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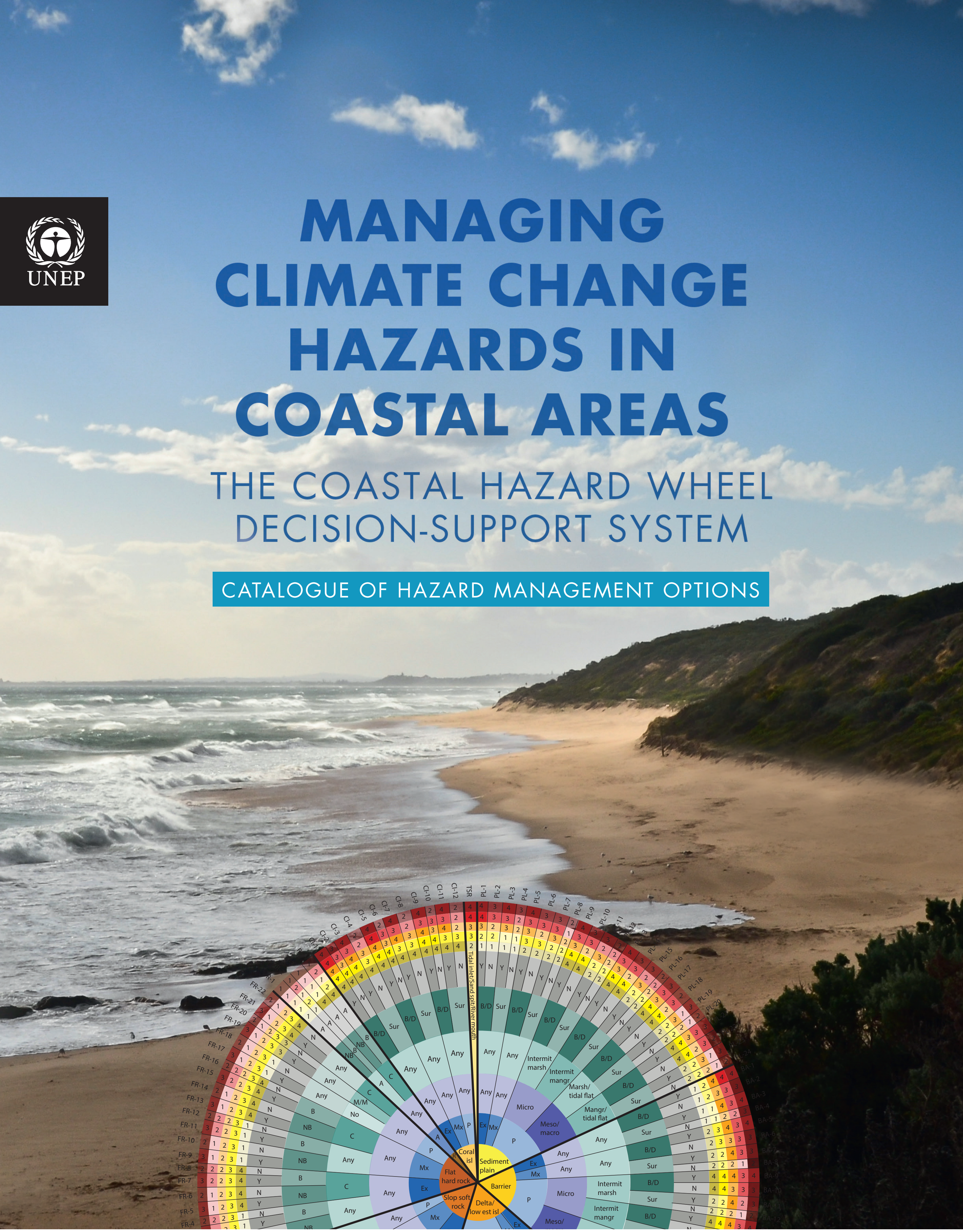
MANAGING CLIMATE CHANGE HAZARDS IN COASTAL AREAS

THE COASTAL HAZARD WHEEL DECISION-SUPPORT SYSTEM

CATALOGUE OF HAZARD MANAGEMENT OPTIONS



25 YEARS 2016
UNEP DTU PARTNERSHIP

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Centre on Water and Environment
UNEP DHI

Managing climate change hazards in coastal areas

The Coastal Hazard Wheel decision-support system

Catalogue of hazard management options

(Partly based on Zhu X, Linham MM, Nicholls RJ, 2010, Technologies for Climate Change Adaptation - Coastal Erosion and Flooding, UNEP).

Lead Authors
Lars Rosendahl Appelquist, Thomas Balstrøm, Kirsten Halsnæs

Contributing Authors and Reviewers
Robert J. Nicholls, Matthew M. Linham, Jason Spensley, Joost Stronkhorst, Peter Koefoed Bjørnsen, Gareth James Lloyd, Gorm Jeppesen, Ole Vestergaard

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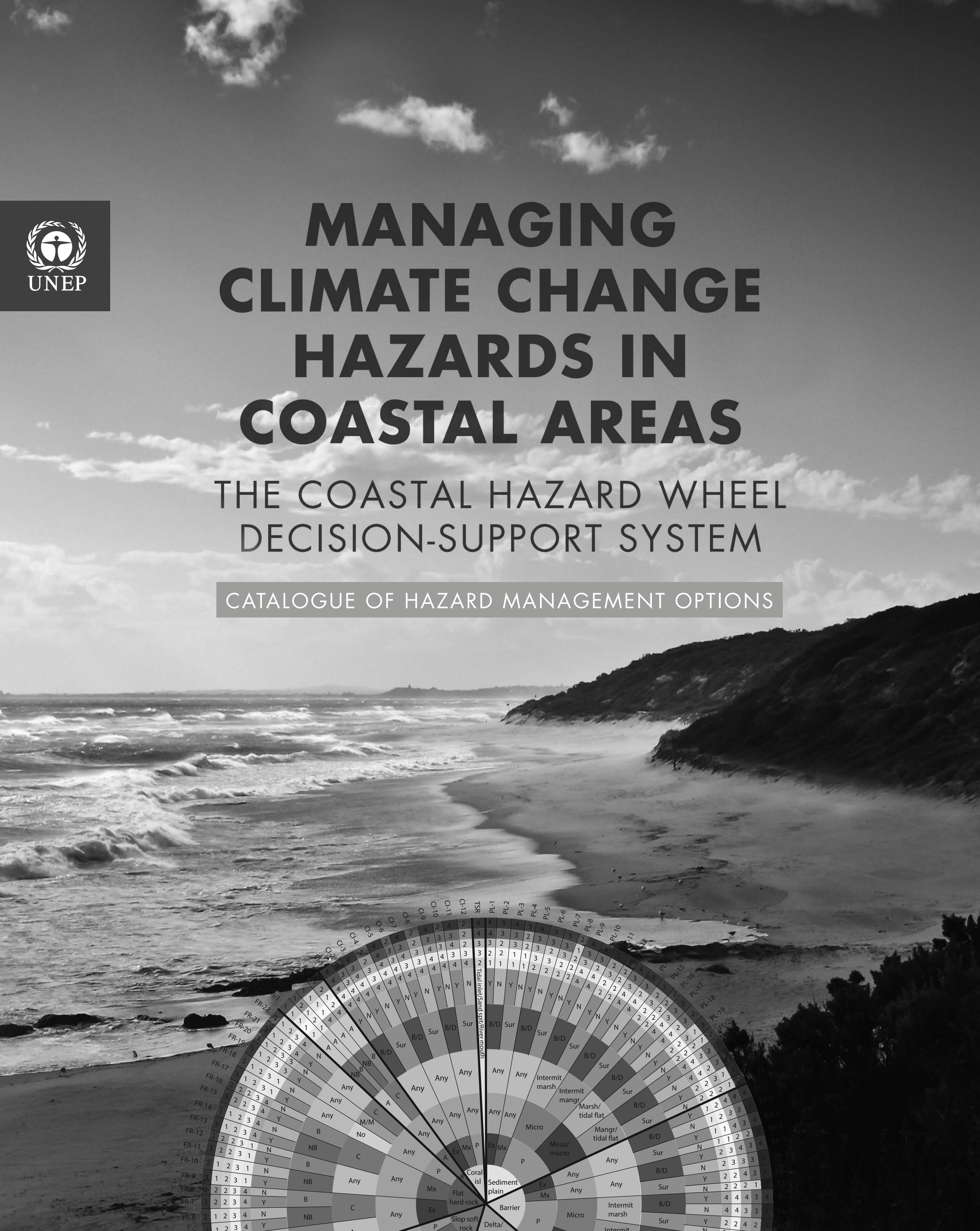

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PL/BA/DE-1	x	x	x	x		
PL/BA/DE-2	x	x	x	x		
PL/BA/DE-3	x	x	x	x		
PL/BA/DE-4	x	x	x	x		
PL/BA/DE-5	x	x	x	x		
PL/BA/DE-6	x	x	x	x		
PL/BA/DE-7	x	x	x	x		
PL/BA/DE-8	x	x	x	x		
PL/BA/DE-9	x		x	x		x
PL/BA/DE-10	x		x	x		x
PL/BA/DE-11	x		x	x		x
PL/BA/DE-12	x		x	x		x
PL/BA/DE-13	x		x	x		x
PL/BA/DE-14	x		x	x		x
PL/BA/DE-15	x		x	x		x
PL/BA/DE-16	x		x	x		x
PL/BA/DE-17	x		x	x		x
PL/BA/DE-18	x		x	x		x
PL/BA/DE-19	x		x	x		x
PL/BA/DE-20	x		x	x		x
PL/BA/DE-21	x		x	x		x
PL/BA/DE-22	x		x	x		x
PL/BA/DE-23	x		x	x		x
PL/BA/DE-24	x		x	x		x
SR-1	x		x			
SR-2	x		x			
SR-3	x		x			
SR-4	x		x			
SR-5	x		x			
SR-6	x		x			
SR-7	x		x			
SR-8	x		x			
SR-9	x		x			
SR-10	x		x			
SR-11	x		x			
SR-12	x		x			
SR-13	x		x			
SR-14	x		x			
SR-15	x		x			
SR-16	x		x			
SR-17	x		x			
SR-18	x		x			
SR-19	x		x			
SR-20	x		x			
FR-1	x		x			
FR-2	x		x			
FR-3	x		x			
FR-4	x		x			
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FR-6	x		x			
FR-7	x		x			
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FR-9	x		x			
FR-10	x		x			
FR-11	x		x			
FR-12	x		x			
FR-13	x		x			
FR-14	x		x			
FR-15	x		x			
FR-16	x		x			
FR-17	x		x			
FR-18	x		x			
FR-19	x		x			x
FR-20	x		x			x
FR-21	x		x			
FR-22	x		x			
R-1	x		x			
R-2	x		x			
R-3	x		x			
R-4	x		x			
CI-1	x		x		x	
CI-2	x		x		x	
CI-3	x		x		x	
CI-4	x		x		x	
CI-5	x		x		x	
CI-6	x		x		x	
CI-7	x		x		x	
CI-8	x		x		x	
CI-9	x		x		x	x
CI-10	x		x		x	x
CI-11	x		x		x	x
CI-12	x		x		x	x
TSR	x		x	x		x

Gradual inundation

Management options (Catalogue section no)	1 Beach nourishment	4 Coastal setbacks	5 Coastal zoning	6 Dikes	9 Floating agricultural system	11 Flood proofing	14 Fluvial sediment management	15 Groundwater management	18 Land claim	19 Managed realignment	22 Storm surge barriers & closure dams	24 Wetland restoration
PL/BA/DE-1	x	x	x	x		x	x	x	x	x		
PL/BA/DE-2	x	x	x	x		x	x	x	x	x		
PL/BA/DE-3	x	x	x	x		x	x	x	x	x		
PL/BA/DE-4	x	x	x	x		x	x	x	x	x		
PL/BA/DE-5	x	x	x	x		x	x	x	x	x		
PL/BA/DE-6	x	x	x	x		x	x	x	x	x		
PL/BA/DE-7	x	x	x	x		x	x	x	x	x		
PL/BA/DE-8	x	x	x	x		x	x	x	x	x		
PL/BA/DE-9		x	x	x	x	x	x	x	x	x		x
PL/BA/DE-10		x	x	x	x	x	x	x	x	x		x
PL/BA/DE-11		x	x	x	x	x	x	x	x	x		x
PL/BA/DE-12		x	x	x	x	x	x	x	x	x		x
PL/BA/DE-13		x	x	x	x	x	x	x	x	x		x
PL/BA/DE-14		x	x	x	x	x	x	x	x	x		x
PL/BA/DE-15		x	x	x	x	x	x	x	x	x		x
PL/BA/DE-16		x	x	x	x	x	x	x	x	x		x
PL/BA/DE-17		x	x	x	x	x	x	x	x	x		x
PL/BA/DE-18		x	x	x	x	x	x	x	x	x		x
PL/BA/DE-19		x	x	x	x	x	x	x	x	x		x
PL/BA/DE-20		x	x	x	x	x	x	x	x	x		x
PL/BA/DE-21		x	x	x	x	x	x	x	x	x		x
PL/BA/DE-22		x	x	x	x	x	x	x	x	x		x
PL/BA/DE-23		x	x	x	x	x	x	x	x	x		x
PL/BA/DE-24		x	x	x	x	x	x	x	x	x		x
SR-1	x		x									
SR-2	x		x									
SR-3	x		x									
SR-4	x		x									
SR-5	x		x									
SR-6	x		x									
SR-7	x		x									
SR-8	x		x									
SR-9	x		x									
SR-10	x		x									
SR-11	x		x									
SR-12	x		x									
SR-13	x		x									
SR-14	x		x									
SR-15	x		x									
SR-16	x		x									
SR-17			x									
SR-18			x									
SR-19			x									
SR-20			x									
FR-1		x	x	x		x				x		
FR-2		x	x	x		x				x		
FR-3	x	x	x	x		x				x		
FR-4	x	x	x	x		x				x		
FR-5		x	x	x		x				x		
FR-6		x	x	x		x				x		
FR-7	x	x	x	x		x				x		
FR-8	x	x	x	x		x				x		
FR-9		x	x	x		x				x		
FR-10		x	x	x		x				x		
FR-11	x	x	x	x		x				x		
FR-12	x	x	x	x		x				x		
FR-13		x	x	x		x				x		
FR-14		x	x	x		x				x		
FR-15	x	x	x	x		x				x		
FR-16	x	x	x	x		x				x		
FR-17		x	x	x		x				x		
FR-18		x	x	x		x				x		
FR-19		x	x	x		x				x		x
FR-20		x	x	x		x				x		x
FR-21		x	x	x		x				x		
FR-22		x	x	x		x				x		
R-1			x									
R-2	x		x									
R-3			x									
R-4	x		x									
CI-1	x	x	x	x		x				x		
CI-2	x	x	x	x		x				x		
CI-3	x	x	x	x		x				x		
CI-4	x	x	x	x		x				x		
CI-5	x	x	x	x		x				x		
CI-6	x	x	x	x		x				x		
CI-7	x	x	x	x		x				x		
CI-8	x	x	x	x		x				x		
CI-9		x	x	x		x				x		x
CI-10		x	x	x		x				x		x
CI-11		x	x	x		x				x		x
CI-12		x	x	x		x				x		x
TSR	x	x	x	x	x	x	x			x	x	x

