CIRIA C731 London, 2013

The International Levee Handbook

US Army Corps of Engineers®

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE

Ministère
de l'Écologie,
du Développement
durable
et de l'Énergie

ciria

The International Levee Handbook

CIRIA

C731 CIRIA 2013 RP957 ISBN: 978-0-86017-734-0

British Library Cataloguing in Publication Data

A catalogue record is available for this book from the British Library

Keywords

Levees, assessment, asset management, coastal and marine, concrete and structures, construction, dams and reservoirs, design, emergency management, environmental good practice, flooding, geotechnics, ground investigation and characterisation, health and safety, hydraulics, inspection, operation and maintenance, refurbishment and repair, resilience, rivers and waterways, risk and value management, sustainable construction, sustainable resource use, water infrastructure

Reader interest	Classification	
Coastal, river and estuarine managers and engineers, consultants, levee owners, levee managers, civil engineers, hydraulic engineers, geotechnical engineers, engineering geologist, environmental regulators, geomorphologists, modellers, planning and other consenting authorities, environmental advisers, contractors, academics	Availability	Unrestricted
	Content	Advice/guidance
	Status	Committee-guided
	User	Coastal and estuarine managers, consultants, contractors, suppliers, consenting authorities, environmental regulators and advisers, researchers

Published by CIRIA, Griffin Court, 15 Long Lane, London, EC1A 9PN, UK

CIRIA Disclaimer

This publication is designed to provide accurate and authoritative information on the subject matter covered. It is sold and/or distributed with the understanding that neither the authors nor the publisher is thereby engaged in rendering a specific legal or any other professional service. While every effort has been made to ensure the accuracy and completeness of the publication, no warranty or fitness is provided or implied, and the authors and publisher shall have neither liability nor responsibility to any person or entity with respect to any loss or damage arising from its use.

USA Disclaimer

Nothing within this handbook is intended to establish a new or additional standard of care related to levee construction, maintenance, or operation by the Government of the United States or any instrumentality thereof.

Foreword

Levees, otherwise known as flood embankments or dikes, are a vital part of modern flood risk management. Many of our towns and cities would be uninhabitable without them. Most countries have many existing levees in their river and coastal systems. It is estimated that there are several hundreds of thousands of kilometres of levees in Europe and the USA alone. The maintenance of these levees in both normal and flood conditions is a major task for flood management authorities. Levees are maintained and improved and new levees are built. Yet many of the techniques used do not necessarily take full advantage of the experience developed in other countries. Only by sharing knowledge internationally can we ensure the most efficient, effective and environmentally-sensitive work programmes.

Our national governments realised that there was the need to sponsor the production of a single reference source on good practice in the management and design of levees, drawing on the skills found across Europe and in the USA. The production of this new handbook is very appropriate, and is the fruits of collaboration between the USA, France and the UK, with additional support from Ireland, the Netherlands and Germany.

This handbook is more than a revision or combination of existing documents within participating countries. It represents more than five years work by an international team of experts supported by an international peer review process. The team has put together an extensive handbook on the safety assessment, management, design and construction of levees, which incorporates all the main elements of good practice. While the handbook is not prescriptive it is our belief that appropriate application of the guidance in this handbook will help to underpin long-term improvements in the management and design of levees and will help to promote conservation of natural systems in balance with the proper protection of human life and property.

We have pleasure in presenting this handbook to everyone involved in managing levees and commissioning new levees on which many communities across the world rely to protect them from flooding.

Rt Hon Lord Smith of Finsbury
Chairman of the Environment Agency

Steven L. Stockton, P.E.
Director of Civil Works Headquarters, US Army Corps of Engineers

Daniel Loudière
Vice-Chairman of the French Standing Committee for Dams and Hydraulic Works

Acknowledgements

Editorial and publications teams

Partner organisations	This handbook is the result of a joint research project of CIRIA (UK) French Ministry of Ecology (France), and USACE (USA)	
Country arrangement	**UK:** The overall co-ordination of the project was under taken by CIRIA. The technical work was carried out by a consortium led by HR Wallingford and included CH2M Hill and Royal HaskoningDHV	
	Ireland: Provided financial contribution and input through the UK and Ireland National Backing Group	
	France: The French contribution to ILH was carried out by a consortium managed by CETMEF and including Irstea, several departments of the Ministry of Ecology, managers of dikes, and several private consultants	
	USA: The US Army Corps of Engineers (USACE), US Department of Homeland Security (DHS), and the National Committee on Levee Safety (NCLS) represented the primary points of contact for this effort in the United States. Each of these organisations carried out specific roles for the development of the handbook. Recognising the multitude of entities with an interest in levees within the United States, USACE, DHS, and NCLS offered several opportunities to participate to a broader group, either as content providers or reviewers, through national conferences and other various organisations	
	Germany: Useful input was received from the committees drafting the relevant German standards	
	The Netherlands: Contributions by several water boards and private consultants was received, facilitated and co-ordinated through STOWA	
Technical Editorial Team (TET)	Henk van Hemert	STOWA, the Netherlands
	Marc Igigabel	CETMEF, France
	Reinhard Pohl	Technische Universität Dresden, Germany
	Michael Sharp (chair)	USACE, USA
	Jonathan Simm	HR Wallingford, UK
	Rémy Tourment	Irstea, France
	Michael Wallis	HR Wallingford, UK
Project technical lead	Jonathan Simm	HR Wallingford, UK
Project managers (CIRIA)	Louise Clarke	
	Jonathan Glerum	
	Kristina Gamst Povlotsky	
	Clare Drake (editor)	
Assistant project managers (CIRIA)	Gillian Wadams	
	Lee Kelly	
Project director (CIRIA)	Owen Jenkins	
Executive Steering Board (including national represenation)	Jackie Banks	Environment Agency, UK/Ireland
	Mervyn Bramley	Independent engineer, UK/Ireland
	Patrick Chassé	CETMEF, France
	Tammy Conforti	USACE, USA
	Henk van Hermet	STOWA, the Netherlands
	Owen Jenkins	CIRIA, UK/Ireland
	Thibaut Mallet	SYMADREM, France
	Enrique Matheu	US Department of Homeland Security, USA
	Reinhard Pohl	Technische Universität Dresden, Germany
	Paul Royet	Irstea, France
	Michael Sharp	USACE, USA
	Jonathan Simm	HR Wallingford, UK/Ireland
	Steven Verigin	GEI Consultants, USA

Funders

France	Ministère de l'Ecologie, du Développement Durable et de l'Energie (Ministry of Ecology, Sustainable Development and Energy)
The Netherlands	Fugro Water Services
Ireland	Office of Public Works
UK	Atkins PLC, BAM Nuttal Ltd, Black & Veatch Ltd, Environment Agency, ICE, Mott MacDonald, Opus International Consulting, Scottish Government
USA	USACE

Chapter teams

Chapter 1	**Introduction**	
	Chapter lead	Michael Sharp, USACE
	Authors	Technical Editorial Team
Chapter 2	**Levees in flood risk management**	
	Chapter lead	Michael Wallis, HR Wallingford
	TET editor	Jonathan Simm, HR Wallingford
	Authors	Mervyn Bramley, Independent engineer; Harry Schelfhout, Deltares; Jonathan Simm, HR Wallingford; Rémy Tourment, Irstea; Tracey Williamson, HR Wallingford
Chapter 3	**Functions, forms and failure of levees**	
	Chapter lead	Yann Deniaud, CETMEF
	TET editor	Henk van Hemert, STOWA
	Authors	Jamie McVicker, USACE; Alexis Bernard, CETE Ouest LR St Brieuc; Bruno Beullac, Irstea; Rémy Tourment, Irstea
Chapter 4	**Operation and maintenance**	
	Chapter lead	Rachel Hersch-Burdick, USACE
	TET editor	Henk van Hemert, STOWA and Reinhard Pohl, Technische Universität Dresden
	Authors	Michael Wielputz, USACE; Nicolas Auger, DREAL Centre; Tom Blackburn, Blackburn Consulting; Ray Costa, Geotechnical Consultant; Les Harder, HDR; Henk van Hemert, STOWA; Kevin Holden, USACE; Harry Jones, GZA GeoEnvironmental; Jean Maurin, DREAL Centre; Patrice Mériaux, Irstea; Christina Neutz, USACE; Rick Robertson, USACE; Leon Skinner, USACE; Jonathan Simm, HR Wallingford; Terry Sullivan, USACE; Michel Vennetier, Irstea; Dana Werner, USACE; Caroline Zanetti, Irstea and ARBEAUSolutions
Chapter 5	**Levee inspection, assessment and risk attribution**	
	Chapter lead	Rémy Tourment, Irstea;
	TET editor	Henk van Hemert, STOWA
	Authors	Christina Neutz, USACE; Michael Wallis, HR Wallingford; Bruno Beullac, Irstea; Graham Bradner, GEI Consultants; Scott Raschke, Schnabel Engineering
Chapter 6	**Emergency management and operations**	
	Chapter lead	Enrique Matheu, DHS and Yazmin Seda-Sanabria, USACE
	TET editor	Michael Sharp, USACE and Rémy Tourment, Irstea
	Authors	Charles Ifft, USACE
Chapter 7	**Site Characterisation and data requirements**	
	Chapter lead	Shaun Wersching, CH2M Hill
	TET editor	Michael Sharp, USACE

	Authors	Rosemary Schmidt, USACE; Nick Armstrong, Fugro Engineering Services Limited; Alan Brown, Stillwater Associates; Michael Briggs, USACE; Marta Roca Collell, HR Wallingford; Rod Eddies, Fugro Aperio Limited; Roger Gaines, USACE; James Hulme, Opus International Consultants Ltd; Robert Hutchison, Opus International Consultants Ltd; Marc Igigabel, CETMEF; Tamara Massong, USACE; Sujan Punyamurthula, URS; Scott Raschke, ASDSO/Schnabel; Jane Smith, USACE; Richard Whitehouse, HR Wallingford; Michael Wielputz, USACE
Chapter 8	**Physical processes and tools for levee assessment and design**	
	Chapter leads	Guillaume Veylon, Irstea and Edouard Durand, CETE Normandie-Centre
	TET editor	Michael Sharp, USACE and Jonathan Simm, HR Wallingford
	Authors	Roger Gaines, USACE; William Allsop, HR Wallingford; Michael Briggs, USACE; Patrick Chasse, CETMEF; David Criado, DREAL PACA; Julien Habert, CETE Nord-Picardie; Mark Morris, SAMUI Design and Management Ltd; André Paquier, Irstea; Tim Pullen, HR Wallingford; Neil Schwanz, USACE; Jean-François Serratrice, CETE Méditerranée; Jane Smith, USACE
Chapter 9	**Design**	
	Chapter lead	Philip Smith, Royal HaskoningDHV
	TET editor	Jonathan Simm, HR Wallingford
	Authors	Roger Gaines, USACE; Said Salah Mars, URS Corporation; Mary Perlea, USACE; Jonathan Simm, HR Wallingford; Michael Wielputz, USACE
Chapter 10	**Construction**	
	Chapter leads	Joe Forbis, USACE and Charlotte Spliethoff, Grontmij Nederland B.V.
	TET editor	Marc Igigabel, CETMEF
	Authors	Malcolm Corlett, BAM Nuttall; Eric Holand, Taylor Engineering and USACE; Marc Igigabel, CETMEF; Andrew Jantzer, Buchart Horn; James P Moore, USACE; Dave Paul, USACE; Michael Wallis, HR Wallingford; Michael Wielputz, USACE

