Paul F. Hudson · Hans Middelkoop *Editors*

# Geomorphic Approaches to Integrated Floodplain Management of Lowland Fluvial Systems in North America and Europe

Springer

Paul F. Hudson • Hans Middelkoop
Editors

# Geomorphic Approaches to Integrated Floodplain Management of Lowland Fluvial Systems in North America and Europe

Springer

*Editors*
Paul F. Hudson
LUC The Hague
Leiden University
Leiden
The Netherlands

Hans Middelkoop
Department of Physical Geography
University of Utrecht
Utrecht
The Netherlands

ISBN 978-1-4939-2379-3 ISBN 978-1-4939-2380-9 (eBook)
DOI 10.1007/978-1-4939-2380-9

Library of Congress Control Number: 2015931071

Springer New York Heidelberg Dordrecht London


Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

# Geomorphic Approaches to Integrated Floodplain Management of Lowland Fluvial Systems in North America and Europe

# Contributors

**Diana Achim** National Institute of Hydrology and Water Management, Bucharest, Romania

**Andrei M. Alabyan** Department of Geography, Moscow State University, Moscow, Russian Federation

**Dmitry B. Babich** Department of Geography, Moscow State University, Moscow, Russian Federation

**Chance Bitner** U.S. Army Corps of Engineers, Kansas City, MO, USA

**Jean-Paul Bravard** Professeur d'université émérite, University of Lyon, France

**Gregory R. Brooks** Geological Survey of Canada, Natural Resources Canada, Ottawa, ON, Canada

**Ştefan Constantinescu** Faculty of Geography, University of Bucharest, Bucharest, Romania

**Michael D. Dettinger** US Geological Survey and Scripps Institution of Oceanography, La Jolla, CA, USA

**Joan L. Florsheim** Earth Research Institute (ERI), University of California, Santa Barbara, CA, USA

**Roy M. Frings** Institute of Hydraulic Engineering and Water Resources Management (IWW), RWTH Aachen University, Aachen, Germany

**Pauline Gaydou** UMR 5600, University Lyon 2, France

**Liviu Giosan** Woods Hole Oceanographic Institution, Woods Hole, MA, USA

**David Granado** Ecología y Territorio, Ecoter S.C., Zaragoza, Spain

**Paul F. Hudson** Leiden University, The Netherlands

**Askoa Ibisate** Deptartment of Geography, Prehistory and Archaeology, University of the Basque Country UPV/EHU, Vitoria-Gasteiz, Spain

**Vadim V. Ivanov** Department of Geography, Moscow State University, Moscow, Russian Federation

**Robert B. Jacobson** U.S. Geological Survey, Columbia, MO, USA

**Richard H. Kesel** Department of Geography and Anthropology, Louisiana State University, Baton Rouge, LA, USA

**Brent C. Knights** U.S. Geological Survey, Upper Midwest Environmental Sciences Center, La Crosse, WI, USA

**Garth Lindner** University of Maryland, Baltimore County, Baltimore, MD, USA

**Molly McGraw** Southeastern Louisiana University, Hammond, LA, USA

**Hans Middelkoop** Department of Physical Geography, University of Utrecht, Utrecht, Netherlands

**Joann Mossa** Department of Geography, University of Florida, Gainesville, FL, USA

**Alfredo Ollero** Department of Geography and Regional Planning, University of Zaragoza, Zaragoza, Spain

**Rafael Real de Asua** Stillwater Sciences, Berkeley, CA, USA

**William B. Richardson** U.S. Geological Survey, Upper Midwest Environmental Sciences Center, La Crosse, WI, USA

**Ioan Rus** Faculty of Geography, University Babeş-Bolyai, Cluj-Napoca, Romania

**Harold L. Schramm** U.S. Geological Survey, Mississippi Cooperative Fish and Wildlife Research Unit, Mississippi State, MS, USA

**Michael Bliss Singer** School of Geography and Geosciences, University of St Andrews, Fife, UK

Earth Research Institute, University of California Santa Barbara, Santa Barbara, CA, USA

**Scott St. George** Department of Geography, University of Minnesota, Minneapolis, MN, USA

# Acknowledgements

The editors kindly thank the editorial team of Springer for their commitment to the project and assistance in production, including Melinda Paul, Zachary Romano, Meredith Clinton, and Abhishan Sharma. We greatly appreciate the authors contributions and dedication to the science of river management, as well as their patience with the completion of the project. All chapters were reviewed by the editors (Hudson and Middelkoop) and one additional external peer reviewer. The editors are especially appreciative of the comments and feedback from external (anonymous) reviewers, which greatly contributed to the overall quality of the volume.

