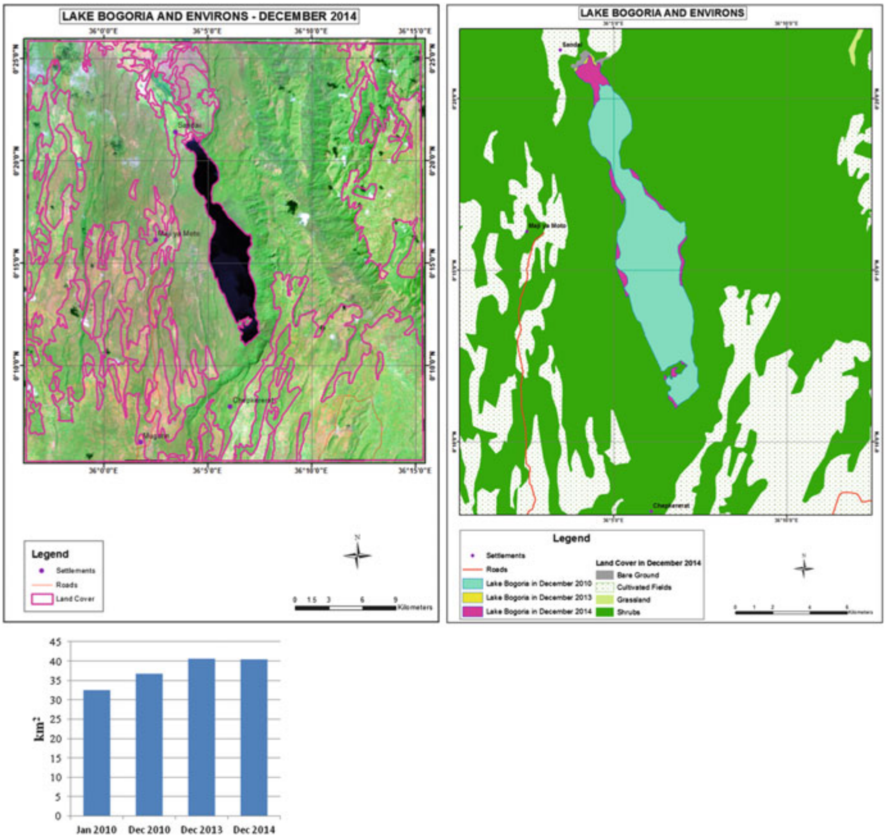

Fig. 12.3 Changes in spatial extent of Lake Bogoria, 2010–2014 Lake Naivasha increased its flood area from a low of 107.7 km^2 in January 2010 to a high of 161.3 km^2 in December 2014, an increase in area of 53.68 km^2 (49.86 %) as indicated in Fig. 12.4. It was the first of the rift valley lakes to overtop its banks. Lake Nakuru increased its flood area from a low area of 31.8 km^2 in January 2010 to a high of 56.28 km^2 in December 2014, an increase of 24.48 km^2 (76.98 % increase by area) (Fig. 12.5)

Water Resources Management Authority (2013) reported that the estimated level of Lake Baringo at the end of August 2012 was +8.5 m and that all gauging equipment had been submerged. The toilets in the Department of Fisheries building, as well as the fish store, were completely submerged, as were several hotels including Lake Baringo Block Hotel, Highland camp, part of Soi Lodge, Roberts camp and the County Council of Baringo Reptile Centre. A number of homesteads in Baringo and Bogoria catchments were submerged, displacing the already vulnerable community members (Figs. 12.8 and 12.9). In addition, health facilities and other essential services were completely submerged or threatened with flooding.

In Lake Bogoria the communities living along the northern shore of the lake within the River Waseges flood plain were displaced and flooding also resulted in

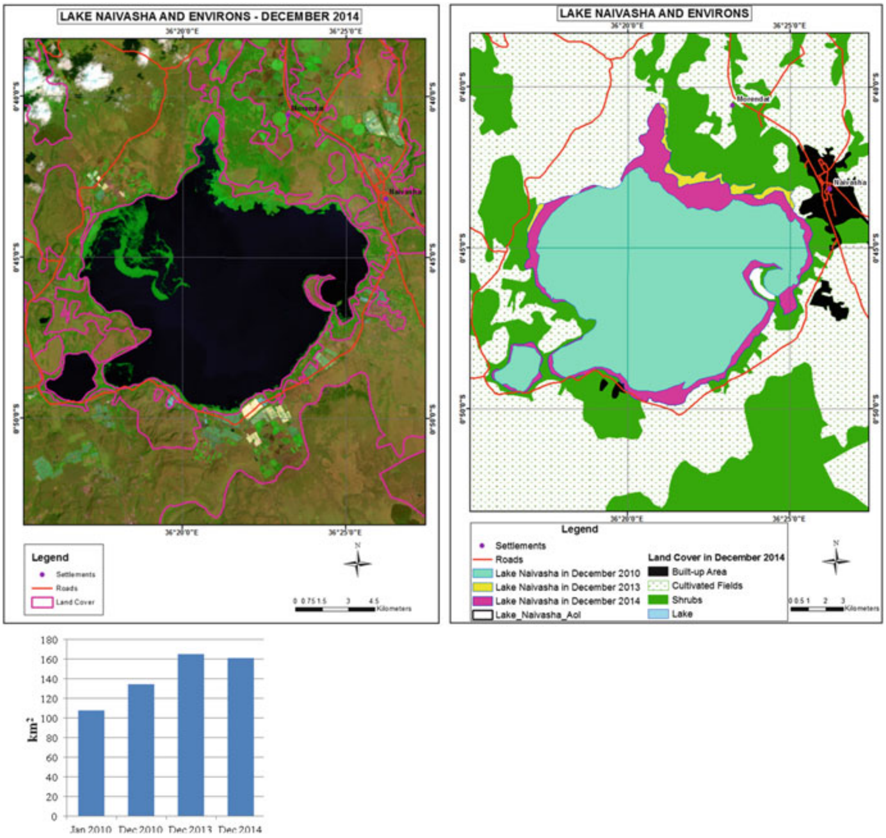

Fig. 12.4 Changes in spatial extent of Lake Naivasha – 2010–2014

drowning or migration of land-based invertebrate and vertebrate animal species to the drier surrounding areas. There was also a change in the water quality, in particular a decrease in salinity thereby affecting the flamingo population.

12.4.3 Impact of Flooding on Tourism

The economic pillar of tourism has also been adversely affected as a result of damage or destruction of infrastructure. Lakes Nakuru and Bogoria were particularly affected with the inner circuit road submerged rendering it difficult and dangerous to access the parks (Figs. 12.10, 12.11, and 12.12). The hot water springs and geysers in Lake Bogoria, the main attraction for tourists, were completely submerged. The hotels and camping facilities close to the Lake Naivasha and Lake Baringo shorelines were all submerged, significantly impacting tourism. The

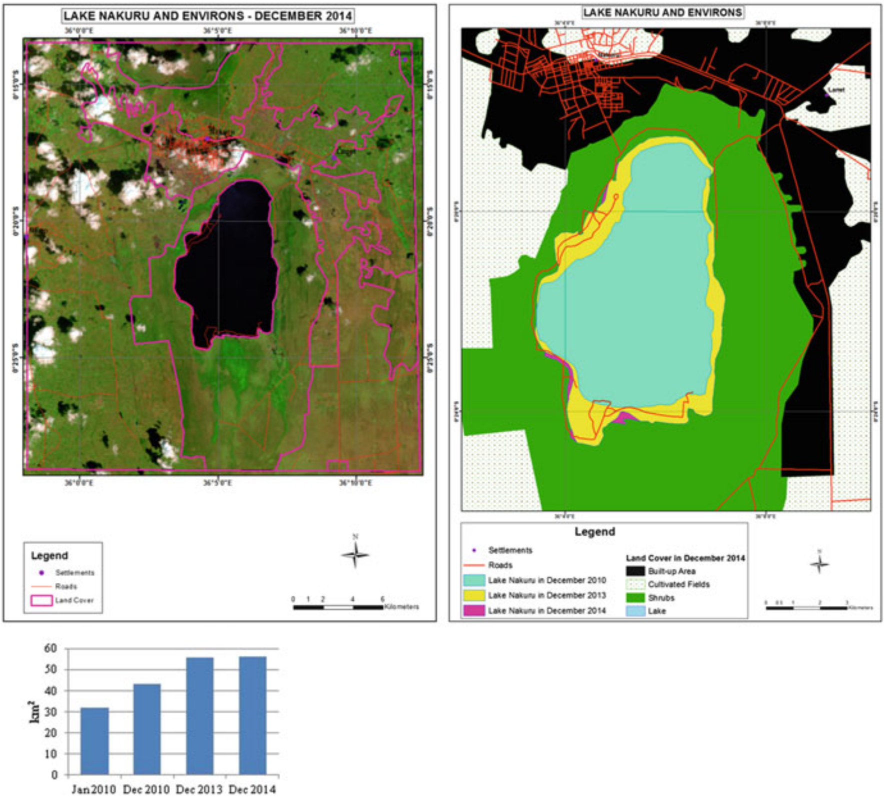

Fig. 12.5 Changes in spatial extent of Lake Nakuru – 2010–2014

number of tourists visiting Baringo County for example indicates a decrease over the period 2010 to 2013 in response to the flood situation (Fig. 12.13).

Both water quality and biodiversity were affected by the submerging floodwaters. The increased recharge of Lake Bogoria from River Waseges, now reaching the lake directly through surface runoff, has led to dilution of the lake water decreasing its salinity. The lowered salinity and siltation has lead to loss of algae on the northern side of the lake leading to lack of food for flamingos. Furthermore, the depth of the lake has increased, compromising its ability to support wading birds in general.

The increased recharge of Lake Baringo is mainly derived from the Molo, Perkerra and Endao Rivers, which now reach the lake directly through surface runoff that has brought sediment and debris into the lake. In the Lake Baringo basin there have been notable changes in water quality and nutrient loading, with notable adjustments by faunal and floral communities in response to the inputs, for example fish species have dispersed into the flooded areas. Crocodile and hippopotamus in the lake are now ranging wider in search of food, and snakes that occupy the Lake Baringo area have migrated to drier areas thereby increasing the risk to the local

Fig. 12.6 Submerged classrooms in Lake Baringo catchment (September 7, 2013)

Fig. 12.7 Grazing area for livestock also flooded. Note the *Prosopis juliflora* in the background (September 2013)

Fig. 12.8 Vulnerable homestead on Kokwe Island of Lake Baringo (December 2013)

population (Kenya Wildlife Service 2014). An increased number of floating mats of waterweed has been observed in the lake, while smaller, low-lying islands have been completely submerged. Meanwhile two ‘new’ islands have emerged as the floodwaters filled the grabens of the fault blocks in the Loruk area on the northern side of the lake.

The increased recharge of Lake Naivasha is derived from the Malewa and Gilgil rivers draining the Kinangop escarpments. At the low water level in January 2010, the so-called Small Lake (Lake Oloidien) had developed alkalinity that allowed a large population of flamingos to inhabit it. By March 2011, the lake level had risen to an extent that the main Lake Naivasha and Small Lake were connected via the southern part of the topographic feature that had originally separated them. This has had a significant impact on biodiversity of the lake, with reported cases of dead tilapia fish floating in the main body of Lake Naivasha following the intrusion of alkaline water. Flamingos migrated away from the Small Lake by September 2013. The raised water level also dislodged loosely anchored *Papyrus*.

Fig. 12.9 Displacement of communities settled in the northern shore of lake Bogoria (December 2013)

Fig. 12.10 Floodwaters cut off the road infrastructure around Lake Bogoria (December 2013)

Fig. 12.11 Submerged lake Nakuru park Offices (September 2013)

Fig. 12.12 Flooded areas for wildlife grazing in Lake Nakuru Park (September 2013)

12.4.4 Underlying Causes of the Water Level Rise

The Central Rift Valley lakes of Kenya increased markedly in level after the long rains of May 2010 and the short rains of September 2010 and continued to increase

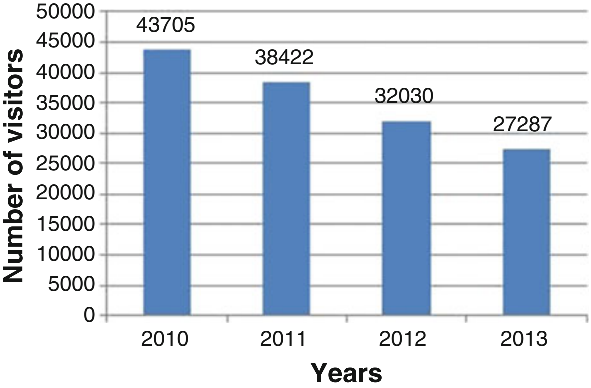

Fig. 12.13 Tourists to Baringo County from 2010 to 2013 (Source: Data from County Warden 2015)

up to September 2013. Previously the lakes had been recorded at their lowest levels due to anthropogenic activities such as overgrazing and deforestation in the catchment, particularly on the shores of Lake Baringo, which led to a much reduced and shallower lake (Johansson and Svensson 2002). Lake Naivasha levels had also been shown to decline over the period 2002 and 2010 (Awange et al. 2013). The recent flooding clearly indicates increased precipitation in the catchments, a situation that has occurred in the past and may indeed be cyclic. For example, Lake Victoria and other East African Lakes were reported to have flooded between 1961 and 1964 (Conway 2002; Mistry and Conway 2003; Conway et al. 2005). The rainfall events during the period were linked to El Niño phenomena and caused widespread flooding and prolonged increases in levels of many lakes in East Africa with significant disruption. El Niño has again been forecasted for the 2015 short rains (Kenya Meteorological Department 2015), with likely effects of flooding in many parts of Kenya.

The four lakes are generally small and endorheic with no outflow and therefore they are very sensitive to the hydrological balance of inflows and evaporation, and very vulnerable to change whether driven by climate variability or human interventions. Small changes in inputs can produce large fluctuations in water levels owing to the shallow nature of these lakes.

Rainfall data from Egerton University Station in Nakuru County (Table 12.3) show a dry January, while the months April to September are associated with high rainfall over the three years. Interviews with stakeholders supported by field observations in September 2013 indicate the occurrence of increased rainfall in the dry season leading to a higher than normal crop yield. For the first time since the mid-1980s, the Enjoro, Larmudiak, Makalia and Enderit Rivers have been flowing, (indeed now for more than three years), signifying abnormal inputs. Lake Baringo has been influenced by consistent recharge from the Molo and Perkerra rivers, while Lake Bogoria has been influenced by input from Waseges River and Lake Naivasha from Malewa and Gilgil Rivers.

Table 12.3 Rainfall data from Egerton University weather station 9035092

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct.	Nov	Dec
2011 mm	3.3	9.6	182.3	20.9	116	216.5	130.1	130	149.3	89.2	146.7	86.4
2012 mm	0	16.3	31.6	287	181.8	166.2	87.2	220.3	192.4	94.3	26.6	152.1
2013 mm	42.7	2.5	85.4	239.7	70.7	137.7	169.3	99.4	154.2	68.5		
Rain days 2011	1	4	16	11	14	19	17	21	16	15	20	11
Rain days 2012	0	6	3	25	22	13	17	16	21	17	10	12
Rain days 2013	8	2	12	21	15	15	18	20	16	11		

12.5 Summary of Impacts from Floodwaters

Flooding has had significant detrimental effects on the ecosystems, biodiversity, human settlements, infrastructure and economic viability of the four lakes and their environs. Loss of biodiversity, especially of acacia trees and other vegetation due to submergence has implications for ecosystem health in general. Elevated risk from malaria and waterborne diseases has implications for the health of local populations who are also affected by contamination of lake waters and borehole water. There are implications for the tourism industry due to infrastructural damage and related loss of income, which may be regarded as especially important given that tourism is a key earner of foreign exchange for the country. There are health risks to the livestock from rift valley fever. Other risks emanate from possible snakebites and crocodile attacks. There is overall disruption to livelihoods and loss of agricultural and grazing land for communities so that there is a clear need to improve monitoring and evaluation of flooding.

12.6 Conclusions and Recommendations

It is clear that the flooding of the lake ecosystems since 2011 has had an adverse effect on both the local populations and lake ecosystems in the central Rift Valley of Kenya. The short- and medium-term effects that have been reported include extensive loss of property, damage to infrastructure and disruption of livelihoods systems. The long-term management of the lakes need to take into account the dynamic nature of water resources over time and the need for flexible management systems that consider the resource base. Given that the Rift Valley lakes are influenced by tectonics, there are possibilities that there could be an influx of geothermal water also contributing to an increase in the lake levels and this needs to be further investigated including the impacts from contaminated surface water and groundwater by use of geochemical methods. This study contributes to knowledge by documenting changes in lake levels. Further analysis of data including discharge of rivers and rainfall will provide deeper understanding of these changes. For instance, an increase in rainfall intensity can lead to increased surface runoff, but requires more consistent and reliable data. Water Resources Management Authority (2013) indicated that the flooding in 2011 and 2012 submerged all gauging equipment. There is also a need for further research on sources and effects of currently increased water volume in the lakes on biodiversity and the community. Further research is planned on the sustainability of the hydrology of the lake basin ecosystems, and on the community vulnerability to environmental dynamics.

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Chapter 13
Rainfall Erosivity and Soil Erosion Risk Assessment in Tropical Island Environments: A Case Study of Mauritius

Paul Sumner, Werner Nel, Soonil Rughooputh, Ravindra Boojhawon, Kumar Dhurmea, Jay Le Roux, and Ryan Anderson

Abstract Small island states are vulnerable to soil erosion due to fragile natural resource bases and, particularly in tropical environments, erosive rainfall. Few studies, however, provide erosion risk assessments for small islands upon which conservation strategies and land use planning can be based. Investigations on Mauritius in the tropical Indian Ocean show the value in providing catchment- and island-scale erosion risk assessments, particularly where land use change may increase erosion rates. Findings also highlight the potential impact of non-cyclonic rainfall events and the effect that island topography has on rainfall erosivity distribution. Where detailed sub-event scale rainfall data are available from automated stations, these data are found to provide for more accurate erosion prediction.

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Field calibration of erosion models, however, remains an important avenue for future research.