Salt water intrusion

Management options (Catalogue section no)	5 Coastal zoning	6 Dikes	7 Dune construction/rehabilitation	9 Floating agricultural system	14 Fluvial sediment management	15 Groundwater management	22 Storm surge barriers & closure dams	24 Wetland restoration
PL/BA/DE-1	x	x	x		x	x		
PL/BA/DE-2	x	x	x		x	x		
PL/BA/DE-3	x	x	x		x	x		
PL/BA/DE-4	x	x	x		x	x		
PL/BA/DE-5	x	x	x		x	x		
PL/BA/DE-6	x	x	x		x	x		
PL/BA/DE-7	x	x	x		x	x		
PL/BA/DE-8	x	x	x		x	x		
PL/BA/DE-9	x	x		x	x	x		x
PL/BA/DE-10	x	x		x	x	x		x
PL/BA/DE-11	x	x		x	x	x		x
PL/BA/DE-12	x	x		x	x	x		x
PL/BA/DE-13	x	x		x	x	x		x
PL/BA/DE-14	x	x		x	x	x		x
PL/BA/DE-15	x	x		x	x	x		x
PL/BA/DE-16	x	x		x	x	x		x
PL/BA/DE-17	x	x		x	x	x		x
PL/BA/DE-18	x	x		x	x	x		x
PL/BA/DE-19	x	x		x	x	x		x
PL/BA/DE-20	x	x		x	x	x		x
PL/BA/DE-21	x	x		x	x	x		x
PL/BA/DE-22	x	x		x	x	x		x
PL/BA/DE-23	x	x		x	x	x		x
PL/BA/DE-24	x	x		x	x	x		x
SR-1	x					x		
SR-2	x					x		
SR-3	x					x		
SR-4	x					x		
SR-5	x					x		
SR-6	x					x		
SR-7	x					x		
SR-8	x					x		
SR-9	x					x		
SR-10	x					x		
SR-11	x					x		
SR-12	x					x		
SR-13	x					x		
SR-14	x					x		
SR-15	x					x		
SR-16	x					x		
SR-17	x					x		
SR-18	x					x		
SR-19	x					x		
SR-20	x					x		
FR-1	x	x				x		
FR-2	x	x				x		
FR-3	x	x				x		
FR-4	x	x				x		
FR-5	x	x				x		
FR-6	x	x				x		
FR-7	x	x				x		
FR-8	x	x				x		
FR-9	x	x				x		
FR-10	x	x				x		
FR-11	x	x				x		
FR-12	x	x				x		
FR-13	x	x				x		
FR-14	x	x				x		
FR-15	x	x				x		
FR-16	x	x				x		
FR-17	x	x				x		
FR-18	x	x				x		
FR-19	x	x				x		x
FR-20	x	x				x		x
FR-21	x	x				x		
FR-22	x	x				x		
R-1	x					x		
R-2	x					x		
R-3	x					x		
R-4	x					x		
CI-1	x	x				x		
CI-2	x	x				x		
CI-3	x	x				x		
CI-4	x	x				x		
CI-5	x	x				x		
CI-6	x	x				x		
CI-7	x	x				x		
CI-8	x	x				x		
CI-9	x	x				x		x
CI-10	x	x				x		x
CI-11	x	x				x		x
CI-12	x	x				x		x
TSR	x	x		x		x	x	

Erosion

Management options (Catalogue section no)	1 Beach nourishment	2 Breakwaters	3 Cliff stabilization	4 Coastal setbacks	5 Coastal zoning	7 Dune construction/rehabilitation	14 Fluvial sediment management	15 Groundwater management	16 Groynes	17 Jetties	18 Land claim	19 Managed realignment	20 Revetments	21 Sea Walls	24 Wetland restoration
PL/BA/DE-1	x	x		x	x	x	x		x		x	x	x	x	
PL/BA/DE-2	x	x		x	x	x	x		x		x	x	x	x	
PL/BA/DE-3	x	x		x	x	x	x		x		x	x	x	x	
PL/BA/DE-4	x	x		x	x	x	x		x		x	x	x	x	
PL/BA/DE-5	x	x		x	x	x	x		x		x	x	x	x	
PL/BA/DE-6	x	x		x	x	x	x		x		x	x	x	x	
PL/BA/DE-7	x	x		x	x	x	x		x		x	x	x	x	
PL/BA/DE-8	x	x		x	x	x	x		x		x	x	x	x	
PL/BA/DE-9				x	x		x				x	x			x
PL/BA/DE-10				x	x		x				x	x			x
PL/BA/DE-11				x	x		x				x	x			x
PL/BA/DE-12				x	x		x				x	x			x
PL/BA/DE-13				x	x		x				x	x			x
PL/BA/DE-14				x	x		x				x	x			x
PL/BA/DE-15				x	x		x				x	x			x
PL/BA/DE-16				x	x		x				x	x			x
PL/BA/DE-17				x	x		x				x	x			x
PL/BA/DE-18				x	x		x				x	x			x
PL/BA/DE-19				x	x		x				x	x			x
PL/BA/DE-20				x	x		x				x	x			x
PL/BA/DE-21				x	x		x				x	x			x
PL/BA/DE-22				x	x		x				x	x			x
PL/BA/DE-23				x	x		x				x	x			x
PL/BA/DE-24				x	x		x				x	x			x
SR-1	x	x	x	x	x		x	x	x			x	x	x	
SR-2	x	x	x	x	x		x	x	x			x	x	x	
SR-3	x	x	x	x	x		x	x	x			x	x	x	
SR-4	x	x	x	x	x		x	x	x			x	x	x	
SR-5	x	x	x	x	x		x	x	x			x	x	x	
SR-6	x	x	x	x	x		x	x	x			x	x	x	
SR-7	x	x	x	x	x		x	x	x			x	x	x	
SR-8	x	x	x	x	x		x	x	x			x	x	x	
SR-9	x	x	x	x	x		x	x	x			x	x	x	
SR-10	x	x	x	x	x		x	x	x			x	x	x	
SR-11	x	x	x	x	x		x	x	x			x	x	x	
SR-12	x	x	x	x	x		x	x	x			x	x	x	
SR-13	x	x	x	x	x		x	x	x			x	x	x	
SR-14	x	x	x	x	x		x	x	x			x	x	x	
SR-15	x	x	x	x	x		x	x	x			x	x	x	
SR-16	x	x	x	x	x		x	x	x			x	x	x	
SR-17			x	x	x		x	x				x			
SR-18			x	x	x		x	x				x			
SR-19			x	x	x		x	x				x			
SR-20			x	x	x		x	x				x			
FR-1					x										
FR-2					x										
FR-3	x	x			x		x		x						
FR-4	x	x			x		x		x						
FR-5					x										
FR-6					x										
FR-7	x	x			x		x		x						
FR-8	x	x			x		x		x						
FR-9					x										
FR-10					x										
FR-11	x	x			x		x		x						
FR-12	x	x			x		x		x						
FR-13					x										
FR-14					x										
FR-15	x	x			x		x		x						
FR-16	x	x			x		x		x						
FR-17					x										
FR-18					x										
FR-19					x		x								x
FR-20					x		x								x
FR-21					x										
FR-22					x										
R-1					x										
R-2	x	x			x		x		x						
R-3					x										
R-4	x	x			x		x		x						
CI-1	x	x		x	x				x			x	x	x	
CI-2	x	x		x	x				x			x	x	x	
CI-3	x	x		x	x				x			x	x	x	
CI-4	x	x		x	x				x			x	x	x	
CI-5	x	x		x	x				x			x	x	x	
CI-6	x	x		x	x				x			x	x	x	
CI-7	x	x		x	x				x			x	x	x	
CI-8	x	x		x	x				x			x	x	x	
CI-9				x	x							x	x	x	x
CI-10				x	x							x	x	x	x
CI-11				x	x							x	x	x	x
CI-12				x	x							x	x	x	x
TSR	x	x		x	x		x		x	x		x	x	x	x

Flooding

Management options (Catalogue section no)	4 Coastal setbacks	5 Coastal zoning	6 Dikes	7 Dune construction/rehabilitation	9 Floating agricultural system	10 Flood mapping	11 Flood proofing	12 Flood shelter	13 Flood warning systems	14 Fluvial sediment management	19 Managed realignment	22 Storm surge barriers & closure dams	23 Tsunami warning system	24 Wetland restoration
PL/BA/DE-1	x	x	x	x		x	x	x	x	x	x		x	
PL/BA/DE-2	x	x	x	x		x	x		x	x	x		x	
PL/BA/DE-3	x	x	x	x		x	x	x	x	x	x		x	
PL/BA/DE-4	x	x	x	x		x	x		x	x	x		x	
PL/BA/DE-5	x	x	x	x		x	x	x	x	x	x		x	
PL/BA/DE-6	x	x	x	x		x	x		x	x	x		x	
PL/BA/DE-7	x	x	x	x		x	x	x	x	x	x		x	
PL/BA/DE-8	x	x	x	x		x	x		x	x	x		x	
PL/BA/DE-9	x	x	x		x	x	x	x	x	x	x		x	x
PL/BA/DE-10	x	x	x		x	x	x		x	x	x		x	x
PL/BA/DE-11	x	x	x		x	x	x	x	x	x	x		x	x
PL/BA/DE-12	x	x	x		x	x	x		x	x	x		x	x
PL/BA/DE-13	x	x	x		x	x	x	x	x	x	x		x	x
PL/BA/DE-14	x	x	x		x	x	x		x	x	x		x	x
PL/BA/DE-15	x	x	x		x	x	x	x	x	x	x		x	x
PL/BA/DE-16	x	x	x		x	x	x		x	x	x		x	x
PL/BA/DE-17	x	x	x		x	x	x	x	x	x	x		x	x
PL/BA/DE-18	x	x	x		x	x	x		x	x	x		x	x
PL/BA/DE-19	x	x	x		x	x	x	x	x	x	x		x	x
PL/BA/DE-20	x	x	x		x	x	x		x	x	x		x	x
PL/BA/DE-21	x	x	x		x	x	x	x	x	x	x		x	x
PL/BA/DE-22	x	x	x		x	x	x		x	x	x		x	x
PL/BA/DE-23	x	x	x		x	x	x	x	x	x	x		x	x
PL/BA/DE-24	x	x	x		x	x	x		x	x	x		x	x
SR-1		x											x	
SR-2		x											x	
SR-3		x											x	
SR-4		x											x	
SR-5		x											x	
SR-6		x											x	
SR-7		x											x	
SR-8		x											x	
SR-9		x											x	
SR-10		x											x	
SR-11		x											x	
SR-12		x											x	
SR-13		x											x	
SR-14		x											x	
SR-15		x											x	
SR-16		x											x	
SR-17		x											x	
SR-18		x											x	
SR-19		x											x	
SR-20		x											x	
FR-1	x	x	x			x	x	x	x		x		x	
FR-2	x	x	x			x	x		x		x		x	
FR-3	x	x	x			x	x	x	x		x		x	
FR-4	x	x	x			x	x		x		x		x	
FR-5	x	x	x			x	x	x	x		x		x	
FR-6	x	x	x			x	x		x		x		x	
FR-7	x	x	x			x	x	x	x		x		x	
FR-8	x	x	x			x	x		x		x		x	
FR-9	x	x	x			x	x	x	x		x		x	
FR-10	x	x	x			x	x		x		x		x	
FR-11	x	x	x			x	x	x	x		x		x	
FR-12	x	x	x			x	x		x		x		x	
FR-13	x	x	x			x	x	x	x		x		x	
FR-14	x	x	x			x	x		x		x		x	
FR-15	x	x	x			x	x	x	x		x		x	
FR-16	x	x	x			x	x		x		x		x	
FR-17	x	x	x			x	x	x	x		x		x	
FR-18	x	x	x			x	x		x		x		x	
FR-19	x	x	x			x	x	x	x		x		x	x
FR-20	x	x	x			x	x		x		x		x	x
FR-21	x	x	x			x	x	x	x		x		x	
FR-22	x	x	x			x	x		x		x		x	
R-1		x											x	
R-2		x											x	
R-3		x											x	
R-4		x											x	
CI-1	x	x	x			x	x	x	x		x		x	
CI-2	x	x	x			x	x		x		x		x	
CI-3	x	x	x			x	x	x	x		x		x	
CI-4	x	x	x			x	x		x		x		x	
CI-5	x	x	x			x	x	x	x		x		x	
CI-6	x	x	x			x	x		x		x		x	
CI-7	x	x	x			x	x	x	x		x		x	
CI-8	x	x	x			x	x		x		x		x	
CI-9	x	x	x			x	x	x	x		x		x	x
CI-10	x	x	x			x	x		x		x		x	x
CI-11	x	x	x			x	x	x	x		x		x	x
CI-12	x	x	x			x	x		x		x		x	x
TSR	x	x	x		x	x	x	x	x		x	x	x	x

Matrix of hazard management options for the different coastal environments (modified from Rosendahl Appelquist and Halsnæs 2015).

