Soil Erosion and Sediment Redistribution in River Catchments

Measurement, Modelling and Management

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Measurement, Modelling and Management

Edited by

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Contents

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Preface

While research on soil erosion and on sediment redistribution in rivers both have long histories, each tends to be conducted in relative isolation and by specialist teams. Recent years have, however, seen a move towards more integrated management of soil–water systems, particularly at the scale of the river basin, which in turn has led to a greater need for more integrated research so as to inform management and assist with the decision-making process. The link between soil erosion and redistribution on land and sediment transport and deposition within rivers and lakes is clear to many, but a culture persists whereby the two groups of scientists rarely interact. This book is in part an attempt to get experts in soil erosion and experts in sediment transport and deposition to cooperate, so that it may be possible to understand the movement of soil and sediment particles from source to sink. The book stems from a conference held at the National Soil Resources Institute (NSRI) at the Silsoe campus of Cranfield University, UK, between 9th and 11th September 2003. The conference was attended by over 80 delegates from more than 15 countries. The chapters in this book represent a selection of oral and poster presentations given during the conference, in addition to an invited contribution. All chapters were peer-reviewed.

We are grateful to a number of individuals who provided help with the conference and book. We would like to thank Prof. Mark Kibblewhite, the Director of NSRI, for supporting us (both personally and financially) in these activities, and several members of staff at NSRI who have helped along the way, including Michelle Clarke, Julia Duzant, Inga Wells and the admin group at Silsoe. We would also like to acknowledge the support and assistance of CABI, in particular Tim Hardwick and Rebecca Stubbs, and also Alison Foskett for her copy-editing work. Finally, we would like to thank the following referees:

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The success of this book and associated conference will be measured by the level of research that they inspire and, ideally, by an increased level of integration between those working in soil erosion and in sediment redistribution within rivers. We also hope that this book will encourage further collaboration between those studying measurement and modelling and those concerned with the implications of these for management. We must not forget that as scientists and researchers our ultimate responsibility is to provide the information and knowledge base needed for informed management of soil–sediment–water systems.

Phil Owens, North Wyke, UK
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1

Introduction

Soil erosion, mass movements and sediment deposition on grazing land after heavy rain in February 2004, Manawatu, New Zealand (photo: Landcare Research, New Zealand).

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1 Introduction to Soil Erosion and Sediment Redistribution in River Catchments: Measurement, Modelling and Management in the 21st Century

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The Importance of Soil Erosion and Sediment Redistribution

There is increasing awareness of the need to protect our natural resources in order to meet present and future requirements. Since economies and environments are dependent on healthy soil and water, it is essential to ensure the sustainable use of the resource base in the face of growing demand.

Excessive or enhanced soil erosion due to poor land management can result in both on- and off-site impacts that are detrimental to a whole range of receptors. Where soil erosion occurs, the soil resource can be severely depleted if the rate of erosion exceeds the rate of natural soil formation. This loss often corresponds to the most agriculturally important topsoil and any fertilizer or pesticide application, causing subsequent reductions in agricultural productivity. Soil erosion is a hazard traditionally associated with agriculture, and often occurs in tropical and semiarid areas (Morgan, 1986). The topic of soil erosion was never so emotive as during the 1930s 'Dust Bowl' in the USA. Whilst soil erosion is still a significant issue in tropical and semiarid areas, it is being increasingly recognized as a hazard in temperate countries. In the UK, for example, the annual present-day value of lost production due to soil erosion is estimated to be £700 million (of the order of €1000 million) (Evans, 1996). It is estimated that erosion affects 40% of arable land, with these soils losing more than 25% of their agricultural productivity (Evans, 1996). The redistribution of eroded soil material within the field, and accompanying changes in soil structure, can also result in habitat damage, reduced crop yields and changes in flood storage capacity.

Significantly, recent interest in soil erosion has been triggered by a growing awareness of the off-site impacts. These impacts are predominantly associated with the movement of eroded soil and sediment particles, and changes in water flows (both through and across the soil). The off-site problems are often more evident, and include the loading and sedimentation of watercourses and reservoirs, and increases in stream turbidity, all of which can disturb aquatic ecosystems and upset the geomorphological functioning of river systems (Owens *et al*., 2005). In China, soil erosion and the off-site effects of sediment deposition have resulted in multiple impacts. For example, since the 1950s, over 90,000 reservoirs have been built in

China, with a cumulative storage capacity of over 400×10^9 m^3. However, increased soil erosion has caused annual sedimentation levels to rise to as much as 10×10^6 m^3, reducing storage capacity by approximately 10%. Sedimentation resulting from soil erosion has adversely affected hydroelectric output, availability of irrigation water, flood control potential and the navigation of waterways (from 172,000 km in the 1960s to 108,000 km today). Furthermore, increased sedimentation along the lower reaches of the Yellow River has caused a 0.10 m annual rise of the river bed, with the result that the Yellow River is in many places 'suspended' above the plains over which it flows, precariously controlled by dikes constructed along its course (Yuqian and Ning, 1986).