Keywords Rainfall erosivity • Mauritius • Soil erosion risk assessment

13.1 Introduction

Small island states of volcanic origin lie predominantly in the tropical regions where rainfall erosivity is generally higher than in temperate regions (Hoyos et al. 2005). Many small islands have locally high population densities, fragile resource bases, and are susceptible to natural hazards and climate change (Hess 1990; Lal et al. 2002). Soil erosion is a global phenomenon but islands are particularly vulnerable to accelerated erosion due to limited land availability and subsequent land use pressures, sensitive soil resources and related economic vulnerability (see Briguglio 1995). Rainfall variability and the characteristics of rainfall, particularly in the low-latitude environments where many small island developing states are located, make these areas sensitive to erosion risks.

Modeling and mapping of erosion risk is typically undertaken to identify high erosion areas where soil and water conservation efforts can be concentrated (e.g. Jain and Goel 2002; Fox et al. 2006; Nigel and Rughooputh 2010a). Empirical models, upon which such mapping is based when incorporated into a GIS, require several input factors including topography, soils, vegetation cover and rainfall characteristics. The erosivity of rainfall depends on the intensity (I) and kinetic energy (E) of the rainfall and at an event-level can be calculated from rainfall measured at short time intervals. The RUSLE (Revised Universal Soil Loss Equation), for example, resolves erosivity at 30-min intervals using the EI_{30} index (Renard et al. 1994). In the absence of detailed rainfall data, models have to apply longer interval measurements such as used when deriving the Modified Fournier Index (Arnoldus 1980) from monthly rainfall totals.

Erosion risk models provide a valuable tool for assessing the spatial and temporal intensity of soil erosion. In an island setting, such a tool can direct soil conservation actions and also help to identify risk areas at coastal catchment outlets (e.g. Nigel and Rughooputh 2010a, b). This chapter first provides an overview of erosion studies on small islands. Mauritius is then used as a case study to highlight recent erosion risk modeling, rainfall erosivity assessments and the effect of island topography on erosion potential. Avenues for future research that may facilitate the understanding of erosion on small islands and direct conservation measures are also addressed.

13.2 Soil Erosion on Small Islands

Relatively few detailed erosion investigations have been undertaken on island environments. Erosion rates have been modeled but rarely measured directly, while erosion risk and rainfall erosivity assessments form more recent focus points (e.g. Nigel and Rughooputh 2010a, b; Nel et al. 2013). In a comprehensive study of a catchment on one of the Hawaiian Islands, Calhoun, Fletcher (1999) determined erosion rates using three methods. They applied the USLE (Universal Soil Loss Equation) at a catchment scale, obtaining field measurement of channel suspended sediments and historical data from cored sediments. The USLE model was found to under-predict measured values for non-agricultural 'wildlands', probably due to the contribution of mass movements to river sediment (Calhoun and Fletcher 1999). On Hawaii, El-Swaify (2002) noted the importance of rainfall erosivity, showed that only a few intense rainfall events can contribute to the major share of erosion, and confirmed the importance of soil cover in reducing vulnerability in a tropical environment.

On other islands, climatic drivers and human impacts in combination are found to be important controls in soil erosion. For example, Brooks and Spencer (1995) considered the effects of a reduced canopy cover through logging on rainfall erosivity on the island of Borneo. They showed a substantial increase in effective erosivity following logging activities and recommended the adoption and application of physically-based models where canopy cover is disturbed in tropical areas. On a central Polynesian island, Kirtch (1996) found erosion rates over the past 5000 years to be influenced mainly by El Nino-Southern Oscillation (ENSO) events. Core sample records also revealed a significant increase in erosion attributed to more recent human influence. In contrast, McDonald et al. (1997) report that eighteenth and nineteenth century plantations appear to have had relatively little influence on erosion on St John in the Virgin Islands. However, growth in infrastructure, tourism and housing since the 1950s significantly contributed as a sediment source. Mieth and Bork (2005) also illustrated an increase in erosion related to recent population growth and development on Easter Island in the southeastern Pacific Ocean.

Mannaerts and Gabriels (2000a, b) found that a few intense rainfall events contributed the bulk of rainfall erosivity on the Cape Verde Islands off the west coast of Africa. They therefore caution that daily rainfall may provide only an approximate predictor of erosion due to the variable erosive nature of individual rain events. More recently, and set in the Mediterranean, Nastos et al. (2010) analysed 52 years of daily rainfall data from Naxos Island. They illustrated that recent climate change has produced heavy rains and intense runoff, a finding that aligns with global projected increases in erosion (IPCC 2007). None of the above studies, however, addresses small islands either from an erosion risk perspective or in the context of climate change.

The island of Mauritius has received particular attention recently in respect of rainfall erosivity and erosion risk mapping. Following the earlier work by Kremer

(2000) on determining erosion risk, Nigel and Rughooputh (2010a) mapped monthly risk for the island and then prioritised high erosion risk areas in the context of sustainable environmental management (Nigel and Rughooputh 2010b). Erosivity attributes, particularly spatial trends in relation to island topography, have also been assessed in detail (Anderson 2012; Mongwa 2012; Nel et al. 2012, 2013) in response to the erosion modeling undertaken by Le Roux (2005). These findings are reviewed below.

13.3 Republic of Mauritius: A Case Study

Mauritius (20°10′S; 57° 30′E; Fig. 13.1) together with Reunion, Agalega, Saint Brandon and Rodrigues, form the Mascarene Islands in the tropical Indian Ocean. The island is an exposed summit of several stages of former volcanism and at the surface measures ~64 km from north to south and ~43 km from east to west. Peak altitude is 828 m a.m.s.l. in the southwest; the island has an areal coverage of 1844 km^2 (Saddul 1995; Proag 2006) (Fig. 13.2).

Mauritius has a long history of visitation and colonization, notably by the Portuguese, Dutch, French and British and finally achieved independence in 1968 with a republic status in 1992. The modern population, of approximately 1.3 m, is primarily engaged in the island's key textile, finance, agriculture, tourism and IT sectors. Sugarcane has long been the foundation of the agricultural community but increasing pressure on the sugar industry has led to diversification and subsequent land-use change (see Le Roux et al. 2005) (Fig. 13.3), some of which may have had negative erosion ramifications

A complex topography of mountains and valleys characterises the island. The dominant geomorphic feature is a raised plateau above approximately 600 m a.m.s.l. which is a former caldera situated in the central and southwestern regions (Figs. 13.1 and 13.2). Two weather seasons are monitored that reveal a warm, wet summer from November–April and a mild, dry winter from May to October (Padya 1989). As a consequence of the topography, the climate is locally both variable and diverse especially in terms of rainfall amount and spatial distribution. Mean annual temperature is 22 °C, although the raised plateau climate is more moderate than that of the coast. While the island's mean annual rainfall is around 2120 mm p.a., the plateau can receive upwards of 4000 mm p.a. and a distinct east-west gradient is apparent, from 1200 mm in the east to as little as 600 mm p.a. on the west coast (WRU 2007; Fowdur et al. 2006, 2014). The rainfall gradient is significantly affected by the raised topography as well as the direction of the dominant rainfall systems.

Due to the island's location and topography, several weather systems of different scales and amplitudes affect the island (Fowdur et al. 2014). The position of the Inter Tropical Convergence Zone (ITCZ) ensures persistent southeast trade winds (easterlies) across the island, although occasionally (typically a few times per year) westerlies prevail when the ITCZ lies south of Mauritius (Fowdur et al. 2014; Staub et al. 2014). Other weather systems include late summer tropical cyclones, the

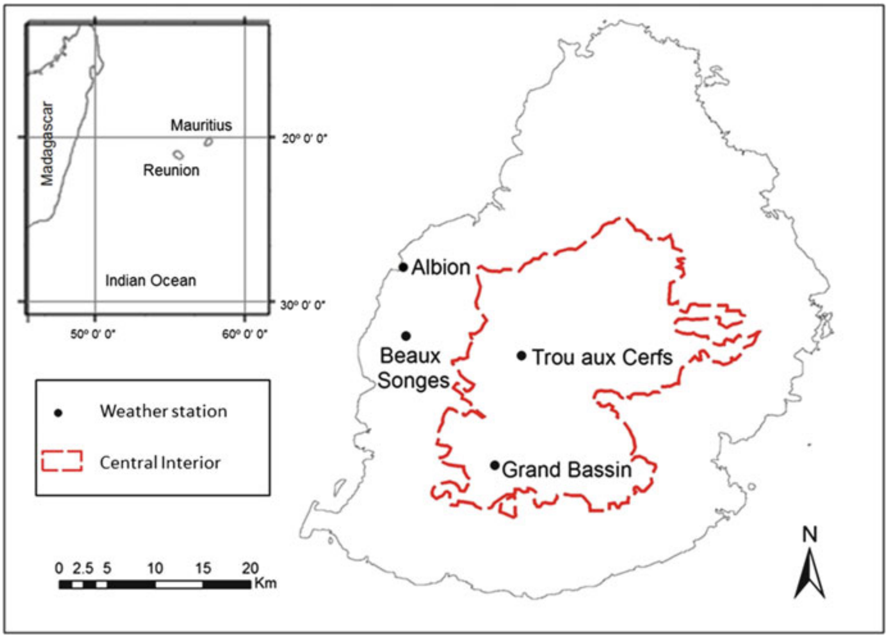

Fig. 13.1 Location of Mauritius in the Indian Ocean. The four automated weather station locations, two of which lie in the raised interior (Arnaud, 576 m a.s.l.) and (Grand Bassin, 605 m a.s.l) and two in the west (Albion, 12 m a.s.l.) and Beaux Songes (225 m a.s.l.) are indicated (after Nel et al. 2013). The central and western area of the island is enlarged in Fig. 13.4

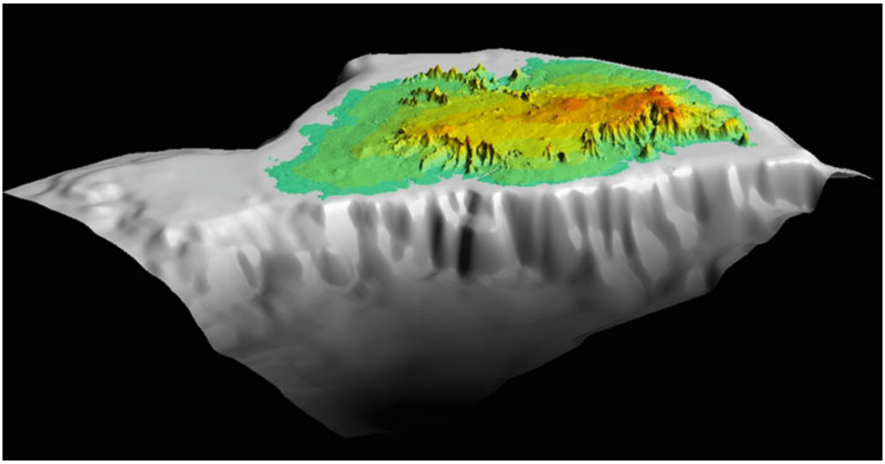

Fig. 13.2 Complex topography and raised interior of Mauritius as viewed from the north west. The north-south axis measures ~64 km and the highest elevation is 828 m a.s.l. in the south west (DEM courtesy of SDDV Rughooputh and KH Mueller, December 2014)

Fig. 13.3 Various crop types, including banana and sugar cane, on a steep slope in the east of Mauritius

periodic influence of mid-latitude cold fronts, anticyclones, easterly wave perturbations in the lower troposphere and upper level lows with associated thunderstorms, although these events remain poorly understood (see Fowdur et al. 2014). The southeast trade winds provide the dominant moisture advection. Together with topographic uplift and sea breezes, the easterlies result in a steep rainfall gradient and the distinct west coast rain-shadow effect that may impact on erosion risk and rainfall erosivity distribution.

13.3.1 Erosion Risk Assessment

Few studies have assessed soil erosion on Mauritius, and these have focused mainly on land supporting sugarcane plantations. Kremer (2000) mapped erosion risk under varying sugarcane cover for the island. At specific field sites, Ng Cheong et al. (2003) measured erosion rates under sugarcane and Seeruttun et al. (2007) contrasted soil erosion both under sugarcane and without soil cover (Nigel and Rughooputh 2010a). Le Roux (2005) modeled erosion rates for a catchment in the south (see also Le Roux et al. 2005) and projected erosion rates under different land use types. Only recently, however, have detailed erosion risk assessments been formulated under various land use types for the entire island.

Four erosion factors are typically incorporated into erosion risk modeling; topography, soil, land cover and rainfall. On this basis, Nigel and Rughooputh (2010a) developed and applied a GIS-based erosion risk model called MauSERM (Mauritius Soil Erosion Risk Mapping) for the island. The model, which in part used monthly rainfall depth data, enabled the identification of monthly erosion risk at a catchment and sub-catchment level for Mauritius. Nigel and Rughooputh (2010b) improved on the model by incorporating slope length and gradient into the topographic factor. Detailed rainfall data at the event scale were not available but, instead of simply using rainfall depth, rainfall erosivity was mapped using the Modified Fournier Index (Arnoldos 1980). From these studies, conservation measures could be better directed towards high priority erosion areas both within the catchments and in the environmentally sensitive coastal wetland sink areas (Nigel and Rughooputh 2010b).

The MauSERM model provides an important tool for erosion risk assessment and promotes better land use and conservation planning efforts. As with the earlier studies, detailed rainfall measurements upon which erosivity at the event scale could be calculated were not available. Ground verification and model calibration also remained speculative.

13.3.2 Rainfall Erosivity

As noted above, Le Roux (2005) modeled potential erosion yields from a southern catchment on Mauritius. Two empirical models were applied: the Revised Universal Soil Loss Equation (RUSLE) and the Soil Loss Estimator for Southern Africa (SLEMSA). The models concurred on the catchment's distribution of sediment source but SLEMSA predicted higher overall yields. RUSLE was also applied under changing land use scenarios, based on the potential for diversification from the dominant sugarcane to alternative crop types, such as vegetables, pineapple or forestry. Where cover increased, such as in forestry, potential erosion declined but two key facets of the study required further investigation. First, the rainfall data: while SLEMSA utilizes monthly rainfall figures when estimating rainfall energy, 30-min data were not available for erosivity calculations in RUSLE. In the absence of such detailed sub-hourly rainfall records Le Roux (2005) computed erosivity based on monthly rainfall data and the Modified Fournier Index (MFI), as applied elsewhere (see Le Roux et al. 2005) and later by Nigel and Rughooputh (2010b). Notwithstanding observations on gully occurrence (Le Roux 2005), some of which can be induced through infrastructure (e.g. Fig. 13.4), model calibration from field data was not conducted.

Several subsequent studies focused on detailed rainfall data in order to resolve rainfall and erosivity attributes on the island. The Mauritius Meteorological Service provided 6-min interval data from 2003 to 2008 from six automated meteorological

Fig. 13.4 A gully incised below an access road on a sugarcane field in the south of Mauritius

stations. The data sets were extensive, providing almost continual annual records from the central region, where rainfall totals are at a maximum, and from the dryer rain-shadowed west. These data provided for the first time the spatial and temporal attributes of erosivity characteristics from a small island setting. The results are given in Mongwa (2012), Anderson (2012), and in Nel et al. (2012, 2013) and the main erosivity findings are as follows.

Erosivity totals mirror the general rainfall patterns on the island with increasing erosivity and the number of erosive events with altitude (Nel et al. 2012, 2013). As anticipated, high altitude areas receive more extreme rainfall events than the coast, which in turn generate above average kinetic energies and erosivity (Fig. 13.5). Unexpected, however, is the finding that more than a third of the rainfall events in winter are deemed 'erosive' events (see Nel et al. 2013 for definitions). An increase in erosivity between the coast and the elevated interior is thus related not only to rainfall depth but also to the timing and nature of the rainfall from the driving weather system.

As anticipated, tropical cyclones generate the highest erosivity risk. However, other weather systems affecting Mauritius can also make a substantial contribution to erosivity totals, contributing to both erosion and flooding hazards. Several such events, from May 2008, are identified in Table 13.1. Significant erosive rainfall fell during May 2008 at all altitudes during the recording period. Two cold fronts crossed the island on the 16 and the 19 of May 2008 followed by easterly waves,

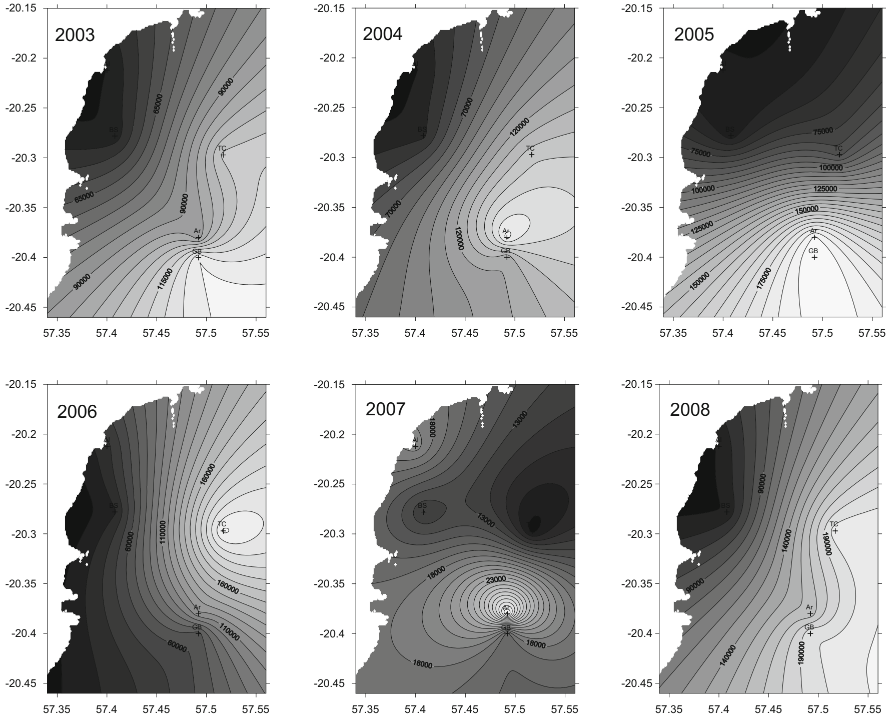

Fig. 13.5 Erosivity maps for the western region of Mauritius based on high resolution rainfall data from 2003 to 2008

with a very unstable atmosphere (Mauritius Meteorological Services 2008). This frontal mesoscale rainfall contributed substantially to the total erosivity recorded during the 5-year period. One rainfall event on 8 March 2004 measured at Albion is also highlighted as the event contributed 13 % of the total erosivity measured at that station for the 5 years as well as the highest intensity (I_{30} of 92 mm/h). The storm lasted an hour and, as very little rainfall was recorded at the other stations, it is assumed that it was not cyclone related and probably due to localized convective rainfall associated with thunderstorm (storm scale) activity. A similar isolated storm event caused extensive flooding in the capital city in March, 2013.