1 BEACH NOURISHMENT

DEFINITION

Beach nourishment is a management technology primarily used in response to shoreline erosion, although flood reduction benefits may also occur. It is a soft engineering approach to coastal protection which involves the artificial addition of sediment of suitable quality to a beach area that has a sediment deficit. Nourishment can also be referred to as beach recharge, beach fill, replenishment, re-nourishment and beach feeding.

DESCRIPTION

Addition of beach material rebuilds and maintains the beach at a width which helps provide storm protection. This approach is mainly used on sandy beaches but the term can also refer to nourishment with shingle or even cobbles. The aim, however, should be to ensure that nourishment material is compatible with the existing natural (or native) beach material (Reeve et al. 2004). Nourishment is often used in conjunction with artificial dune creation (see Section 7).

The benefit of beach nourishment comes from wave energy dissipation; when waves run up a beach and break, they lose energy. Different beach profile shapes and gradients interact with waves to differing extent. The cross-sectional shape of a beach therefore affects its ability to attenuate wave energy. A 'dissipative' beach – one that dissipates considerable wave energy – is wide and shallow while a 'reflective' beach – one that reflects incoming wave energy seawards – is steep and narrow and achieves little wave energy attenuation. The logic behind beach nourishment is to turn an eroding, reflective beach into a wider, dissipative beach, which increases wave energy attenuation (French 2001).

As well as helping to dissipate incoming wave energy, beach nourishment addresses a sediment deficit: the underlying cause of erosion. This is achieved by introducing large quantities of beach material to the coastal sediment budget from an external sediment source, also referred to as a borrow site. The term 'sediment balance' is used to describe the careful balance which exists between incoming and outgoing sediment. Much like a bank account, when more material is added than removed, a build-up occurs and the shore builds seaward; conversely, when more material is removed than deposited, erosion occurs (Morton 2004). Nourishment addresses a sediment deficit – the cause of erosion –
by introducing large quantities of beach material to the nearshore system. In turn, this can cause the shore to build seaward.

It is important to note that beach nourishment does not *halt* erosion, but simply provides sediment from an external source, upon which erosional forces will continue to act. In this sense, beach nourishment provides a sacrificial, rather than a fixed barrier against coastal erosion.

Continuing erosional forces will likely return the beach to a state where re-nourishment is required. Fig 1.1. shows the beach volume at a nourished beach in the UK, over time. It can be seen that over time the volume of the beach declines as a result of natural erosion. When the beach reduces to a critical volume, re-nourishment should be undertaken to avoid damage to coastal infrastructure.

“As well as helping to dissipate incoming wave energy, beach nourishment addresses a sediment deficit: the underlying cause of erosion.”

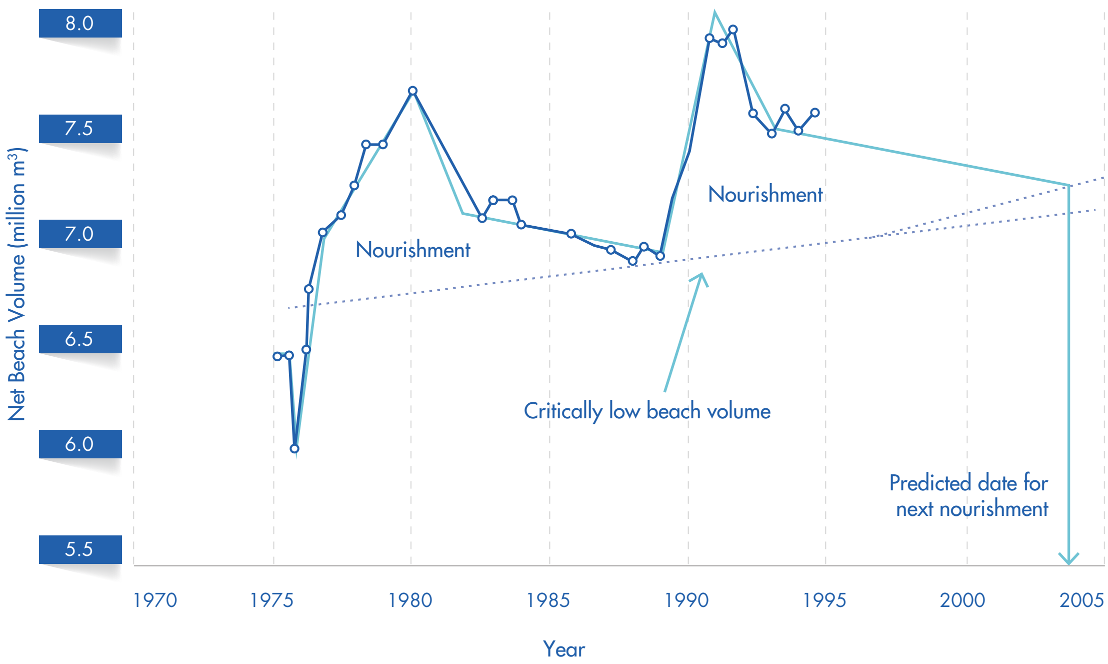

Fig. 1.1. *Data illustrating beach volume at Bournemouth Beach, UK. The solid lines represent actual and predicted beach volume (in millions of cubic metres) and the dashed line represents the beach volume at which re-nourishment will be required (Source: Adapted from Laessing 2005).*

Several methods of nourishment can be utilised, including placement by dredge, trucks or conveyor belts. Sand can be placed to create an extension of the beach width or as an underwater deposit which will be gradually moved onshore under the normal action of waves – this follows current practice in the Netherlands (VanKoningsveld et al. 2008). Placement as an underwater deposit also serves to encourage the dissipation of wave energy, therefore reducing its impact at the shore (Dean 2002).

Supply of nourishment material by offshore dredging is often favoured because it allows for large quantities of material to be obtained from an area where its removal and onshore transport is reasonably non-disruptive to shoreline communities (Dean 2002). During dredging, sediment is removed from the seabed along with significant quantities of water. The mixture is referred to as a 'slurry' and its liquid characteristics allow for it to be transferred ashore by floating or submerged pipelines or by the 'rainbow method' (see Fig 1.2.).

Fig. 1.2. *Beach nourishment with Trailing Suction Hopper Dredger and Rainbowing method for transferring nourishment material ashore. Slurry is discharged via a jet at the bow of the ship once it has been sailed as close to the shore as possible (Photo: Rohde Nielsen).*

An alternative to offshore dredging is the removal of beach-grade sediment from land-based sources. Sediment is then transported to the target site by truck haul. Only a small percentage of nourishments are carried out in this way and the approach is more suited to smaller-scale operations because of the more labour-intensive way of transportation (Dean 2002).

Once sediment has been transported to the target beach, it must be deposited appropriately. If utilising offshore dredge sites, sediment *can* be dumped as an underwater deposit. However, nourishment more commonly brings sediment ashore. Once ashore, sediment may be reworked to form a flat beach. If desired, artificial dunes may also be created on the landward portion of the beach (see Section 7), through the use of bulldozers or other means.

ADVANTAGES

If performed well, the benefits of nourishment are many and varied. Most importantly, beach nourishment reduces the detrimental impacts of coastal erosion by providing additional sediment which satisfies erosional forces. Shoreline erosion will continue to occur, but the widened and deepened beach will provide a buffer to protect coastal infrastructure and other assets from the effects of coastal erosion and storm damage.

Beach nourishment is a flexible coastal management solution, in that it is reversible. This is highly beneficial as it allows the widest range of coastal management options to be passed to the next generation.

Alongshore redistribution of the added material will occur through a process known as longshore drift, under the action of waves, tides and wind. Longshore drift is caused by waves approaching the shore obliquely, carrying beach sediments with them. When waves return to the sea, however, the movement is always perpendicular to the shore. This initiates a gradual alongshore movement of sediment as shown in Fig 1.3. As a result of sediment redistribution by longshore drift, beach nourishment is likely to positively impact adjacent areas which were not directly nourished. This may provide wider benefits including reduced beach and cliff erosion for the entire coastal cell[1].

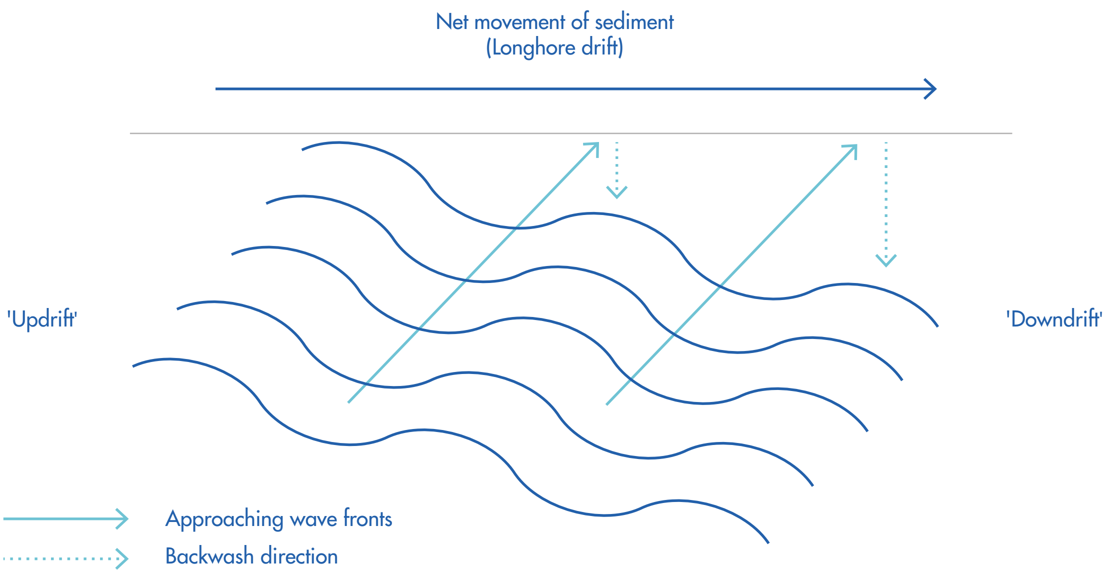

Fig. 1.3. *Schematic illustration of longshore drift. Incoming waves approach from an angle causing sediment to gradually move alongshore in a zig-zagging manner. The terms 'updrift' and 'downdrift' refer to locations either up- or down-stream of this movement of sediment (Source: Redrawn by authors).*

Beach nourishment can complement hard protection measures such as sea walls (see Section 21), which may continue to be used as a last line of defence. The existence of a wide, sandy beach in front of such structures greatly reduces the wave energy reaching them, thus providing additional protection.

Addition of sediment which closely resembles the native beach material will help retain the natural landscape of the beach, while providing an increased capacity for coping with coastal erosion and flooding. The natural appearance of nourishment projects also means these schemes are aesthetically pleasing.

Coastal tourism depends heavily on 'sun, sea and sand'. As a result, beach nourishment has the potential to promote recreation and tourism through beach widening (Nicholls et al. 2007). This may serve to enhance pre-existing tourism or may serve to attract tourists to the area, thus encouraging development.

It is also possible to provide ecological benefits through beach nourishment. Schemes have been shown to provide enhanced nesting sites for sea turtles when designed with the requirements of these creatures in mind (Dean 2002). This in turn, may serve to promote 'eco-tourism', with consequent development benefits.

1 A coastal cell is a stretch of coastline within which sediment movement is self-contained. Sediment within one coastal cell is not transported or shared with adjacent cells.

Today, nourishment is very popular in developed countries but has also found application in developing nations, such as Brazil (Vera-Cruz 1972; Elfrink et al. 2008), Nigeria (Sunday & John 2006), Korea (Kim et al. 2008), Ghana (Nairn et al. 1998) and Malaysia (Brøgger & Jakobsen 2008). The technology and methods involved are well established and many contractors experienced in beach nourishment are available worldwide to undertake such projects.

DISADVANTAGES

As already stated, nourishment is not a permanent solution to shoreline erosion. Periodic re-nourishments, or 'top-ups', will be needed to maintain a scheme's effectiveness. This will require regular re-investment but can be viewed as a maintenance cost, such as those associated with hard engineered structures.

As with any type of shore protection works, reducing the risk of coastal flooding and erosion will result in an increased sense of security. To some extent, this is desirable. However, even in the presence of protective measures, the coastal zone remains susceptible to extreme coastal flooding and erosion events, and will remain exposed to natural disasters with long return periods. If not carefully regulated, protective measures may promote unwise development in these risky areas as a result of the increased sense of security.

Depositing sediments onto beaches can generate a number of negative environmental effects, including direct burial of animals and organisms residing on the beach, lethal or damaging doses of water turbidity – cloudiness caused by agitation of sediments – and altered sediment compositions which may affect the types of animals which inhabit the area (Dean 2002). As a result, projects must be designed with an understanding of, and concern for, the potential adverse consequences for the environment. Special consideration should be given to the impacts upon important or rare species resident in the coastal zone.