Other key contributors

Chapter 2	Jackie Banks, Environment Agency; Bruno Beullac, Irstea; Roger Gaines, USACE; Jamie McVicker, USACE
Chapter 3	Lacey Albers, USACE; Ira Artz, TETRATECH; Nicolas Auger, DREAL Centre; Gérard Degoutte, Irstea; Jaap-Jeroen Flikweert, Royal HaskoningDHV; Mark Freitas, GEI Consultants; Jean-Jacques Fry, EDF; Roger Gaines, USACE; Luc Hamm, ARTELIA; Henk van Hemert, STOWA; Torsten Heyer, IWD; Christien Huisman, Grontmij Nederland B.V.; Andreas Kortenhaus, Technische Universität Braunschweig; Thibaut Mallet, SYMADREM; Jean Maurin, DREAL Centre; Raymond McCollum, USACE; Reinhard Pohl, Technische Universität Dresden; Rick Robertson, USACE; Paul Royet, IRSTEA; Céline Trmal, CETE Méditerranée
Chapter 4	Jackie Banks, Environment Agency; Herb Bessey, USACE; George Bielen, USACE; Gerard A (Jerry) Colletti, USACE; Maureen K Corcoran, USACE; Joseph Dunbar, USACE; Marty Eisenman, USACE; Jaap-Jeroen Flikweert, Royal HaskoningDHV; Erin Rae Gore, USACE; Henk van Hemert, STOWA; Charles Ifft, USACE; Richard John, Environment Agency; James Kelly, USACE; Yves Nédélec, CETE du Sud-Ouest; Patrik Peeters, FHR; Jenna Peterson, USACE; Kaylee Peterson, USACE; Michel Pinhas, AD Isère Drac Romanche; Reinhard Pohl, Technische Universität Dresden; Amy Powell, USACE; Yvo Provoost, Rijkswaterstaat; Harry Schelfhout, Deltares; Jim Spencer, USACE; Charlotte Spliethoff, Grontmij Nederland B.V.; Jan Tigchelaar, Hoogheemraadschap van Delfland; Quiling Yao, IWHR; Al Zarnoski, USACE
Chapter 5	Jackie Banks, Environment Agency; Ben Gouldby, HR Wallingford; Pierre Maurel, Irstea; Patrice Mériaux, Irstea; Mike Panzeri, HR Wallingford; Laurent Peyras, Irstea; Paul Royet, Irstea
Chapter 6	Ray Alexander, USACE; Jackie Banks, Environment Agency; Neil Cash, USACE; Siamak Esfandiary, Federal Emergency Management Agency; Jaap-Jeroen Flikweert, Royal HaskoningDHV; Jeff Jensen, USACE; James Kelly, USACE ; Bas Kolen, KKV Consultants; Thibaut Mallet, SYMADREM; Steve Marruffo, USACE; Reinhard Pohl, Technische Universität Dresden; Jonathan Simm, HR Wallingford; Nicholas Sleptzoff, Federal Emergency Management Agency; Charlotte Spliethoff, Grontmij Nederland B.V.

Chapter 7 William Allsop, HR Wallingford; Michael Bailey, USACE; Graham Bradner, GEI Consultants; Anita Branch, USACE; Dwain Butler, USACE; Drew Clemens, USACE; Manuela Escarameia, HR Wallingford; G v d Ham, Deltares; Luc Hamm, ARTELIA; Henk van Hemert, STOWA; Christien Huisman, Grontmij Nederland B.V.; Lewis Hunter, USACE; Meg Jonas, USACE; Keith Kelson, Fugro; Andrew Morang, USACE; Ernst Niederleithinger, BAM; Justin Pearce, Fugro; Mary Perlea, USACE; Reinhard Pohl, Technische Universität Dresden; Edmond Russo, USACE/ERDC; Harry Schelfhout, Deltares; Kim Tremaine, Tremaine and Associates

Chapter 8 Nadia Benahmed, Irstea; Stéphane Bonelli, Irstea; Gerard Degoutte, Irstea; Bruce Ebersole, USACE, retired; Patrick Foley, USACE; Greg Hanson, US Department of Agriculture, Agricultural Research Service; Meg Jonas, USACE; Andreas Kortenhaus, Technische Universität Braunschweig; David Lheritier, Egis Eau; Julien Lhomme, HR Wallingford; Sebastien Mercklé, Irstea; Thierry Monier, SOGREAH; Andrew Morang, USACE; Mark Morris, Samui Design and Management; Pierre Philippe, Irstea; Reinard Pohl, Technische Universität Dresden; Paul Royet, Irstea; Roger Smith, Hesselberg Hydro; Martin Teal, West Consultants; Michael Wielputz, USACE

Chapter 9 William Allsop, HR Wallingford; Rajendram Arulnathan, URS Corporation; Peter Buck, SAFCA; Michael Deering, USACE; Gérard Degoutte, Irstea; Jeff Harris, USACE; Henk van Hemert, STOWA; Thibaut Mallet, SYMADREM; Sathish Murugaiah, URS Corporation; Christina Neutz, USACE; Paul Royet, Irstea; Harry Schelfhout, Deltares; Roger Smith, Hesselberg Hydro

Chapter 10 Rick Draeger, DSOD; Jean-Marc Flohr, EGIS; Patrick Garcin, EGIS; Werner Halter, Fugro; Gregory Kpegli, EGIS; David St. Marie, HNTB; Martin van der Meer; Fugro; Harry Mols, Witteveen+Bos; Rob Mullins, Stantec Consulting Services Inc; Mathieu Normand, EGIS; Michel Pinhas, AD Isère Drac Romanche; Reinhard Pohl, Technische Universität Dresden; Jana Steenbergen-Kajabová, Grontmij Nederland B.V.

Chapter reviewers

Nicolas Auger, DREAL Centre; Jackie Banks, Environment Agency; Geoff Baxter, Environment Agency; Jean-Pierre Becue, SAFEGE; V van Beek, Deltares; Raphaël Bénot, CETE de l'Ouest; Bill Blanton, Federal Emergency Management Agency; Arnaud de Bonviller, Institut franco-allemand de recherches de Saint-Louis; Chris Bowles, cbec; Mervyn Bramley, Independent engineer; Michael Collins, Office of Public Works; Malcolm Corlett, BAM Nuttall; Anna Daggett, Federal Emergency Management Agency; Michael Deering, IWR-HEC; Yann Deniaud, CETMEF; Paul Dobie, USACE; Brian Doyle, NI Rivers Agency; Sébastien Dupray, DREAL Languedoc Roussillon, formerly CETMEF; François Dussaud, TRAMAF; Jean Ernult, CETMEF; Manuela Escarameia, HR Wallingford; Jaap-Jeroen Flikweert, Royal HaskoningDHV; Jean-Marc Flohr, Patrick Garcin, EGIS; Gale Fraser, National Association of Flood & Stormwater Management Agencies; Jean-Jacques Fry, EDF; Roger Gaines, USACE; Thomas Garday, USDA - National Resource Conservation Service; Pierre Gaufrès, CETMEF; Richard Groom, Environment Agency; Michel Guéret, TRAMAF; David Gutierrez, California Department of Water Resources; Luc Hamm, ARTELIA Eau & Environnement; G v d Ham, Deltares; R.'t Hart, Deltares; Henk van Hemert, STOWA; Wouter ter Horst, Infram; Peter Hradilek, HDR Engineering; Charles Ifft, USACE; Marc Igigabel, CETMEF; Stichting IJkdijk, STOWA; Andrew Kirby, Mott MacDonald; H Kruse, Deltares; David Lasoski, USACE; Mathijs van Ledden, Royal HaskoningDHV; Sérgio Palma Lopes, IFSTTAR; Tamara M Massong, USACE; Jean Maurin, DREAL Centre; P Meijers, Deltares; Dolf Moerkens; Mark Morris, SAMUI Design and Management Ltd; Rob Mullins, Stantec Consulting Services, Inc; James Murphy, URS Corporation; Muskrat Control Netherlands; Hervé Nabonnand, TRAMAF; Herb Nakasone, National Association of Flood & Stormwater Management Agencies; Michael Navin, USACE; Yves Nedelec, Laboratoire Régional de BORDEAUX; Patrik Peeters, Departement Mobiliteit en Openbare Werken; Carlos Peña, US International Boundary Water Commission; Nicolas Rouxel, CETE de l'ouest; Céline Perherin, CETMEF; Reinhard Pohl, Technische Universität Dresden; Guirec Prévot, BETCGB; William Puckett, USACE; Rick Robertson, USACE; Mike Roll, Brown and Caldwell; Arno Rozing, Deltares; Steve Sanders, Sanders & Associates Geostructural Engineering, Inc; Neil Schwanz, USACE; Michael Scheffler, FM Global; Harry Schelfhout, Deltares; George Sills, Independent Consultant; Jonathan Simm, HR Wallingford; Robert Slomp, Rijkswaterstaat; Justin Solobay, US Department of Homeland Security; Brian Stenehjem, USACE; Terry Sullivan, USACE; Martin Teal, West Consultants; Technical Committee on Dikes and Levees, International Society of Soil Mechanics and Geotechnical Engineering; Jan Tigchelaar, Hoogheemraadschap van Delfland (waterboard); Céline Trmal, CETE Méditerranée; Stuart Ulsh, FM Global; USACE HQ Committee on Channel stabilisation; Meindert Van, Deltares; Jan Vandenbroeck, TRAMAF; Steve Verigin, GEI Consultants; Scott Vollink, USACE; Wout de Vries, Deltares/Infram; Michael Wallis, HR Wallingford; B Wichman, Deltares; John Winkelman, USACE