If eroded soil carries with it nutrients, contaminants and pathogens, it can present serious problems in terms of watercourse and groundwater pollution and eutrophication, threatening habitat and human health (Owens *et al*., 2005). The cost of eutrophication (including the loss of drinking water supplies, reduction in the value of waterside property, decline in the recreational and amenity value of water-bodies, and impacts on water for industrial uses and commercial fisheries), mainly due to phosphate enrichment, is estimated at £128.5 million per annum in the UK alone (Pretty *et al*., 2000).

Since the 1990s, environmental management legislation in both the USA and Europe has switched primarily to the control of off-site impacts, as mentioned above. For example, the European Union has implemented several directives (including the Water Framework Directive, Habitats Directive, Fisheries Directive, and Bathing Water Directive) that aim to prevent off-site impacts on economics, environment and people caused by waste, water and soil (see Owens and Collins, Chapter 28, this volume). That said, emerging EU policy under development within the Thematic Strategy for Soil Protection is likely to be more soil-centric. Should this succeed, it is likely to recognize not only the impact of soil erosion and sediment transfer on other receptors (Owens, 2004) but also draw attention to the intrinsic value of the soil as a resource and the need to prevent soil erosion and sediment transfer for soil protection (Van-Camp *et al*., 2004).

The Significance of the River Basin Scale

Since soil erosion and sediment redistribution have implications for both soil and water resources, and scientists have established that the movements of soil, sediment and water are intrinsically linked, it is critical to implement integrated resource protection strategies. Soil erosion and sediment redistribution (transport, storage and remobilization) are controlled by hydrological and geomorphological processes, which operate within the context of a river basin. The river basin therefore represents a convenient and meaningful unit for the management of soil erosion and sediment redistribution, since the shape and characteristics of the river basin control the pathways and fluxes of soil, water and sediment (Owens *et al*., 2004). It is, therefore, encouraging that policy-makers and managers are now opting to manage soil erosion and sediment transfers at a catchment or river basin scale, as has been proposed in the EU Water Framework Directive, for example. This issue is discussed further below and in Owens and Collins (Chapter 28, this volume).

The Three Themes of this Book: Measurement, Modelling and Management

In order to effectively protect and manage natural resources there is a need to develop the science and to assemble the necessary information on which to base decision-making. There are several *measurement* and *modelling* tools available to scientists and managers for use in *management* of soil erosion and sediment redistribution in river basins. Here, these terms are defined as:

- *Measurement tools*: tools for identifying and quantifying the magnitude, rate, severity and timescale of erosion and sediment sources, pathways, sinks and impacts.
- *Modelling tools*: tools, including physically based, conceptual, statistical and stochastic models, to predict or understand spatial patterns and trends in soil erosion and sediment transfers. Models require sufficient data, both spatial and temporal, for

development and validation, and hence there is a feedback loop between measurement and modelling, as shown in Fig. 1.1 below.

- *Management*: an all-embracing term, referring to identifying the problem, quantifying its importance, planning and implementing a strategy to control or mitigate it, and evaluating the effectiveness of the solution. Management strategies are informed by the data collected, or trends predicted within measurement and modelling. Also, once a management strategy has been implemented, further measurement or modelling is required in order to evaluate or appraise success, and where necessary plan modifications.

Management can relate to any stage in the soil erosion–sediment redistribution continuum and may include the following generic range of management options, all of which have the potential to manipulate either soil erosion or sediment transport within the landscape:

- *Source control*: includes soil conservation techniques, reducing runoff risk or protecting against erosion.
- *Control of sediment pathways and delivery to receptors*: includes interception and retention methods.
- *Remediation at the sink*: includes removing sediment through filtering and dredging, or immobilizing and cleaning polluted material.