Placement of fill material on the beach can disrupt beach and ocean habitats, such as bird and sea turtle nesting, if schemes are not designed appropriately. This is especially the case if sand grain size/composition does not match the native beach materials (IOC 2009).

The application of beach nourishment is expected to grow in the future and as a result, there may be higher demand for high quality sediment. Limited availability of large contractors, coupled with an increase in demand for nourishment projects have already caused cost increases for nourishment projects in the Netherlands where it is widely applied (Hillen et al. 2010). This upward trend is likely to be observed elsewhere in future.

COSTS AND FINANCIAL REQUIREMENTS

Linham et al. (2010) extensively researched the unit costs of beach nourishment. Costs were shown to typically vary from US\$3-15/m^3 (at 2009 price levels) where dredge sites are available locally (Linham et al. 2010). The most important determinant of nourishment costs appears to be the transport distance for the beach material.

Most of this data was collected in developed countries because this is where the vast bulk of nourishment occurs today. In developing countries, costs would, in general, be expected to be similar or possibly higher, due to their less developed coastal engineering industry.

Wide variation in costs is apparent between and within countries. This is a result of the numerous factors detailed in Box 1.1.

- Project size and resulting economies of scale
- Distance between dredge and target sites
- Number of journeys required between dredge site and nourishment area
- Seabed shape at the borrow site – determinant of the dredger size which can be used and therefore affects the number of journeys that must be made
- Recharge material – coarser material causes greater equipment wear and tear which is likely to be passed on to customers by contractors
- Estimated material losses
- Availability (and size) of dredgers
- Degree of site exposure – determines type of dredger to be used and may also shorten working hours when a site is subjected to energetic winds and waves
- Tidal range – large tidal ranges provide time constraints on when dredgers are able approach close enough to shore to deposit material. This is turn can affect the time required to complete a project
- Third party requirements

Box 1.1. *Factors affecting unit costs of nourishment (from CIRIA 1996; Linham et al. 2010).*

To be able to roughly estimate the cost of beach nourishment for a particular coastline it is necessary to have more detailed information on the cost components that make up the general price levels. Therefore data has been collected on the approximate cost of the different project components from the two dredging companies Boskalis and Van Oord (Rosendahl Appelquist and Halsnæs 2015). Table 1.1. provides a realistic example of the magnitude of the different cost components in 2012 for projects carried out by the dredging company Boskalis. The table includes two different cost examples where the beach nourishment is carried out by a small and large hopper dredger, and realistic numbers for mobilization costs, operation costs, sailing distance and sailing speed have been listed and used to calculate realistic examples of nourishment costs. The examples of the total cost in $\$/m^3$ sand are shown without including the mobilisation cost, as the project size has a major influence on the mobilization cost/m^3 sand. It should be noted that these numbers only provides an indicative example of the magnitude of cost and the costs may increase by 10-50 % for areas with high business risks such as developing countries. Also, mobilisation costs may be significantly higher for developing countries.

Cost of beach nourishment (Boskalis example)	
Beach nourishment with small hopper dredger - 1,000 m^3 vessel	
Mobilisation cost (assuming sailing distance of 1000 Nautical miles)	130,000 USD
Operation cost	130,000 USD/week
Assumed sailing distance between source and deposition site	15 km
Assumed vessel speed	10 knots
Daily sand transport with 4 hour cycles (both ways)	6,000 m^3/day
Weekly sand transport with 7 days operation	42,000 m^3/week
Approximate cost per m^3 sand (without mobilisation costs)	3 USD/m^3
Beach nourishment with large hopper dredger - 10,000 m^3 vessel	
Mobilisation cost (assuming sailing distance of 1000 Nautical miles)	900,000 USD
Operation cost	900,000 USD/week
Assumed sailing distance between source and deposition site	15 km
Assumed vessel speed	10 knots
Daily sand transport with 4 hour cycles (both ways)	60,000 m^3/day
Weekly sand transport with 7 days operation	420,000 m^3/week
Approximate cost per m^3 sand (without mobilisation costs)	2 USD/m^3

Table 1.1. *Realistic example of cost components for beach nourishment by Boskalis in 2012 prices (Rosendahl Appelquist and Halsnæs 2015; Paulsen 2012).*

Table 1.2. displays the magnitude of costs for beach nourishment in 2012 for projects carried out by the dredging company Van Oord. Here, different cost examples are provided depending on the geographical conditions and project size. It should be noted, however, that these cost numbers can vary significantly depending on local conditions. As can be seen from Table 1.1. and 1.2., the cost levels for the two examples are of the same magnitude.

Cost for beach nourishment (Van Oord example)	
Cost in Europe based on sailing distance of ca. 15 km	6-8 USD/m^3
Cost for increasing sailing distance up to extra 25 km	0.3 USD/m^3/km
For large projects in more remote locations where dredgers are not nearby	9-10 USD/m^3
For small projects in more remote locations where dredgers are not nearby	40 USD/m^3

Table 1.2. *Realistic example for cost of beach nourishment by Van Oord in 2012 prices (Rosendahl Appelquist and Halsnæs 2015; Lindo 2012).*

The cost of beach nourishment for a particular coastal site also strongly depends on the amounts of sand needed and the frequency of nourishments. This depends on several factors including beach profile, wave exposure and sediment balance and the appropriate material needs should be estimated on a case-by-case basis. In order to provide a rough indication of the magnitude of sand needed for different coastal environments, however, one can generally look at coastlines with different wave exposures and sediment deficits (Rosendahl Appelquist and Halsnæs 2015). For an *exposed* coastline, the magnitude of sand needed for an indicative example could be 100-200 m^3/meter beach, with a possible extended span of 50-1000 m^3/meter beach. If the sediment deficit is moderate, the nourishment could be carried out every second year, while it could be carried out annually in locations with a large sediment deficit.
For a *moderately exposed* coastline, the magnitude of sand needed for an indicative example could be 20-50m^3/meter beach, with nourishments carried out every third year in cases with moderate sediment deficits and every second year in cases with a large deficit (Paulsen 2012). It should be noted, however, that these amounts are purely indicative but may provide a general picture of the magnitude of material needs.

INSTITUTIONAL AND ORGANIZATIONAL REQUIREMENTS

Large-scale beach nourishments will typically require extensive engineering studies and specialised knowledge and equipment. This may include dredgers and pipelines that need to be hired from a specialised contractor. However, it is also possible to conduct nourishment on a smaller scale. Beach-grade sediment can be transferred from land-based sources or from depositional to erosional areas by truck haul. Because of the smaller-scale nature of this approach and because readily available equipment could be used, nourishment by truck haul may be more practicable at a local level.

Once nourishment has been carried out, ongoing beach monitoring is needed in order to evaluate nourishment success and to determine when re-nourishment will be required. Given appropriate training and technology, monitoring should be possible at a local/community level. Nourishment schemes should be evaluated as a whole, however, which may require the participation of multiple communities if nourishment is undertaken on a large scale.

BARRIERS TO IMPLEMENTATION

Beach nourishment requires a suitable source of sediment to be identified in close enough proximity to the nourishment site. This ensures that costs are kept at a reasonable level. Sediment availability is highly variable around the globe and suitable sources may not be easily found. The increasing popularity of beach nourishment worldwide may therefore cause sediment availability problems as demand increases. This problem is already being experienced in small island settings where sand is frequently carried long distances for nourishment projects.

Beach nourishment requires highly specialised equipment and knowledge including dredgers and pipelines that will need to be hired from a specialised contractor. Hillen et al. (2010) have noted the limited number of large contractors available and also highlighted the associated cost increase due to high demand. Local site characteristics will also influence the type and size of dredger which can be used – this can further limit the availability of dredgers.

Public awareness of how beach nourishment schemes work can also present a barrier. This is especially the case when using shoreface nourishment or underwater sediment deposition. Using these techniques, the advantages of nourishment may not be immediately noticeable and unless the public are educated on how the scheme works, they may doubt the benefits of nourishment and oppose such projects. The public should also be made aware that nourishment is not a permanent solution and that re-nourishments will be required. If this is not communicated, the public may again believe the scheme has failed and resent further spending on re-nourishment. This will be especially the case if public funding is used to cover nourishment costs.

OPPORTUNITIES FOR IMPLEMENTATION

Beach nourishment can act as a cost-effective disposal option for maintenance dredging of harbours and channels. The use of dredge material also combats the potential lack of suitable sediments offshore. Care must be taken when utilising dredge material however, as harbour dredges can contain high levels of pollutants which must be carefully monitored.

Beach nourishment can also be employed in conjunction with other management technologies and can help to address the drawbacks of these hard technologies, which include beach lowering and downdrift sediment starvation.

If nourishment provides ecological benefits, it can also serve to encourage ecotourism and will provide an income stream for the local economy.

2 BREAKWATERS

DEFINITION

Detached or offshore breakwaters are shore-parallel structures situated just offshore of the surf zone and are designed to intercept and reduce incoming wave energy at the shoreline. This encourages accumulation of sediment in the lee of the structure, leading to widening of the beach. They are generally very solid, durable structures and are considered a hard-engineering protection measure.

DESCRIPTION

Breakwaters are typically and necessarily constructed of durable materials such as rock armour, poured concrete, dolos or tetrapods (Davis Jr and Fitzgerald 2004). Structures are often built using marine equipment e.g. barges and floating cranes (Brampton 2002) often in a series of shorter breakwaters so as to reduce construction costs and protect longer coastal stretches.

Breakwaters are normally built at *exposed* and *moderately exposed* sedimentary coastlines, mainly to address erosion hazards but can also have some secondary effects on flooding hazards as they can protect dune fields, sea walls and dikes from wave attack (Rosendahl Appelquist and Halsnæs 2015). By reducing incoming wave energy, breakwaters provide a sheltered beach area and modify wave refraction/diffraction patterns. This modifies and moderates longshore drift, thus reducing cross shore sediment losses to adjacent sections of shoreline and leading to sediment deposition in the lee-side of the structure. This promotes progradation of the beach, sometimes resulting in salient or tombolo formation (see Fig 2.1 below).

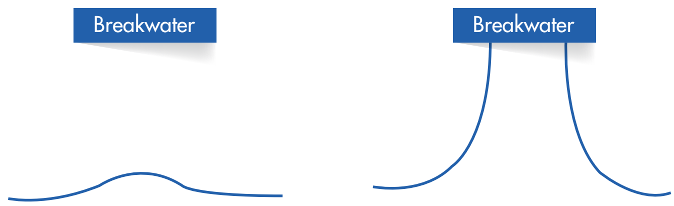

Fig. 2.1. *Detached breakwater construction leading to the creation of a 'salient' (left) or 'tombolo' (right) through beach progradation.*

Generally, breakwaters form a good alternative to groynes and are able to support beach formation without blocking the littoral drift, provided they are designed to avoid tombolo formation. However, the structures must be large and robust to withstand the high wave exposure of deeper water and can suffer damage during storm events (Masselink and Hughes 2003; Davis Jr and Fitzgerald 2004).

Key design parameters include the gap between the breakwaters, their length, their off-shore distance and the size of the construction material (Masselink and Hughes 2003; Paulsen 2013). These factors have a significant bearing on the cost of construction. Furthermore these elements are key to predicting the formation of tombolos and therefore the wider impacts of breakwater construction at the coastline in question and the adjacent areas.

> "As breakwaters are long-lasting structures which have a great impact on the natural coastal environment, it is important that the design process is properly prioritized."

Fig. 2.2. *Breakwater structures in Denmark.*

ADVANTAGES

When designed well, offshore breakwaters provide stable and robust coastal protection by reducing incident wave energy, whilst still allowing the shoreline to interact with natural forces. Breakwaters encourage the formation of stable, crenulate bays between breakwater structures which provides benefits in terms of coastal protection and recreation.

The construction of shorter breakwaters in series allows some wave action at the coast which can be beneficial for recreation as well as allowing water exchange with the open sea which is positive in terms of water quality.

The construction of an offshore breakwater may also serve to establish a new environment, effectively acting as a reef environment (French 1997). This may provide benefits for local ecology, fisheries and recreation.

When constructed, the protective function of breakwaters can be maintained for many years, requiring only basic monitoring and maintenance.

DISADVANTAGES

The disadvantages of breakwaters are primarily related to interference with longshore sediment transport. When poorly considered, these structures are capable of significantly disrupting longshore sediment transport, with the capacity to cause sediment starvation downdrift of the structure. As such, it is extremely important to consider the wider impact of these structures on adjacent coastlines prior to implementation.

Downdrift sediment starvation may be ameliorated at the construction stage through simultaneous addition of sediment to the beach during the construction phase (Brampton 2002). Nevertheless, this is associated with an additional financial cost.

To have their greatest effect, many breakwaters are required to stand proud of the water surface, thus affecting the visual appearance of the coastline and possibly restricting access to the coast by ships and pleasure craft (French 1997). Moreover, the deep holes and circulation currents that can develop between breakwaters can present a hazard to recreational use of the coast (Davis Jr and Fitzgerald 2004).

Finally, significant changes to the sediment balance and wave exposure at the shoreface and foreshore may impact local ecology, affecting the viability of existing communities (French 1997).

COSTS AND FINANCIAL REQUIREMENTS

The cost of breakwaters generally consists of a large construction cost, followed by some varying O&M costs. The cost depends on a range of parameters including type of material, availability of material, labour costs, equipment cost and the related socioeconomic and geographical context. As breakwaters are often constructed from rock amour, data has been collected on the cost components for rock amour structures using this material, if constructed by international dredging companies. It should be noted that the cost numbers may differ if structures are built using local material and contractors.