National teams

National backing groups	Three national backing groups were established to guide the project and represent the stakeholders of the partner countries	
UK national backing group	***National manager***	***CIRIA***
	Chair: Mervyn Bramley, Independent engineer Jackie Banks, Environment Agency; Geoff Baxter, Environment Agency; Alan J Brown, Stillwater Associates; Louise Clarke, CIRIA; Michael Collins, Office of Public Works; Malcolm Corlett, BAM Nuttall; Brian Doyle, Northern Ireland Rivers Agency; Jaap-Jeroen Flikweert, Royal HaskoningDHV; Robert Hutchison, Opus International; Stan Irving, Scottish Government; Owen Jenkins, CIRIA; Richard John, Environment Agency; Andrew Kirby, Mott MacDonald; Rachel Sandham, Arup; Jonathan Simm, HR Wallingford; Philip Smith, Royal HaskoningDHV; Andy Tan, Environment Agency; Paul Taylor, Atkins; Michael Wallis, HR Wallingford; Shaun Wersching, CH2M Hill; Mark Wheeler, Black & Veatch; Doug Whitfield, Environment Agency	
French national backing group	***National manager***	***CETMEF***
	Chair: Patrick Chassé, CETMEF; former Chair Sébastien Dupray, DREAL Languedoc Roussillon formerly CETMEF Nicolas Auger, DREAL Centre; Dominique Batista, CETE Méditerranée; Jean-Pierre Becue, SAFEGE; Brigitte Boyer, CETMEF; Christophe Chevalier, IFSTTAR; Yann Deniaud, CETMEF; Luc Deroo, ISL; Thierry Dubreucq, CETE Sud-Ouest; Edouard Durand, CETE Normandie-Centre; Mohamed El Fadili, CETMEF; Jean-François Fayel, ISL; Jean-Marc Flohr, EGIS; Jean-Jacques Fry, EDF; Patrick Garcin, EGIS; Serge Gravelat, FUGRO; Luc Hamm, ARTELIA; Marc Igigabel, CETMEF; Isère-Drac-Romanche; Jean-Marc Kahan, DGPR; Xavier Kergadallan, CETMEF; Pascal Lebreton, CETMEF; David Lhéritier, EGIS; Michel Lino, ISL; Thibaut Mallet, SYMADREM; Jean Maurin, DREAL Centre; Vincent Mazeiraud, ARTELIA; Nicolas Monié, DGPR; Thierry Monier, ARTELIA; Pascal Naulleau, DDTM Vendée; Sergio Palma-Lopès, IFSTTAR; Céline Perherin, CETMEF; Michel Pinhas, AD Isère Drac Romanche; Amélie Roche, CETMEF; Nicolas Rouxel, CETE Ouest; Paul Royet, Irstea; Laurence Tabard, DGPR; Rémy Tourment, Irstea; Céline Trmal, CETE Méditerranée; Jan Vandenbroeck, SDI/TRAMAF; Guillaume Veylon, Irstea; Anne-Laure Tiberi-Wadier, CETMEF	
USA national backing group	***National manager***	***US Department of Homeland Security***
	The USA National Backing Group consisted of working through several overarching organisations. The following were the main overarching organisations: American Council of Engineering Companies American Society of Civil Engineers Association of State Dam Safety Officials Association of State Floodplain Managers US Department of Homeland Security – Levee Sub-sector Coordinating Council Federal Emergency Management Agencies Federal Interagency Floodplain Management Task Force National Association of Flood and Stormwater Management Agencies National Committee on Levee Safety US Army Corps of Engineers US Society on Dams	

Authors of the scoping report

Sébastien Dupray	CETMEF, France
Rémy Tourment	Irstea, France
Reinhard Pohl	Technische Universität Dresden, Germany
Harry Schelfhout	DELTARES, the Netherlands
Tracey Williamson	HR Wallingford, UK/Ireland
Kristina Gamst Povlotsky	CIRIA, UK/Ireland
Michael Sharp	USACE, USA

Contents

Foreword . . . iii

Acknowledgements . . . iv

1 Introduction . . . 1

1.1 Use of levees . . . 4
1.2 Background to the handbook . . . 4
1.3 Scope . . . 5
1.4 Structure of the handbook . . . 5
1.5 Target readership . . . 8

2 Levees in flood risk management . . . 9

2.1 Managing flood risk . . . 13
2.2 Measures and instruments for flood risk management . . . 22
2.3 Levee management . . . 29
2.4 Roles and responsibilities in levee management . . . 39
2.5 References . . . 46

3 Functions, forms and failure of levees . . . 49

3.1 Functions of levees . . . 54
3.2 Forms and functions of levee components . . . 83
3.3 Forms of levees . . . 99
3.4 Structures associated with levees . . . 116
3.5 Understanding failure of levees . . . 156
3.6 References . . . 176
3.7 Further reading . . . 177

4 Operation and maintenance (O&M) . . . 179

4.1 Applying asset management principles to O&M . . . 183
4.2 Operations . . . 198
4.3 Maintenance . . . 201
4.4 Encroachments . . . 203
4.5 Vegetation management . . . 211
4.6 Burrowing animals . . . 224
4.7 Erosion and bank caving . . . 230
4.8 Depressions and rutting . . . 232
4.9 Settlement and subsidence . . . 234
4.10 Seepage . . . 238
4.11 Instability . . . 242
4.12 Cracking . . . 246
4.13 Levee slope and bank protection . . . 249
4.14 Closure structures . . . 256
4.15 Culverts and discharge pipe systems . . . 262
4.16 Levee transitions . . . 273
4.17 Flood walls . . . 278
4.18 References . . . 282
4.19 Further reading . . . 284

5 Levee inspection, assessment and risk attribution . . . 285

5.1 Framework for analysis and decision making . . . 289
5.2 Risk analysis and attribution . . . 292
5.3 Levee performance assessment and diagnosis methodology . . . 319
5.4 Inspections . . . 336
5.5 Investigations, instrumentation and monitoring . . . 358

5.6 Levee knowledge and data management . . . 365
5.7 References . . . 376

6 Emergency management and operations . . . 381
6.1 Emergency management principles . . . 387
6.2 Emergency planning . . . 389
6.3 Readiness and preparedness . . . 399
6.4 Event and crisis management . . . 403
6.5 Intervention techniques . . . 416
6.6 Response to external erosion and techniques for intervention . . . 421
6.7 Response to internal erosion and techniques for intervention . . . 431
6.8 Response to instability and techniques for intervention . . . 436
6.9 Breach management and techniques for intervention . . . 438
6.10 Innovative technologies for crest raising . . . 441
6.11 References . . . 446

7 Site characterisation and data requirements . . . 447
7.1 Principles of site characterisation . . . 455
7.2 Morphological, hydraulic and other natural actions on levees . . . 478
7.3 Morphology and hydraulic actions for riverine levees . . . 485
7.4 Morphology and hydraulic actions for coastal and shoreline levees . . . 535
7.5 Morphology and hydraulic actions for estuarine levees . . . 557
7.6 Human actions on levees . . . 560
7.7 Ground investigation for levees . . . 563
7.8 Geotechnical parameters . . . 584
7.9 Site investigation methods . . . 642

8 Physical processes and tools for levee assessment and design . . . 745
8.1 Principles . . . 752
8.2 External hydraulic processes . . . 754
8.3 Internal hydraulic processes . . . 791
8.4 External erosion . . . 805
8.5 Internal erosion . . . 830
8.6 Slope stability . . . 846
8.7 Settlement . . . 875
8.8 Seismic analysis . . . 882
8.9 Stability of flood walls . . . 905
8.10 Breach . . . 929
8.11 Flood inundation . . . 943
8.12 References . . . 954
8.13 Further reading . . . 971

9 Design . . . 975
9.1 Principles of levee design . . . 982
9.2 The levee design process . . . 991
9.3 Reporting and documentation . . . 1004
9.4 Levee layout and alignment . . . 1012
9.5 Levee geometry . . . 1018
9.6 Surface protection measures . . . 1035
9.7 Control of seepage and uplift . . . 1050
9.8 Control of internal erosion . . . 1061
9.9 Mass stability throughout levee life . . . 1065
9.10 Analysing failure mechanisms . . . 1079
9.11 Transitions . . . 1095
9.12 Design for serviceability . . . 1102
9.13 Levee earthworks . . . 1112
9.14 Spillways . . . 1135
9.15 Associated structures . . . 1158
9.16 Design input – construction and operation stages . . . 1179

10 Construction **1193**
10.1 Organisation of construction process 1198
10.2 Allowing for hydro-meteorological conditions 1223
10.3 Setting up and managing the site 1230
10.4 Fundamentals of earth construction 1242
10.5 Methods of construction 1262
10.6 References 1290
10.7 Further reading 1291

Glossary **1293**

Abbreviations **1324**

Notation **1326**

1 Introduction

Courtesy BeeldbankVenW.nl, Rijkswaterstaat

CHAPTER 1 CONTENTS

1.1 Use of levees 4
1.2 Background to the handbook 4
1.3 Scope 5
1.4 Structure of the handbook 5
1.4.1 Use of the handbook 6
1.5 Target readership 8

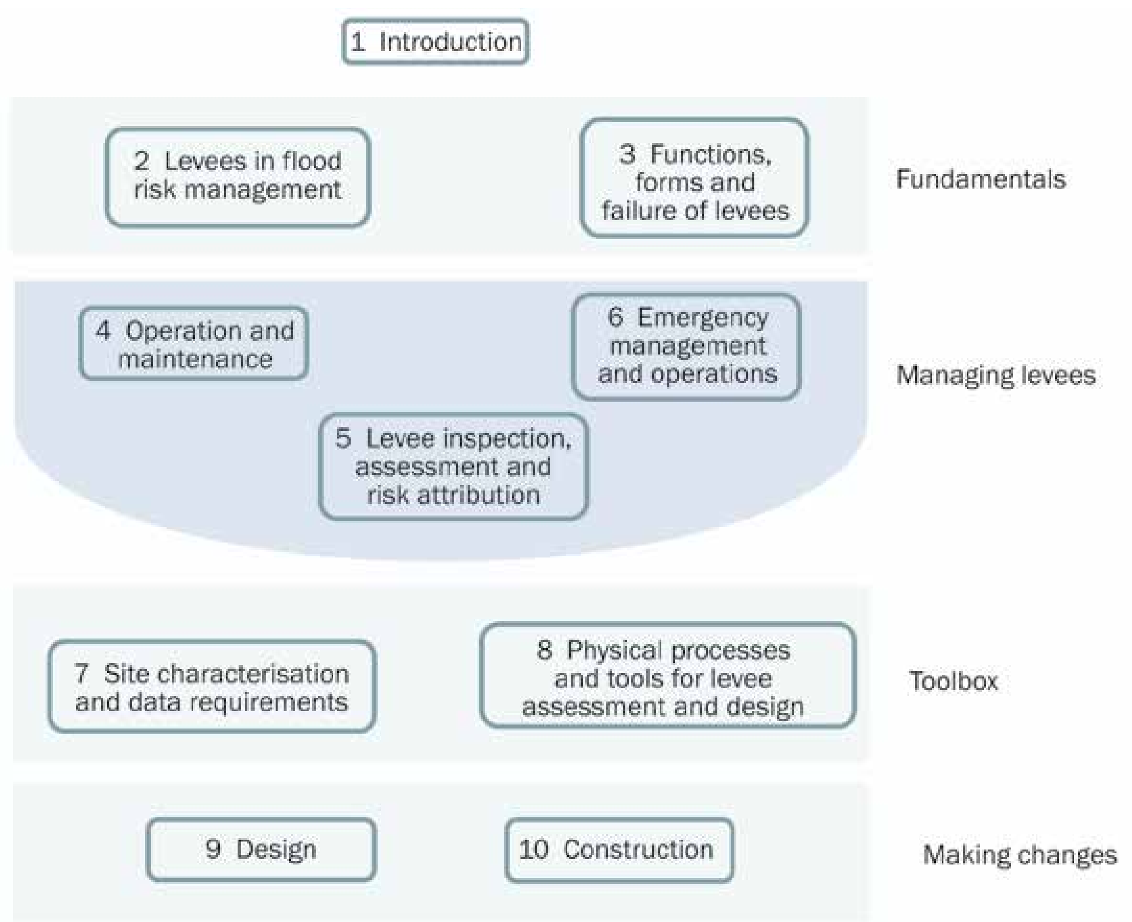
1 INTRODUCTION

Chapter 1 introduces the handbook and presents the motivation and process that led to its development. The chapter gives the reader an overview of its contents and explains how to use it.