# Contents

# Integrated Floodplain Management, Environmental Change, and Geomorphology: Problems and Prospects

**Paul F. Hudson and Hans Middelkoop**

**Abstract** Recognition of the failure of old perspectives on river management and the need to enhance environmental sustainability has stimulated a new approach to river management over the past couple of decades. The manner that river restoration and integrated management are implemented, however, requires a case study approach that takes into account the influence of historic human impacts to the system, especially engineering. The process of engineering frequently results in an embanked floodplain to reduce the impact of flooding. It is increasingly recognized that floodplain embankment, while usually effective at minimizing flood risk, results in a variety of adverse consequences to the functioning of the river and associated ecosystem health. New, geomorphic-based approaches, which take into account the different modes of adjustment under the framework of integrated management, are now largely seen as the way to move forward. Implementation of such an approach, however, requires a sophisticated understanding of the fluvial system.

**Keywords** Integrated floodplain management · Fluvial geomorphology · Embanked floodplains · Lowland rivers · Environmental change

## 1 Scope and Rationale

The purpose of this volume is to provide a comprehensive perspective on geomorphic approaches to the management of lowland alluvial rivers in North America and Europe. Lowland rivers constitute a distinctive type of fluvial system characterized by broad floodplains, complex flood regimes, and often have laterally active meandering channels. In North America and Europe, many lowland rivers have been heavily managed for flood control and navigation for decades or centuries, resulting

P. F. Hudson (✉)
Leiden University, The Netherlands
e-mail: p.f.hudson@luc.leidenuniv.nl

H. Middelkoop
Department of Physical Geography, University of Utrecht, Utrecht, Netherlands





P. F. Hudson, H. Middelkoop (eds.), *Geomorphic Approaches to Integrated Floodplain Management of Lowland Fluvial Systems in North America and Europe*,
DOI 10.1007/978-1-4939-2380-9_1

in engineered channels and embanked floodplains with substantially altered sediment loads and geomorphic processes. Over the past decade, floodplain management of many lowland rivers has taken on new importance because of concerns about the potential for global environmental change to alter floodplain processes, necessitating revised management strategies that minimize flood risk while enhancing environmental attributes of floodplains influenced by local embankments and upstream dams. Although such floodplains are heavily modified, it remains essential to understand their controlling geomorphic processes to design effective plans for environmental management and restoration (Florsheim and Mount 2003; Singer and Aalto 2009), and to evaluate their longer-term impact on the fluvial system. Concurrently, the science of geomorphology is increasingly recognized as vital for designing effective management for dealing with different forms of global environmental change, thereby placing geomorphologists within a critical team of floodplain management specialists which also includes engineers, planners, and ecologists.

Integrated river management is commonly approached from the drainage basin perspective, which necessitates considering fundamental tenets of fluvial systems, specifically runoff and sediment sources, sediment transport, channel dynamics, and floodplain processes. The following chapters include case studies which emphasize the important role of geomorphology in river-floodplain management. These include case studies which consider the impact of different anthropogenic influences (dikes, dams, cutoffs…) to fluvial processes, as well as management and restoration approaches developed in response to both past and forecasted types of environmental change. European and North American alluvial rivers are of keen interest because of their long documented efforts at floodplain management and river engineering, an abundance of published literature available for syntheses, and because management agencies exists across governmental scales (e.g., local, state, federal). Additionally, because the timescales at which specific management styles have been implemented vary, there are important lessons to be learned by making a comparison across different river systems. Indeed, many ideas about river and floodplain management were exchanged between Europe and North America during the twentieth century (Reuss 2002; Hudson et al. 2008). Flood disasters over the past decade and a general concern about global environmental change suggests a vibrant exchange of ideas between Europe and North America concerning effective floodplain management strategies will continue well into the present century (e.g., US Congress 2005).