Table 2.1. provides an overview of the magnitude of the different cost components in 2012 for rock armour structures constructed by the dredging company Boskalis (Rosendahl Appelquist and Halsnæs 2015). The costs are broken down into the cost of rock quarrying and delivery on a large pontoon at the shipment site, long distance transport by pontoon, short distance transport by pontoons at the project site and placement by grab-dredger. The numbers shown are realistic examples of the magnitude of costs for standard projects. The costs are expected to increase by 10-50 % for projects with higher business risks such as projects in developing countries (Paulsen 2012).

Cost of rock armour structures (Boskalis example)	
Rock quarry & delivery on large pontoon at shipment site	
Large rocks bigger than 1 ton	40 USD/ton
Mixed size rocks	25 USD/ton
Long distance transport with large pontoon	
Cost for pontoon	13,000 USD/day
Capacity	10,000 ton
Approximate cost for long distance rock transport	1.3 USD/ton/day
Pontoon speed	5 knots
Shuttle pontoons for short distances to placement site	
Cost for pontoon loading	1.5 USD/ton
Cost for pontoons (with two pontoon shift)	2.5 USD/ton
Cost for tugboat	1.5 USD/ton
Placement ship - grab dredger	
Operation cost	130,000 USD/week
Capacity	100 ton/hour
Approximate weekly capacity	10,000 ton
Approximate cost for placement	13 USD/ton

Table 2.1. *Realistic example of cost components for rock armour structures by Boskalis in 2012 prices (Rosendahl Appelquist and Halsnæs 2015; Paulsen 2012).*

In order to provide data from two independent sources, Table 2.2. shows an example of the different cost components for rock amour structures by the dredging company Van Oord in 2012 (Rosendahl Appelquist and Halsnæs 2015). The table is less detailed than Table 2.1. and shows the cost of purchase and transport of rocks, assuming a transport distance of 50 km and the cost of combined dry and waterborne placing. It should be mentioned that these costs are rough examples and can vary significantly depending on the quality of the rock/quarry, transport conditions, physical conditions at the project site and other business risks. However, it can be seen that the cost levels for the two data sources listed in Table 2.1. and Table 2.2. are relatively similar.

Cost of rock armour structures (Van Oord example)	
Breakwaters/Groynes/Jetties/Revetments	
Purchase and transport of rocks based on transport distance of 50 km	25 USD/ton
Placing (combination of dry and waterborne placing)	40 USD/ton

Table 2.2. *Realistic example of cost components for rock armour structures by Van Oord in 2012 prices (Rosendahl Appelquist and Halsnæs 2015; Lindo 2012).*

Generally, breakwaters in both *exposed* and *moderately exposed* locations make use of larger rocks of the size of 1-3 ton, but smaller rocks of < 1 ton can be used for the breakwater core. Breakwaters are constructed in the form of a trapeze and can vary significantly in size depending particularly on wave exposure. However, it is possible to provide some rough magnitude examples as follows:

An *exposed* breakwater constructed at 4 metres water depth could be 8 metres high and have top and bottom widths of 7 metres and 20 metres respectively. The rock requirement could be approximately 2.1 tons rock/m^3 breakwater, if large rocks are used (Paulsen 2012). A breakwater constructed at a *moderately exposed* coastline at 2 metres water depth could be 3 metres high and have top and bottom widths of 3 metres and 8 metres respectively. The rock need could be similar to an exposed breakwater of approximately 2.1 tons rock/m^3 breakwater (Paulsen 2012). Geotextile is often used below breakwaters, groynes and revetments and has an approximate cost of 25 $/m^2 (Paulsen 2012). The length and space between the breakwaters depends on the specific breakwater scheme and can vary significantly and the same applies to maintenance needs (Rosendahl Appelquist and Halsnæs 2015).

While costs are likely to vary between projects, factors which are likely to affect the unit costs of implementing such a scheme are likely to include:

- Requirement for localised data collection to inform scheme design;
- Selected construction material and availability of such;
- Anticipated wave loadings and the requirement to source large construction units to prevent movement in extreme wave conditions;
- Availability and proximity of marine equipment for the purposes of construction;
- Effective spacing between breakwater structures to dissipate sufficient incoming wave energy whilst allowing continued water circulation – larger spacing between structures will reduce overall construction costs;
- The need for supplementary defense schemes such as beach nourishment, revetments, seawalls, etc.;
- Availability and cost of human resources including expertise.

INSTITUTIONAL AND ORGANIZATIONAL REQUIREMENTS

The implementation of a breakwater scheme requires detailed initial design studies including analysis of wave conditions and sediment transport by specialized institutions. Doing so will ensure effective design which considers the likely coastal response to these structures. Furthermore, the impacts on adjacent coastlines must also be considered so as not to simply transfer problems alongshore. To do so, at least basic design guidance must be afforded.

During the construction phase, heavy construction work will require large machinery and is often carried out by a specialized contractor. If the construction material is rock armour, it is necessary to have a quarry in the vicinity of the construction site or rely on shipment of rock material from other locations.

In addition to the actual design and construction phase, it is necessary to establish a monitoring and maintenance scheme to ensure breakwaters are kept in proper condition.

BARRIERS TO IMPLEMENTATION

Barriers to construction of breakwaters mainly relates to the significant construction costs, availability of construction material and availability of data for the initial design phase. As breakwaters are long-lasting structures which have a great impact on the natural coastal environment, it is important that the design process is properly prioritized.

OPPORTUNITIES FOR IMPLEMENTATION

If breakwaters are designed and maintained properly, they are robust structures that can be used for long-term stabilization of coastlines used for societal activities. When this solution is employed, it is possible to maintain a relatively high recreational value of the beach environment behind the breakwaters, especially if combined with beach nourishment. Encouragingly, there is extensive global experience with this management option.

3 CLIFF STABILIZATION

DEFINITION

Cliff stabilization relates to measures carried out to minimize erosion of sloping soft rock coasts and thereby stabilize the coastline. Stabilization measures may take a wide range of forms including re-grading, smoothing, vegetative cover and improved drainage.

DESCRIPTION

Cliff stabilization is especially relevant at *exposed* and *moderately exposed sloping soft rock coasts*. These landforms are susceptible to erosion due to their relatively uncompacted sediments which are particularly vulnerable to attack by erosive forces such as waves, winds, tides, nearshore currents, storms and sea level rise. In addition to these elements, slope processes, encompassing a large range of land-sea interactions also have the capacity to significantly affect these coastal types. Such processes are likely to include drainage issues, soil weathering and undercutting of the cliff base through the action of waves, tides and nearshore currents (Eurosion 2004).

Cliff stabilization aims to address erosion issues related to slope processes, targeting geo-technical instability and subsequent sliding/collapse of the slope (Mangor 2004). A number of measures may be taken to address these issues, for example through construction of revetments, which is described separately in this catalogue. This helps prevent further erosion of the cliff foot, thus stabilising the cliff slope. However, where cliffs are already so steep that sliding and weathering continues to occur, this can be counteracted by different stabilization techniques as outlined below:

- Artificial smoothing or re-grading of the slope to flatten out steep slopes which are prone to instability under hydraulic action. This may be implemented, provided there is sufficient space at the foot and top of the cliff to allow the slope to be adjusted. This approach aims to reduce the extent of future sliding and weathering caused by stability issues (Mangor 2004);
- Smoothing of the slope by filling with granular material at the foot of the cliff if there is sufficient space at the cliff foot for this filling (Mangor 2004);
- Establishing vegetative cliff cover which aims to protect against weathering and groundwater seepage and therefore sliding. Vegetation cover is likely to be more stable if combined with slope smoothing (Mangor 2004);
- Drainage of groundwater to prevent the cliff from sliding due to high groundwater pressure and poor drainage conditions. This can be achieved using horizontal and vertical drains and regulation of surface water run-off (Mangor 2004);
- Slope reinforcement, for example, through the use of piles to transfer load to an intact geological underlayer or through the construction of large buttresses (Clark and Fort 2009).

Generally, the first step in a cliff stabilization process is to stabilize the cliff foot as this has a significant impact on the overall stability of the cliff. An integral element of cliff stabilization is to address ongoing foreshore erosion through hard or soft coast protection measures (Clark and Fort 2009).

“An integral element of cliff stabilization is to address ongoing foreshore erosion through hard or soft coast protection measures (Clark and Fort 2009).”

Alternative and low technology approaches such as dumping of rubbish, tree branches etc. over the cliff is generally a poor solution since this does not prevent the risk of sliding but is more likely to destroy the vegetation cover and thereby increase possible erosion.

ADVANTAGES

Cliff stabilization can be a useful management option for coastal stabilization in densely populated areas. As coastal infrastructure and properties on *sloping soft rock coasts* can be of significant value, cliff stabilization can prevent erosion of valuable land and maintain the current coastline.

By stabilising cliffs, it is also possible to reap the benefits of improved public safety. This is particularly the case where cliffs are in danger of collapse or landslip. This may help to maintain the amenity value of these areas which can be important for recreation and tourism.

Provided cliffs are stabilised sympathetically, they may retain their natural appearance. As such, stabilization techniques need not adversely affect the local landscape. Once again, this can be important in areas where tourism and beach recreation are valuable.

DISADVANTAGES

Because cliff stabilization in many cases involves hard structures as revetments, it interferes with the natural coastal dynamics. Eroding cliffs are part of the natural coastal landscape and a source of sediment to the coastal system and should therefore be kept unaltered where possible in order to maintain a carefully balanced sediment budget. By protecting and stabilising cliffs, this sediment input is reduced which can lead to negative effects downdrift. However, eroding cliffs are often not feasible in densely populated areas.

The smoothing and re-grading of slopes causes land loss. The cliff toe may be moved seaward and cliff top landward in an attempt to reduce unstable slopes but in doing so, causes loss of potentially valuable beach frontage and cliff top areas which are often the site of seafront properties. This type of land loss may be opposed by local stakeholders if the benefits are not made clear by early and thorough consultation.

COSTS AND FINANCIAL REQUIREMENTS

The cost of cliff stabilization is highly dependent on the local conditions and individual situation. Factors which are likely to affect the cost of cliff stabilization include the following:

- Requirement for localised data collection to inform scheme design;
- Requirement for land take and compensation in the event of cliff re-grading;
- Availability of suitable local materials to stabilise cliff frontages;
- Requirement for drainage (necessary in the majority of schemes but of greater significance in some areas than others);
- Complexity of site access for heavy equipment and availability of suitably qualified contractors;
- The degree of detailed engineering required to ensure scheme success;
- The need for supplementary defence scheme such as beach nourishment, revetments, seawalls, etc. to protect the toe of the cliff.

Cost estimates for supplementary defence schemes are outlined elsewhere in this catalogue in the relevant sections. Of particular interest, are likely to be costs associated with the construction of revetments, which are often applied alongside cliff stabilization measures (see section 20).

INSTITUTIONAL AND ORGANIZATIONAL REQUIREMENTS

If revetments are constructed, the institutional requirements are further described in the revetment section. Generally, cliff stabilization requires some level of baseline data collection. Furthermore, feasibility assessment followed by implementation of the specific activity by a specialized contractor is also required.

Knowledge and understanding of local geology, geomorphology and coastal processes will clearly aid the design of the most targeted and effective stabilization techniques. Where possible, approaches should consider the local and regional geographical context including geomorphology, geology, hydrogeology, landslide processes and coastal processes in order to provide the most effective stabilization techniques (Clark and Fort 2009).

BARRIERS TO IMPLEMENTATION

Barriers to the implementation mainly relates to the cost of implementing the stabilization measures and limited space to implement the various stabilization components due to human activities. *Sloping soft rock coasts* are often used recreationally and are also frequently populated. This can produce greater barriers to implementation due to the involvement of a large number of potential stakeholders.

Cliffs can be important environmentally and ecologically meaning that stabilization methods may need to be sympathetic to these needs. Artificial smoothing or re-grading may detrimentally affect the ecosystem or aesthetic value of these environments. As such, stabilization techniques should consider these issues carefully during the design phase. In some instances, this consideration may be associated with potentially higher implementation costs.

OPPORTUNITIES FOR IMPLEMENTATION

Basic cliff stabilization can be a low-tech management option which may be implemented by a skilled contractor. Furthermore, there is considerable scope for implementing this approach alongside other adaptation responses such as managed realignment, coastal setbacks, beach nourishment and construction of hard defences such as revetments and seawalls.

In many cases, complementary management approaches form an integral part of cliff stabilization. For example, rock and concrete armouring, seawall construction, beach holding structures and beach nourishment have been widely applied alongside cliff stabilization measures in the UK. In many instances, these works, in addition to preventing erosion, can act as a toe weight to the cliff, helping to prevent further slippage (Clark and Fort 2009).

4 COASTAL SETBACKS

DEFINITION

Coastal setbacks are a prescribed distance to a coastal feature such as the line of permanent vegetation, within which all or certain types of development are prohibited (Cambers 1998). A setback may dictate a minimum distance from the shoreline for new buildings or infrastructure facilities, or may state a minimum elevation above sea level for development. Elevation setbacks are used to adapt to coastal flooding, while lateral setbacks deal with coastal erosion (see Fig 4.1.).

DESCRIPTION

The 'setback' area provides a buffer between a hazard area and coastal development (Fenster 2005). The idea is to allow room for the average high water mark to naturally move inland by sea level rise throughout the economic lifetime of the property. Setbacks provide protection to properties against coastal flooding and erosion by ensuring that buildings are not located in an area susceptible to these hazards. Two types of setback can be distinguished; elevation setbacks to deal with flooding and lateral setbacks to deal with erosion (see Fig 4.1.).

> “Unlike hard structures, setbacks help to maintain the natural appearance of the coastline and preserve natural shoreline dynamics (NOAA 2010).”