The chapter flow chart shows the conceptual links between the technical chapters that follow this introduction. It is repeated at the start of each chapter but is expanded to show more detail of the contents of that chapter. It indicates that the handbook is split into four major parts:

- **fundamentals** – setting out what all users need to appreciate
- **managing levees** – focusing on what managers of existing levees need to know
- **toolbox** – providing detailed technical information (data equations etc) for use by all users
- **making changes** – focusing on the needs of those involved in design and construction of new or improved levees.

This flow chart shows where to find information in the chapter and how it relates to other chapters. Use it in combination with the contents page to navigate the handbook.



1 2 3 4 5 6 7 8 9 10

1.1 USE OF LEVEES

Levees are raised, predominantly earth, structures (also called dikes, digues or flood defence embankments) that are not reshaped under normal conditions by the action of waves and currents, whose primary objective is to provide protection against fluvial and coastal flood events along coasts, rivers and artificial waterways (Figure 1.1).

Levees form part of flood defence systems that may also include flood walls, pumping stations, gates closure structures, natural features, and other associated structures. In many instances levees have been built up and extended over decades or sometimes centuries. Few of these were originally designed or constructed to modern standards and records of their construction and historical performance may not exist.

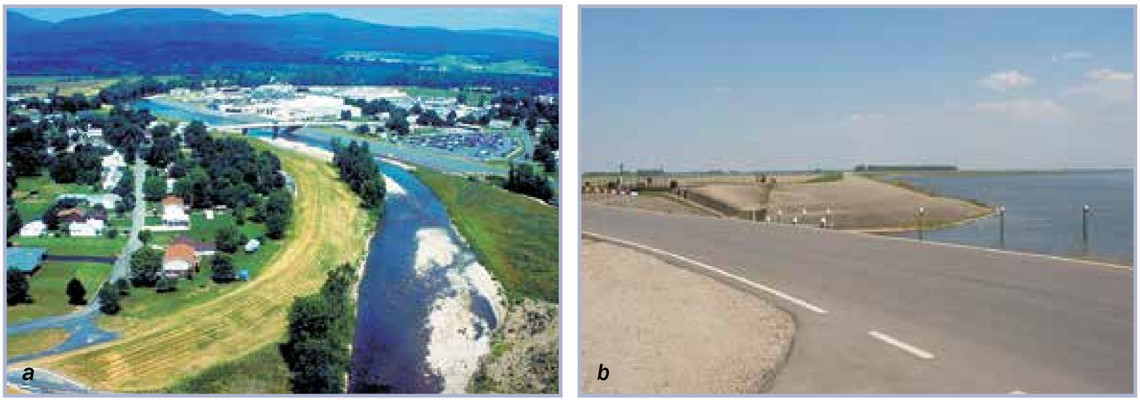


Figure 1.1 Typical riverine levee (a) (courtesy USACE) and typical coastal levee (b) (courtesy STOWA)

Despite their apparent simplicity, levees can be surprisingly complex structures. They have generally been constructed by placing locally won fill material onto alluvial flood plains (with all their inherent natural variability). Unlike engineered structures, levees can be irregular in the standard and nature of their construction and can deteriorate markedly over time if they are not well maintained. Furthermore, levees are generally long linear structures that are part of an overall system. Such systems should be considered as chains that are only as strong as the weakest link.

Evidence-based assessment, good design, effective adaptation, good inspection and routine maintenance are vital if levees (particularly those representing the weakest parts of levee systems) are to perform well on the occasions when they are loaded in storm or flood events. It should be noted that levees may stand for much of their lives without being loaded to their design capacity. This can create a false sense of security in the level of protection they will provide.

1.2 BACKGROUND TO THE HANDBOOK

Coastal and riverine flooding continues to produce devastating consequences, in both life and economic losses, around the world. With economic growth, urbanisation and the ensuing concentration of population and property, people are moving in increasing numbers to flood-prone areas in many countries. Where flood protection defenses have been improved, have not been fully tested, or experience infrequent flooding, residents become complacent and less aware of the threat of floods. In such cases, they are hardly prepared for floods and by no means assured of proper actions to take, consequently suffering more serious damage once a flood occurs.

Flood and storm events around the world continue to lead to critical flood defence failures resulting in tragic losses of life and the devastation of large areas. Also, levees have been severely tested by exceptional rainfall events. However, despite their critical importance in mitigating flood risk, interest and investment in levees has tended to be lower than in other critical water retaining infrastructure such as dams. In particular, in many countries, levees have lacked the legal and technical framework necessary to promote an appropriate level of performance.

In September 2008, organisations from six countries (France, Germany, Ireland, the Netherlands, United Kingdom, and the United States of America) expressed a desire in principle to participate in an international project to learn from one another's experiences and to share the effort to produce good practice guidance – The International Levee Handbook (ILH). That desire resulted in several international meetings and workshops, development of a scoping report and ultimately culminating in this handbook.

The principal objective of the handbook is to provide a comprehensive and definitive guide to good practice in the evaluation, design, implementation, maintenance and management of levees. The handbook is a non-prescriptive reference and should be used in conjunction with other relevant national and international codes and manuals. It is not intended to be a prescriptive code of practice for decision making but should be regarded as an important document in decision support and for reference in the application of international codes and manuals.

The handbook has been written by a core team of experts and practitioners from the full range of relevant disciplines drawn from the partner countries. The development of the handbook followed an agreed set of processes that was managed by a technical editorial team, and supported by an executive steering board drawn from national backing groups of the partner countries. Management support was provided by CIRIA (UK) who also prepared the resulting document for final publication. The document was made available to a broader international audience for review and comment during the development process.

1.3 SCOPE

The handbook takes a risk, performance and systems based approach. Any levee will have a primary function of flood management or coastal defence to which performance objectives or standards will apply. All levees will also have various secondary functions, eg environmental, amenity, health and safety, access, which can impose significant performance requirements. The handbook also follows a tiered approach to all aspects of managing and maintaining a levee or levee system such that concepts are applicable to levees in both urban and rural settings.

In drafting the handbook, the author teams considered the various management interventions that are needed to achieve the performance requirements of the levee or levee system over its whole life cycle. So the handbook addresses the assessment of existing riverine, coastal and estuarine flood protection levees (possibly for new or changed performance requirements), their adaptation or replacement, their operation and maintenance, as well as new design and removal. Consideration is also given to the fact that management interventions range from major construction projects carried out by external constructors through to routine maintenance by the involved authorities' own work force.

The handbook does not address levees constructed for purposes other than flood protection. Also, it does not cover the design of other water retaining structures. Associated structures are addressed because they influence the performance of a levee structure or its operation. The handbook also recognises the importance of structures that stabilise levees by managing riverine and coastal morphology such as beaches, dunes and groynes. Where necessary, reference to other management guidance is given for such structures.

1.4 STRUCTURE OF THE HANDBOOK

The handbook contains information that is useful for both existing and newly designed levees, however the structure of the handbook is such that existing levees are treated first followed by newly designed levees. Details about each chapter are presented in the rest of this section. Figure 1.2 presents a high level view of the handbook showing how each chapter contributes information to understanding a levee system as presented by the source-pathway-receptor conceptual model.

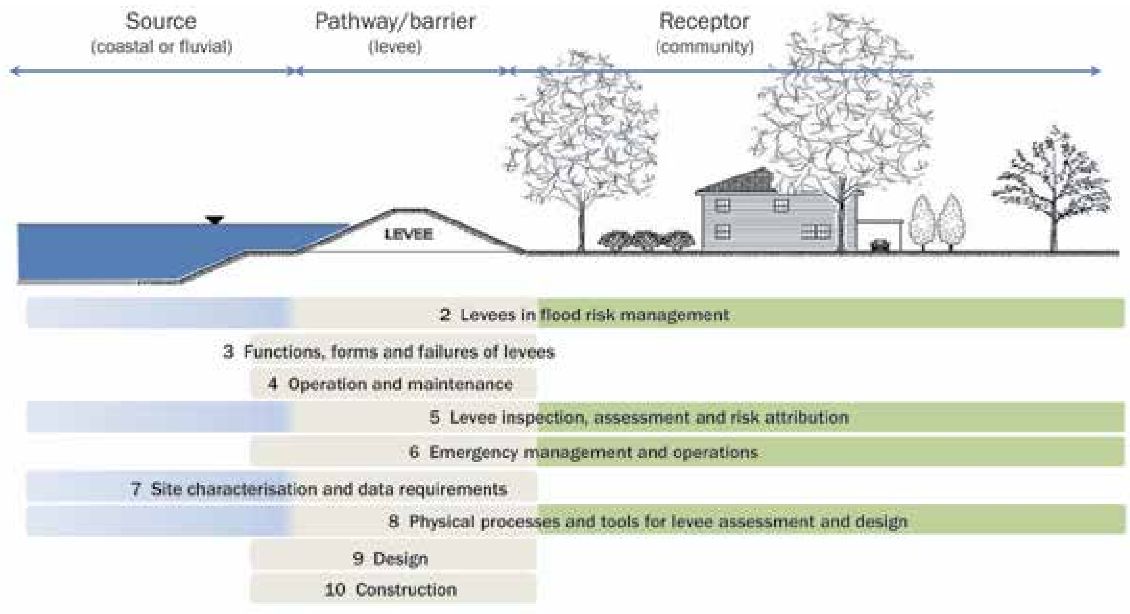


Figure 1.2 Illustration of chapter contents relative to the source-pathway-receptor conceptual model

1.4.1 Use of the handbook

The following features are designed to assist the reader in navigating the handbook:

- **diagram of general structure:** Table 1.1 provides a layout of the structure and contents of the complete handbook. It also suggests a relationship between the main phases of a typical project
- **diagram of content relevance to different users:** Table 1.2 presents an evaluation of the content from different users' perspectives to assist the reader in finding information relevant to their needs
- **high-level contents list:** this is given for the complete handbook at the start of the book
- **detailed contents list:** at the start of each chapter there is a contents list for that chapter only
- **structure of each chapter:** the front end of each chapter includes a detailed contents list for that chapter, an introductory box that describes what is included in that chapter, and a flow chart to demonstrate links with other chapters
- **where am I?** each page tells the reader their current location in the handbook. The chapter number is shown on the navigation bar running down the outer edge of right-hand pages, and the chapter title is given on the page header
- **electronic version:** the complete manual is available to downlaod from CIRIA's website: www.ciria.org