Calculation of rainfall erosivity within soil erosion models is key to understanding erosion risk but different resolution rainfall data provided substantial differences in erosivity totals (Nel et al. 2013). Of particular concern is the apparent over-calculation of erosivity when applying the MFI. Using the MFI may over-predict erosion yields (see Nel et al. 2013), which may also account for the SELMSA/RUSLE discrepancies in Le Roux et al. (2005), whereby the latter model proves more sensitive to rainfall parameters. In tropical environments, where storm to synoptic-scale systems dominate the risk for soil erosion, models should where

Table 13.1 Significant non-tropical cyclone rainfall events in May 2008 and March 2004 for four automated stations located in the central and western regions of the island (see also Fig. 13.1)

Date	Station	Depth (mm)	Duration (min)	I_{30} (mm/h)	I_6 (mm/h)	Total kinetic energy (J m^{-2})	Erosivity (J mm m^{-2} h^{-1})	Synoptic circulation or weather system
8/3/2004	Albion	59	60	92	116	1425	131,136	Thunderstorm
14/05/08	Albion	34.8	330	49.6	80	727	36,058	Pre-cold frontal uplift
14/05/08	Arnaud	32.6	276	23.2	56	583	13,528	Pre-cold frontal uplift
16/05/08	Albion	14	348	17.6	62	234	4110	Cold frontal rainfall
16/05/08	Arnaud	255.4	2448	52.8	84	4469	235,963	Cold frontal rainfall
16/05/08	Beaux Songes	19.2	432	14.4	40	306	4403	Cold frontal rainfall
16/05/08	Grand Bassin	209.2	2268	51.6	120	3657	188,688	Cold frontal rainfall
18/05/08	Arnaud	21.2	528	8.4	30	325	2734	Pre-cold frontal uplift
18/05/08	Arnaud	33	630	21.6	44	553	11,955	Pre-cold frontal uplift
18/05/08	Grand Bassin	41.2	618	33.2	74	718	23,846	Pre-cold frontal uplift
19/05/08	Albion	19.2	12	29.6	48	372	11,001	Cold frontal rainfall
19/05/08	Grand Bassin	23.6	330	18	28	392	7060	Cold frontal rainfall
23/05/08	Grand Bassin	72.4	1344	16.4	36	1130	18,527	Easterly waves

possible incorporate smaller rainfall time-scales to increase the accuracy rainfall erosivity assessments.

13.4 Discussion

Erosion risk models provide a valuable tool for assessing the spatial and temporal intensity of soil erosion. On an island setting, a catchment-scale assessment such as that of le Roux et al. (2005) can provide relative erosion rates under different, or changing, land use practices. A tool such as MauSERM (Nigel and Rughooputh 2010a) effectively directs soil conservation actions at a sub-catchment to island-scale and also identifies risk areas at coastal catchment outlets. The MFI, used in both of the above studies to compute rainfall erosivity, appears to over predict sediment yields (Nel et al. 2013). However, in the absence of detailed rainfall data the MFI is still considered to be an effective predictive tool for relative differentiation of erosivity and risk assessments.

Recent findings from Mauritius provide clarity on three other issues or uncertainties relevant to modeling on islands and may thus assist in directing future erosion research. First, where topography is dissected, such as on an island with elevated terrain, rainfall erosivity can be highly variable spatially, with high values experienced where slopes are steepest in the uplands. However, low rainfall areas, such as the rain-shadowed western region of Mauritius, may also experience erosive rain that can be particularly damaging where vegetation cover is sparse (see also Brooks and Spencer 1995).

Second, in order to provide for accurate models, detailed spatial and temporal rainfall data are required. State meteorological services normally record daily rainfall and enter such data, typically as monthly reports, into the public domain. Mauritius has excellent coverage with some 250 stations on the island (Nigel and Rughooputh 2010a) although many are not automated. However, the value of automated stations that provide minute-scale monitoring of rainfall events is demonstrated here. In the absence of such data, erosion models can only predict relative trends, the accuracy of which is dependent in part on the distribution of weather stations, but which are unlikely to portray values corresponding to actual erosion rates (see Nel et al. 2013). Long term and detailed rainfall data sets are thus required if erosivity is to be effectively incorporated into risk modeling, particularly where climate is variable or where climate change scenarios are anticipated.

Third, field data for verification of erosion models and risk assessments are mostly absent for small islands. Field observations of areas under high risk may provide for qualitative ground verification (Nigel and Rughooputh 2010b) but the need for erosion rate or sediment yield measurements, such as those determined by Calhoun and Fletcher (1999) on Hawaii, remain scarce. On small islands, catchment discharge is rapid and sediment sink areas for coring and obtaining historical data are rare. Sedimentation in estuarine wetlands may provide evidence for interpreting sediment delivery rates and hence facilitate erosion risk model calibration.

13.5 Conclusions

On an island setting, where resources are limited, erosion risk modeling can provide a valuable tool in identifying soil erosion and directing conservation efforts (Nigel and Rughooputh 2010a, b). In the absence of detailed rainfall data, modeling of rates of erosion is, however, somewhat restricted. Although the Modified Fournier Index has been utilized in the past and provides effective relative erosion rates, rainfall data at the event-scale are needed for more accurate rate predictions (Nel et al. 2013). Detailed rainfall data, such as the 6-min interval data provided by the Mauritius Meteorology Service (see Mongwa 2012; Anderson 2012; Nel et al. 2012, 2013) are unfortunately rare for most islands settings and this will remain a constraint in accurate risk modeling.

On the island of Mauritius, winter rainfall and frontal synoptic events are found to contribute erosive rainfall events in the tropical setting. The dissected topography of Mauritius also highlights the uneven distribution rainfall erosivity due to both the elevation and rain-shadow effects. Erosive rain is thus not restricted to tropical cyclone events, is recorded throughout the year and can be highly variable over short distances. This emphasizes limitations in the application of point-sourced rainfall data from a restricted spatial and temporal physical coverage of rainfall stations. Finally, field data verification (e.g. Calhoun and Fletcher 1999) are rare but can in future facilitate the verification of erosion models and associated risk assessments.

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Chapter 14
Evolution of a Coastal Beach/Barrier/Marsh System in Response to Sea Level Rise, Storm Events and Human Impacts: A Case Study of Trunvel Marsh, Western Brittany

Hervé Regnauld, Riwalenn Ruault, Jean Noël Proust,
Jean-Jacques Tiercelin, and François Pustoc'h

Abstract The evolution of coastal sites such as beach/barrier/marsh systems is known to be strongly forced by sea level rise and controlled by storms, sediment input and human impacts. The relative weight of each may vary in time. However, it is difficult to determine the relative importance of these forcing controls and, therefore, how coastal systems evolve through time. In order to study this evolution we have selected the case study of Trunvel marsh, western Brittany, France, which is directly exposed to the most violent storms and has been extensively depleted of sediment during and since WW2. The relative balance of anthropogenic and meteorological controls and relative sea level rise is compared. Sediment cores have been obtained from within the marsh, cross sections of the barrier have been studied and air photos and old maps have been analysed. From 4000 BP to recent times the system has behaved in a simple way: the beach and the barrier accumulated sand and gravel, seeming to migrate inland with relative sea level rise and the marsh was alternatively eroded by the local river or fed by aeolian drifted sands. Very occasional storms may have breached the barrier and temporarily invaded (flooded) the marsh. Conversely, large events of river discharge may have breached the barrier, although there appears to be some natural resilience and the barrier rebuilds itself after each storm and the marsh is, once again isolated from the sea. At the beginning of the Roman period land use change appears to have modified the river discharge, following which the marsh seems to have been in its natural condition again until WW2, although some dykes were built and channels excavated. During WW2 the gravel was almost totally removed and used for concrete to build fortifications along the coast. After WW2, the system was totally controlled

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by management practices, the aim of which was to recreate a “natural” environment so that today this is a “human made natural landscape” and is now classified as a nature reserve. The barrier is no longer able to withstand storms and the river discharge does not always reach the sea. Therefore human management of water level in the marsh is today the main morpho-dynamic control for the whole system.

Keywords Western Brittany • Coastal lagoon • Human impacts • Holocene • Storm impact • Relative sea level rise

14.1 Introduction

The French coastline is settled by an increasing number of people who live there permanently or during holidays. In response, an important law was passed in 1985, stating that any new building was forbidden within 100 m of the coastline (highest spring high tide plus known storm surge) and that new constructions should not be built closer to the coastline than those already in existence. While there are some exceptions, the regulation is well respected and large stretches of coast are, today, without any buildings. Undeveloped coastal land is usually considered as natural and much of it has been purchased by a government agency (“Conservatoire du Littoral et des Rivages Lacustres”), which endeavours to maintain this natural state. The problem is that many of these so called natural areas, even when they officially are designated as nature reserves, are not totally natural since they have, over a long period, been settled, for example, by fishermen, by the navy or by private landowners who later sold the land to the state. Human impacts go back to late Neolithic and at most of the sites Celtic and Roman impacts are still visible (Le Bihan and Villard 2001; Daire and Langouet 2011; Daire et al. 2011). An important question deals with the so-called natural aspect of these coasts (Costa et al. 2013; Baillif et al. 2014). How has the coastline responded to past changes together with the inherited human control practices and how will it change under the current conditions of sea level rise and increased frequency and magnitude of storms? (Schoenenwald 2013; Jouan 2005; Dupuis et al. 2006; Ferreira et al. 2006).

A suitable site to explore the long-term evolution of controls (human and natural) on the behaviour of the coast is a set of marshes located behind a mixed gravel and sand barrier in Western Brittany, the Baie d’Audierne (Fig. 14.1). This coast is exposed to the west with almost no offshore islands or rocky outcrops (an unusual situation in Brittany). Archeological (Neolithic to iron age) sites are known along the present coast and Celtic remains are numerous, with Roman ones also, albeit to a lesser degree. There are no visible signs of either Medieval or modern coastal management interventions. It seems (Montfort 1985) that the area returned to a “natural state” at the beginning of the twentieth century. The most significant human impact was during WW2, when the barrier was stripped of virtually all of the gravel which was utilised to make concrete for the construction of defensive blockhouses. In the 1990s and early 2000s, the site was declared a

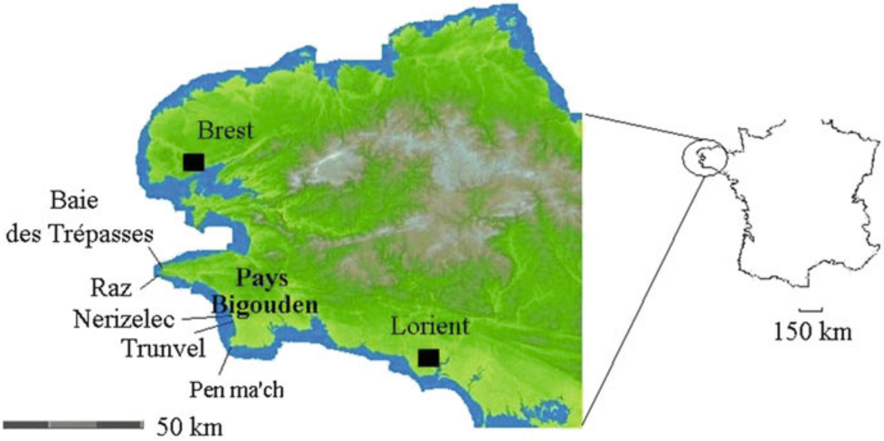

Fig. 14.1 Location of the main sites mentioned in the text

nature reserve. This part of the coast provides an interesting example of the many shifts in coastal behaviour imposed by a diverse range of natural changes and human activities over the last three millennia. Trunvel marsh, and its associated physical environmental features, is an excellent place to study the evolving relationship between development and geomorpho-dynamics over the longer term.

14.2 The Study Site

Trunvel marsh is located in a part of Brittany known as the Pays Bigouden and was chosen because morpho-dynamic evidence already exists to the north, at Baie des Trépassés, Pointe du Raz (Haslett and Bryant 2007) and to the south, at Penmarc'h (Van Vliet et al. 2014). Additional research has also been conducted on another marsh nearby, Nérizelec (Regnauld 1999). The Trunvel marsh is a very small ria (Fig. 14.2) carved in metamorphic rocks (mainly micaschists) and is separated from the sea by a low gravel ridge which is covered by a series of dunes, some of them prograding on the marsh. The dunes are about 4–6 m high and the marsh has a maximum depth of about 2 m.

14.3 Aims and Methods

The aim of the paper is to reconstruct the late Holocene evolution of the Trunvel barrier/marsh system and to elucidate the relative importance of sea level, storm frequency and intensity and human impact. The methods used follow the guidelines

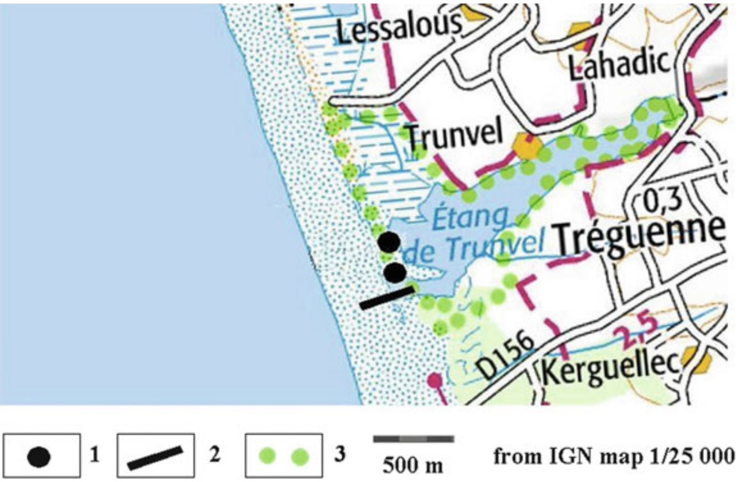

Fig. 14.2 Location of sample sites. *1* Cores, *2* cross section, *3* limits of the modern nature reserve

set in the region for studying such environments (Morzadec-Kerfourn 1995; Regnauld et al. 1995; Monnier 1979). The first part of the work involved the collation of all written archives, from old maps to present day local council decisions. Older maps were found to be relatively imprecise as, obviously this type of marsh was too dynamic in time to warrant very accurate mapping. From the beginning of the twentieth century to the present, maps prove to be accurate enough to produce reliable information. Old texts are sometimes interesting but typically remain very vague when describing coastal morphodynamics (Montfort 1985). The most useful information was found in local council documents and in the archives of management agencies that date from WW2 to the present.

Aerial photography was used to map the dynamics of the marsh over the past 70 years. There are oblique photos only from the WW2 era but six sets of vertical air photos made by the Institut Géographique National are available covering the period from 1952 to 2013. Analysis of these was complemented by ground-truthing fieldwork from 2011 to 2014 under the auspices of the Observatoire des Sciences de l'Univers of Rennes University. This analysis has facilitated the reconstruction of the land use history of the area for the last 70 years and to establish the role of human impact and human management policies. This also enables assessment of the modern geomorphological behaviour of the marsh. In order to compare the present situation with the longer-term situation, two sediment cores were obtained from within the marsh and a cross-section through the dune cordon was studied. The chronology of the cores, which were 7.0 and 7,8 m long respectively, was established by 15 radiocarbon ages. The sediments in the two cores were described in detail and subject to particle size analysis.

14.4 Results

14.4.1 History of the Trunvel Marsh: 3–2 kyr BP

The two cores provide information on the evolution of the marsh sediments over the late Holocene (Figs. 14.3 and 14.4). The sediments are comprised predominantly of aeolian sand (mean particle size around 125 μm) accounting for approximately 90 % throughout the sequence. In the lower part of the cores some isolated broken shell layers, with coarser sands are observed, while there are some clay/silt layers in the upper part.

The coarser sand/ shell fragment layers indicate the transport of marine material into the marsh by storm events. The clay/silt layers are non-marine sediments with rootlets of brackish/freshwater plants and are interpreted as episodes during which biogenic accumulation dominates over aeolian inputs. Radiocarbon ages for the shell layers indicate that the oldest of the shell layers accumulated around 3920 ± 30 BP, while the most recent occurred around 2350 ± 30 BP.[1] The clay/silt layers are dated from 1990 ± 30 BP to present.

The late Holocene history of the site may be reconstructed with this information. During period from approximately 3000–2000 (cal year BP) the Trunvel barrier exhibited resilience. It was a mixed gravel/sand barrier and wind carried sand into the back barrier area, which was at this time probably not a marsh since no organic sediment accumulated the land and was more likely an area of exposed sand flats traversed by a small river to form a seasonal outlet. This interpretation is consistent with both a lower sea level and a lower water table. Estimations of a local sea level at this time indicate indeed that a minor regression occurred around this time and that sea level was some 2,5 m lower than today (Stephan 2011; Costa et al. 2013). The Trunvel barrier was probably occasionally breached by high amplitude storms and, during these episodes, wash-over deposited coarse marine sand and shells onto the sand flats. The barrier was subsequently resilient enough to rebuild itself and to return to its former condition so that the wash-over scattered on the sand flats was in turn buried by aeolian sand. Figure 14.5 presents a schematic illustration of this behavior.

14.4.2 Recent History of the Trunvel Marsh

Nothing is known of the area dating from Roman through to Medieval times and so the history of the marsh system during and just after WW2 is the next period of interest. On the basis of texts (Morel 1995), archives and rare oblique photos, the evolution of the barrier marsh system during and just after WW2 can be

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[1] The radiocarbon date 4040 ± 30 BP is not in chronostratigraphic order and is rejected.