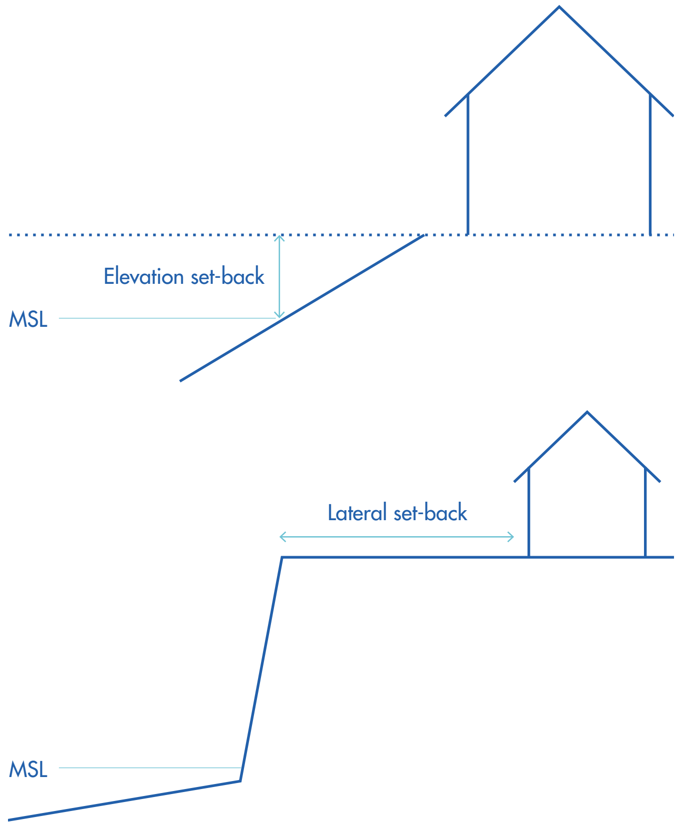

Fig. 4.1. *Types of coastal setback. Elevation setback (top) to cope with coastal flooding and lateral setback (bottom) to cope with coastal erosion (Source: The authors).*

The approach allows erosion to continue along strategic sections of a coast while further development is restricted. This allows eroded sediment to be transported to areas alongshore, thus enhancing the level of protection afforded by helping to maintain wide, natural beaches. By managing the coast in this natural state, adjustments by the coastline to changing conditions such as sea level rise can be made without property loss (Kay 1990).

Setback distances are determined either as: (1) a fixed setback which prohibits development for a fixed distance landward of a reference feature; or (2) a floating setback which uses dynamic, natural phenomenon to determine setback lines and can change according to an area's topography or measurements of shoreline movement (Fenster 2005).

Control of development is achieved either by defining a linear exclusion zone along the whole of an administrative unit, or by specifying distinct coastal exclusion zones (Kay 1990). Ideally, setbacks should be established based on historic erosion rates or extreme water levels rather than adopting arbitrary distances which do not truly represent the threat from erosion or coastal flooding.

Setback policies are widely used across the world; schemes have been implemented in many countries including Canada, Barbados, Aruba, Antigua, Sri Lanka, USA, Australia (IPCC 2001), Denmark, Germany, Norway, Finland, Poland, Spain, Sweden and Turkey (Fenster 2005).

ADVANTAGES

Setbacks provide a highly effective method of minimising property damage due to coastal flooding and erosion, by removing structures from the hazard zone. They provide a low-cost alternative to shoreline erosion or flood protection works such as sea walls or dikes which have their own disadvantages (see Sections 21 and 6 respectively).

Unlike hard structures, setbacks help to maintain the natural appearance of the coastline and preserve natural shoreline dynamics (NOAA 2010). This allows natural erosion/accretion cycles to occur (Fenster 2005) and helps to maintain the local sediment budget. Enhanced downdrift erosion as observed when using hard defences is also less likely to occur. As such, setbacks can contribute significantly to sustainable management of coastal systems (Fenster 2005).

Setbacks also help to maintain shoreline access by preventing development immediately on the seafront (NOAA 2010) as well as providing open space for the enjoyment of the natural shoreline. Coastal setback zones are commonly promoted as open public recreational space and they can also provide recreational and beach access.

Minimum elevation setbacks also provide higher levels of protection when compared to hard defences. For example, if a water level in excess of the design standard occurs, an elevation setback will result in shallower and less extensive flooding of developed areas than would occur if hard defences were employed instead; this is shown in Fig 4.2.

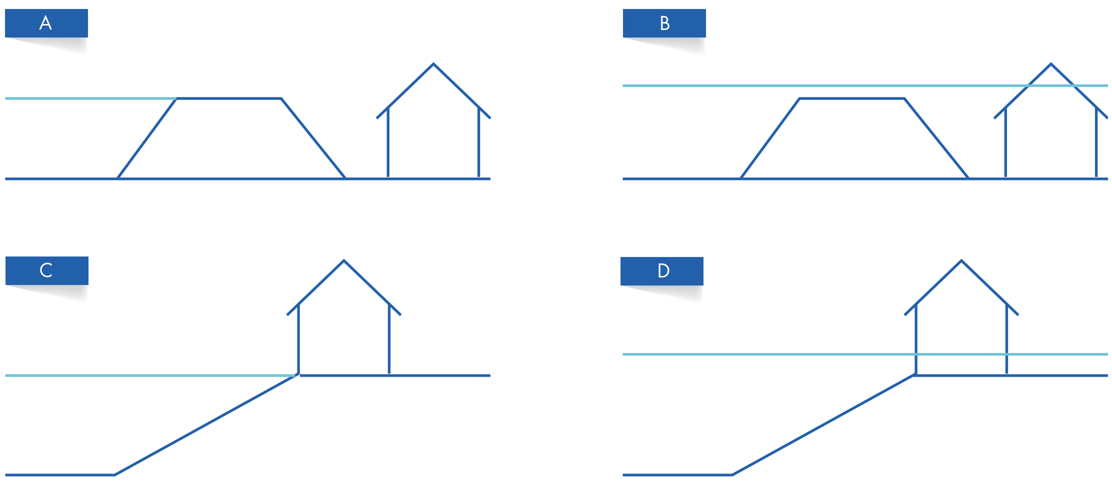

Fig. 4.2. *Differing levels of protection offered by structural defences and setbacks. In the event of a flood event in excess of design standard, setbacks offer greater protection (Source: Linham et al. 2010).*

DISADVANTAGES

Over time, sea level rise will reduce the size of the buffer zone between structures and the sea. As a result, setbacks will need to be periodically reviewed to ensure that buffer zones continue to provide sufficient protection; in the US states of South Carolina and Florida, setback distances are reassessed every 10 years (Healy & Dean 2000).

It is important to emphasise that the establishment of setbacks does not guarantee that the coast in question will be shielded from strong storms and the associated coastal flooding and erosion (Healy & Dean 2000). As with all coastal adaptation measures, residual risk will remain, meaning that the protected areas are still subject to *some* risk in the case of an event larger than the measure can cope with. More cautious measures can be taken to reduce residual risk.

Problems may arise as a result of setback reviews. For example, reviews may reclassify coastal areas as no-build zones. This could create conflict if these areas have already been purchased with development in mind. Secondly, revision of the setbacks may mean existing structures are now within the buffer zone. Typically, these structures would be allowed to remain, but if significantly damaged or destroyed by a storm, they would usually be required to be reconstructed in line with the new setback line. In both these instances, compensation may be required for land owners who have lost development potential or have experienced physical loss of property (NOAA 2010).

Good quality scientific or historic data are required to establish setbacks according to coastal flood or erosion threats. Such data is not always readily available, especially in developing countries where monitoring programmes are less well established. In the absence of such data, it is possible that setbacks established either provide too little protection or are too restrictive of shoreline development (Fenster 2005).

Setbacks do not serve to protect existing structures in the hazard zone. If these are to be protected, other management approaches are required. Additionally, setback policies only serve to *prolong* the lifetime of structures built on the shoreline. With continued shoreline erosion or sea level rise, another shoreline policy will eventually be needed if these structures are to be preserved (NOAA 2010).

COSTS AND FINANCIAL REQUIREMENTS

The costs of implementing a coastal setback approach will be variable, depending on local conditions. A number of costs will be incurred when implementing setback in any situation. They are discussed below.

Firstly, a decision must be taken as to how far to set back. Costs involved in taking this decision include the collection and analysis of historic erosion rates or water levels, the cost of modelling likely shoreline evolution, and the associated cost of buying in modelling services and expert consultation. The cost at this stage will vary depending on the method used to determine setback distance. Less technical solutions are likely to be cheaper.

Secondly, the setback policy must be communicated to relevant bodies in order that the policy is taken into account in the planning process. Costs involved at this stage may also involve the additional costs of incorporating coastal setback into local planning policies.

Finally, enforcement is essential. The cost of enforcement may however be low as it is possible to enforce setback via pre-existing local planning bodies.

Additional costs may be incurred if private landowners are required to be compensated for loss of development potential and also when the setback distance undergoes periodic review.

Coastal setbacks are generally accepted to be an inexpensive solution. In a study by Shows (1978), engineering costs of installing a coastal setback line in Florida, USA, were estimated to be US$11,700/km with mandatory five-year reviews expected to cost US$23,000/km. Annual administrative costs were estimated at approximately US$4,800/km (costs converted to 2009 prices) (Shows 1978).

Implementation of a setback policy is likely to have the lowest costs when implemented proactively, before significant, inappropriate development occurs. In this way it should be possible to minimise compensatory payments to private landowners.

INSTITUTIONAL AND ORGANIZATIONAL REQUIREMENTS

In order to implement setbacks as an adaptive response to climate change, it is necessary to implement the measure *proactively*. Because of the largely predictable nature of coastal erosion and the long lead times involved in sea level rise, planning policies can be put in place now to restrict inappropriate development which would be susceptible to coastal flooding or erosion in future (Kay 1990).

In the past, hard defences have been employed, sometimes for political reasons such as wanting to be ‘seen to be doing something'. A proactive setback policy must bear this political factor in mind by stressing the acceptability of a setback policy via a full coastal research and monitoring programme, together with public education and participation schemes (Kay 1990).

It should be relatively straight forward to implement setbacks at a local level. The approach can be incorporated into pre-existing land-use planning regulations and building codes, where these exist. If a meaningful rather than arbitrary setback is to be employed however, factors such as the coastal type, presence of physical defences and the influence of coastal processes must be accounted for (Sanò et al. 2010).

In addition to the differences in the type of setback which may be used, variations exist with respect to how setbacks are administered and who administers them. The technical standards for establishing setbacks vary widely in practice (Fenster 2005).

Although setback distances may be best informed when based on the findings of scientific models[1], defining a setback need not be a highly scientific endeavour. Arbitrary setbacks require less advanced technology and therefore, may be more usable on a local scale. Even using high technology, the degree of uncertainty in assigning a setback is significant. Therefore, investing heavily in high-tech modelling solutions which provide more accurate setbacks may still be misguided. Ultimately, it is preferable to be conservative (Healy & Dean 2000) although this can lead to implementation of sub-optimal setback distances.

[1] The SCAPE model (Walkden & Hall 2005) predicts shoreline erosion based on the type of material the coast is composed of, wave conditions and other forcing factors. CLIFFPLAN (Meadowcroft et al. 1999) is another process-based simulation model for cliff erosion.

BARRIERS TO IMPLEMENTATION

One of the most significant barriers to the implementation of setbacks, is public opposition. This is especially likely to be the case if the public believe setbacks are too large or, in the case of individual landowners, if their land packets fall within the new restricted development zone. In this case it is important to communicate the need for large setbacks to the public. Compensating private landowners for lost development potential is also likely to make implementation smoother.

Setbacks may also be opposed by residents who are now deemed to live within the new building exclusion zone. Although in most cases, structures will be allowed to persist within the no build zone, restrictions may be placed upon rebuilding in the event of damage or destruction during storms. In most cases, it is accepted practice that reconstruction or significant modifications to structures within the exclusion zone are not permitted.

Retroactive application of coastal setbacks is unlikely in a number of cases: (1) coastal cities and urbanisations, (2) industrial areas and uses associated with maritime activities and, (3) traditional developments integrated with the coastal landscape (Sanò et al. 2010). This may prove a barrier to the effectiveness of coastal setbacks because coastal vulnerability remains for those who are allowed to persist in the hazard zone.

In order to implement effective and meaningful setbacks, information on historic erosion rates or extreme water levels is required. Without this information, creation of effective setbacks is problematic. It is also recommended that coastal process-based models be used to help predict long-term shoreline evolution. In order to operate these models, a degree of expertise is required.

Although setbacks may be more effective when these approaches are used, it is nevertheless possible to implement setbacks in their absence, using conservative but more arbitrary setback distances.

In many coastal areas, there is pressure to develop the coastal zone, especially when attempting to encourage tourism. As a result, coastal regulations are often ineffective and developments within the exclusion zone proceed regardless (Sanò et al. 2010).

OPPORTUNITIES FOR IMPLEMENTATION

A significant opportunity for the implementation of setbacks lies in the potential to tie the policy in with existing land use and building regulations. There is potential for the same bodies that regulate building standards and planning permissions to ensure that new developments do not occur within the setback zone.

Setbacks can also be implemented in combination with complementary schemes such as sand dune reconstruction (Section 7) or wetland restoration (Section 24). Setbacks would ensure that these environments are given sufficient space to develop and adapt to climate change. This provides the double benefit of maintaining natural protective features, as well as providing a buffer zone against coastal flooding and erosion.

5 COASTAL ZONING

DEFINITION

Coastal zoning is the division of coastal areas into zones which can be assigned different purposes and user restrictions. It is a way of allowing multiple users to benefit from a coastal area under a broader sustainable management strategy, and coastal zoning schemes can constitute the regulatory and planning framework for the implementation of other management options listed in this catalogue.