Whilst soil erosion and sediment redistribution are influenced by the characteristics of the river basin, and should be managed at such a scale (Owens *et al*., 2004; Owens, 2005), generation and delivery processes vary spatially with different kinds of processes dominating at various locations (Verstraeten *et al*., 2002). Often a different soil conservation or sediment control measure is required to combat each specific type of soil erosion or sediment transport process, and therefore the 'broad-brush' application of a conservation technique across an entire catchment may not be feasible. An effective conservation strategy should therefore integrate a variety of suitably located control techniques into a catchment or river basin management plan (Verstraeten *et al*., 2002).

In all three themes, measurement, modelling and management, the appropriate mantra is *integration*: between various soil, sediment

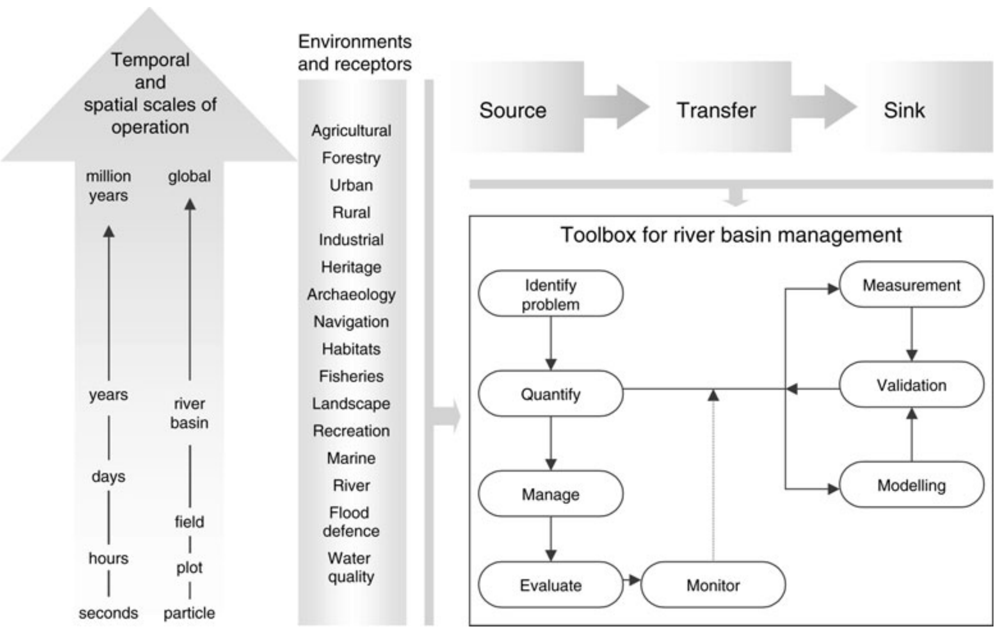

Fig. 1.1. Overview of the river basin management of soil erosion and sediment redistribution.

and water disciplines to allow holistic land–river management, and between scientists and managers to ensure that the science is producing tools as well as management strategies that are accessible and practical to implement.

Overview of the Following Chapters

Many of the chapters that follow reiterate the key themes presented in this chapter – the need for integration in our science and management of natural resources. Where possible, the chapters have been chosen to represent the variety of temporal and spatial scales of operation, from the modelling of dynamic event-based processes to the annual monitoring of a site to determine longer term trends. The chapters also explore some of the many environments in which erosion and sediment redistribution occur, and indeed the unique controls that these environments may exert on geomorphological functioning. These environments may also qualify as the main receptors affected by erosion and/or sediment redistribution. Figure 1.1 demonstrates these varying issues as well as the toolbox available for river basin scale management of both erosion and sediment redistribution, and how the chapters that follow may contribute to the scientific rationale and basis for that management.

Measurement

Chapters in Part II of the book use a variety of contrasting techniques (both traditional and novel) to measure soil erosion on land and sediment fluxes in rivers, including deposition within lakes and reservoirs. They have been broadly arranged so as to illustrate the differences and similarities in the techniques used to measure soil–sediment transfers from land to rivers to lakes.

Walling (Chapter 2) presents examples of methods for linking erosion with sediment delivery in a review of traditional measurement techniques in the research area and the new challenges and opportunities we can look to within the science. This chapter also traces the changes in policy that have directed concerns from on-site problems associated with soil erosion to off-site problems resulting from sedimentation. This, he argues, has resulted in a shift from traditional soil erosion monitoring methods to more sophisticated sediment tracing techniques. The comparison of traditional and recent (i.e. tracing) soil erosion assessment techniques is continued by Peart *et al*. (Chapter 3), who explore the usefulness of caesium-137 (^{137}Cs) and erosion plot data from a hillslope region in Hong Kong. Whilst the two techniques were in broad agreement, there were problems associated with calibrating the ^{137}Cs measurements. Similarly, Belyaev *et al*. (Chapter 4) describe some of the various measurement techniques available to assess the contribution of sheet, rill and ephemeral gully erosion, as well as tillage translocation, for two arable catchments in Southern Russia, and what factors may be causing observed local differences.