The issue of effective river and floodplain management is pressing along large alluvial rivers in North America and Europe, particularly in those regions with a high population density and economic activities (Kundzewicz et al. 2007). Such settings have a complex floodplain geomorphology and sedimentology, possibly influenced by ground subsidence and river avulsion processes (Stouthamer and Berendsen 2001; Aslan et al. 2005; Leigh 2008). These factors influence floodplain adjustment and increase flood risk but were often inadequately considered in the design of "traditional" flood control infrastructure (e.g., NRC 1995; ASCE 2007). Traditional flood control approaches utilized hard engineering to modify floodplain structure. Such approaches often did not consider the inherent dynamics of fluvial systems which drive abrupt changes over short timescales, the longer-term adjustments to regional controls (such as neotectonics), or the unintended consequences of floodplain engineering which unfold over longer timescales (Hesselink et al. 2003; Hudson et al. 2008; Singer and Aalto 2009). Additionally, these approaches are often focused on "local" management rather than considering the entirety of drainage basin controls. Modern—integrated—floodplain management is inherently more flexible and is designed to minimize flood risk, and at the same time to restore environmental attributes of embanked floodplains by "working with the river" (e.g., Ayres et al. 2014 for European river restoration).

Fluvial geomorphology provides an important conceptual framework and toolkit for design and implementation of river and floodplain management. Although reference to the importance of fluvial geomorphology to floodplain management can be found as far back as half a century, it did not strongly emerge until about the past 20 years within the United Kingdom and continental Europe (Downs et al. 1991; Middelkoop 1997; Middelkoop and Van Haselen 1999; WMO 2004). The inclusion of geomorphic approaches was formally advocated in the European Union's sweeping "Water Framework Directive" (European Council 2000). Scientific communities in North America have also recognized the importance of floodplain geomorphology to effective management strategies over the past couple of decades, but the importance of integrating geomorphic approaches to floodplain management may be characterized as "patchwork," occurring basin by basin, with individual states and "river authorities" (management districts) often adapting different approaches for different motivations (Ramin 2004). Indeed, within the USA, there exist strong regional contrasts in expenditures and management styles between the Mississippi basin, the west coast, and the Southern United States (Bernhardt et al. 2005).

Geomorphic approaches to floodplain management include diverse management plans that explicitly consider the physical processes and sedimentological and topographic frameworks in which modern processes function and engineering structures are emplaced (Hudson et al. 2008; Singer and Aalto 2009). Such approaches may include strategies such as dike (levee) realignment to increase the space for flood water retention (WMO 2004), channel planform and migration in relation to bank material (sedimentology), reconnection of meander bends or floodplain bottoms by levee breaches (Florsheim and Mount 2003), water resources and geomorphic processes (Asselman et al. 2003; NRC 2005; ASCE 2007), dike and flood control infrastructure with a knowledge of subsidence rates and neotectonics (Li et al. 2003; Dokka 2006; Törnqvist et al. 2008), and rates of floodplain sedimentation with management of floodplain water bodies (Middelkoop and Van Haselen 1999; Zeug and Winemiller 2009). These approaches require an understanding of the base-line physical processes for successful implementation.

There is much to be learned by examining different river basins across different physical landscapes and governmental settings. In this volume, we compile a range of case studies to consider the varying roles of geomorphology for river and floodplain restoration, and also to consider different approaches overseen by agencies charged with the task of designing effective strategies for floodplain management, and flood control.

## 2 Channel Dynamics

River management agencies have increasingly becoming aware of the linkages between channel dynamics and geomorphology as related to floodplain management. To date, most large-scale floodplain management plans, particularly for flood control, also include river channel management for bank stabilization and protection of flood control infrastructure. A common approach to flood control is river channelization (straightening) by artificial cutoffs of meander necks and sinuous reaches (Gregory 2006). Channel alignment and stabilization, however, is dependent upon knowledge of the sedimentary framework in which channels are active, specifically the channel-bed material (particle size) and bedload (volume) and the floodplain bank deposits (cohesive or noncohesive) (Frings et al. 2014). Additionally, channelization of sinuous reaches results in channel-bed incision, thereby decreasing the frequency of overbank events and sedimentation.