DESCRIPTION

Coastal zoning is a relatively simple and effective way of managing and separating incompatible or multiple uses of a coastal area. In a particular zone, certain activities can be allowed, allowed with permission or forbidden and the zoning can be applied for a range of different uses of the coast including economic development, tourism and conservation (Australian Government 2015a; Haslett 2009). Furthermore, coastal zoning can be implemented to ensure that development does not occur in flood prone areas or is compatible with the anticipated flood levels. The zoning is generally managed and enforced by public authorities and can be developed in consultation with different coastal stakeholders and combined with scientific monitoring programs.

Coastal zoning is basically a land use system for regulating development activities by dividing coastal areas into designated zones with different purposes and restrictions. The zoning system generally requires a high level of coordination and public participation and is regulated at different administrative levels. National guidelines can provide the broader framework for the zoning system while regional plans can provide binding plans for local development and local plans can handle management of specific project activities.

In many countries, laws, acts and planning regulations are already in place and a hazard management strategy would therefore have to be closely integrated with these regulatory conditions. New coastal protection activities would have to be compatible with the assigned purpose and regulatory framework for a specific coastal area and it may be necessary to obtain special permits to implement some hazard management measures. This could e.g. be the case for the construction of hard protection structures in an area with restrictions on development activities.

The implementation of an Integrated Coastal Zone Management (ICZM) process, where all key interests and physical conditions are considered, is recommended before the design of a broader zoning scheme and the regulatory framework. This can then be followed by more detailed management plans and special requirements for implementation of Environmental Impact Assessments (EIAs) where appropriate. The most common types of management plans and planning documents are described by Mangor (2004).

> "Coastal zoning schemes can help maintaining local coastal livelihoods, coastal biodiversity and broader economic activities for the benefit of all stakeholders."

A well-known example of a coastal zoning scheme that covers both coastal and marine areas is the Great Barrier Reef Marine Park in Australia that consists of zones with different purposes and restrictions. Examples of zonation in the area include zones for general use, for habitat protection, for conservation parks, for buffers, for national parks and for preservation (Australian Government 2015a; Haslett 2009). The general regulatory framework for the zones is then supplemented by local elaboration of permitted activities.

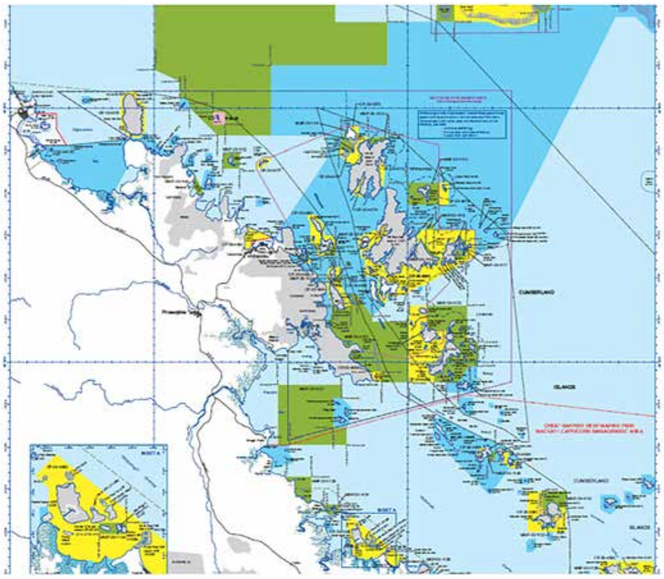

Fig. 5.1. *Example of zoning map for Great Barrier Reef Marine Park (Australian Government 2015b).*

ADVANTAGES

The advantage of coastal zoning is the ability to manage multiple uses of the same coastal area to the benefit of all users. It can be used to protect natural coastal areas and nursing grounds for marine fisheries while at the same time allowing some level of economic and recreational activities.

DISADVANTAGES

The disadvantage of coastal zoning is that it requires a relatively high degree of public management, monitoring and enforcement to ensure the zoning system remains functional. If such a system is not in place, the zoning system can easily be violated by different users with conflicting interests.

COSTS AND FINANCIAL REQUIREMENTS

The cost of implementing a zoning system largely depends on the complexity of the zoning system, the different governance setups and the size of the coastal area in question. However, there may also be significant economic benefits from such a system by optimizing value generation from the different coastal activities.

INSTITUTIONAL AND ORGANIZATIONAL REQUIREMENTS

Coastal zoning requires a well-functioning institutional and organizational setup with dedicated resources to continued management of the zoning system. Depending on the size of the coastal area in question, different organizational setups can be used, but generally it requires a clear management structure and an outreach and communication scheme to guide the public. If the area in question is ecologically sensitive, it may be relevant to combine the zoning system with a scientific monitoring program to allow for iterative management improvements over time. Generally, the management of the zoning system should be carried out in a transparent manner, involving all relevant stakeholders to ensure broad public support and to minimize violations.

BARRIERS TO IMPLEMENTATION

Barriers to implementation of a coastal zoning system relates to the institutional capacity, data and knowledge of the coastal area in question. Before a coastal zoning system is implemented, it is important to have a well-developed strategy for the overall scheme based on an ICZM approach.This includes obtaining broader support from the affected stakeholders through stakeholder involvement and consultations, to prevent systematic and repeated violation.

OPPORTUNITIES FOR IMPLEMENTATION

Coastal zoning has great potential to allow multiple users to benefit from the services provided by coastal areas. Furthermore, coastal zoning schemes can help maintaining local coastal livelihoods, coastal biodiversity and broader economic activities for the benefit of all stakeholders.

6 DIKES

DEFINITION

The primary function of sea dikes is to protect low-lying, coastal areas from inundation by the sea under extreme conditions (Pilarczyk 1998a). Dikes are not intended to preserve beaches which may occur in front of the structure or any adjoining, unprotected beaches.

These structures have a high volume which helps to resist water pressure, sloping sides to reduce wave loadings and crest heights sufficient to prevent overtopping by flood waters. They may also be referred to as dykes, embankments, levees, floodbanks and stopbanks.

DESCRIPTION

Dikes are widely used to protect low-lying areas against inundation. As such, they have been widely applied in countries such as Vietnam, Bangladesh, Thailand, the Netherlands and the USA. Fig 6.1. shows a typical dike cross-section. It is a predominantly earth structure consisting of a sand core, a watertight outer protection layer, toe protection and a drainage channel. These structures are designed to resist wave action and prevent or minimise overtopping.

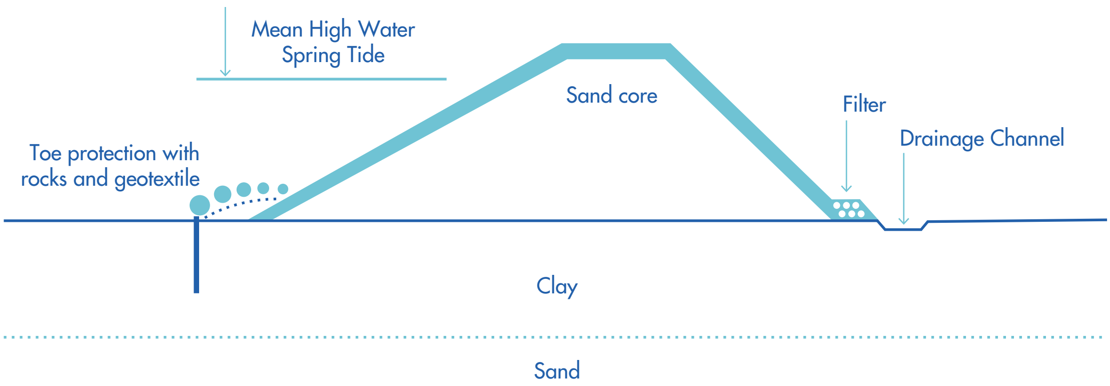

Fig. 6.1. *Typical sea dike cross section (Source: The authors).*

> “Dikes provide a high degree of protection against flooding in low-lying coastal areas. They often form the cheapest hard defence when the value of coastal land is low (Brampton 2002).”

Dikes have been extensively utilised as flood defences in the Netherlands over the past several hundred years. As such, the Dutch have extensive experience in their design. As a result, many countries apply Dutch design practice in dike construction.

Typical Dutch practice employs the following design guidelines:

- Sloped seaward face at a gradient of between 1:3 to 1:6 – this can reduce wave loadings;
- Sloped landward face at a gradient of between 1:2 to 1:3 – this minimises land take and maximises stability;
- Impermeable cover layer – this is usually composed of clay but is sometimes supplemented by asphalt. It serves to protect the sand core (Barends 2003);
- Toe protection – used as supplemental armour for the beach and prevents waves from scouring and undercutting the structure (Pilarczyk 1998b);
- Dike core usually composed of sand to ensure that water that *does* enter can drain away. The core provides support for the cover layer and gives the structure sufficient volume and weight to resist high water pressures (Barends 2003);
- Drainage channel – allows any water which *does* enter the structure to drain away, therefore ensuring the structure is not weakened by water saturation (Barends 2003).

A number of zones can be distinguished on the seaward slope of a sea dike. The base of the dike, up to MHW will be regularly submerged and will experience constant, low-level loadings. The zone above MHW can be heavily attacked by waves, but the frequency of this occurrence reduces as you move further up the slope. Toward the dike crest, above the design water level, the structure should only be subjected to wave run-up.

ADVANTAGES

Dikes provide a high degree of protection against flooding in low-lying coastal areas. They often form the cheapest hard defence when the value of coastal land is low (Brampton 2002).

The sloped seaward edge of a dike leads to greater wave energy dissipation and reduced wave loadings on the structure compared to vertical structures. This is achieved because the seaward slope forces waves to break as the water becomes shallower. Wave breaking causes energy dissipation and is beneficial because the process causes waves to lose a significant portion of their energy. Because the waves have lost energy, they are less capable of causing negative effects such as erosion of the shoreline. By reducing wave loadings, the probability of catastrophic failure or damage during extreme events is also reduced.

When compared to vertical structures, dikes also have reduced toe scour. This is because the wave downrush is directed *away* from the base of the structure, as shown in Fig 6.2. This is beneficial for structural stability and helps to reduce the risk of undermining.

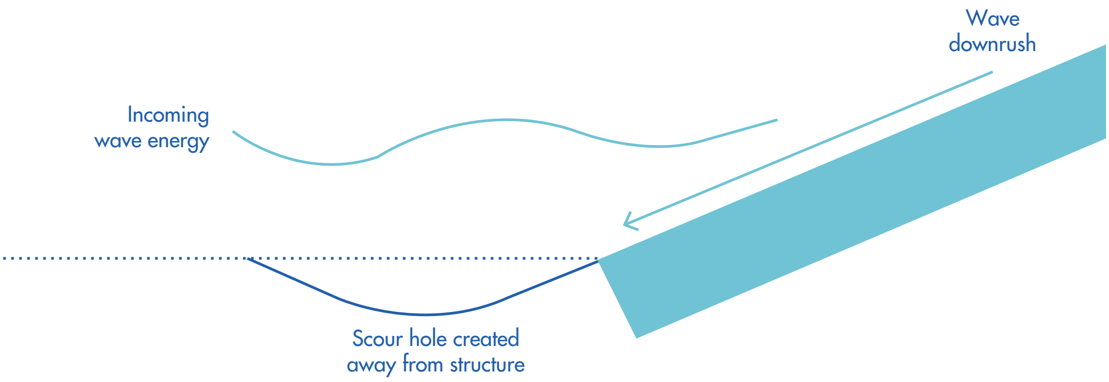

Fig. 6.2. *Toe scour on sloping structures. Toe scour is reduced in sloping dikes compared to vertical structures because the downrush is directed away from the toe (Source: The authors).*

DISADVANTAGES

Dikes require high volumes in order to resist high water pressures on their seaward faces (Barends 2003). As a result, their construction uses large volumes of building materials, including sand, clay and asphalt, which can be costly.

Another disadvantage of applying dikes is that the shallow slopes applied to facilitate wave energy dissipation cause dikes to have large footprints; i.e. their construction requires significant areas of land. This can increase dike construction costs where coastal land is valuable.

Raising dikes in response to sea level rise can cause the area of land required for dike construction to grow if slope gradients are maintained (see Fig 6.3.). The area of land take can be problematic as coastal areas often have high associated land values. Further, construction of dikes prevents use of the coastal area for other development, hence, leading to competition for land. Extending dikes seaward may overcome this problem, but it raises costs significantly.

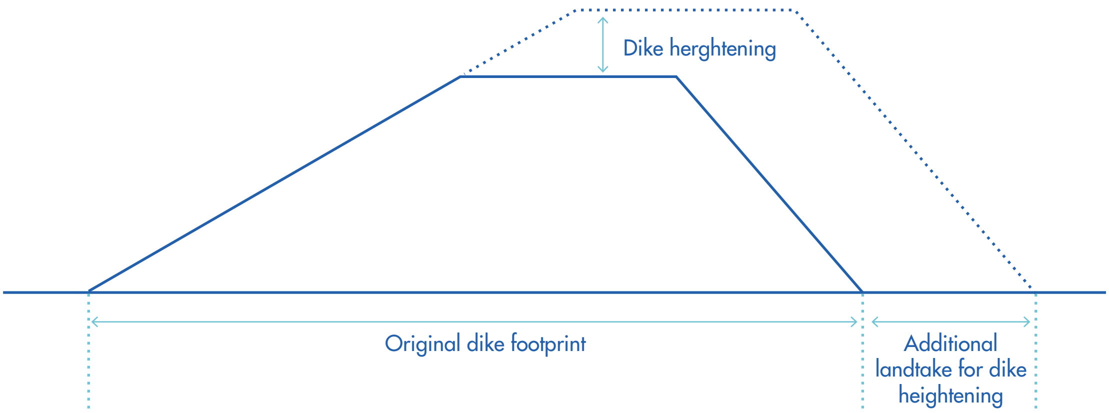

Fig. 6.3.
Land area requirements for sea dikes. Schematic illustration of the large land areas required for dike construction and the additional land take required upon dike heightening (Source: The authors).