Table 1.1 *Structure and content of the handbook*

	Chapters	Description
Fundamentals	***Chapter 2*** Levees in flood risk management	Sets out the context of flood risk management in which levees and levee management should be seen, discussing the influence of environmental change. It explains roles and responsibilities in flood risk and levee management and why it is important to manage levees throughout their life cycle.
	Chapter 3 Function, form and failure of levees	Introduces an overview of levee functions within a flood risk management system and the multi-functionality of levees. It describes and illustrates the main types of forms of levees and presents the main structures associated with levees. The chapter concludes with a discussion of the processes of levee failure and how these are connected to the forms and functions of levees.
Managing levees	***Chapter 4*** Operation and maintenance	Addresses both operational and maintenance aspects of managing existing levees, including organisational aspects and the management of encroachments and vegetation. Maintenance requirements are described and related to the identification and resolution of defects arising from various deterioration and damaging mechanisms
	Chapter 5 Levee inspection, assessment and risk attribution	Presents levee assessment-related activities and their integration. The chapter provides a tiered approach to the assessment of levee systems including risk analysis, assessment and inspection. Data collection methods and related issues are described including inspections, investigations and monitoring. Data management systems to support levee management are also discussed given the importance of data availability and treatment for assessment activities.
	Chapter 6 Emergency management and operations	Sets out the principles of emergency management detailing preparedness and response and how the management of levees relates to the wider picture. It describes the various emergency intervention techniques including equipment and activities for minimising levee overtopping and damage and for subsequent repair and closure of breaches.
Toolbox	***Chapter 7*** Site characterisation and data requirements	Having described the basic principles of site characterisation for levees and their environment, the majority of the chapter is focused on giving detailed investigation and analysis techniques to establish the hydraulic and geotechnical boundary conditions at levees and also the condition of existing levees. It provides relevant equations and techniques for assessing the hydraulic and morphological conditions. It describes desk study procedures, intrusive and non-intrusive techniques for sampling and field investigation of geotechnical properties as well as relevant laboratory testing techniques and approaches to data interpretation that are suited to levees and the ground that levees are built on. The chapter also explains methods and procedures for determining appropriate parameters for design.
	Chapter 8 Physical processes and tools for levee assessment and design	Provides the engineering and scientific tools for the analysis and design of existing and new levees, embracing both geotechnical and hydraulic engineering disciplines. It details external and internal hydraulic, geotechnical and seismic actions on levees, sets out the physical processes that control the performance of levees, their protection systems, and associated floodwalls and indicates the analytical engineering methods and techniques (from simple equations to numerical techniques and modelling) that best represent the relevant mechanisms. The chapter concludes with a description of methods of assessing levee breach and subsequent inundation.
Making changes	***Chapter 9*** Design	Sets out principles of levee design, roles and responsibilities of those involved in design and the required reports and documentation. The chapter then explains how to determine levee layout and alignment and levee crest levels and geometry. Information on design calculations and detailing including methods of analysing failure mechanisms according to various codes of practice are included with further details on the specifics of design for seepage and internal erosion, surface protection measures and for limiting serviceability changes. The chapter concludes with advice on earthworks materials selection and compaction, and the design of spillways and of the levee earthworks around embedded/associated structures, including crest walls and pipes.
	Chapter 10 Construction	Describes levee preparation for construction concerning organisational aspects, programming and the management of construction risk. It focuses on the specifics of earthworks including the suitability of the soils, their treatment and handling. The stages of construction for earthworks are described for new build, adaptation, repair and decommissioning. The incorporation of non-earthworks structures is also discussed.

1.5 TARGET READERSHIP

Potential users of the handbook include planners, developers, structure owners, asset managers, regulatory bodies engineers, risk analysts, designers, constructors, emergency planners and responders, environmental organisations, educational institutions and the public.

The handbook is written to assist a technically competent practitioner with a broad (but not necessarily expert) knowledge of the field of application to arrive at the best approach for a particular levee or levee system. In this regard the handbook aims to provide information to support decision making rather than to direct it. The handbook will also seek to provide the intelligent client (ie a client with a technical background, but no particular specialist knowledge) with sufficient background information to understand the main issues and general procedures likely to be followed by an experienced practitioner.

The handbook has been written to address two major viewpoints:

1. **The manager** of the operating authority's physical structures who has the overall task of owning, maintaining, upgrading, adding to and disposing of its stock of flood or coastal levees.
2. **The designer** who will tend to focus on the need for, design of and implementation of improvements and new works.

In addition, the handbook provides some useful information for constructors (or other organisations) that may be advising the manager or designer carrying out maintenance, or carrying out new construction work.

Table 1.2 Relevance of chapters for different stakeholders and users

Stakeholder/user	**Chapter**								
	2 Levees in flood risk management	*3 Functions, forms, failures of levees*	*4 Operation and maintenance*	*5 Levee inspection, assessment and risk attribution*	*6 Emergency management and operations*	*7 Site characterisation and data requirements*	*8 Physical processes and tools for levee assessment and design*	*9 Design*	*10 Construction*
Planner	★	★	○	○	★	○	○	*	★
Developer	*	★	*	●	○	●	○	●	*
Structure owner	*	★	★	★	★	●	●	○	★
Asset manager	*	★	★	★	★	●	*	*	*
Regulatory body	*	*	●	★	*	○	○	○	★
Geotechnical engineer	○	★	★	★	★	★	★	★	★
Hydraulics engineer	○	★	★	★	★	★	★	★	★
Risk analyst	*	★	○	★	●	*	*	○	○
Designers	*	★	*	★	○	★	*	★	★
Constructor	●	★	*	○	●	●	●	*	★
Emergency planners and responders	●	★	*	★	★	○	○	○	*
Environmental organisation	*	*	★	○	○	○	○	○	★
Educational institution	*	*	*	*	*	*	*	*	*

Note

The relevance of material to each stakeholder or user group is indicated by the following symbols:

★	High	●	Medium-low
*	Medium-high	○	Low

2 Levees in flood risk management

Courtesy Bart van Eyck, Rijkswaterstaat

CHAPTER 2 CONTENTS

2.1 Managing flood risk 13
2.1.1 Flood management systems 13
2.1.1.1 Environmental context of managing flood risk 13
2.1.1.2 Sources, pathways and receptors 13
2.1.2 What is flood risk management? 15
2.1.2.1 The flood risk management process 15
2.1.2.2 Frameworks for flood risk management 17
2.1.2.3 The approach to decision making 17
2.1.3 Flood risk management process 18
2.1.3.1 Identifying flood risks 18
2.1.3.2 Flood risk analysis 18
2.1.3.3 The tiered approach to flood risk analysis 19
2.1.3.4 Flood risk evaluation 19
2.1.4 Changes in flood risk and associated responses 20
2.1.4.1 Causes of changes to flood risk 20
2.1.4.2 Resulting outcome with time 21
2.2 Measures and instruments for flood risk management 22
2.2.1 Measures – structural and non-structural 24
2.2.2 Instruments – financial and regulatory 24
2.2.2.1 Flood management policy and standards 24
2.2.2.2 Environmental regulatory considerations 25
2.2.3 Formulating portfolios of measures and instruments 26
2.2.4 Options appraisal 28
2.3 Levee management 29
2.3.1 Performance requirements 29
2.3.1.1 Risk-based approach to levee performance 29
2.3.2 Functional objectives 29
2.3.2.1 Environmental viability 31
2.3.2.2 Social acceptability 31
2.3.2.3 Economic viability 31
2.3.3 The levee management life cycle 31
2.3.3.1 Approaches to levee asset management 34
2.3.4 Managing performance and failure of levees 35
2.3.4.1 Knowledgebase of levee performance 35
2.3.4.2 Assessments and reviews of levee performance and reliability 36
2.3.4.3 Measures to reduce the probability of levee failure 38
2.4 Roles and responsibilities in levee management 39
2.4.1 Participants in levee management 39
2.4.1.1 Internal and external ‘actors’ 39
2.4.1.2 Institutional arrangements 41
2.4.1.3 Working partnerships and public participation 41
2.4.2 Communication – why and how? 41
2.4.2.1 Communicating risk 42
2.4.2.2 Communication planning 43
2.4.2.3 Forms of communication 44
2.5 References 46
Statutes 47

1
2
3
4
5
6
7
8
9
10

2 LEVEES IN FLOOD RISK MANAGEMENT

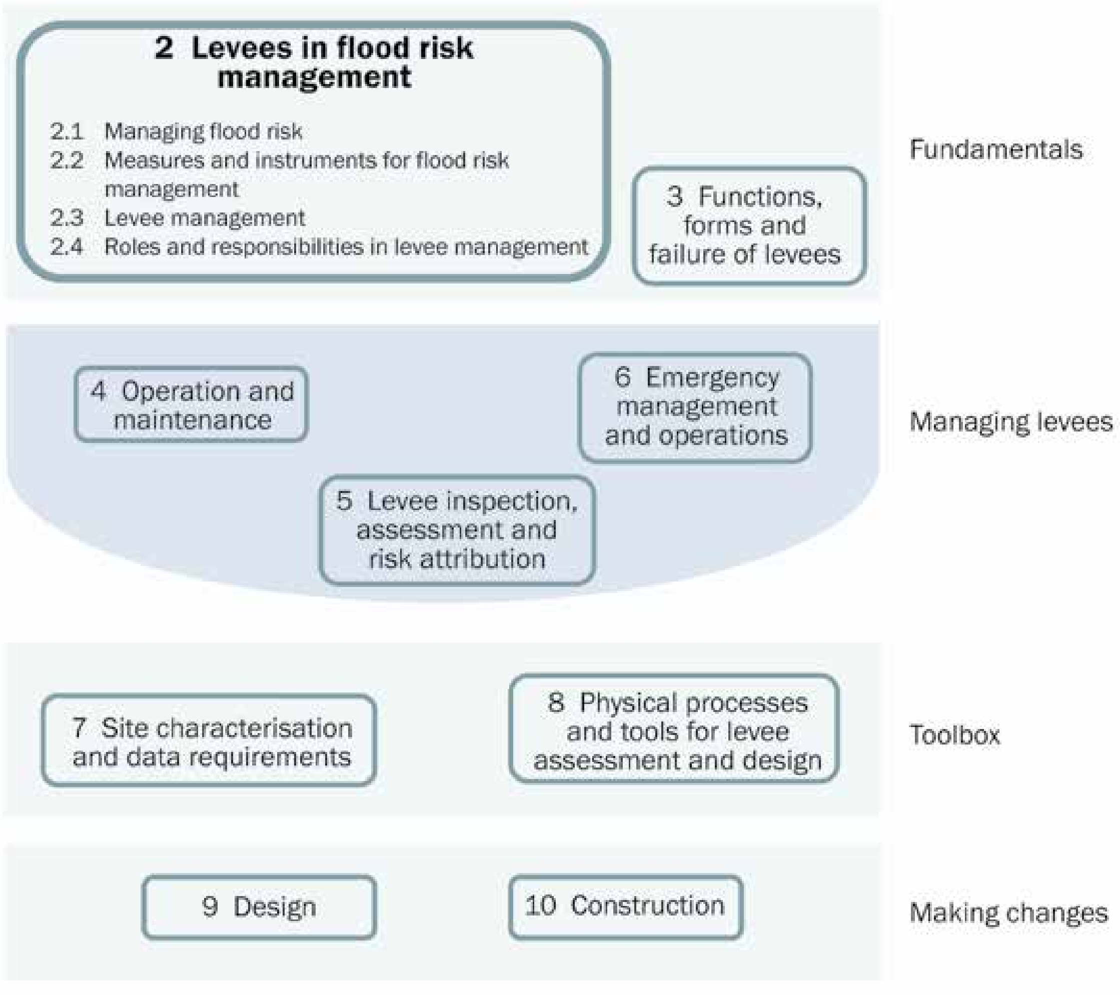
Chapter 2 sets levees in the wider context of flood risk management. General principles for levee management for use throughout the handbook are introduced.

Key outputs to other chapters

- starting point ⇨ **levee management**
- **conceptual and risk management frameworks** ⇨ all chapters

Note: The reader should revisit **Chapters 2 and 3** throughout the levee life cycle for a reminder of important issues.

This flow chart shows where to find information in the chapter and how it relates to other chapters. Use it in combination with the contents page to navigate the handbook.