An important consideration is that channel bank protection infrastructure (groynes, revetments, etc.) was commonly designed for specific discharge regimes based on historic time-series data. Considerable modeling efforts have simulated changes in discharge regime (e.g., timing and magnitude of floods) in relation to regional climate change scenarios (e.g., IPCC 2007), but it is also essential to consider changes in rates of channel bank erosion and planform geometry as rivers adjust to changing discharge regimes. Most flood-control infrastructure was constructed without considering river channel avulsion processes. While perhaps requiring a century or so to occur, the initiation of a channel avulsion influences modern fluvial processes over decades, about the same timescale in which flood-control infrastructure is conceived and implemented. The slow, gradual process of channel switching changes discharge allocation and results in channel-bed aggradation that subsequently alters stage-discharge relations and flood regimes, which often requires further channel engineering as well as modification to flood-control infrastructure.

## 3 Embanked Floodplain Geomorphology, Flood Control, and Environmental Management

Flooding is one of the most significant ways in which climate change is manifest (AR5/IPCC 2014). Floods are natural events vital to river and floodplain geomorphic and ecosystem processes (NRC 2005). When humans are impacted, however, floods become "natural disasters" (White 1945; WMO 2004; Pinter 2005; Benito and Hudson 2010). Knowledge of fluvial processes and sedimentology is an important consideration in the design of flood control. For example, painful lessons were learned after the 2005 Hurricane Katrina disaster as regards the design and placement of dikes and flood walls in relation to subsurface sedimentology and changing topography. This is a critical issue to floodplain management and flood control, because as subsidence rates and climate change scenarios become integrated into flood forecasts it requires reengineering, which includes fortification and heightening or relocation of dike sections. An additional consideration concerns the linkages between sedimentology (historic floodplain geomorphology) and alluvial groundwater. This is vital as concerns the floodplain storage capacity for flood waters, but also because of controls on subsurface flow and dike seepage, which initiate sand boils (Davidson et al. 2013), as well as the management of groundwater resources.

Knowledge of embanked floodplain geomorphology is also vital to effective environmental management. A well-documented approach involves the removal of cohesive overbank sediments (clay—fine silt) for the creation of side channels and wetlands for environmental management and restoration. In densely populated regions, such as northern Europe, this becomes an essential approach because of limited space for dike relocation and the recognition of the need to adapt flood-control plans for climate change. Nevertheless, the removal of fine-grained top stratum deposits creates a risk of enhancing dike underseepage (Cobb et al. 1984) and should only be attempted with detailed knowledge of the underlying floodplain sedimentary architecture.

Large lowland river floodplains are mosaics of sedimentary deposits and topographic features created by various different geomorphic processes, which influences alluvial aquifers and surface flow paths of water, sediment, and nutrients (Nienhuis and Leuven 2001; Thoms 2003). Within embanked floodplains such processes represent fundamental controls on the dynamics and maintenance of ecosystems associated with floodplain water bodies such as oxbow lakes (Zeug and Winemiller 2009), but also artificially constructed water bodies such as dike breach ponds and borrow pits associated with the construction of flood-control dikes (Cobb et al. 1984; Jurada et al. 2004). Our understanding of overbank processes has advanced tremendously over the past couple of decades, particularly flood-pulse dynamics (Tockner et al. 2000), sedimentation (Day et al. 2008), channel-floodplain connectivity, as well as the exchange of nutrients and ecological processes. Integrating knowledge of these processes with floodplain management lead to more effective ecological management (NRC 2005). For example, the intentional breaching of levees to distribute sediment and nutrients has been found to be very effective at replenishing floodplain wetlands (Florsheim and Mount 2003), and is becoming a common option for integrated floodplain management.