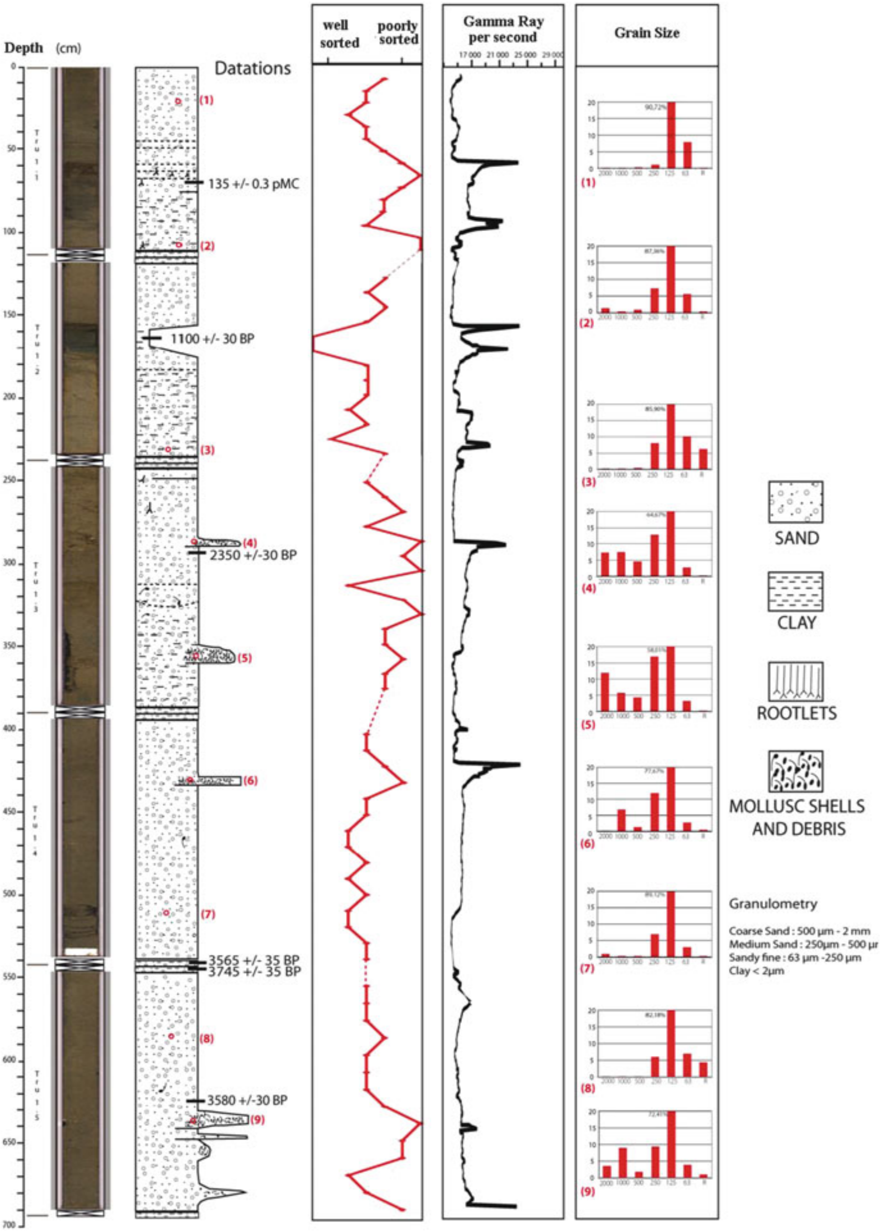

Fig. 14.3 Trunvel Marsh core 1

reconstructed. From 1943 to 1944, gravel was extracted from the barrier by the German occupying forces using the local population as labourers and used to construct defensive concrete blockhouses throughout Brittany. The gravel was

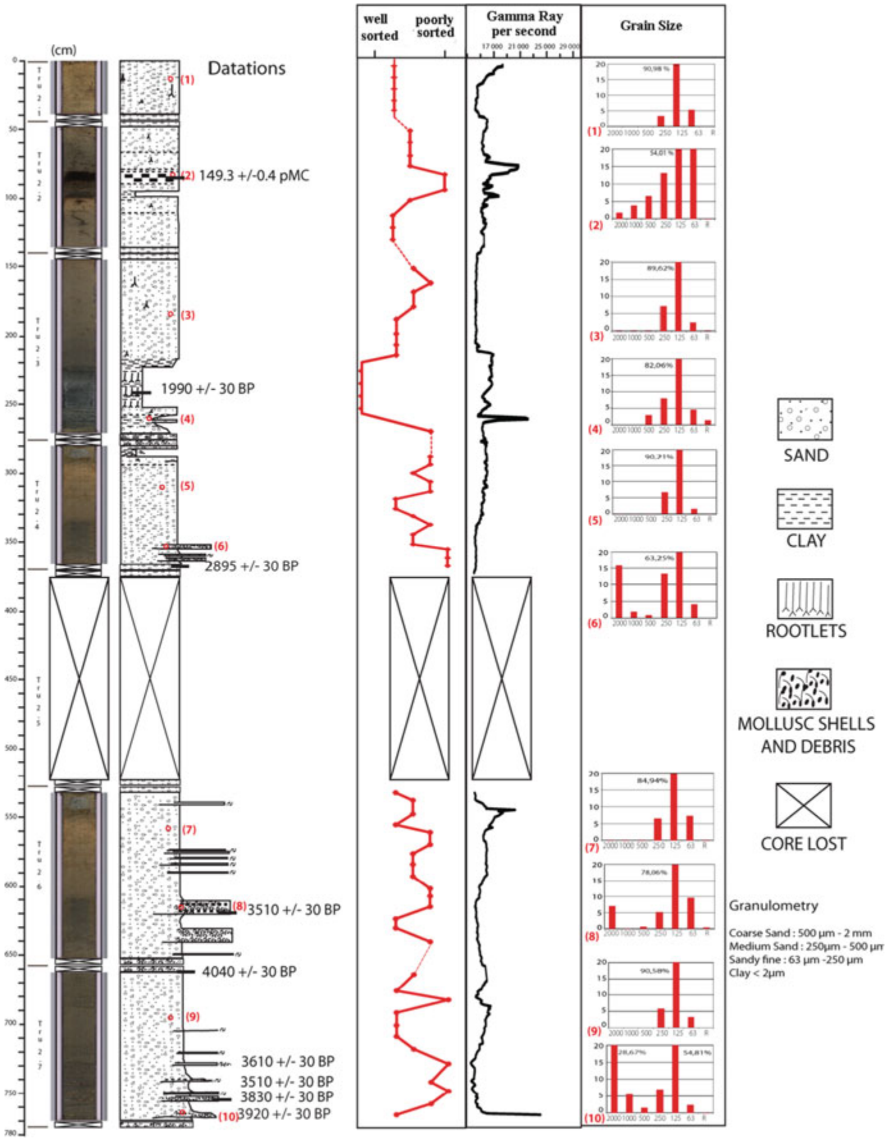

Fig. 14.4 Trunvel marsh core 2

collected all along the Baie and transported via a small railway constructed on the landward side of the barrier. A second railway, 1 km to the south of Trunvel was used to take the gravel further inland and was itself protected by a large blockhouse. After the war, gravel continued to be extracted and was used for concrete in the reconstruction of the main cities of the region (Brest, Lorient) which had been destroyed by allied bombing in 1944. The total amount of extracted gravel is

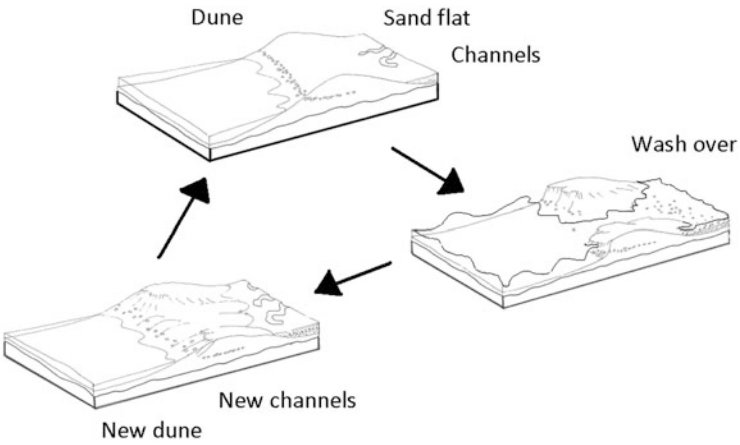

Fig. 14.5 A schematic illustrating the Trunvel response to storms during the late Holocene, with a lower than present sea level and water table. Relative to sea surface the barrier is high and the marsh contains moderate amounts of water (first diagram). Only very intense storms (with associated surges) breach the barrier and disperse wash-over sediments in the back barrier area of sand flats and channels (second diagram). After the storm, the marsh is quickly rapidly evacuated; the mean wind conditions make it possible to reconstruct the barrier and the wash-over material is progressively buried by fresh aeolian sediment. New channels may then form (third diagram)

estimated at 500,000 m^3 which represents as much as 95 % of the original barrier volume.

Air photos provide very clear information since 1952 as to the more recent behaviour of the barrier (Fig. 14.6). The overall picture is one of coastline retreat, which ranges from 60 to 120 m over the period in question. From 1952 to 1969, the dune front retreated parallel to itself as if it was simply tracking back in response to sea level rise. At the beginning of this phase, the marsh had a relatively small extension (light grey area on Fig. 14.6) and two outlets that are contained by the barrier (at least at the time of the 1952 image). After 1969, the marsh began to expand and the two outlets the breached the barrier. From 2000 to the present the retreat was maintained, although by now there is only one outlet and it is narrower than before. This evolution is clearly influenced by the local uses of the marsh area. In the 1950s and 1960s it was used for pasture and the water level was kept low so that a maximum surface was available for grazing. During the 1980 to 1990s it was mainly used for hunting fowl and the water level was kept high at least during the hunting season (October to January). As a consequence, the outlets had much more water to evacuate and were able to breach through the barrier easily during the winter and in summer when grazing was still in place. Hunting activities are now restricted to one half of the marsh, which has been declared a nature reserve, and the water level is negotiated between different stakeholders. Artificial breaching may be engineered by excavation of the barrier if the level is considered too high and threatens to flood nearby properties but the overall strategy is to maintain a high

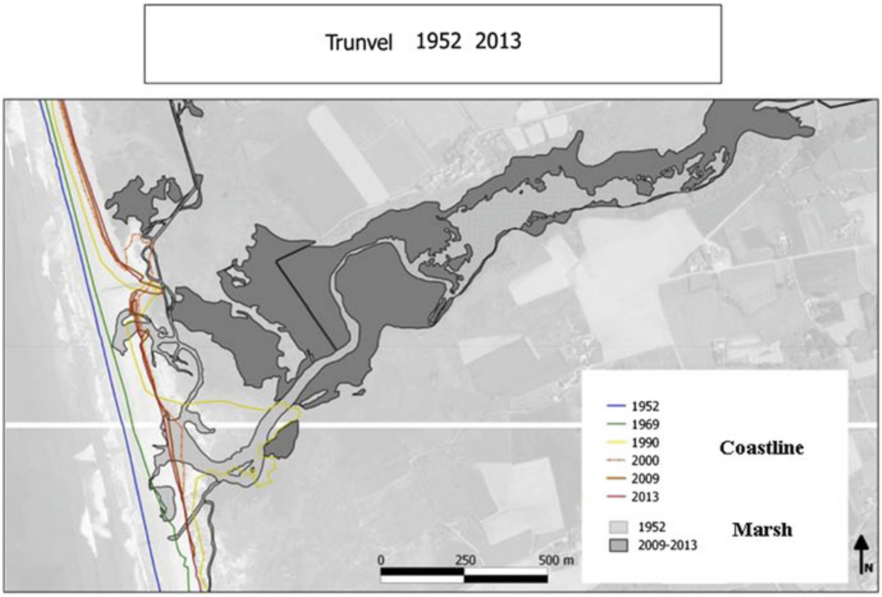

Fig. 14.6 Location of the dune front 1952–2013 mapped on the basis of available sequential aerial photography

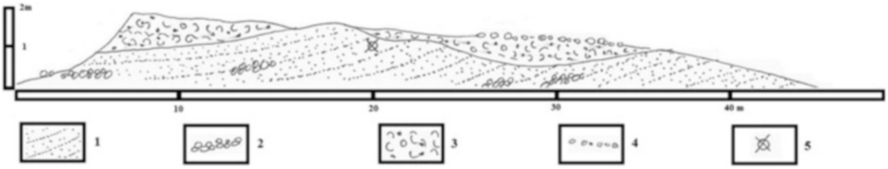

Fig. 14.7 Cross-section along the artificial breach of 2011. *1* Wind blown sands, *2* gravel, *3* storm surge deposits of coarse to medium sands, shells, gravels and seaweed, *4* gravel – rich layer on *top* of the storm surge, *5* plastic artefact with 'sell-by' date of April the 15th 2002 representing maximum age of sediments at this point in the due

level throughout the year so that nesting birds may be protected from human disturbance. Grazing no longer occurs within the marsh area.

The cross section through the dune (Fig. 14.7) assists in developing an understanding of the behaviour of the system during the recent period. Present accumulation rates of sand on dunes in Brittany (Costa et al. 2013) vary between 0.05 and 0.25 m a year. Along a coast which is regularly polluted by debris from by passing ships, very often modern debris (plastic bottles with a "best before" date, plastic nets for fishing, plastic bags...) may be found on the beach, many of which are transported by the wind and become part of the accumulated material in the dune. This cross-section was artificially exposed in 2011 by the local authorities in order to lower the water level in the marsh. It clearly shows the remaining gravel, the post war dune and the truncation of it by a storm, which has deposited a wash over on the truncation surface. The “best before” date of the bottle is April 15th 2002. Eyewitness accounts suggest that the event in question was a large storm in 2008, which was associated with a surge of 0.78 m during the peak high tide at nearby Concarneau (Cariolet et al. 2010). Based on sediments in the cross-section, sand accumulated to a depth of at least 0.8 m, although this is likely an underestimate since some material may have been deflated subsequently. This is similar to rates estimated in other localities along the coastline of Brittany, although in this case the plastic refuse ‘best before’ methodology enables a more accurate assessment of age. During each large storm associated with a surge (often occurring during spring high tide, as in 2008) the marsh is flooded by seawater but as soon as the tide flows out the marsh empties with the ebb currents. It may be flooded again with the next high tide but the surge does not usually persist for long enough for the water to reach the same level.

The modern behaviour of the marsh contrasts with its responses earlier in the Holocene. Although wind blown sand dominates the earlier sediment there is no evidence in the record of any equivalent over-wash process. This is probably linked to a relative rise in sea level, which reached its present level by the beginning of the Roman times. The water table was then higher and the sand flats were flooded much more frequently. Drainage seaward of such large amounts of water required large outlets, at least seasonally. Not all flooding episodes were the same and some appear to have lasted long enough to facilitate colonization by brackish water vegetation, while others did not.

The complete absence of storm layers at these levels is interesting because it is difficult to believe than no intense storm occurred during the last 2000 years. It is difficult to imagine that there were major storm surges but that they failed to breach the barrier and therefore left no wash-over deposits. So the problem is reduced to trying to understand why the wash-over deposits were not preserved as discrete layers in the sediment. A possible explanation is that these storms had an impact similar to the current ones, which do not leave wash-over in the marsh. In the present day, when a storm occurs and breaches the barrier it deposits wash-over material in two different situations, viz. on the top the dune where they do remain in situ (as in the cross-section Fig. 14.7), or deposited within the marsh where they are almost immediately evacuated by the currents when the marsh discharges into the sea after the surge. The currents are strong because the amount of water is greater than during the preceding period where the sea level and the water table were lower. Figure 14.8 presents a schematic of this scenario.

Between 2 ky BP and WW2, there is no direct or indirect (documentary) evidence but the Trunvel barrier was probably subject to low intensity human impact throughout this time. The impact of gravel removal and erosion during and after WW2 was huge by comparison with any other effects, either natural or anthropogenic, and the barrier had to rebuild itself almost completely since then. The present dunes have been slowly accumulating during post WW2 period. The modern marsh is now totally managed through the opening or the closing of

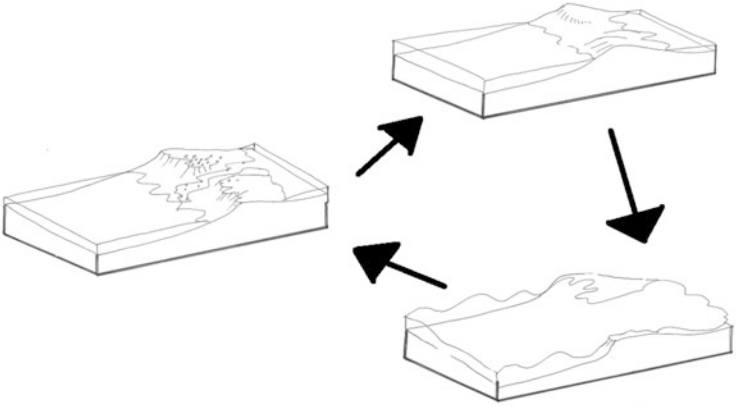

Fig. 14.8 Schematic illustrating the behavior of the Trunvel barrier and marsh during the high sea level and water table episode spanning the period 2 ky BP to WW2. Relative to sea level, the barrier is low and is easily breached by many storms. The marsh contains substantial amounts of water. The over-washed sediment deposited on the surface of the dune remains. Sediments deposited in or close to the drainage outlet are returned to the sea as the strong currents scour the outlet. The two cores extracted close to a former outlet show no storm layers preserved for this period

breaches, aimed at maintaining a system that provides suitable habitat for breeding waterfowl. Remarkably, this artificial action mimics the behaviour of the marsh from beyond 2000 years ago and has facilitated the recovery of the barrier since its WW2 destruction.

14.5 Discussion

Along this Atlantic coast of Brittany two issues are of particular interest in relation to the complex interaction of sea level rise, meteorological events and human activity. The first concerns the possible impact of high magnitude events such as tsunamis. Haslett and Bryant (2007) reveal clear evidence of the 1755 Lisbon Tsunami at nearby Baie des Trépassés. At Ushant island, Regnauld et al. (2010) demonstrate, on the other hand, that it is very difficult to resolve the relative importance of tsunamis as a factor in coastal morphodynamics because subsequent storm events may rework the tsunami deposits. At Trunvel there is no evidence of any such tsunami events, although this may be because of sediment removal during the WW2 gravel works. The second issue concerns the frequency and magnitude of storm events during the Holocene, which, according to Van Vliet et al. (2014), may be linked to the dynamics of the North Atlantic Oscillation (NAO) in response to changes in solar activity. At Trunvel, storm deposits are frequent between 3 and 2 ky BP but later absent, a change that is, however, more likely related to anthropogenic effects on coastal morphodynamics that eroded any storm deposits. In this respect, sedimentary evidence at Trunvel is not well suited to palaeoenvironmental reconstruction as excavation and related human impact have led to the loss of much of the sedimentary archive.