CHAPTER CONTENTS AND TARGET USERS

This chapter consists of four sections, providing an overview of the management of flood risk systems and levees, and the basic roles and responsibilities of those organisations and individuals involved. All users of this handbook are recommended to read Chapter 2 before continuing to subsequent chapters as it provides an overview of key principles and concepts behind the detailed levee management and design information contained in the remainder of the handbook. As well as introducing the subject, it helps the reader (by suitable cross references) to identify the chapters in the handbook that are most relevant for their requirements.

Managing flood risk

The principles of risk and flood risk management are explained in Section 2.1, setting these in the context of the wider environment. Generic frameworks are illustrated and described for flood systems, flood risk management processes, and flood risk identification, analysis and assessment. Causes of, and responses to, changes in flood risk are also discussed.

Measures and instruments for flood risk management

In the context of developing flood risk management policy, Section 2.2 discusses structural and non-structural flood risk reduction measures, financial and regulatory instruments, and formulating portfolios of options for reducing flood risk.

Levee management

Section 2.3 explains how performance objectives and safety standards for levees are used to deliver flood risk mitigation policy aims and objectives. A framework for the life cycle of a levee is defined. This section also introduces approaches to levee asset management, including assessments and reviews of levee performance and reliability, and techniques for failure analysis.

Roles and responsibilities in flood risk management

Section 2.4 discusses the roles and responsibilities of those involved in managing levees and levee systems, including authorities, regulators, managers, designers, engineers. The importance and means of communication of risks to the wider public and local community is also discussed along with the importance of educating and empowering local communities.

2.1 MANAGING FLOOD RISK

Flooding is a worldwide phenomenon. Over the last few decades the world has experienced a rising number of devastating flood events. The trend in such natural disasters is increasing. Also, escalations in both the probability and magnitude of flood hazards are expected in places as a result of climate change. Past disasters have triggered many governments to embark on *flood risk management* initiatives, such as flood control schemes (including levees), early warning systems and evacuation planning, with the ultimate aim of defending their inhabitants from the vagaries of nature.

Although this handbook is primarily about the management of levees for flood risk reduction it is appropriate for this chapter to place levees in the wider context of flood risk management. The management of levees must be seen alongside a broader range of activities such as land use planning and emergency preparedness that may help to reduce flood risk. Also, levees do not normally provide flood control on their own. In any particular location on a river, estuary or coast, an individual levee segment will work together with other levees, structures and flood risk reduction measures. This interrelationship of structures and activities is often referred to as a flood risk management system. Sections 2.1 and 2.2 of this chapter provide this broader systems context. Sections 2.3 and 2.4 then move on to more specific material about levee management and communication.

2.1.1 Flood management systems

2.1.1.1 Environmental context of managing flood risk

The structures and components of a flood management system including levees are constructed and managed within an existing environment. Appropriate consideration of the environmental characteristics in which levees are located is central to the satisfactory and sustainable design, construction and/or operation of flood management systems. Such considerations include:

- ecosystems, habitats and species
- geology, ground conditions and foundations
- geomorphological processes and waterway navigation
- hydrology and hydraulic loading on the system
- land use, occupancy, transport, critical infrastructure, and agriculture
- availability of materials
- amenity, access and public safety
- land drainage and flood water storage
- the effects of seasonal climate variability and of climate change
- the effects of human development.

Conflicting interests may need to be taken into account in achieving a solution that is appropriate to the particular location. Section 3.1 discusses these issues in further detail as they relate to levees.

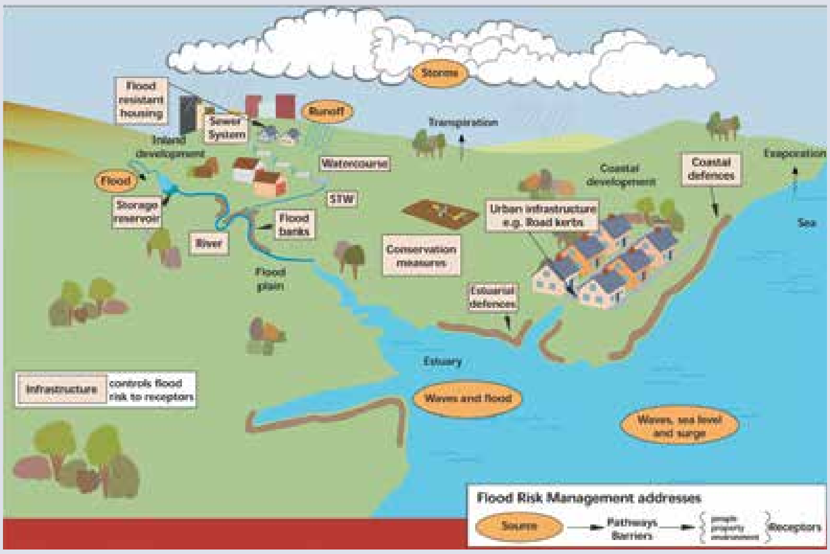
2.1.1.2 Sources, pathways and receptors

Floods, whether small or large, may be considered to be part of the natural behaviour of rivers, lakes, estuaries and the sea. But they may cause harm to society, and that is where the term hazard comes in. A hazard is a physical event or human activity with the potential to result in harm to people and damage to goods and property. In flood risk management, the interest is only in floods that constitute a hazard. A hazard does not automatically lead to a harmful outcome, but identification of a hazard does mean that there is a possibility of harm (or adverse consequences) occurring.

Floods are a complex phenomenon and consist of different *sources* (sea, rivers, lakes etc) of water, and *pathways* through which the flood can impact various types of *receptors*. The complexity of flooding can be illustrated using the source-pathway-receptor model shown in Box 2.1. For a risk to arise (Figure 2.1) there must be:

- a hazard that consists of a source or initiator event (ie high rainfall)
- a receptor (eg floodplain, people and properties)
- a pathway between the source and the receptor (ie flood routes including through, over or around flood control structures and the routes by which water spreads in the floodplain).

Box 2.1 ***The flooding system and the source-pathway-receptor framework***



Note
STW = sewage treatment works

Figure 2.1 ***The flooding system (courtesy M Bramley)***

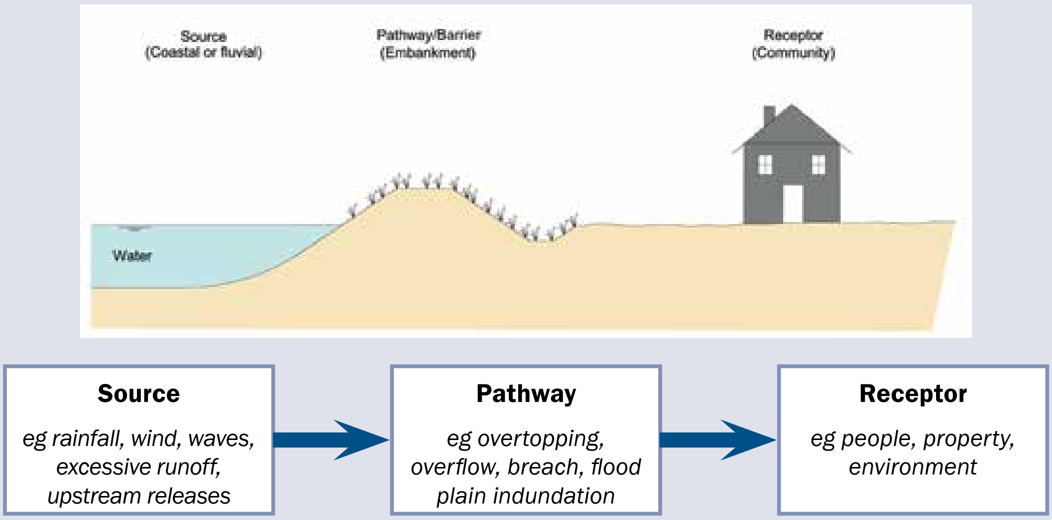


Figure 2.2 ***Source-pathway-receptor conceptual model (from Morris et al, 2007)***

- **sources:** typically, hydraulic loadings that impinge on defences including river levels, flows, waves, tidal and surge water levels and their associated probability of occurrence (singular or jointly) and that depend on driving factors such as meteorology (including wind) and hydrological and hydraulic factors that determine the patterns and volume of rainfall and runoff
- **pathways and barriers:** the behaviour under loading from sources of defences (depending on their nature, extent and condition) and of floodplains (depending on topography and land use)
- **receptors:** the exposure and vulnerability of the people, property and environmental features that may be harmed by a flood.

2.1.2 What is flood risk management?

Given the source-pathway-receptor framework, flood risk management can be seen to be about reducing the probability of floods of a particular severity occurring and/or reducing the magnitude of the impacts should flooding occur. The associated definition of flood risk is given in Box 2.2.

Box 2.2 ***The definition of flood risk***

Flood risk is a function of the ***probability*** of both the flood occurring and of any associated breaches in the flood defence system and the ***consequence*** within the leveed area of the undesirable outcome should a flood event occur (loss of lives, habitat and economic losses due to damages to goods and property). So:

Risk = fn (probability, consequence)

In flood risk management this is normally simplified to:

Risk = probability × consequence

An estimate of the total flood risk will normally require some form of integration across all possible flood events, breaches and consequences (see Section 5.2).

Figure 2.3 shows the relationship between the factors that influence flood risk and probability and consequences.

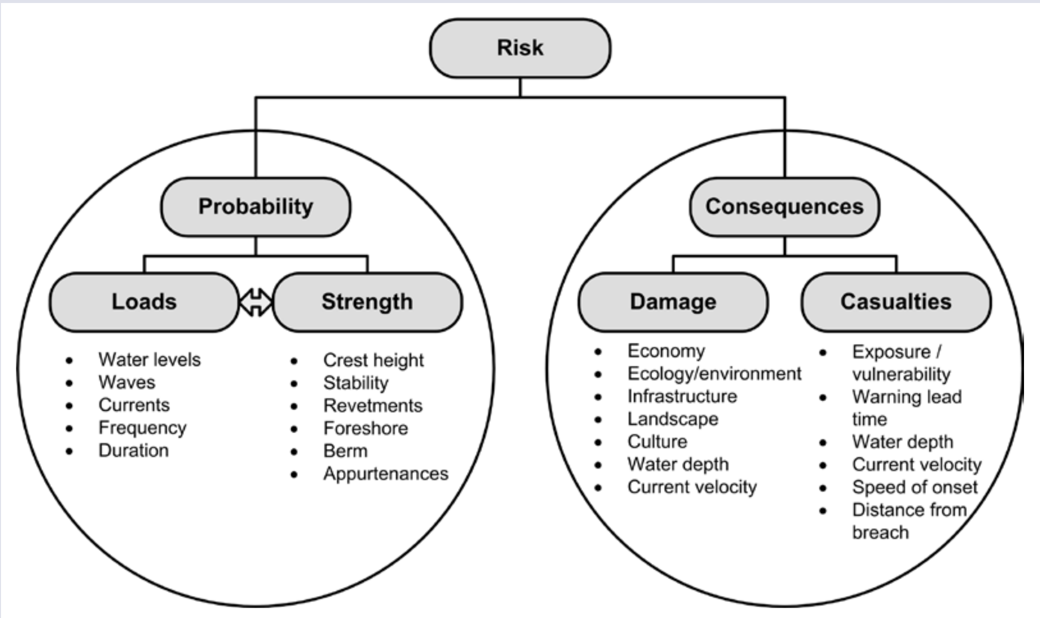


Figure 2.3 ***Governing factors that influence flood risk (courtesy H A Schelfhout)***

All of these factors change over time. For example:

- hydraulic loads will change as the climate changes, with perhaps higher or more erratic rainfall patterns
- levees can become weaker as their structure deteriorates and materials weaken due to climatic variation
- an accidental incident may damage a levee section at some point, reducing its strength
- land use in the area behind a levee may change over time, such as becoming more or less occupied or developed, or changing from agricultural land to industrial use or even residential housing.