This volume presents distinct approaches utilized for floodplain management of large alluvial rivers in Europe and North America, with particular focus to the role of geomorphology. The river basins examined in the subsequent 12 chapters (Fig. 1) provide a representative coverage of the drainage of North America and Europe, taking into account a range of climatic and physiographic provinces. The case studies are large basins and collectively drain a wide swath of North American and European landscapes, and as such can be viewed as representative of many other situations. The river basins include the (1) Sacramento (California, US), (2) San Joaquin (California), (3) Missouri (Missouri), (4) Red (Manitoba and Minnesota), (5) Mississippi (Louisiana), (6) Kissimmee (Florida), (7) Ebro (Spain), (8) Rhone (France), (9) Rhine (The Netherlands), (10) Danube (Romania), and (11) Volga (Russian Federation) Rivers. The case studies covered in this chapter span

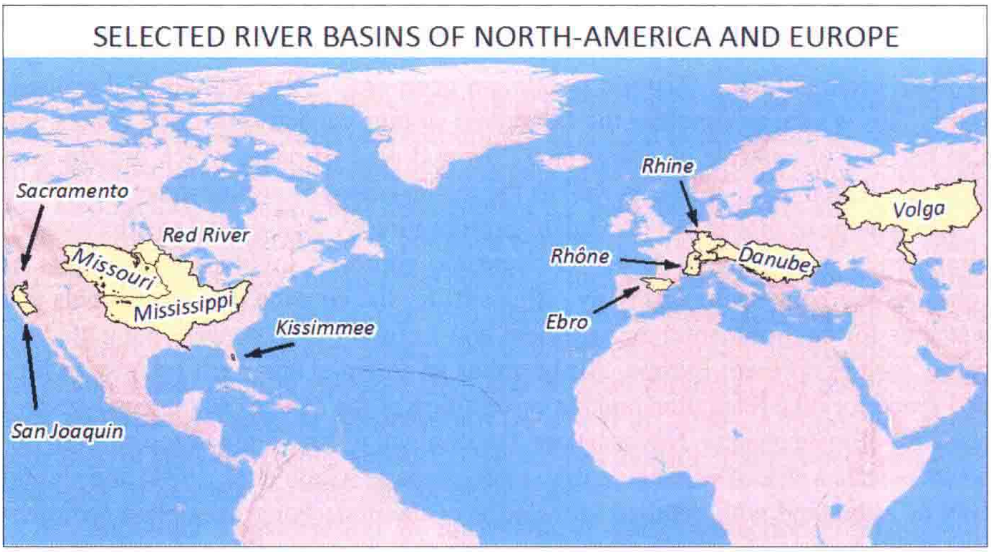


**Fig. 1** Featured drainage basins of North America and Europe

a range of fluvial modes of adjustment, including sediment, channel, hydrologic regime, floodplains, as well as ecosystem and environmental associations.

## References


American Society of Civil Engineers (ASCE). (2007). The New Orleans hurricane protection system: What went wrong and why? American society of civil engineers hurricane Katrina external review panel, 92 p.

Aslan, A., Autin, W. J., & Blum, M. D. (2005). Late Holocene avulsion history of the Mississippi river, south Louisiana, U.S.A. *Journal of Sedimentary Research, 75,* 648–662.

Asselman, N. E. M., Middelkoop, H., & Van Dijk, P. M. (2003). The impact of changes in climate and land use on soil erosion, transport and deposition of suspended sediment in the river Rhine. *Hydrological Processes, 17,* 3225–3244.

Ayres, A., Gerdes, H., Goeller, B., Lago M., Catalinas, M., García Cantón, A., Brouwer, R., Sheremet, O., Vermaat, J., Angelopoulos, N., & Cowx, I. (2014). Inventory of river restoration measures: Effects, costs and benefits. Report D1.4 of the EU REFORM project, Deltares, Utrecht.

Benito, G., & Hudson, P. F. (2010). Flood hazards: The context of fluvial geomorphology. In I. Alcántara-Ayala & A. Goudie (Eds.), *Geomorphological hazards and disaster prevention.* Cambridge: Cambridge University Press.

Bernhardt, E. S., Palmer, M. A., Allan, J. D., Alexander, G., Barnas, K., Brooks, S., Carr, J., Clayton, S., Dahm, C., Follstad-Shah, J., Galat, D., Gloss, S., Goodwin, P., Hart, D., Hassett, B., Jenkinson, R., Katz, S., Kondolf, G. M., Lake, P. S., Lave, R., Meyer, J. L., O'Donnell, T. K., Pagano, L., Powell, B., & Sudduth, E. (2005). Synthesizing U.S. river restoration efforts. *Science, 308*(5722), 636–637.