Perhaps the most interesting aspect of the barrier marsh system is the manner in which it responds to storm systems today. This reaction is likely to be manifest as long term “roll over” behaviour as identified by Orford and Anthony (2013). Each storm brings sediment onshore, some of it remains (the over-wash), while some of it returns to the sea, although the overall balance produces a net movement of sediment landward. The storms and surges thus force the barrier to migrate landward over the long term (several decades). This process illustrates the coastal response to relative sea level rise and suggests that observed coastal retreat may not only be a consequence of a sediment deficit but also a resilient reaction to rising sea levels.

14.6 Conclusion

The Trunvel barrier and marsh system is today in effect a “human-made natural system” and presents a fine example of the potential of recovery of disturbed coastal systems even in situations whereby original structures were almost totally destroyed. Although modern conditions are different from the past in respect of sea level and in so far as the marsh drainage is closely managed in a way that differs from former practices, the Trunvel barrier and marsh complex behaves in a way that seemingly meets the combined and complex challenges of nature conservation and coastal protection, along with the needs of the local population. Society can be seen here to have defined how the environmental system should work. The Trunvel study illustrates clearly that local people have their own idea of how a landscape should behave and that this does not necessarily conflict with nature.

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Chapter 15
Integrating Estuarine, Coastal and Inner Shelf Sediment Systems in a Common Conceptual Framework as a Basis for Participatory Shoreline Management

Jonathan R. French, Helene Burningham, Gillian D. Thornhill, and Robert J. Nicholls

Abstract Coastal and estuarine margins are home to an increasing proportion of the global human population and its activities. Within this context, landforms play a critical role in mediating the translation of erosion and flood risk to human receptors in environmental settings that are vulnerable to the likely impacts of climate change. Predicting how coastal and estuarine landforms will evolve in response to changes in sea level and wave climate is thus of considerable importance. This is naturally a modelling problem but previous efforts have often failed to translate generic principles into models that do justice to the place-specific interactions between contemporary processes, antecedent geology, sea level history, historical morphology, engineering interventions and, not least, broader societal concerns. Progress clearly requires better models but, as we argue here, more sophisticated conceptual frameworks are also needed. Accordingly, we outline a new Coastal and Estuarine System Mapping (CESM) approach that captures the configuration of estuarine, coastal and inner shelf landform complexes within a unifying framework that also explicitly resolves the multitude of human interventions that influence shoreline change. An illustrative application to the Suffolk coast of eastern England demonstrates the potential of CESM to encourage a more participatory approach to regional shoreline management and the application of scientific understanding to the challenge of living with human and climate change impacts at the coast.

Keywords Coastal geomorphology • Systems theory • Ontology • Conceptual model • Coastal management

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15.1 Introduction

Coastal and estuarine margins are home to an increasing proportion of the global human population and its activities (McGranahan et al. 2007; Lichter et al. 2011) and that over 200 million people are vulnerable to annual flooding during storms and surges (Nicholls 2011). The attendant potential for loss and damage to human lives and assets due to erosion, storm surges, extreme waves and tsunamis means that coasts, in the widest sense of the term, constitute one of the riskiest environments (Kron 2013). In the twenty-first century, the challenge of continuing to manage these risks is exacerbated by the prospect of a significant increase in damage costs as the effects of widespread erosion and progressive inundation due to sediment deficits and subsidence combine with climate change impacts on sea-level and coastal wave climate. There is little realistic prospect of mitigating the rate of climate-driven sea-level rise over decadal scales given the substantial inertia of the coupled atmosphere, cryosphere and oceans (Nichols and Lowe 2004), and the prospect that annual coastal flood damage costs alone could potentially amount to between 0.3 and 9.3 % of global GDP by 2100 (Hinkel et al. 2014) will likely stimulate a significant adaptation effort (Brown et al. 2014).

Historically, continuing advances in engineering capability have favoured protection as a strategy for adapting to erosion and flood risk (Charlier et al. 2011; Nicholls 2011; Nordstrom 2014). The influence of engineered structures on shoreline dynamics is now pervasive (van Koningsfeld et al. 2008; Brown et al. 2011; Bernatchez and Fraser 2012). The cumulative legacy of intervention is such that, at the scale of the United States, rates of shoreline change along the open coast are strongly constrained by varying levels of development (Hapke et al. 2013). Naturally dynamic estuarine systems are similarly held away from natural equilibrium morphologies, in artificial meta-stable, states by extensive flood defences, training walls and inlet jetties (e.g. Huang et al. 2004; Smits et al. 2006; Wetzel et al. 2014). Efforts to secure and maintain socially acceptable levels of protection against erosion and flooding have latterly been conducted within a shoreline management paradigm (Nicholls et al. 2013) under which a traditional reliance on engineering has been supplemented by a growing awareness that coastal engineering problems are also geomorphological ones.

The role of geomorphologists in coastal engineering and shoreline management has stemmed partly from the realisation that erosion problems are typically rooted in interruptions of natural sediment pathways or constraints on sediment supply (Allen 1981; Kana 1995; Runyan and Griggs 2003; Hapke et al. 2010). This understanding is underpinned by the related concepts of the sediment budget (Bowen and Inman 1966) and the littoral cell (Inman and Frautschy 1966; Davies 1974). Littoral cells are easily defined on compartmented bay-headland coasts (Shih and Komar 1994; Storlazzi and Field 2000; Barnard et al. 2012), with divergences or convergences in transport flux or estuary inlets being used to structure the sediment system on more open coasts (Stapor 1973; Motyka and Brampton 1993; Bray et al 1995). Hierarchies of littoral cells provide a geomorphological framework for management planning at a wide range of scales that has clear advantages over schemes based primarily on administrative boundaries (Komar 1996; Cooper and Pethick 2005; Psuty and Pace 2009; Stul et al. 2012).

At the landform scale, coastal engineering has also undergone a shift in emphasis from a reliance on hard structures towards softer approaches that seek to work with, rather than against, natural processes of sediment movement. Structural interventions increasingly attempt to mimic natural features (e.g. Hsu et al. 2010), and the role of beaches, dunes and wetlands in dissipating wave energy and attenuating extreme water levels is widely appreciated (e.g. Hanley et al. 2014; Luo et al. 2015). Landforms are also integral to widely used conceptual models of erosion and flood risk. The Source-Pathway-Receptor model (Sayers et al. 2002; Narayan et al. 2012), for example, highlights the role of landforms as one of the pathways that mediate the transmission of flood risk from marine and fluvial sources to human receptors in low-lying areas (e.g. Batten et al. 2015). Given the extent to which the sources of risk are anticipated to change over the course of the twenty-first century and beyond, it is important that we develop our understanding of how coastal morphology will evolve and how this will influence erosion and flood risk. In this context, the ability to quantitatively predict coastal morphological change at decadal to centennial scales thus assumes considerable importance.

Predictions of coastal change are often derived from analysis of historical behaviour on the premise that the future can somehow be extrapolated from the recent past. However, landform and sediment system behaviour is often highly non-linear (e.g. Werner 2003) and past configurations often contain insufficient information to generate quantitative predictions of future behaviour (Gelbaum and Kaminisky 2010; French and Burningham 2013). Modelling of coastal morphological change has consequently become a very active area of research. However, devising robust mechanistic schemes capable of resolving the morphological evolution of whole landforms, let alone complexes of interacting landforms, presents many challenges. Applications of reductionist sediment dynamics principles to coastal morphodynamic problems are becoming ever more sophisticated (Roelvink and Reniers 2012; van Rijn et al. 2013) and, with advances in computing power, simulation over decades and even centuries is feasible for certain environments (e.g. nearshore bars (Ruggiero et al. 2009); tidal basins (Dastgheib et al. 2008) and estuaries (Hibma et al. 2004; van der Wegen and Roelvink 2008). Computational cost still limits the extent to which rigorous calibration and sensitivity analysis are possible, however, and long-term morphological change predicted in this way is typically very sensitive to initial conditions that can usually only be approximated and also to simplifications in the external hydrodynamic forcings (Walstra et al. 2013). An alternative strand of modelling effort embraces more synthesist approaches that are explicitly designed to resolve those aspects of coastal behaviour that emerge naturally at a mesoscale measured in decades to centuries and tens to hundreds of kilometres (Murray et al. 2008; French et al. 2016b). These range from highly aggregated aspatial models that capture selected aspects of mesoscale coastal and estuarine morphodyamics (e.g. Stive et al. 1998; Kragtwijk et al. 2004) to more mechanistic spatially distributed models (e.g. Walkden and Hall 2011).

Irrespective of the quantitative modelling approach adopted, generic principles need to be translated into models that take account of the place-specific contexts in which contemporary processes interact with antecedent geology, sea level history, historical morphology and engineering interventions, and landform dynamics are forced by tidal, wave and sediment supply boundary conditions at broader scales. This requires robust conceptual frameworks for the formalisation of existing knowledge; formulation of relevant scientific questions and management issues; development and implementation of predictive models; and, not least, meaningful engagement with stakeholders. Despite undoubted progress with the development of mesoscale coastal behaviour models (e.g. Walkden and Hall 2011; Castedo et al. 2012) our conceptualisations have not evolved at a similar pace to support a geomorphologically-informed assessment of erosion and flood risk over the twenty-first century and beyond (Nicholls et al. 2012). In particular, a reliance on littoral cells as an organising framework makes it difficult to conceptualise the complex web of interactions between the sediment systems of estuaries, open coasts and the inner shelf.

In this chapter, we show how the recently developed Coastal and Estuarine System Mapping (CESM) approach of French et al. (2016a) provides a basis for integrating open coast, estuaries and the inner shelf in a single conceptual framework. CESM captures the configuration of the sediment system, with all its human constraints, at time and space scales relevant to management. It also identifies locations where there is potential for step-changes in configuration, for example due to the breakdown of a spit or breakdown of a barrier. Finally, CESM encourages a more participatory approach to shoreline management by formalising disparate sources of knowledge and drawing stakeholders into the process of defining problems and deploying model-based scientific understanding to find solutions to them.

15.2 Integrating Our Understanding of Coastal Sediment Systems

Under the shoreline management paradigm that has prevailed in many countries (Leafe et al. 1998; Hunt et al. 2011; Mulder et al. 2011; Nicholls et al. 2013), open coasts have hitherto been treated separately from estuaries. This division of effort has much to do with administrative boundaries and differences in the state agencies responsible for dealing with erosion (more prevalent along open coast) and flood risk (concentrated in estuaries). While such geohazards do present different sets of problems, a divergent approach to their management has led to a lack of appreciation of the nature, extent and significance of the sedimentary and morphodynamic interactions between estuaries and the open coast, and indeed the wider shelf.

The need for a more integrative perspective has become more pressing as the strategic application and evaluation of management and engineering options has evolved to address the broader time and space scales at which progressive shifts in shoreline position occur in response to climate change and sea-level rise (French and Burningham 2013). A key area of concern is the fact that littoral cells (Fig. 15.1a) primarily reflect short-range transfers of 'beach-grade' sediment and are not well suited to resolving broader scale linkages between estuarine, coastal and offshore systems (Cooper and Pontee 2006). This limitation is especially apparent where long-range coastal shelf suspended sediment transport fluxes drive morphological change in estuaries (e.g. Kirby 1987; Dyer and Moffat 1998; Keen and Slingerland 2006). Cooper and Pontee (2006) also highlight concerns over the criteria used to delimit littoral cells, and the stability of cell boundaries, especially under significant changes in wave climate or sediment supply. In the UK, these issues were tackled in the FutureCoast project (Burgess et al. 2002), which embedded littoral cells within a spatial hierarchy of geomorphological units (effectively individual landforms), shoreline behaviour units (sub-systems, such as embayments and estuaries) and regional coastal behaviour systems. Applied to the entire open coast of England and Wales, the FutureCoast methodology allowed identification of the scale and nature of the linkages that govern coastal morphological change at the decadal to century timescale and underpinned a second generation of SMPs (Burgess et al. 2004; Hunt et al. 2011).

The concept of the 'coastal tract' developed by Cowell et al. (2003) provides an alternative, though complementary, perspective on coastal morphodynamics at scales directly relevant to shoreline management. Identification of sediment-sharing tracts (Fig. 15.1b) is motivated by the observation that many of the most pressing management issues arise not from the short-term variability that often dominates the observational record but from progressive trends. Accordingly, the tract concept is formulated around a temporal hierarchy in which landforms and complexes of landforms evolve under lower order geological constraints (Holocene/Quaternary scale) while subject also to the residual effects, accumulated over larger time scales, of unresolved fine-scale processes. At the same time, successful treatment of coastal tracts requires an expanded spatial scope that includes exchanges of sediment with the lower shoreface as well as interactions between open coast and backbarrier lagoonal and estuarine environments. As French et al. (2016b) observe, contrary to the generally assumed correlation of time and space scales, coupled estuary – coast – inner shelf behaviour is driven by sediment exchanges at multiple nested spatial scales (see also, Fig. 15.2). These are primarily related to distinct sediment size fractions (Keen and Slingerland 2006; van der Kreeke and Hibma 2005), as well as to different sets of anthropogenic natural forcing factors (Fenster and Dolan 1993; Hapke et al. 2013). Beach morphological change tends to occur in response to relatively local sand and gravel transport dynamics, often fed by proximal sea cliff or fluvial sources (e.g. van Lancker et al. 2004; Komar 2010). In contrast, cohesive sediments from fluvial or coastal cliff sources can sustain estuarine sedimentation hundreds of kilometres from the sources (McCave 1987; Dronkers et al. 1990; Gerritsen et al. 2000).

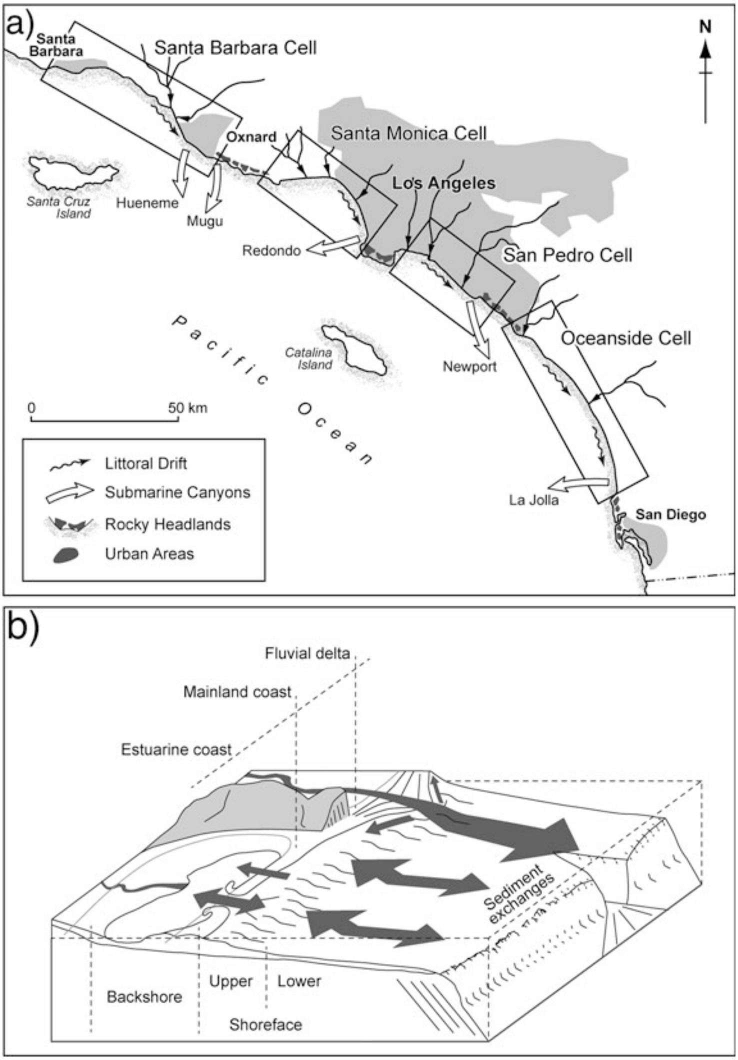

Fig. 15.1 (**a**) Coastal, or littoral, cell concept (After Inman and Frautschy 1966); (**b**) visualization of coastal tracts (After Cowell et al. 2003)

In addition to sediment sharing between coupled landforms and complexes of landforms, other kinds of interaction also influence coastal behaviour. Shelf bank systems (e.g. MacDonald and O'Connor 1994; Park and Wells 2005; Hequette et al. 2008; Hequette and Aernouts 2010) and submarine channels (Browder and McNinch 2006) can both play a role in modifying coastal wave climate, either by reducing wave energy at the shoreline or else focusing it. These systems are often morphologically active but may still have little direct sediment exchange with contemporary coastal systems (Antia 1996).

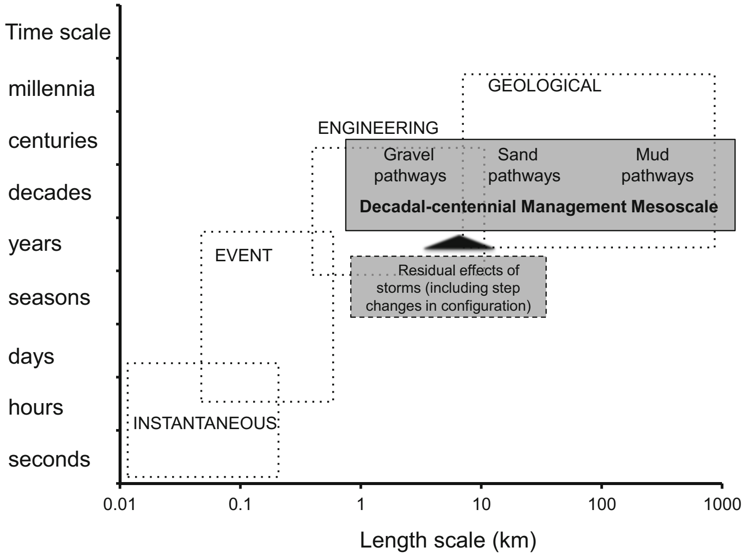

Fig. 15.2 Schematization of temporal and spatial scales of coastal behaviour (based on Cowell and Thom 1994), highlighting a decadal to centennial management mesoscale at which grainsize-dependent sediment system pathways nest at multiple spatial scales. Mesoscale coastal configuration also reflects residual effects (accumulated over larger time scales) of short-term storms, which can effect state changes, for example, by breaching of barriers

15.3 A Spatial Ontology of Estuary: Coast: Inner Shelf Sediment System Interactions

As a first step towards articulating the vision outlined above, French et al. (2016a) present an idealised spatial ontology for coupled estuary-coast-inner shelf sediment systems. The term ontology refers to a formal specification of a conceptualisation (Gruber 1993), although this is interpreted rather loosely here to refer to a hierarchical classification of components and a set of permitted interactions between them. As outlined in Fig. 15.3, this scheme reflects certain aspects of the coastal tract concept (Cowell et al. 2003) in its hierarchy of morphologically-active sediment-sharing landforms and landform complexes. These are embedded within the geological context of a shoreface that can be considered time-invariant at decadal to centennial timescales. In contrast to the primarily temporal tract hierarchy (Cowell et al. 2003), our scheme emphasises spatial nesting of discrete landform components within landform complexes, and explicitly represents varied human interventions and the way in which these constrain morphological change. Landform complexes, in turn, are embedded within coastal behaviour systems at a broad regional scale; this parallels the thinking behind the FutureCoast work (Burgess et al. 2002).