Such changes can occur over a wide range of timescales (see Section 2.1.4).

2.1.2.1 The flood risk management process

As depicted in Figure 2.4, the process of flood risk management is about a sequence of first identifying flood risk, then assessing the level of risk, and finally about creating policies and plans to control the risk and to reduce it to an ‘acceptable’ level.

Figure 2.4 The process of flood risk identification, assessment and control

The process of flood risk management may be characterised in more detail as successively embracing (Figure 2.5) the following:

- **risk identification:** the process of recognising and recording risks
- **flood risk analysis:** which depends on risk identification and estimation, using current tools and methodologies to analyse and combine the likelihood and consequences of flooding (including, for estimates of future flood risk, allowances for future climate change, deterioration and socio-economic change. See Section 5.2)
- **flood risk assessment:** which involves an evaluation of the significance of the risk, an analysis of cost–benefit and formulation of recommendations through options appraisal
- **flood risk treatment:** which involves the combined use of policy and planning instruments (including preventative, control and mitigation) as well as decision making on all aspects of safety with design, implementation and maintenance of structural measures.

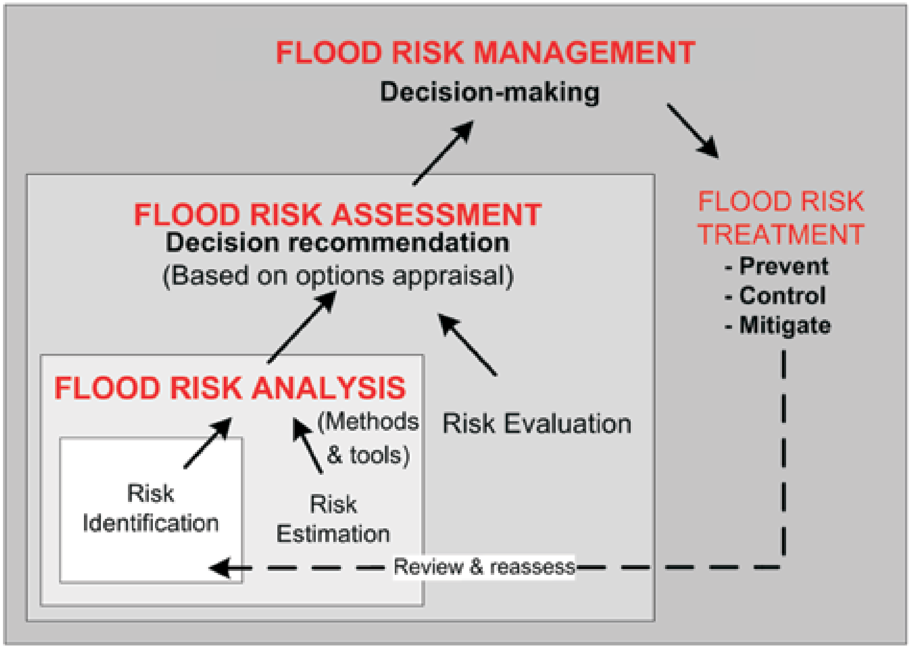


Figure 2.5 Illustration of an approach to flood risk management (from Bowles et al, 1999)

The process in Figure 2.5 is exemplified within the EU Floods Directive 2007, which has successive requirements for European Union (EU) nation states to prepare preliminary flood risk assessments, flood risk maps, and finally flood risk management plans.

Although different countries have the same overall aims for flood risk management and follow the basic process set out in Figure 2.5, the detail of their approaches and the way they are described do vary. For example, the Netherlands uses the 'safety chain' concept (shown in Box 2.3) to describe and evaluate flood risk management policies, and to link it in with the overall approach set out in the EU Floods Directive 2007.

Box 2.3 ***A multi-layer safety approach to flood risk management in the Netherlands***

Layer 3: disaster control and evacuation

Layer 2: durable spatial arrangement and flood resistant buildings

Layer 1: prevention of floods by reduction of probabilities and consequences

Figure 2.6

Example of a safety chain approach to flood risk management (from Kolen et al, 2010)

The safety chain (EU Floods Directive 2007)

- **recovery and lessons learned:** returning to normal conditions as soon as possible and mitigating both the social and economic impacts on the affected population
- **emergency response:** developing emergency response plans in the case of a flood including training of operational staff in event and breach management
- **preparedness:** informing the population about flood risks and what to do in the event of a flood. Training operational staff
- **protection:** taking measures, both structural and non-structural, to reduce the likelihood of floods and/or the impact of floods in a specific location
- **prevention:** preventing damage caused by floods by avoiding construction of houses and industries in present and future flood-prone areas, by adapting future developments to the risk of flooding, and by promoting appropriate land use, agricultural and forestry practices.

2.1.2.2 Frameworks for flood risk management

An effective framework for flood risk management will provide a structure within a nation, state or organisation in which policies, processes and procedures should reside and operate. It should include an integrated programme that covers the entire process previously described in Section 2.1.2.1 and also has provision for:

- the context and objectives of the organisation
- the selection of appropriate methods and techniques for flood risk assessment
- decision making on the extent and type of flood risks that are tolerable, and how unacceptable flood risks are to be treated
- identifying and analysing appropriate environmental information and any significant environmental impacts.

As part of this framework, an organisation responsible for managing flood risks should be clear about how the flood risk management relates to its responsibilities, authorities and accountabilities and how it integrates into its organisational processes, including:

- the resources available to conduct the assessments and prepare and implement the management plans
- how the flood risk assessments, maps and management plans will be reported, reviewed, recorded and communicated
- procedures for making the business case for resources for selected interventions to reduce risks
- procedures for managing environmental incidents and ensuring legal compliance (eg environmental permitting).

Issues of organisation and communication are discussed in more detail in Section 2.4.

2.1.2.3 The approach to decision making

Decisions in flood risk management should seek to balance the competing and complementary factors that affect flood risk. Where possible, interventions should be adopted that provide the largest reduction in flood risk for the least societal cost (economic, environmental and social). This balancing act often requires the use of a decision support system (DSS) that highlights different strategic alternatives, and helps to assess their costs and benefits across a range of possible futures (or planning scenarios). However, it must be remembered that although flood risk may be reduced by such an approach, it can never be removed completely. The remaining, or residual, flood risk, needs to be addressed through emergency management processes and procedures (see Section 6.1).

2.1.3 Flood risk management process

This section describes in more detail the flood risk management process set out in Figure 2.5.

2.1.3.1 Identifying flood risks

In the context of this handbook, flood risk (see Box 2.2) results from threats associated with the sea, rivers, lakes and loads to flood risk mitigation structures such as levees. Such threats include:

- very high water levels (including those arising from rapid onset or flash, and long duration floods)
- extreme wave attack
- strong currents.

Risk identification is the process of recognising and recording the risks arising from such threats. The purpose of risk identification is to identify what *might* happen or what situations might arise (often referred to as scenarios) that might affect particular receptors. This process should identify the causes and source(s) of the risk events, situations or circumstances that would have a material impact upon human lives, the environment and the local economy.

The following list gives examples of some of the factors or characteristics that could be included in flood risk identification:

- flood loading conditions (hydro-meteorological events) and their probabilities
- probability of flood inundation without a levee breach (ie loading event overflows or overtops the levee crest)
- levee condition and its probability of failure under load (ie levee reliability)
- characteristics of the floodplain and inundation (depth, velocity, geographical extent etc)
- nature, extent and vulnerability of the receptors (human, environmental, economic) to inundation
- existing risk control mechanisms and measures, and their effectiveness (eg emergency response)
- uncertainty in data and knowledge about the above factors.

To determine these characteristics, knowledge of previous flooding incidents may be used. However, for rare events this may not suffice and, in any case, the circumstances (eg the activities in the floodplain area) may have changed. So, it is necessary to use appropriate predictive calculations to assess the probabilities and magnitudes of all possible floods.

2.1.3.2 Flood risk analysis

Flood risk analysis allows all known contributory factors that make an area vulnerable to inundation to be brought together. It also enables consistent assessment and comparison of potential interventions to influence, control or reduce flood risk. The scope of a levee flood risk analysis should be commensurate with the needs of the decision being informed by the process.

Risk analysis methods are scalable and can vary in their approaches between countries and in their level of effort, detail, and certainty (accuracy). Factors that influence the selection of risk analysis techniques and methods can be described in terms of:

1
2
3
4
5
6
7
8
9
10

- the complexity of the problem and the methods needed to analyse it
- the nature and degree of uncertainty of the risk analysis based on the amount of information available and what is required to satisfy objectives
- the extent of resources required in terms of time and level of expertise, data needs or cost
- whether the method is required to provide quantitative or qualitative output.

The overall degree of uncertainty in the analysis can be determined by combining assessments of uncertainty in different parts of the source-pathway-receptor system. In this handbook, uncertainty is discussed in the following contexts:

- issues in analytical tools (Sections 7.3.13 and 8.11.6)
- risk assessment (Section 5.2.2)
- design (Section 9.5 and 9.10) during construction (Section 10.2).

2.1.3.3 The tiered approach to flood risk analysis

A tiered approach is a risk-based approach in which, following a preliminary risk assessment, the amount of effort put into further investigation and analysis is adjusted according to the severity of the problem and the magnitude of the consequences of failure. As flood risk analysis can be time-consuming and expensive, implementation of a tiered approach can save time and money. This tiered approach can be used in all aspects of the source-pathway-receptor framework (Figure 2.2), with the effort used at each stage to assess each aspect of flood risk being proportionate to its relative importance. An example characterisation is shown in Figure 2.7.

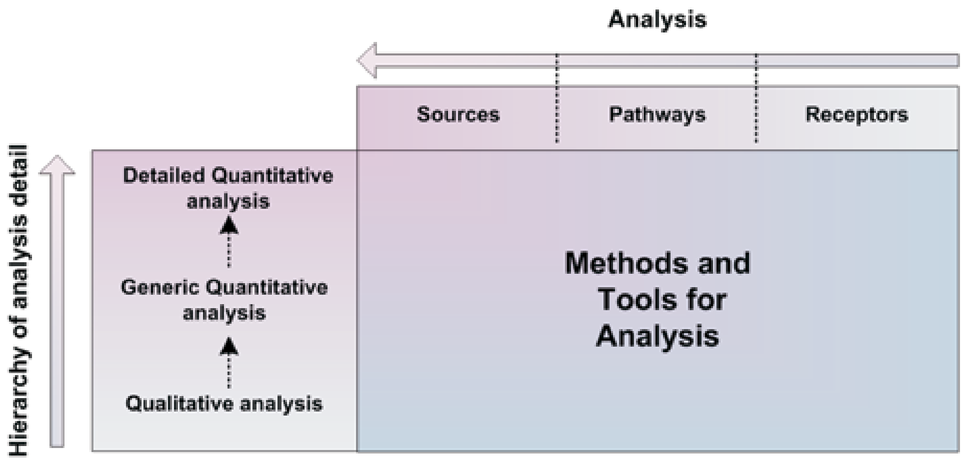


Figure 2.7 An example of a tiered approach to risk analysis (UK approach)

The concept of a tiered approach where the level of detail and associated effort is related to the level of risk can be applied to all aspects of flood management, not just risk analysis.