The implications of land use and climate change on soil erosion and sediment redistribution are considered in several chapters. Shakesby *et al*. (Chapter 5) present hillslope erosion response following forest fires in Australia, and explore the link between fire-induced soil water repellency and erodibility. The paper is an interesting insight into the effects of acute and catastrophic triggers on soil erosion, and has important implications for environments where climate change may result in an increase in such events. Blake *et al*. (Chapter 6) continue the theme of soil water repellency, attempting to link soil magnetic signatures to water repellency in order to quantify soil and sediment export from catchments of varying wildfire burn severity in Australia. Evans (Chapter 7) examines the link between land use and sediment delivery. He stresses the importance of understanding and quantifying the respective contributions of various sources in order to effectively manage sediment redistribution. In Chapter 8, Farguell and Sala explore the impact of severe rainfall events on resulting suspended sediment loads for a semiarid catchment in the Iberian Peninsula. The same theme is applied to a study area with a contrasting climate in the chapter by Hejduk *et al*. (Chapter 9). These authors present data on discharge and suspended sediment transport in a small lowland catchment in central Poland during rainfall and snowmelt events.

The final set of chapters in Part II present measurement techniques and data that link soil erosion and sediment redistribution with water quality and aquatic ecosystems. The survival of salmonid populations in County Antrim, Northern Ireland, was the driver for a study on sediment transport dynamics by Evans and Gibson (Chapter 10). The work illustrates techniques available for elucidating the link between soil erosion and downstream sediment delivery, and for informing sediment management. In contrast, Petticrew (Chapter 11) describes how salmonids influence both the amount and composition (including organic matter content and type, and aggregate structure) of fine-grained sediment stored in gravel bed streams in British Columbia, Canada. In the final chapter of the measurement theme (Chapter 12), Foster presents lakes and reservoirs as the ultimate components of the sediment transfer story. The UK case studies presented provide a history of sediment and associated phosphorus concentrations in reservoir catchments and the impact of land management, including land drainage, on sediment sources.

Modelling

The chapters in Part III explore some of the common advantages and problems associated with modelling approaches, and new developments within the science. The chapters recommend refinements and methods to improve the availability and reliability of data, parameterization of key factors and approaches for modelling components previously neglected in soil erosion and sediment research. As with the chapters in Part II, the chapters follow the progression from soil erosion to sediment redistribution.

Nearing (Chapter 13) examines the critical link between measurement and modelling, by focusing on the importance of having data that can be fed into modelling and prediction tools to support management decisions and inform policy. He argues this is best achieved by collecting and managing data effectively and consistently to avoid temporal and spatial variability. Kuhn (Chapter 14) examines methods for the assessment of erodibility for inclusion in dynamic event-based models. In this study he assesses the suitability of techniques based on soils from Canada and Mexico, and how appropriately characterizing erosion processes can improve dynamic process-based prediction. Sidorchuk *et al*. (Chapter 15) argue for a third generation of erosion models to account for the stochastic nature of soil erosion, and outline a method called ‘double averaging’. Kinnell (Chapter 16) also focuses on the refinement of models to improve prediction. He presents a modified version of the Universal Soil Loss Equation (USLE) to include runoff as a factor in accounting for event erosivity.

Several of the chapters discuss the development and application of models that consider gully erosion and landslides in addition to rill and interrill erosion. Recent research quantifying erosion rates due to roads, fires, landslides and harvesting is presented by Elliot (Chapter 17). These data are used to explore the performance of GeoWEPP (Water Erosion Prediction Project) modelling to understand the source, production and attenuation of sediment from upland forested catchments. Elliot also makes suggestions to improve model performance, especially in sediment and flood routing components. The WEPP model is also applied by Licciardello *et al*. (Chapter 18) to a small Sicilian watershed in order to assess its performance compared with other physically based erosion models in Mediterranean areas. The authors also suggest possible improvements in the WEPP (and GeoWEPP) model. Jetten *et al*. (Chapter 19) discuss the lack of explicit modelling for gully incision and formation. The authors propose combining landscape indicators with process modelling in order to improve the simulation of ephemeral gully incision, presenting a method requiring little additional data above basic erosion modelling.