Cobb, S. P., Pennington, C. H., Baker, J. A., & Scott, J. E. (1984). Fishery and ecological investigations of main stem levee borrow pits along the lower Mississippi river. Final Report on lower Mississippi river environmental program report No. 1, US Army Corps of Engineers, Vicksburg, MS, 122 p.

Davidson, G. R., Rigby, J. R., Pennington, D., & Cizdziel, D. V. (2013). Elemental chemistry of sand-boil discharge used to trace variable pathways of seepage beneath levees during the 2011 Mississippi river flood. *Applied Geochemistry, 28,* 62–68. doi:10.1016/j.apgeochem.2012.10.018.

Day, G., Dietrich, W. E., Rowland, J. C., & Marshall, A. (2008). The depositional web on the floodplain of the Fly River, Papua New Guinea. *Journal of Geophysical Research, 113,* F01S02. doi:10.1029/2006JF000622.

Dokka, R. K. (2006). Modern-day tectonic subsidence in coastal Louisiana. *Geology, 34,* 281–284.

Downs, P. W., Gregory, K. J., & Brookes, A. (1991). How integrated is river basin management? *Environmental Management, 15,* 299–309.

European Council. (2000) Council Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy, Official Journal of the European Union, L 327, 22.12.2000.

Florsheim, J. L., & Mount, J. M. (2003). Changes in lowland floodplain sedimentation processes: Pre-disturbance to post-rehabilitation, Cosumnes river, CA. *Geomorphology, 56,* 305–323.

Frings, R. M., Döring, R., Beckhausen, C., Schüttrumpf, H., & Vollmer, S. (2014). Fluvial sediment budget of a modern, restrained river: The lower reach of the Rhine in Germany. *Catena, 122,* 91–102.

Gregory, K. J. (2006). The human role in changing river channels. *Geomorphology, 79,* 172–191.

Hesselink, A. W., Weerts, H. J. T., & Berendsen, H. J. A. (2003). Alluvial architecture of the human-influenced river Rhine, The Netherlands. *Sedimentary Geology, 161,* 229–248.

Hooijer, A., Klijn, F., Pedroli, G. B. A., & Van Os, A. G. (2004). Towards sustainable flood risk management in the Rhine and Meuse river basins: synopsis of the findings of IRMA-SPONGE. *River Research and Applications, 20,* 343–357.

Hudson, P. F., Middelkoop, H., & Stouthamer, E. (2008). Flood management along the lower Mississippi and Rhine rivers (The Netherlands) and the continuum of geomorphic adjustment. *Geomorphology, 101,* 209–236.

IPCC. (2007). In M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, & C. E. Hanson (Eds.), *Climate change 2007—Impacts, adaptation and vulnerability. Working Group II contribution to the fourth assessment report of the IPCC (intergovernmental panel on climate change)*. Cambridge: Cambridge University Press.

Jurada, P., Ondrackova, M., & Reichard, M. (2004). Managed flooding as a tool for supporting natural fish reproduction in man-made lentic water bodies. *Fisheries Management and Ecology, 11,* 237–242.

Kondolf, G. M. (2011). Setting goals in river restoration: When and where can the river "Heal Itself"? In Stream restoration in dynamic fluvial systems: Scientific approaches, analyses, and tools geophysical monograph series 194, American Geophysical Union. 10.1029/2010GM001020.

Kundzewicz, Z. W., Mata, L. J., Arnell, N. W., Döll, P., Kabat, P., Jiménez, B., Miller, K. A., Oki, T., Sen Z., & Shiklomanov, I. A. (2007). Freshwater resources and their management. Climate change 2007: Impacts, adaptation and vulnerability. Contribution of working group ii to the fourth assessment report of the intergovernmental panel on climate change, M.L. Parry, O.F. Canziani, J.P.

Leigh, D. S. (2008). Late quaternary climates and river channels of the Atlantic Coastal Plain, USA. *Geomorphology, 101,* 90–108.