2.1.3.4 Flood risk evaluation

Risk cannot be entirely eliminated. The flood risk analysis of each possible intervention will determine residual risks, which then need to be evaluated in terms of how acceptable or tolerable they will be to stakeholders. The risk evaluation provides an opportunity to manage levees and flood risk using a framework that is common to all major hazards. Even though there is no one measure of what is 'tolerable', the evaluation stage does allow societal, regulatory, legal, owner and other values and judgments to enter the management and decision making process.

This evaluation should be conducted before comparing and selecting potential measures and instruments (Section 2.2) to reduce flood risks. Formal risk evaluation is not necessary after every periodical risk analysis, but if conducted, it should ideally be performed by an independent team, rather than the one who conducted the analysis.

Risk analysis and how it is applied varies between countries, so it is not surprising that international variations, and even within-country variations, are more evident in risk evaluation than in other stages in the risk assessment process. More information on these aspects of risk evaluation can be found in Section 5.2.11.

2.1.4 Changes in flood risk and associated responses

2.1.4.1 Causes of changes to flood risk

Causes of change to flood risk can either be *drivers*, such as climate change, or *responses* in the form of the measures and/or instruments (see Section 2.2) that are used to control or mitigate flood risks. Both of these affect the whole source-pathway-receptor flooding system and so will affect flood risk, as illustrated in Figure 2.8.

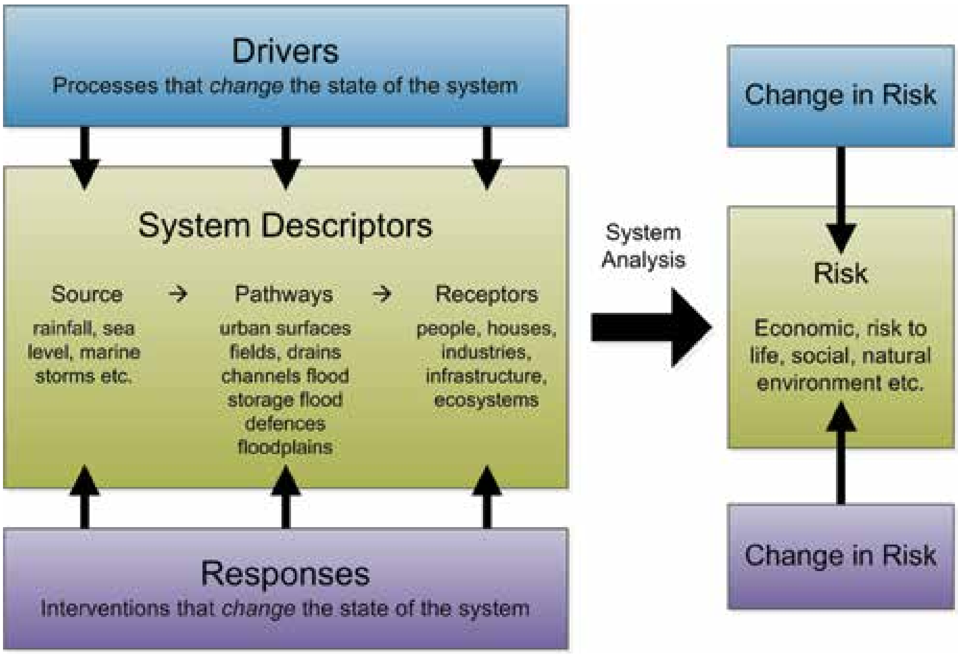
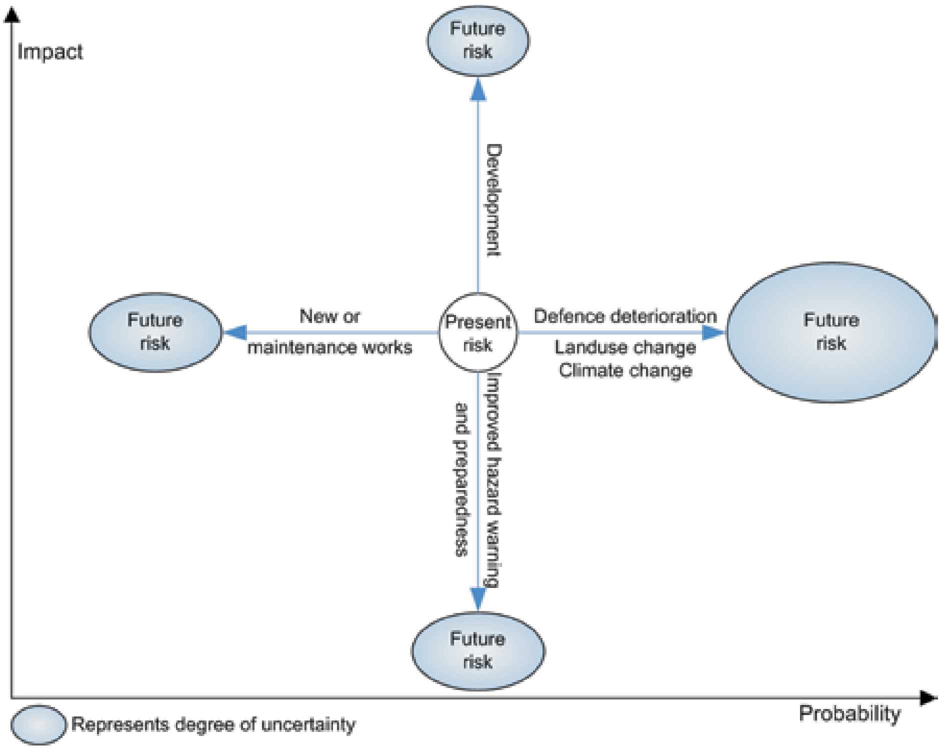


Figure 2.8 Drivers and responses changing the risk in a source-pathway-receptor flood system (Evans et al, 2008)

The resulting change in flood risk can also be viewed within a 'probability – consequence/impact space' as illustrated in Figure 2.9. The figure shows how example risk drivers (Box 2.4) can increase either the probability component of flood risk, such as climate change, defence deterioration, or the land use change. Risk drivers can also affect the impact/consequence component of risk, for example urban development. The extent to which the impact of these various changes is taken into account in the planning, design and management of flood management systems is generally a matter of national policy.

Figure 2.9 also shows how responses can decrease either the probability component of flood risk (eg by defence improvements) or the impact/consequence component (eg by improved hazard warning and preparedness). The various kinds of measures and instruments that can be used to reduce flood risk are discussed in more detail in Section 2.2.



Note
Size of ellipses represents the size of the uncertainty in the risk

Figure 2.9 ***Flood risk expressed in a probability-consequence space, showing ways of modifying it (adapted from Sayers et al, 2003)***

2.1.4.2 Resulting outcome with time

Understanding the resulting influence of these flood risk drivers and responses on flood risk requires assessments over a range of different scenarios, and over a long period of time. The length of time over which changes in flood risk are evaluated is often dictated by national policy, but typically it can be between 50 to 100 years. Once evaluated, the flood risk estimates generated from such assessments should ideally be expressed over common timeframes. For example, in cost–benefit assessment this integration is achieved by determining the present value of the stream of expected annual damages.

However, the prediction of future change in flood risk is inherently uncertain, and this introduces uncertainty into the risk assessment and into the evaluation of corresponding intervention options. Dealing with this uncertainty is one of the main challenges facing flood risk managers.

Chapter 7 describes methods of translating sea level rise to water levels and loadings on levees. How to account for ground subsidence in the design of levees is described in Section 9.12.

Box 2.4 Some drivers of flood risk

Source risk drivers

Climate variability and change is a major component of **source** risk drivers. Net warming of the atmosphere in the past several decades has induced many changes in the water cycle including changes in rainfall patterns and intensity, greater frequency and extent of drought, increased atmospheric water vapour, and changes in soil moisture and runoff. Increased land surface saturation and runoff to rivers, lakes and reservoirs results in **higher river discharges**, which can affect:

- levee structures and flood risk through increased water velocities and the potential for scour and erosion of the levee soil
- the likelihood of failure due to an increased level and frequency of hydrodynamic loading
- the likelihood of overtopping due to a reduction in freeboard (the distance between the water level and the crest of the levee).

The warming of the atmosphere and the resultant warming of the sea and widespread melting of snow and sea ice appear to have driven **sea level rise**. A rise in sea level means higher loads (water levels and wave conditions) on flood defence systems and structures. How these loads affect specific structures also depends on:

- the region or location (coast, estuary, river or lake)
- the geometry of the foreland (with potential for a loss of the foreshore) and the hinterland
- the type of hydrodynamic loads (high water level and/or wave attack).

Relative sea level rise (which is particularly important for coastal and estuarine levees) in a particular location is also affected by:

- **isostacy:** the vertical movement of the land mass, which varies across the continents (regional isostacy). Isostacy is, itself influenced by climate change as melting of ice sheets in the polar regions is reducing loads on continental land masses that carry them, and allowing them to rise
- **subsidence:** generally subsidence is caused by local soil conditions, increasing loads, or human activities such as mining or the pumping of water from underground aquifers. Climatic influences are also evident for certain land types and geomorphology (eg settlement by oxidation of peaty soils). However, **increased wave attack** can also arise because of either increased storminess or relative sea level rise increasing water depths and allowing more severe wave conditions to penetrate as far as coastal levees.

Pathway risk drivers

The **deteriorating condition of levees and flood walls** (or their components) due to various physical, chemical and biological mechanisms changes their state and reduces their reliability. This can leave them more vulnerable to failure under flood loading. Even defences that are rebuilt or adapted to a higher elevation can leave people vulnerable to a higher level of flooding impact should the structure(s) overtop or fail (effective communication of flood risk is essential to prevent occupants from forming a false sense of security when a flood defence is modified with increased height or size).

Receptor risk drivers

Land use and occupation can change over time with local and regional development such as:

- the draining of coastal lowlands for agriculture
- population movement and growth and the expansion of residential housing into flood risk areas
- spatial planning policies such as the creation of commercial and industrial enterprises in floodplains and estuaries.

In areas of high development there will often be an associated increase in supporting infrastructure, ie transport links, schools, service industries, utilities, hospitals and retail premises.

Subsidence of the ground surface can also increase potential inundation depths during a flood, resulting in increased harm to the people living in the flooded area and damage to goods and property.

2.2 MEASURES AND INSTRUMENTS FOR FLOOD RISK MANAGEMENT

Physical **measures** and financial and regulatory **instruments** are the means by which either the probability of flooding is reduced or, if inundation does occur, the impacts can be reduced (see Table 2.1). They are usually instigated and managed by flood risk management authorities.

In practice, measures and instruments are closely linked categories. It is virtually impossible to implement any structural measure without appropriate regulatory instruments, without justification for its implementation, and possibly without some financial compensation for those affected by it. Regulatory and financial instruments will influence the behaviour of people as much as they influence the requirement for structural measures.