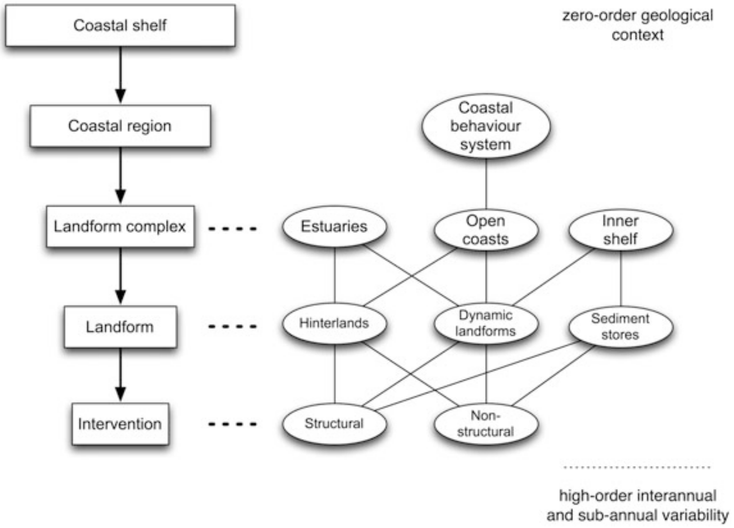

Fig. 15.3 Spatial ontology of coupled estuary–coast–inner shelf geomorphic systems (Modified from French et al. (2016a)

15.3.1 Landform Complexes

Classification invariably involves a trade-off between the desire to simplify and the need to resolve significant diversity. Several attempts have been made to reduce the wide variation in estuary morphology and origin to a small set of sub-types. In a New Zealand context, Hume and Herdendorf (1988) identified five major modes of estuarine basin formation, within which 16 estuary sub-types occur. A more elaborate scheme incorporating several distinct levels of controlling factors was presented by Hume et al. (2007). Davidson and Buck's (1997) classification of British estuaries into eight types was rationalised to seven generic types by ABPmer (2008), based on the consideration of 163 estuaries around the entire UK coast. This scheme (Fig. 15.4a) was adopted for CESM by French et al. (2016a) on the basis that its simplicity reduces the potential for variation between maps produced by different 'experts' due to subjective classificatory judgements.

For open coasts, a similarly minimal classification is feasible. That shown in Fig. 15.4b recognises mainland coast (cf. Cowell et al. 2003), and augments this with headlands and bays for coasts that exhibit more obvious geological control. Cuspate forelands and spits are locally prominent around the British coast and some are large enough to be afforded the status of a landform complex (Plater et al. 2009), as are a variety of barrier features (Bray 1997; Funnell et al. 2000). For application in other geographical contexts, additional complexes would clearly be required (most obviously deltas, which do not feature on the contemporary British coast).

Individual landforms are less abundant over much of the inner shelf, although the interaction between drowned palaeo-landscapes of the last glacial (Harris

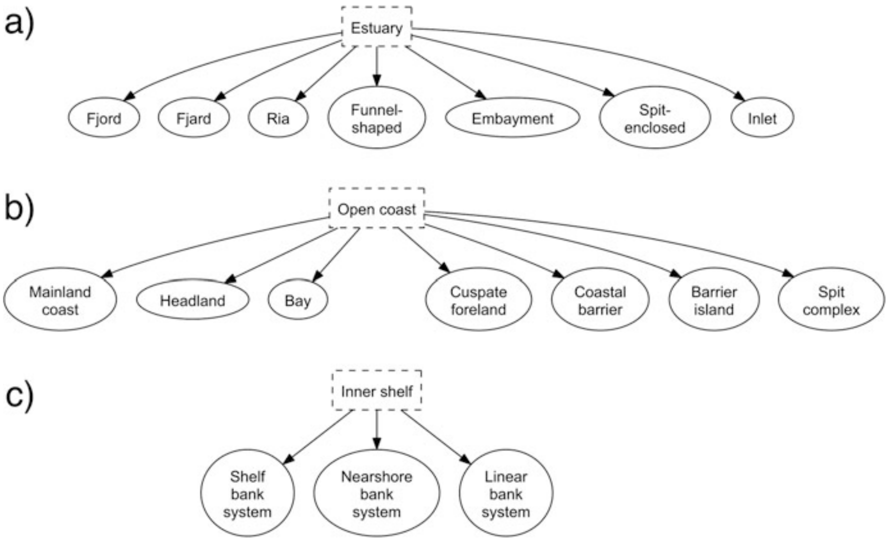

Fig. 15.4 Classification of UK estuary (**a**), coastal (**b**) and inner shelf (**c**) landform complexes (Modified from French et al. (2016a)

et al. 2013) and modern shoreline dynamics is attracting increasing attention (McNinch 2004). Many shallow shelf seas are characterized by bank systems that differ in morphology, organization and origin (e.g. Swift and Field 1981; Belderson 1986; Hequette and Aernouts 2010). In a UK context, sand bank complexes (and isolated features) are common in the North Sea (Caston 1972; Burningham and French 2011), where they are known to influence contemporary shoreline behaviour by modifying coastal wave climate (Dolphin et al. 2007) and via their role in sediment pathways (Robinson 1966; Chang and Evans 1992). Figure 15.4c distils a detailed analysis by Dyer and Huntley (1999) into three distinct types. Shelf bank systems may or may not be morphologically active and, at decadal to centennial scales, chiefly act to modify coastal wave climate (e.g. Chini et al. 2010). They are also associated with tidal interactions controlling broader bedload sediment transport pathways and residual currents influencing fine sediment transport (e.g. Dyer and Moffatt 1998). Linear bank systems are associated with larger meso- to macro-tidal estuaries (e.g. Burningham and French 2011). Nearshore bank systems include the various forms of headland-attached ridge (Caston 1972; Schmidt et al. 2007).

15.3.2 Landforms

Estuarine, open coastal, and inner shelf complexes are aggregations of individual landforms (Table 15.1). The same landform type may occur within more than one type of landform complex (e.g. tidal flat, which can occur in both open coast and

Table 15.1 Landform components common to open coastal, estuarine and inner-shelf complexes. These comprise morphologically active landforms, as well as sediment reservoirs, and hinterlands that are not considered to evolve their morphology at timescales of decades to centuries

Landform		Hinterland	Sediment store
Cliff	Inlet channel	High ground	Seabed gravel
Shore platform	Ebb delta	Low ground	Seabed sand
Beach	Flood delta	Reclaimed	Seabed mud
Beach ridge	Bank		Suspended mud
Tombolo	Channel		
Dune	Tidal flat		
Spit	Saltmarsh		
Rock outcrop	Brackish marsh		
Lagoon	River		

Note that this set has been devised for application in a UK context; other settings may involve landforms not represented here

estuarine settings). Other landform types such as spits and ebb tidal deltas occur at the interface between estuary and open coast and, as such, could be considered to be part of either complex. Spits are a special case in that larger examples can be mapped as a complex (including landforms such as beach, beach ridge, dune and saltmarsh) while minor features can be considered to be landforms embedded within a larger complex. At decadal to centennial scales, hinterland imposes an essentially static boundary condition control. Terrain that rises well above current and projected future tide and surge elevations and would be expected to show a largely erosional response to sea-level rise is referred to as high ground. Low ground is identified as being more susceptible to inundation, although erosion can also lead to increased flood risk such that the two hazards are not independent. Reclaimed areas have been converted from former subtidal or intertidal landforms, and are protected from tidal inundation by fixed defences.

Coastal, estuarine and shelf sediment systems also include reservoirs of sediment that can be locally important in mediating landform behaviour. The inner shelf is typically veneered by patches of sediment, some of which are inactive under present sea level, wave climate and tidal regime, and some of which exchange sediment with coastal or estuarine environments. Seabed stores can be classified according to grain size, and their interaction with the contemporary sediment system elucidated by consideration of shelf sediment pathways (e.g. Poulos and Ballay 2010), possibly augmented by sediment transport modelling (Barnard 2013; Brown et al. 2015).

15.3.3 Human Interventions

As noted above, present-day coastal behaviour is strongly conditioned by a multitude of human interventions. The effects of coastal protection works are evident locally (Runyan and Griggs 2003; Basco 2006), regionally (Clayton 1989; Dawson et al. 2009; Brown et al. 2011) and even nationally (van Koningsfeld et al. 2008; Hapke et al. 2013). The most obvious interventions are structural, installed with the aim of preventing erosion, reducing flooding or facilitating reclamation. Engineering practice has evolved to incorporate varied local experiences and requirements, and this is reflected in a diverse terminology for structures that perform the same function. It is therefore useful to adopt a highly generic classification of intervention types according to the function that they perform. In the scheme summarised in Table 15.2, most interventions have the effect of arresting movement, for example through limiting erosional retreat or channel migration. Some, such as groyne fields, represent a direct intervention to retain or restore a sediment store and any associated littoral drift pathway. Non-structural interventions in coastal and estuarine sediment systems are also common, not only through dredging and aggregate extraction (Hitchcock and Bell 2004) but also through ‘softer’ and more adaptive approaches to coastal management including beneficial reworking of sediment (including various forms of nourishment or recharge) to restore known deficits and enhance the resilience of degraded environments (Khalil et al. 2010; van Slobbe et al. 2013).

15.3.4 Interactions

The ontology described above includes about 60 components, distributed over four hierarchy levels. From a functional perspective, components influence each other through a complex web of interactions. Interactions in the broadest sense refer to any cause-effect relation between components. For example, a jetty exerts an effect on an inlet channel, stabilising its location and also influencing its cross-sectional characteristics. Some components (e.g. beach, inlet channel, channel) are far more connected than others (including the less common landforms and structural interventions). Some interactions are bidirectional, such as the interplay between a seawall and a beach (Basco 2006). A sub-set of the interaction network involves transfers of mass and these sediment pathways define the sediment budget. Some of the linkages may be unidirectional, for example where sequential beach units define a littoral drift system. Others may represent more complex causality: a cliff may source sediment to a fronting beach (mass transfer) and the beach may influence the cliff (via an influence whereby beach morphology feeds back into the cliff recession rate; Walkden and Hall 2011).

Consistency in the representation of system interactions is clearly important and can be achieved through careful tabulation of permitted interactions, their nature and directionality, and a supporting logic backed by references to the scientific literature. Table 15.3 presents an illustrative portion of an interaction matrix for selected system components. Three types of interaction are possible: (1) None – paired components exert no direct influence on each other; (2) Influence, where there is a process interaction, such as wave sheltering, but no direct sediment

Table 15.2 Minimal classification of generic structural and non-structural interventions in estuary, coast and inner shelf sediment systems, with their indicative purpose

Structural	(Indicative purpose)	Non-structural	(Indicative purpose)
Seawall	Erosion protection	Dredging	Navigation; mining
Revetment	Erosion protection	Dredge disposal	Spoil disposal
Bulkhead	Erosion protection	Sediment recharge	Restoration of sediment deficit (beach, intertidal)
Embankment	Flood protection	Sediment bypassing	Continuity of sediment pathway; navigation
Barrage	Flood protection	Sediment recycling	Resilience (beach profiling); navigation
Breakwater	Wave energy reduction		
Detached breakwater(s)	Wave energy reduction		
Groyne(s)	Sediment retention		
Training wall	Channel stabilisation/ navigation		
Jetty	Varied		
Outfall	Drainage/dispersal		
Quay	Navigation/trade		
Dock	Navigation/trade		
Weir	Regulation of river gradient and/or tidal limit		

exchange; and (3) Sediment pathway – a direct exchange of sediment between components. The entire set of system components can be treated in this way, such that the ontology goes beyond a simple classification to specify which landforms can be assembled into complexes, the manner in which they interact, and the effect of various human interventions. Whilst local circumstances may generate situations that require special provision, a priori specification of system interaction types is essential to ensure consistency when system mapping is applied in practice.

15.4 Coastal and Estuarine System Mapping (CESM)

The CESM approach (French et al. 2016a) provides a means of capturing the configuration of the key morphological components, human interventions, and the sediment and other influence pathways that connect them. Given the emphasis on system behaviour at decadal to centennial scales, seasonal and interannual variability is excluded in favour of more persistent interactions. The result is a time-averaged view of system configuration as conditioned by present processes and human constraints. Behavioural dynamics are not resolved, although in certain situations it is possible to envisage event-driven changes in gross configuration,

Table 15.3 Illustrative paired examples of interaction rules for landforms and interventions

From	To	Interaction	Logic (literature source)
Cliff	Beach	Sediment pathway (sand, gravel)	Cliff sources beach-grade sediment (mud lost offshore)
Beach	Cliff	Influence	Presence and morphology of beach feeds back into cliff recession rate (e.g. Walkden and Hall 2011)
......	......	......	......
Seawall	Beach	Influence	Presence of seawall may cause lowering of beach (e.g. Basco 2006)
Beach	Seawall	Influence	Beach protects toe of seawall and reduces wave energy on face
......	......	......	......
Jetty	Inlet channel	Influence	Jetty exerts stabilising influence on channel position and constrain width adjustment
Inlet channel	Jetty	None	No direct causal relation in this direction

such as the breakdown of a barrier to create to create a new tidal inlet. Configurational state changes of this nature are considered further below.

The workflow for CESM (Fig. 15.5) commences with ‘specification’ of the problem at hand, for which a formal statement of the application is required. A suitable time-averaging period over which to characterise the configuration of the coastal sediment system is chosen at this stage. For strategic management problems, including those relating to climate change impacts, relevant timescales are usually decades to centuries (French et al. 2016b). The level of spatial detail required, as well as the geographical scope, are also determined at this stage. The latter might vary from regional mapping to guide the preparation of a shoreline management plan to mapping of individual intertidal flat, saltmarsh and reclaimed flood compartments to provide context for a specific flood defence management scheme. The next step is to determine the most effective route to formalising the current state of understanding. For well documented and/or understood systems, a lone expert or small team of experts may be able to achieve a relatively uncontentious synthesis of existing knowledge. Where a system is less well understood, CESM provides a starting point for the development of a conceptual model and a larger team might be required to achieve a consensus. This might be a joint effort or else achieved through rival efforts that highlight areas of divergent opinion. Finally, background knowledge (published papers, reports etc.) and plain data (aerial images, bathymetry, historical shoreline change analyses etc.) are assembled to support subsequent stages of the mapping process.

Mapping may then follow a ‘top down’ route, in which landform complexes are identified first and then populated with landform detail, or a ‘bottom up’ route whereby landforms and interventions are mapped in detail and then organised into broader-scale complexes. Both require a robust protocol for the identification of discrete system components and the interactions between them.

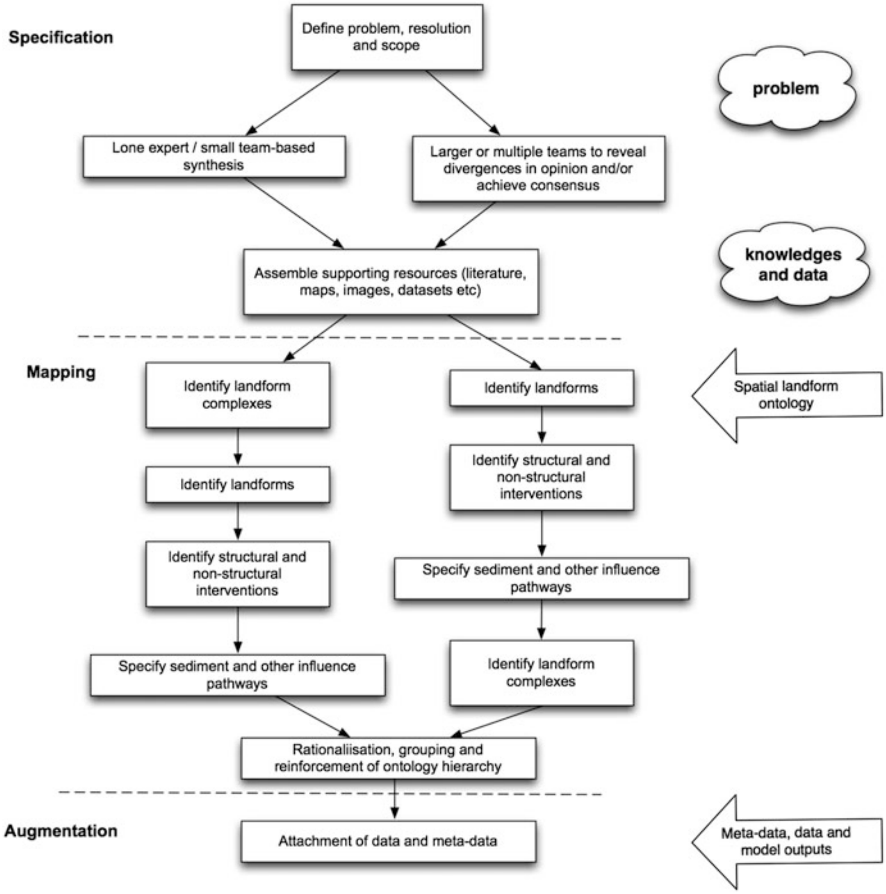

Fig. 15.5 Workflow for Coastal and Estuarine System Mapping (After French et al. 2016a)

Figure 15.6 illustrates this for an example case of the interactions between a small spit-enclosed estuary and a sandy open coastal bay bounded by headlands formed in more resistant geology. Mapping of the open coast proceeds by identifying distinct hinterland – backshore – nearshore sequences and any local constraints due to structures or known non-structural interventions (e.g. beach nourishment or sediment bypassing programmes). This is similar to the approach taken by Hanson et al. (2010) in their scheme for mapping barrier and non-barrier coasts based on sequential transitions in cross-shore profile type and a set of prescribed landform elements. Figure 15.7a illustrates a portion of the open coast, showing backshore to hinterland sequences of landforms together with human interventions (including a minor jetty and extensive groynes, bulkhead and embankments). Alongshore intervals are chosen to segment the coast into units that can be considered to function more-or-less as an integrated whole. Interaction pathways are then added, with the directionality of the sediment pathways

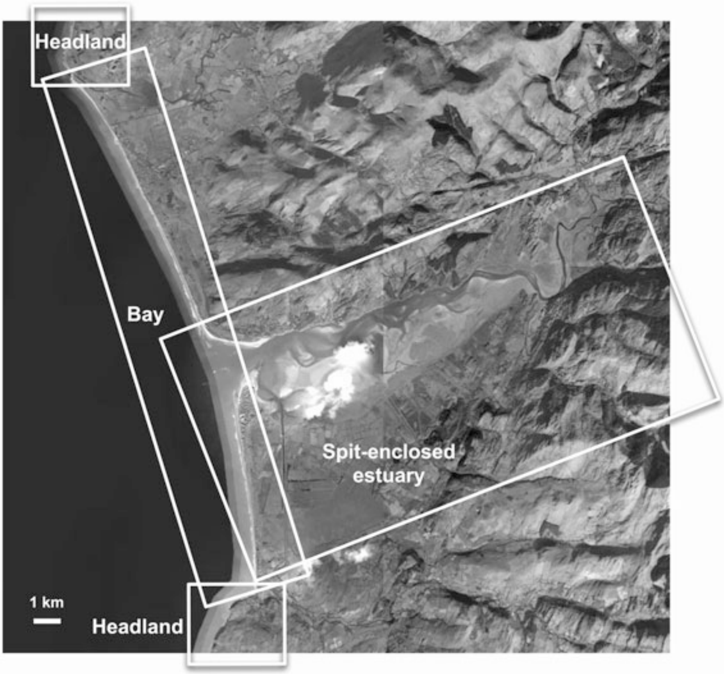

Fig. 15.6 Illustrative composition of open coast and estuary landform complexes

indicated, and distinction made between these and 'influence only' interactions that are not part of the sediment system.