The final chapter in this section, by Jarritt and Lawrence (Chapter 20), investigates the application of a new model, INCA-Sed, to simulate sediment delivery processes at the catchment scale. The model is applied to catchments in southern England to demonstrate the effectiveness of the approach in reproducing supply- and transport-limited conditions.

Management

In Part IV the chapters look at the effect of various land management practices on the generation of erosion and sediment and the implications for receptors in forested, agricultural and urban areas in temperate and tropical environments. In attempting to control these effects, the case studies highlight the dependency of management strategies on the outputs of measurement and modelling tools. The scale and accuracy of the data on which management decisions are based, and the need for correct characterization of processes and parameters, are identified as being of critical importance.

Wood *et al*. (Chapter 21) open the management part by demonstrating the link between the three themes of this book. They illustrate how the data from measurement and monitoring studies can be used to model and then map at larger spatial scales the delivery of eroded sediment from land to water, and how this could be used as an effective management tool. Spatial scale issues are considered further by Rickson (Chapter 22), who presents an interesting debate on the importance of scale when assessing the effectiveness of erosion and sediment control practices. Her work illustrates how the performance of control practices can vary depending on the scale of the data and, reiterating the sentiments of Nearing (Chapter 13), suggests that accurate and reliable data are critical for effective implementation and policy-making.

Collectively, the subsequent four chapters (Chapters 23–26) underline how detailed and appropriate scientific information on soil erosion and sediment redistribution can be used for effective and targeted management in contrasting river catchments. Walsh *et al*. (Chapter 23) examine changes in the spatial distribution of erosion within a catchment in the rainforests of Borneo. The changes over a 10-year monitoring period are shown to be attributable to the management of the catchment and the effect of practices such as selective logging. Continuing with the tropical environment, albeit in a lowland setting, Visser (Chapter 24) offers an insight into practical erosion management on sugarcane plantations on tropical floodplains. Her data have implications for controlling sediment delivery to rivers, and particularly illustrate the importance of the connectivity between land and rivers. Nunny *et al*. (Chapter 25) examine the impact of land clearance to create plantations on sediment delivery to the barrier reef in Belize, Central America. They argue that whilst the land management practices appear to be loading rivers with sediment, turbidity at the reef is decoupled from such effects by wave and current action.

Most of the chapters in this book focus on natural and agricultural environments, but it is important to also address sediment redistribution in urban environments, especially given that the proportion of people living in urban areas, and therefore the amount of land that is urbanized, is expected to increase dramatically this century. Droppo *et al*. (Chapter 26) present methods for determining the distribution, structure and behaviour of urban sediments in watersheds within Ontario, Canada. The authors demonstrate how this information can be used to improve water management strategies in the urban environment.

The final words in Part IV go to Morgan (Chapter 27), who provides a personal perspective on current practices and future visions for managing sediment in the landscape. He highlights the importance of integrated and holistic approaches to land and river management at the catchment or river basin scale. Morgan suggests that as more countries establish legislation for soil protection, the true measure of success will be the ability to connect a variety of disciplines and involve all stakeholders, including the local community.

Conclusion

Soil and water resource protection are clearly crucial for productive and sustainable economies and environments. Both soil and water resources can be threatened by processes of soil erosion and sediment redistribution, and the chapters in this volume illustrate some of the main forces driving research in this area, such as concerns with aquatic ecosystems, tropical forests and urban systems.

It is evident from the work presented here that great strides are being made within the soil erosion and sediment redistribution research area. Both science and policy communities are raising soil and water protection up the political agenda to encourage future research in this key topic (see Owens and Collins, Chapter 28). However, it is critical that before we embark on further research we learn from the conclusions and recommendations of existing research, attempt to plug the gaps and meet the requirements of end-user groups. These lessons include, first, the recognition that measurement and modelling are the basic tools necessary to inform and allow the implementation and evaluation of management strategies and practices. Secondly, that the data derived or generated from these tools must be at the appropriate scale and level of complexity for end-users. Thirdly, that the management of soil erosion and sediment redistribution is integrated and focused at the river basin scale. Several of the chapters that follow outline some of the tools and approaches available to do this.

Finally, without doubt the true value of our science will only be realized through communication of the key messages to stakeholders, including catchment managers, policy-makers and the local community, and this is discussed further by Morgan (Chapter 27) and Owens and Collins (Chapter 28). Our task as a scientific community must be, therefore, not only to continue to build the science and the tools as described in this book, but to develop effective language and dissemination skills to communicate them.

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