Li, Y., Craven, J., Schweig, E. S., & Obermeier, S. F. (2003). Sand boils induced by the 1993 Mississippi river flood: Could they one day be misinterpreted as earthquake-induced liquefaction? *Geology, 24,* 171–174.

Middelkoop, H. (1997). Embanked floodplains in the Netherlands. Netherlands Geographical Studies 224 (341 pp.). KNAG/Faculteit RuimtelijkeWetenschappen Universiteit Utrecht.

Middelkoop, H., & Van Haselen, C. O. G. (1999). Twice a river. Rhine and Meuse in The Netherlands. Institute for inland water management and waste water treatment. RIZA report 99. 003, 127 p.

Middelkoop, H., Kwadijk, J. C. J., Van Deursen, W. P. A., & Van Asselt, M. B. A. (2002). Scenario analyses in global change assessment for water management in the lower Rhine delta. In M

Beniston (Ed.), *Climatic change: Implications for the hydrological cycle and for water management. Advances in global change research 10* (pp. 445–463). Dordrecht: Kluwer.

National Research Council. (1995). *Flood risk management and the American river basin: An evaluation. water science and technology board, division on earth and life studies*. Washington, DC: The National Academies Press.

National Research Council. (2005). *The science of instream flows: A review of the Texas instream flow program. Committee on review of methods for establishing instream flows for Texas rivers. Water science and technology board, division on earth and life studies*. Washington, DC: The National Academies Press.

Nienhuis, P. H., & Leuven, R. S. E. W. (2001). River restoration and flood protection: Controversy or synergism? *Hydrobiologia, 444,* 85–99.

Pahl-Wostl, C. (2008). Requirements for adaptive water management. In C. Pahl-Wostl, P. Kabat, & J. Möltgen (Eds.), *Adaptive and integrated water management: Coping with complexity and uncertainty* (pp. 1–22). Berlin: Springer.

Pinter, N. (2005). One step forward, two steps back on U.S. floodplains. *Science, 308,* 207–208.

Ramin, V. (2004). The status of integrated water resources management in Canada. In D. Shrubsole (Ed.), *Canadian perspectives on integrated water resource management* (pp. 1–33). Cambridge: Canadian water resource association (Chap. 1).

Reuss, M. (2002). Learning from the Dutch. Technology, management, and water resources development. *Technology and Culture, 43,* 465–472.

Schumm, S. A. (1977). *The fluvial system* (338 p.). New York: Wiley.

Singer, M. B., & Aalto, R. (2009). Floodplain development in an engineered setting. *Earth Surface Processes and Landforms, 34,* 291–304.

Stouthamer, E., & Berendsen, H. J. A. (2001). Avulsion history, avulsion frequency, and intervulsion period of Holocene channel belts in the Rhine-Meuse Delta (The Netherlands). *Journal of Sedimentary Research, 71,* 589–598.

U.S. Congress. (2005). Safety in the Netherlands, Statement to the United States Congress by Jan R. Hoogland Director of Rijkswaterstaat, Oct. 20, 2005.

Thoms, M. C. (2003). Floodplain–river ecosystems: Lateral connections and the implications of human interference. *Geomorphology, 56,* 335–349.

Tockner, K., Malard, F., & Ward J. V. (2000). An extension of the flood pulse concept. *Hydrological Processes, 14,* 2861–2883.

Törnqvist, T. E., Wallace, D. J., Storms, J. E. A., Wallinga, J., Van Dam, R. L., Blaauw, M., Derksen, M. S., Klerks, C. J. W., Meijneken, C., & Snijders, E. M. A. (2008). Mississippi Delta subsidence primarily caused by compaction of Holocene strata. *Nature Geoscience, 1,* 173–176.

White, G.(1945). Human adjustment to floods. University of Chicago Department of Geography, Research Paper No 29 (1942), 119 p.

World Meteorological Association (WMO). (2004). Integrated flood management. The Associated Programme on Flood Management, 1, Geneva, SZ, 30 p.

Zeug, S. C., & Winemiller, K. O. (2009). Relationships between hydrology, spatial heterogeneity, and fish recruitment dynamics in a temperate floodplain river. *River Research and Applications, 24,* 90–102.