Within the estuary, distinct subtidal – intertidal – hinterland transitions are similarly mapped with reference to the dominant axis of the estuary. This is illustrated for part of the outer estuary in Fig. 15.7b. This particular spit-enclosed estuary exhibits an asymmetric cross-sectional morphology, with a northern shore (left edge of figure) flanked by high ground and cliffs (partly protected by seawalls) and a southern shore with wide tidal flats, saltmarsh and embankments protecting reclaimed wetlands. The estuary exchanges sand with adjacent beaches via the paired spits, one of which is welded to the northern shore, and the tidal delta sand bodies. Sand dredged from the harbour channel is used to nourish dunes to the north.

Mapping of landform components and interventions connected by various forms of influence effectively represents a system as a network graph. This allows for more quantitative analysis, ranging from simple inventories and interaction probabilities to more sophisticated inferences of overall system behaviour based on network topology (e.g. Phillips 2012). Network graph analyses are sensitive to the way the system is rendered in terms of discrete components (network nodes) and interactions (edges or links). In the case of geomorphological systems, this process involves subjective judgement regarding the demarcation of discrete landforms

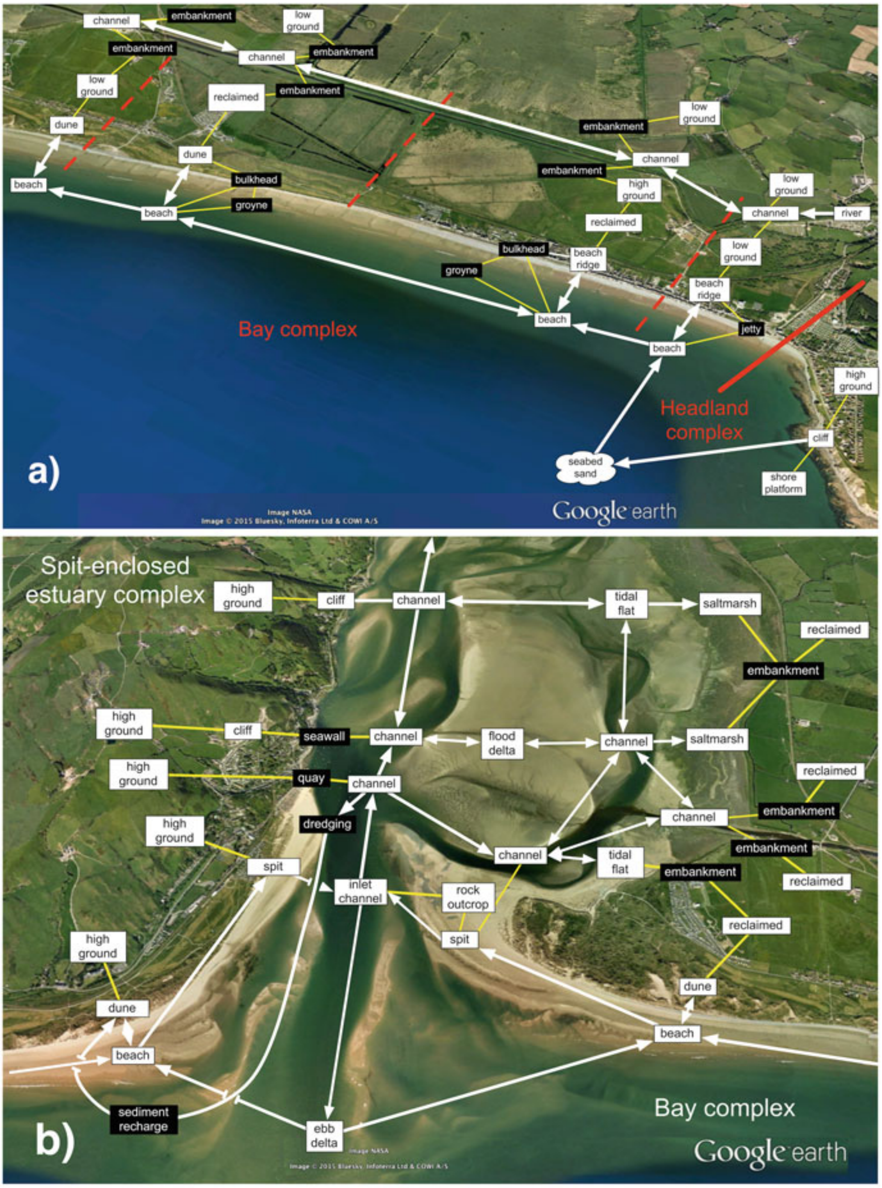

Fig. 15.7 (**a**) Illustrative open coast mapping for a portion of bay complex showing segmentation into distinct cross-shore transitions (demarcated with broken *red lines*), with directional sediment pathways (*white*) and 'influence only' interactions (*yellow*); (**b**) equivalent mapping of outer estuary, showing contrasting intertidal – backshore – hinterland sequences either side of central channel

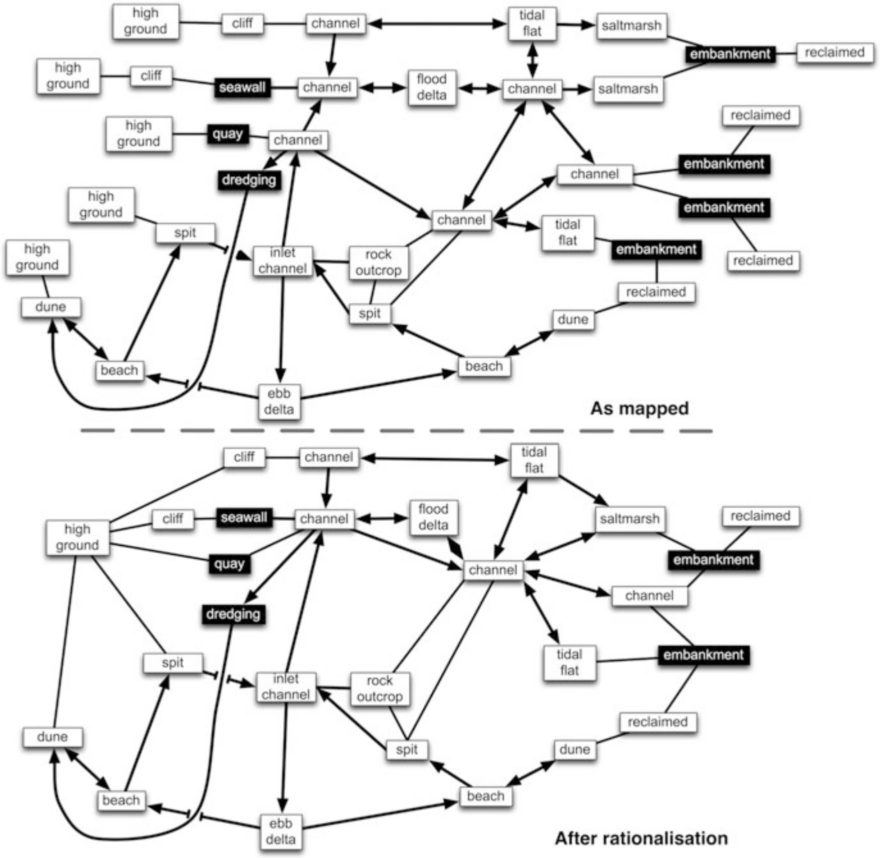

Fig. 15.8 Rationalisation of the outer estuary network graph (Fig. 15.7b) to remove multiple instances of the same component where possible

within continuous landscapes. Moreover, CESM generates multiple instances of individual landforms where these are considered to participate in more than one alongshore or along-estuary segment. Rationalisation of the map topology is therefore needed to merge multiple instances of the same geomorphic feature. Figure 15.8 illustrates this for the outer estuary. Duplicate landforms and interventions are merged where possible but channels or beaches may be associated with known convergences or divergences in sediment flux, such that their disaggregation into multiple functional components is then justified. Note that, since hinterland is represented as a bounding effect on the active coastal and estuarine system rather than a dynamic landscape component, its labelling is determined from a purely aesthetic perspective.

The workflow in Fig. 15.5 incorporates a final ‘augmentation’ stage, in which the system map can be annotated to include metadata (e.g. references and active links to relevant research and datasets) as well as data (e.g. digital research documents, images, observational datasets and model outputs). This functionality is facilitated by implementation of CESM a geospatial software environment, as outlined below.

15.4.1 Implementation of CESM Within an Open-Source GIS Framework

Initial development of the CESM approach (French and Burningham 2009) was undertaken using concept mapping software (CmapTools; Cañas et al. 2005) that lacked the ability to produce georeferenced system maps or to directly utilise geospatial datasets. To address this, French et al. (2016a) developed bespoke CESM software that operates within a Geographical Information System (GIS) framework. The open source QGIS (http://www.qgis.org) was selected as a geospatial platform on account of its support for multiple operating systems and growing user base. The CESM workflow has been implemented as a QGIS plugin (coded in Python) that enables system components to be mapped interactively over one or more QGIS data layers.

System mapping is performed within the QGIS environment with reference to a base layer that defines the projection and co-ordinate system. This base layer may take the form of digital mapping, Web Map Server-based layers (including Google Maps or Bing maps), or digital photography. Additional 'helper layers' can be loaded into the GIS to aid the identification of landform types and identify human interventions. Airborne LiDAR raster layers are especially useful, as are digital bathymetric charts and geological maps, and vector databases of flood and coastal defence infrastructure.

A key feature of the QGIS CESM plugin is specification of the ontology in an external file that can be edited as required to suit particular regional situations. Sets of components (landforms, landform complexes, interventions) are read from the ontology and used to populate Graphical User Interface (GUI) palettes. These provide the user with a pre-determined set of system elements and impose constraints on how these can be combined. The user may also interactively define the linkages between components and specify the type and directionality of the connection (influence, sediment transfer). It is also possible to include numerical values for sediment fluxes where these are known quantities. Aggregation of landforms into complexes is also checked against ontology rules. This ensures consistency and helps minimise differences of interpretation where the same region is mapped by different users. Final maps comprise a point layer of components and a line layer of connections and can be saved in the widely used ESRI shape file format.

15.4.2 Illustrative Application: Suffolk Coast, Eastern England

The CESM approach and software are presently being used within the Integrating Coastal Sediment Systems (iCOASST) project (Nicholls et al. 2012) to support the development of new quantitative models of coastal and estuarine morphological change. In iCOASST, system maps provide a means of determining how best to break down a regional coastal behaviour system into a set of complexes of constituent landforms that can be simulated by specific coastal and estuarine models. Identification of discrete landform components, interventions and interactions between them at a sub-complex scale then informs the development of specific model codes. A novel feature of the project is that the model codes being developed are compliant with the OpenMI coupling standard (Harpham et al. 2014). By assembling 'compositions' of models that exchange information at run time, coupled coastal and estuarine behaviour can be simulated at a regional scale.

The Suffolk coast, eastern England, is one of the main iCOASST model validation regions (Nichols et al. 2012). Extending from Lowestoft in the north to Felixstowe in the south, the open coastal length of approximately 77 km can be broken down into a sequence of open coastal, estuarine and inner shelf landform complexes (Fig. 15.9). The mainland coast largely comprises stretches of cliff-backed sand and gravel beaches (Burningham and French 2015) interspersed with discrete barrier-enclosed lagoons (Spencer and Brooks 2012). The cliffed coastline north of the Blyth estuary has a long history of erosion, with recession rates up to 5 m year^{-1} (Brooks and Spencer 2014; Walkden et al. 2015), but sediments released through this erosion are largely sand and gravel. The alongshore continuity of the open coast is punctuated by the inlets of the Blyth, Alde/Ore and Deben estuaries, all of which have extensive, predominantly muddy, intertidal flat and saltmarsh. These estuaries were extensively embanked and reclaimed for agriculture in the eighteenth and nineteenth centuries, and many of the defensive embankments are now susceptible to overtopping and breaching under extreme tidal surges (French 2008). The predominantly muddy sedimentation within these estuaries is sustained by long range fluxes of mud within the coastal waters of the southern North Sea (Dyer and Moffat 1998; French et al. 2008), presumably originating in cliff to the north in Norfolk and Yorkshire given that local cliff retreat contributes virtually no muddy material.

Figure 15.10 illustrates the development of the system map using the QGIS software. The screenshot highlights some of the local interactions between estuary and adjacent coastal in the vicinity of the Alde/Ore estuary inlet and Orfordness. This includes cyclical sediment bypassing via spit growth and breaching and ebb shoal migration (Burningham and French 2007; Burningham 2015) that has historically sustained downdrift beaches. This figure also illustrates the use of a LiDAR-derived elevation raster layer, a bathymetry vector layer and Bing aerial imagery to assist the mapping process within the QGIS plugin tool.

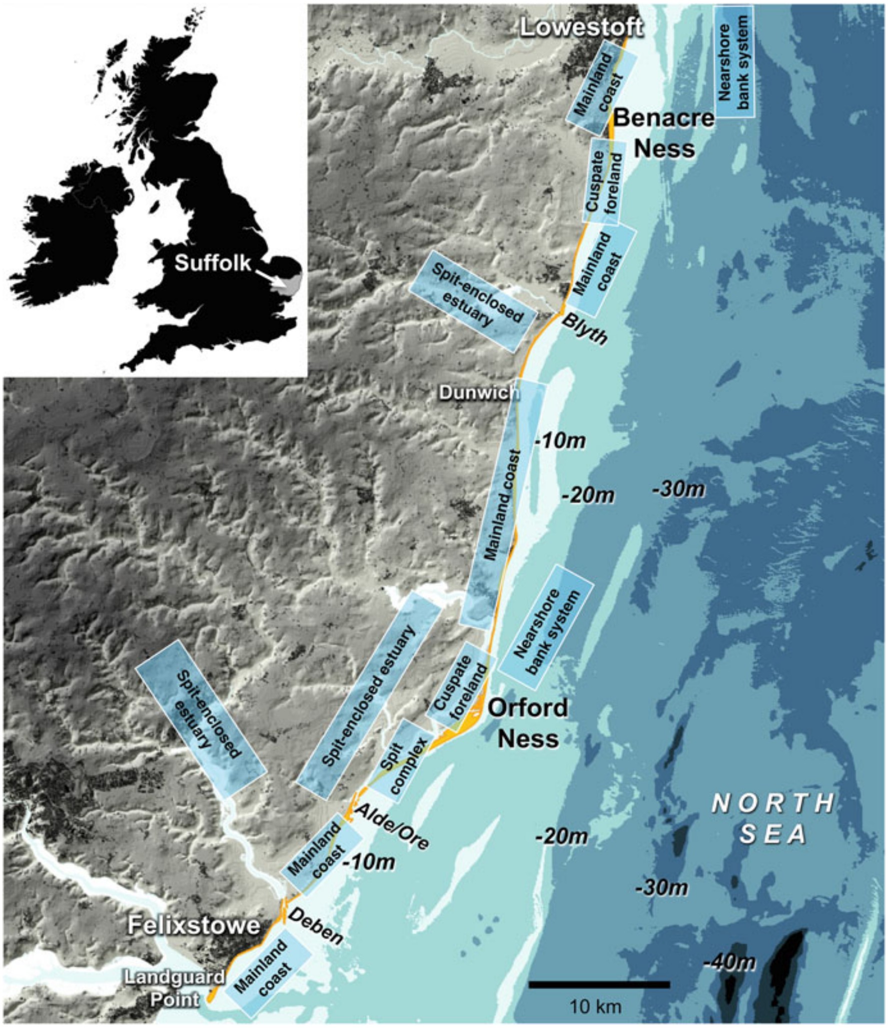

Fig. 15.9 Division of the Suffolk coastal behaviour system into open coast, estuary and inner shelf landform complexes

In its simplest form, the map of components and interactions presents a highly accessible representation of the structure of the coastal and estuarine system. In Fig. 15.10, landforms along the open coast are connected by a littoral sediment transport corridor that is intersected by the estuary inlets. Estuarine landforms are connected to more distant fine sediment sources through channel-open sea suspended sediment transport pathways. As noted earlier, it is also possible to analyse the system map as a network graph. Phillips (2012) explores some quite sophisticated graph-based analyses of geomorphic system structure, but even quite simple visualisations of the occurrence of the different landforms and interactions

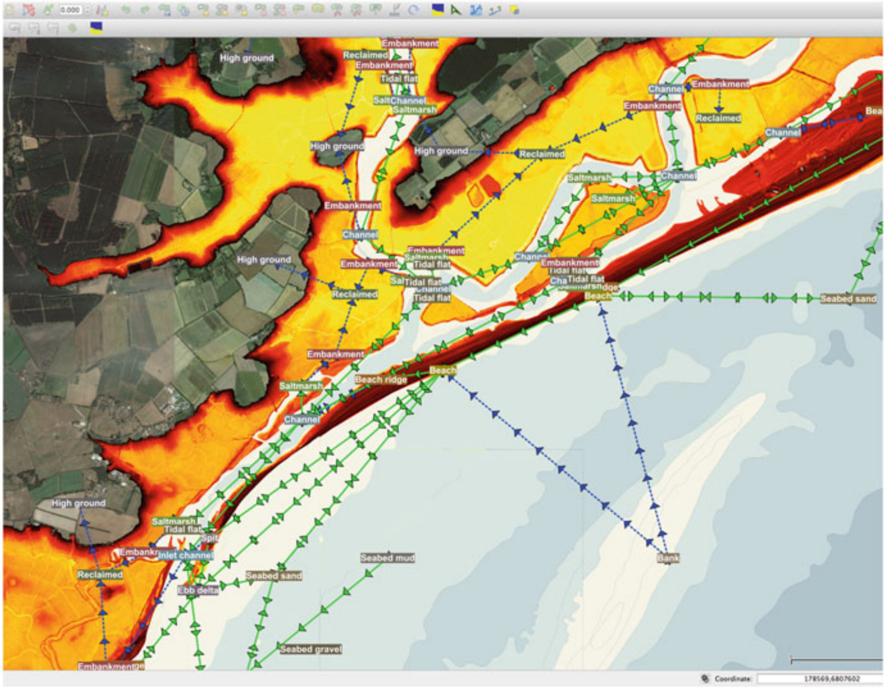

Fig. 15.10 Illustrative screenshot showing development of system map for region around mouth of the Alde/Ore estuary using CESM QGIS plugin. Terrain shading is a LiDAR DEM overlaid on vertical aerial photography

can be extremely effective as a means of communicating with stakeholders. For example, normalised interaction probability matrices (Fig. 15.11) have generated considerable interest at stakeholder workshops conducted in the iCOASST project. This type of analysis for Suffolk highlights the dominant sediment fluxes within the littoral (beach-beach/beach ridge) and estuarine (channel-channel/saltmarsh) subsystems. The influence matrix also demonstrates the importance of embankments in controlling estuary morphology.

15.5 CESM as a Means of Identifying Potential Changes in State

Much of geomorphology is concerned with the determination or prediction of incremental changes in process rates or morphology. Over short timescales at least, these are increasingly resolved using reductionist modelling founded on fundamental hydrodynamic and sediment transport principles (e.g. Roelvink and Reniers 2012; Villaret et al. 2013). As the scale of investigation is expanded,

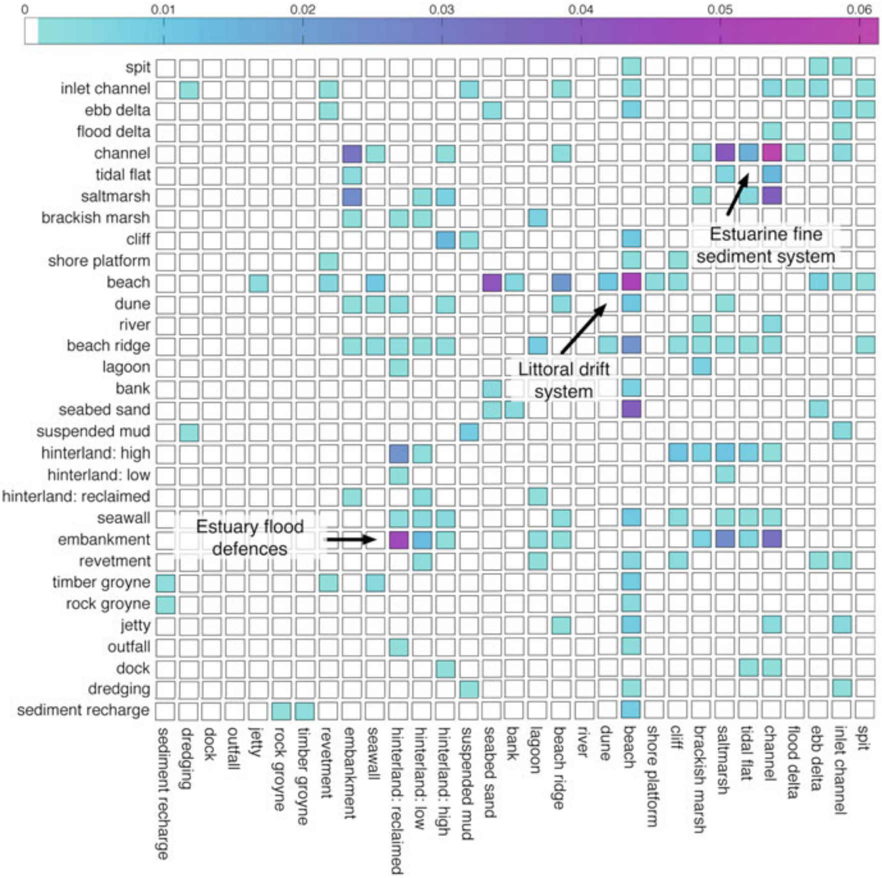

Fig. 15.11 Normalised interaction probability matrix landforms and human interventions within the entire Suffolk coastal behaviour system. White cells indicate interactions that do not occur in this system map and colour-coded cells show the varying probability of the interactions that do exist. In this visualisation, both directions of any bi-directional linkages are considered to be separate interactions

qualitative changes in state are sometimes encountered. These include changes in some critical aspect of system dynamics (e.g. a shift from flood-dominance to ebb-dominance in an estuary) as well as changes in gross configuration (as in the breaching and detachment and degradation of a spit).

Phillips (2014) presents a comprehensive overview of the various forms of state change encountered in geomorphic systems more generally. Some are prevalent enough in coastal and estuarine settings to merit immediate attention from landform behaviour modellers. The most straightforward case involves a sequential transition between discrete states, as in the classic tidal flat, lower saltmarsh, upper saltmarsh sequence. A second case involves a sequence that repeats in a cyclical manner; examples are some circumstances of tidal flat – saltmarsh alternation (Pedersen and

Bartholdy 2007; Singh Chauhan 2009) or bypassing cycles that involve growth, detachment, migration and reattachment of inlet sediment shoals (Burningham and French 2006). Other important modes of state change involve either divergent or convergent evolution. Divergence is of particular interest in that it implies the existence of multiple evolutionary pathways that may culminate in alternative stable states. An important example in the present context is the potential for evolution towards either wave- or tide-dominated intertidal sedimentation (Fagherazzi and Wiberg 2009; Kirwan et al. 2010). Here, state changes may simultaneously encompass both changes in configuration (e.g. replacement of tidal flat by saltmarsh or vice-versa) and shifts in process dynamics (e.g. a shift from estuary sediment import to export; French et al. 2008). Configuration state changes, such as the breaching of coastal barriers, are not especially prevalent at sub-annual to low interannual timescales but may be significant at decadal to centennial scales (e.g. Orford and Jennings 2007).

We see considerable potential in the application of CESM to identify alternative future states based on the formalisation of our knowledge of particular geographical contexts. By way of illustration, Fig. 15.12 shows the potential for locally divergent coastal futures on a stretch of the Suffolk coast that comprised alternating soft rock headlands punctuated by short sections of gravel barrier beach backed by shallow brackish lagoons (Spencer and Brooks 2012). Here, system mapping (simplified for illustrative purposes) depicts a possible change in configuration at the landform scale arising from a persistent breaching of one of the low gravel barriers, leading to the formation of a new tidal inlet. In modelling terms, this could be handled through an adaptive composition of coupled model codes, in which breaching is evaluated in terms of forcing and state parameters (e.g. using the Barrier Inertia Method; Obhrai et al. 2008) the likely persistence of any barrier breach is evaluated using an inlet stability analysis and, if necessary, a tidal inlet model is then invoked to handle the creation of a new complex of this class.

15.6 Integrating Geomorphology, Engineering and Society in Participatory Coastal and Estuary Management

The challenge of coastal and estuarine management is not simply one of devising models that can generate scientifically satisfying answers to questions generated by experts in the field of climate change science. Such efforts are clearly vital but, as in other areas of convergence between environmental science and policy, coastal problems increasingly require the combining of natural and social science perspectives and scientific and lay knowledges to achieve politically and socially acceptable solutions. One aspect of this convergence has been the emergence of participatory modelling as means of achieving meaningful engagement between scientists, policy makers and stakeholders (Voinov and Bousquet 2010; Gray et al. 2014). There are several strands to this process. Firstly, communication is

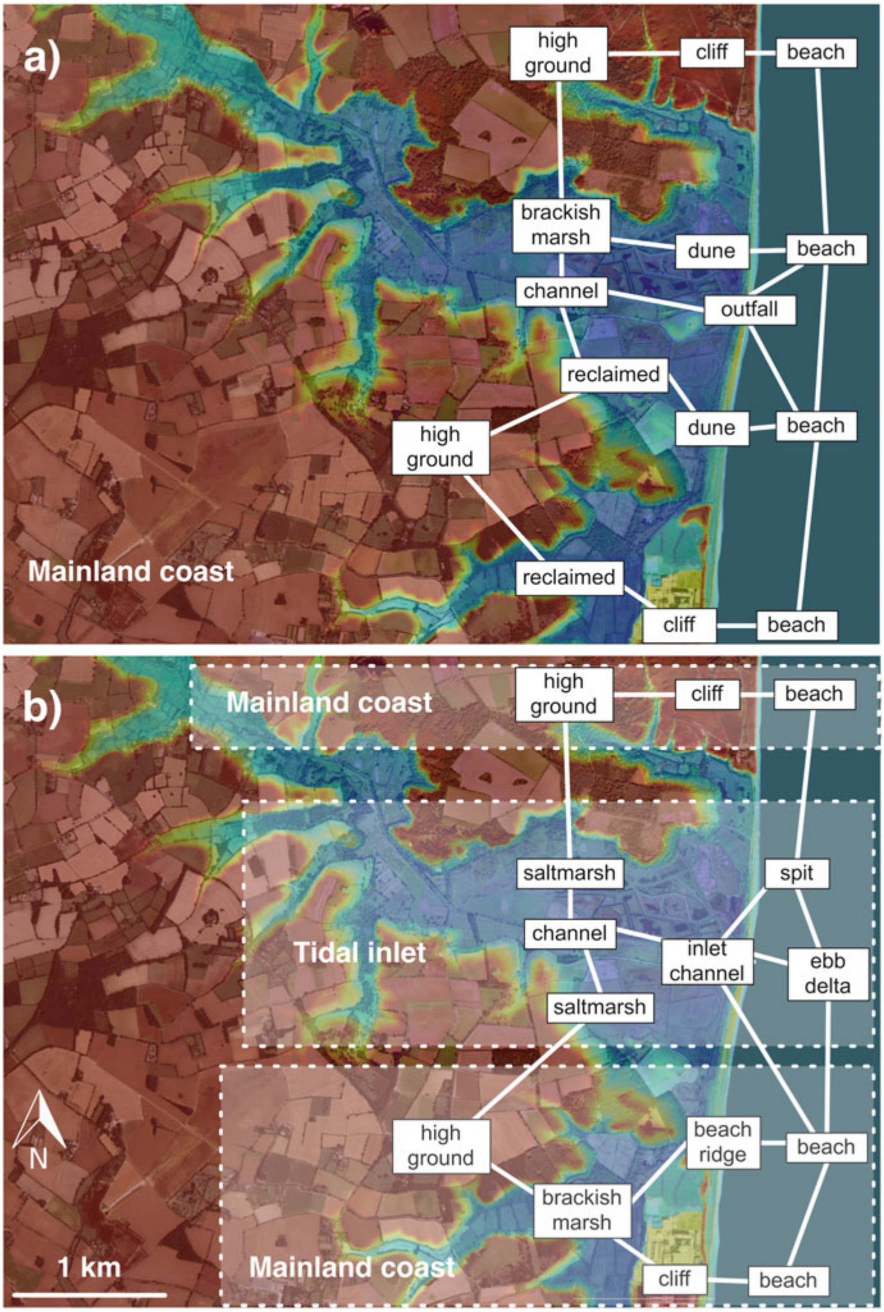

Fig. 15.12 Highly simplified mapping of a 5 km stretch of the Suffolk coast, eastern UK, illustrating (**a**) a current mainland coast complex, dominated by a barrier beach backed by alternation of brackish lagoons and elevated cliff headlands; and (**b**) a potential future configuration following hypothetical barrier breaching and the creation of permanent tidal inlets

of paramount importance as science has become almost wholly founded on models. Hall et al. (2014) draw parallels with climate science, where public understanding and confidence have been impaired by poor communication of the nature and purpose of simulation models. They further observe that it is not just articulation of the technical aspects of model formulation and application that are important, but also the provision of clear and unambiguous explanatory definitions for the basic concepts that underpin them. Qualitative modelling has a clear role as a means of arriving at shared understanding of the system being studied and the nature of the problems that need to be addressed (e.g. Sano et al. 2014). We see CESM emerging as an effective tool for identifying the most important processes (and associated management issues) to be included in more quantitative modelling studies.

As Hall et al. (2014) observe, it is equally important to achieve some fusion of scientific and lay conceptualisations of how the world works. The CESM approach is intended, at least in part, to engage with this challenge. It has the advantage of rendering the complexity of coastal and estuarine geomorphological systems as a fairly simple ontology of components and interactions, and depicting these in a visual form that provides a highly effective catalyst for discussion and debate between scientist, stakeholder agencies and organisations, and local citizens (Fig. 15.13). Within the iCOASST project (Nicholls et al. 2012), system maps have been enthusiastically received by a diverse group of stakeholders that includes, inter alia, management agencies and regional authorities, non-governmental organisations, representatives of industry and agriculture, and local inhabitants. In the case of the Suffolk study region, discussions have centred on matters of detail, such as the omission of local geological controls on shoreline position, as well as broader scale divergences in opinion – notably concerning the consistency of the littoral drift direction (see also French and Burningham 2015). These discussions have been extremely valuable in capturing stakeholder knowledge and feeding this into both data-driven analyses and modelling studies. As Schmolke et al. (2010) have argued elsewhere, the capturing of valuable local knowledge and its incorporation into the formulation of a problem and an approach to it, are key elements of good modelling practice that have all too often be neglected.

In contrast to many of the predictive models traditionally used by engineering consultants, CESM is transparent and accessible to a wide range of users. This is partly a consequence of its implementation in open-source software. This counters one of the major shortcomings of a ‘top down’ approach to shoreline management planning that has historically been heavily reliant on proprietary closed-source model codes and GIS software that is available to the larger consultancies but not to local communities and smaller consultants. The open source paradigm of computer science is a good model here (Voinov and Gaddis 2008), in that it demonstrates the benefits of genuine community effort, both in terms of transparency and accessibility and also in terms of legacy. CESM has the potential to create conceptual models that are community efforts, thereby stimulating a greater sense of shared endeavour between modellers and stakeholders than has thus far been possible. The outputs of too many major projects (including, in the UK, the

Fig. 15.13 CESM being used to structure stakeholder discussion relating to the contemporary functioning of part of the Suffolk coast and estuary system as part of the iCOASST project (Photo by Alice Milner)

FutureCoast project; Burgess et al. 2002) have become fossilised and inaccessible within a closed data and proprietary software model. The greater accessibility of CESM allows conceptual models and linked databases to evolve beyond individual project timelines through the continuing involvement of a community of researchers and stakeholders. The system maps thus constitute information products that are not finalised at a project end date but, instead, remain free to evolve as knowledge accumulates and agendas change over time.

15.7 Conclusions

Geomorphology is pivotal to understanding how coasts and estuaries, and their associated populations and infrastructures, will be impacted by climate change at decadal to centennial scales. Our success in predicting and then adapting to these impacts will be substantially determined by our success in developing better quantitative models of landform change. At the same time, it is vital that our conceptual frameworks allow us to formulate management problems in a scientifically meaningful way. This problem is compounded by the pervasive influence of human agency on contemporary shorelines and by the multitude of stakeholders involved and their differing interests. Effective translation of research into policy requires frameworks that formalise scientific understanding of human – environment systems in a transparent and accessible way and also permit the assimilation of diverse lay knowledges as a basis for a more participatory approach to management planning.

Our approach to Coastal and Estuarine System Mapping (CESM) is intended to contribute to this interface between science, policy and management by offering a geomorphological framework that resolves a more complete web of interactions than the littoral cell-based mapping that has hitherto guided shoreline management planning. Preliminary work with CESM as an open-source geospatial software tool demonstrates potential on several important fronts. Firstly, a hierarchical landform ontology integrates estuary, coast and parts of the inner shelf in a coherent conceptual scheme that is able to accommodate multi-scale sediment sharing pathways and explicitly resolves the localized human interventions that constrain their natural operation. Secondly, the mapping process constitutes a form of knowledge formalisation in which disparate sources of information (published research, imagery, mapping, plain data etc.) are generalised into a conceptual model of geomorphological system configuration that can guide the development and application of predictive models. Thirdly, configurational state changes (such as the creation of a new estuary following barrier overtopping and breaching) are not handled well by reductionist hydrodynamic and sediment transport models. The conceptual framework provided by CESM encourages such instances to be identified, a priori, such that divergences in geomorphic system state can be incorporated explicitly into adaptive compositions of coupled landform behaviour models. Conceptualising the spatial structure of a geomorphological system in advance of model development and application allows for locally divergent changes in configuration to be anticipated in the design of compositions of coupled models. This paves the way for exciting new broader-scale simulations of coastal behaviour that go beyond incremental changes in position and rate. Finally, CESM articulates scientific understanding of the structure and function of complex geomorphological systems in a way that is transparent and accessible to diverse stakeholder audiences. As our predictive models of mesoscale landform behaviour increase in ambition and sophistication, this provides a platform on which to build a much more participatory approach to the conduct and communication of model-based coastal and estuarine science and management.

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