As with all hard defences, dikes can create a false sense of security on the landward side of defences, promoting further development landward of the dike. Hence, once protected, it is difficult to change the management policy.

The construction of hard defences permanently fixes the position of the coastline. This can have detrimental impacts because the coast is a naturally dynamic system. Fixing the position of the coastline can prevent natural coastal processes, such as responses to sea level changes, beach/dune interactions and sediment input from coastal erosion (French 2001). Stopping these processes not only impacts the immediate environment, but because the coastal system shares sediments within a coastal cell, knock-on impacts can also be felt elsewhere along the coast.

Significant shoreline hardening measures can be aesthetically displeasing, especially in areas which are dependent on a tourist economy where natural shorelines are valuable (IOC 2009).

COSTS AND FINANCIAL REQUIREMENTS

The best available cost information for sea dikes is compiled by Hillen et al. (2010) in a review of Vietnam, the Netherlands and New Orleans. The information is presented as the cost of dike heightening in millions of US dollars per linear km of defence. Heightening of dikes is reported to cost from US$0.9 to 29.2 million per metre rise in height, per km length (in 2009 US dollars) (Hillen et al. 2010).

Vietnamese costs of dike construction, reported in Hillen at al. (2010) are perhaps most relevant to developing countries. In Vietnam, dike construction costs were shown to vary from US$0.9 to 1.6 million per metre rise in height, per km length – significantly less costly than construction in either the Netherlands or New Orleans (Hillen et al. 2010). Costs were variable due to varying costs of material, land-use and applied inner/outer protection of the dike's slopes. When comparing completed projects within Vietnam, labour costs were observed to be highly variable even within the country.

Dike construction costs are shown by Hillen et al. (2010) to vary considerably between rural and urban areas with dike construction in rural areas shown to be consistently less costly. This is the case worldwide. Costs are also influenced by a number of other factors, detailed in Box 6.1.

- Land availability and cost. As shown in Fig 6.3., dike construction needs significant land input. Accurate cost studies often draw a distinction between rural and urban construction costs to reflect differential land values
- Selected dike design and in-built margin for safety. This can affect the volume of the structure and the required materials
- Anticipated wave loadings; higher wave loadings require more robust and expensive structures. Wave loading is affected by wave breaker types, cleanness of the breaking wave, seabed shape and individual storm characteristics such as storm duration, wind strength and storm orientation in relation to the structure
- Single or multi stage construction; aggregate costs are lower for single stage construction (Nicholls & Leatherman 1995)
- Proximity to and availability of raw construction materials
- Availability and cost of human resources including expertise

Box 6.1. *Factors affecting unit costs of sea dike construction.*

Maintenance costs are an ongoing requirement for sea dikes, to ensure the structure continues to provide design levels of protection. Information on maintenance costs is limited, although annual dike maintenance costs per linear km of dikes are reported to range from US$0.03 million in Vietnam (Hillen 2008) to US$0.14 million in the Netherlands (AFPM 2006). These costs are presented in 2009 US dollars. The variability in these costs is largely due to the fact that while dike maintenance in the Netherlands is well organized and given high priority, in many other locations, maintenance programmes are less rigorous. To a lesser extent, local factors such as labour and material costs, and the presence of different types of dikes/coastal defence measures will also influence costs (Hillen, pers comm.).

The construction and maintenance costs are likely to increase into the future in response to sea level rise (Burgess & Townend 2004; Townend & Burgess 2004). This is caused by increases in water depth in front of the structure which in turn, causes increased wave heights and wave loadings on the structure.

INSTITUTIONAL AND ORGANIZATIONAL REQUIREMENTS

Construction of sea dikes is possible on a local scale. However, the improved science and technology base that the involvement of larger organizations brings can significantly improve a structure's effectiveness. This is seen in Vietnam where poor dike design and insufficient funding resulted in dikes providing lower levels of protection than initially intended (Mai et al. 2008).

Ad-hoc construction of coastal defences is likely to give much less consideration to the water levels, wave heights and wave loadings occurring during an extreme event. This is largely because these events are hard to foresee without a well-developed knowledge. As such, ad-hoc defences typically offer lower levels of protection.

Dikes designed and constructed by local communities are likely to employ local materials and traditional methods. This may not necessarily constitute the most effective approach, although it may be the only available option. Provision of design and construction guidance, even for small details such as recommended slopes and materials, is likely to improve the performance of defence structures.

Dikes can be expensive measures to employ with costs ranging between US$1 and 7.6 million per km length of dike depending on the global location (Linham et al. 2010) and with additional annual maintenance costs. As such, external funding may be required before a successful dike construction project can proceed.

If community level implementation goes ahead, it is essential that the wider impacts of hard defences on the coastal zone are not overlooked. When implementing projects at a local level, it is easy to focus on local benefits and neglect the bigger picture. As stated under the disadvantages of dikes, some impacts of dike construction may be felt considerable distances from the implementation site. Dike implementation at a local level may pay little attention to reduce these impacts.

Extreme caution should be exercised if ad-hoc, community implementation of sea dikes goes ahead. Because dikes are often designed to protect extensive areas of low-lying land, catastrophic failure caused by poor design is likely to be associated with a threat to the lives of significant numbers of people.

BARRIERS TO IMPLEMENTATION

The high space requirement for sea dikes is one barrier to implementation. This factor will be especially important in areas where the value of the coastline plays an important role in deciding adaptation technologies. The availability of materials, labour and specialised machinery for the construction of dikes may also pose a barrier to the implementation of this technology.

The cost of implementing an effective dike system can prove a barrier in some cases. This will especially be the case in high wave-energy areas where additional protective elements such as rip-rap will be required (IOC 2009).

The most effective dikes are those designed in accordance with good quality, long-term environmental data, such as wave height and extreme sea level information. One of the main barriers to the building of an effective dike which accounts for local conditions is therefore the availability of long-term datasets. The cost of collecting such data can be expensive. However, by accounting for these local conditions, dike design is typically more effective. The additional costs of data collection and exclusive design may for a barrier to implementation in some circumstances.

OPPORTUNITIES FOR IMPLEMENTATION

Where large areas of high value coastal land, which cannot be surrendered to the sea under a managed realignment policy, exist at elevations close to, or below sea level, there are often few other choices available than the construction of dikes.

Dikes are capable of providing very high levels of protection against coastal flooding if designed appropriately. This can enable significant development to take place behind them, even if land is low-lying. This is demonstrated by Schiphol Airport, Amsterdam, in the Netherlands – the area is enclosed by dikes but lies 4.5 m below MSL (Pilarczyk 2000). Long-term sustainability considerations should be borne in mind if this technology is adopted, however.

Dikes are a tried-and-tested method of coastal protection. Construction methods and design principles for these structures are well known and publicised. Although specialised dikes, designed with local conditions in mind pose the most effective defences, it *is* also possible to implement more generic or lower quality designs at a lower cost. This makes diking more affordable but compromises safety and protection levels.

Dikes can be implemented in conjunction with other erosion and flood protection works, such as beach nourishment (Section 1) and managed realignment (Section 19). This has the potential to address the negative impacts associated with the technology and also means the benefits associated with each technology can be realised.

7 DUNE CONSTRUCTION/ REHABILITATION

DEFINITION

Naturally occurring sand dunes are wind-formed sand deposits representing a store of sediment in the zone just landward of normal high tides (French 2001). Artificial dunes are engineered structures created to mimic the functioning of natural dunes.

Dune rehabilitation refers to the restoration of natural or artificial dunes from a more impaired, to a less impaired or unimpaired state of overall function, in order to gain the greatest coastal protection benefits.

Artificial dune construction and dune rehabilitation are technologies aimed at reducing both coastal erosion and flooding in adjacent coastal lowlands.

DESCRIPTION

Dunes naturally occur along most undeveloped, sandy coastlines. A typical example is shown in Fig 7.1. Where they are present, their coastal defence role is two-fold:

1) They represent a barrier between the sea and land, in a similar way to a sea wall .
2) Dunes are ‘dynamic’, i.e. the dune/beach system interacts a great deal and is constantly undergoing small adjustments in response to changes in wind and wave climate or sea level. As such, dunes are able to supply sediment to the beach when it is needed in times of erosion, or store it when it is not (French, 2001).

> “With careful management, dunes are able to offer a high degree of protection against coastal flooding and erosion.”

Fig. 7.1. *Coastal sand dunes at Sylt, Germany (Photo: Michael Thaler/ Shutterstock).*

Clearly natural sand dunes are an effective defence against coastal flooding and erosion. However, a problem arises in that wide, sandy beaches – the environment where most sand dunes occur – are highly appealing for development. As such, natural sand dunes are in decline. Coupled with an increased chance of dune erosion caused by sea level rise and more energetic wave climates, sand dunes are at risk.

The importance of dunes in coastal protection has now been recognized however, and the construction of artificial dunes and rehabilitation of existing ones are potential technologies for adapting to climate change in the coastal zone.

At its simplest, artificial dune construction involves the placement of sediment from dredged sources on the beach. This is followed by reshaping of these deposits into dunes using bulldozers or other means. As a result, dune construction is most frequently carried out at the same time as beach nourishment (see Section 1), because sand is readily available.

There are a number of methods of dune rehabilitation. One such method is to build fences on the seaward side of an existing dune to trap sand and help stabilise any bare sand surfaces (USACE, 2003). This method can also be used to promote dune growth after a structure has been created using bulldozers (Nordstrom & Arens 1998). Natural materials such as branches or reed stakes are commonly used for fence construction, because they break down once they have accomplished their sand-trapping objective (Nordstrom & Arens 1998).

Alternatively, vegetation planting may be used to stabilise natural or artificial dunes. This promotes the accumulation of sand from wind-blown sources around their stems – over time, this causes dune growth. Planting can be achieved by transplanting vegetative units from nursery stocks or nearby intact dunes (USACE 2003). It can be undertaken at the community level using widely available tools. Over time, dune vegetation root networks also help to stabilise the dune.

Artificial dune creation and dune restoration can be carried out on existing beaches, beaches built through nourishment, existing dunes, undeveloped land, undeveloped portions of developed areas and areas that are currently fully developed but may be purchased so that dunes can be restored (Nordstrom et al. 2000).

ADVANTAGES

Section 1 has already stated the importance of sandy beaches in dissipating wave energy. However, sandy beaches are in a constant state of flux, because they continuously react to constantly changing wave climates and sea levels. As such, the volume of sand held upon a beach is constantly fluctuating. During periods of low beach volume, the shoreline is susceptible to erosion and it is at these times, that sand dunes can be particularly valuable as a store of sediment which can be accessed in order to satisfy erosional forces. This compensates for the sand removed from a beach and helps to maintain wide, sandy beaches which will continue to dissipate incoming wave energy. This process is illustrated in Fig 7.2. The volume of erosion can be calculated using the Vellinga (1983) equation which requires knowledge of wave height, extreme water level and sediment fall velocity.

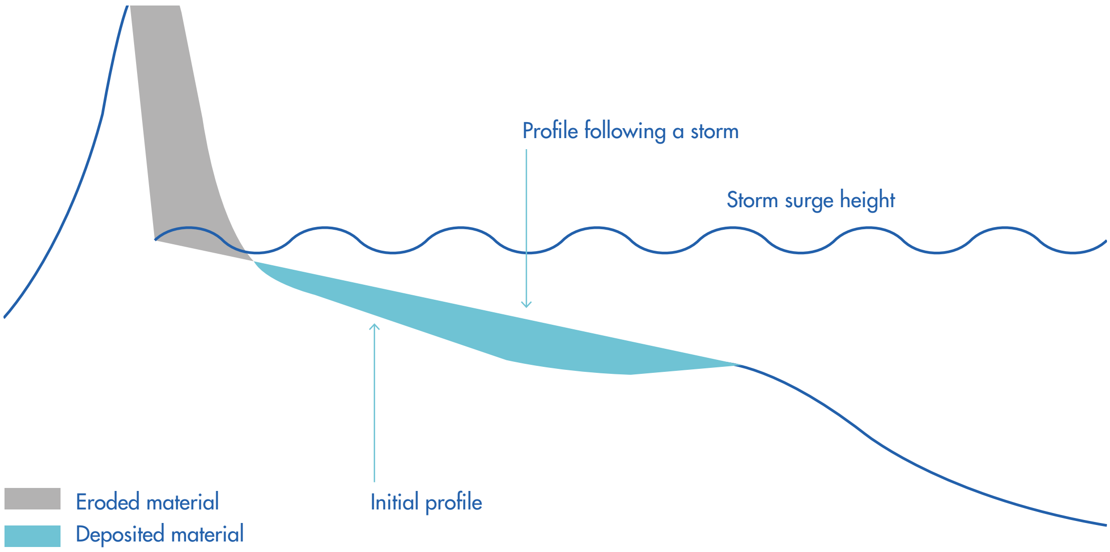

Fig. 7.2. *Simplified illustration of dune erosion caused by storm surge. Vellinga (1983) found that during storms, sediment is eroded from dunes and deposited on the underwater portion of the beach profile. This maintains a wide, sandy beach which continues to dissipate wave energy (Source: Redrawn by the authors).*

With careful management, dunes are able to offer a high degree of protection against coastal flooding and erosion. Because dunes provide both a physical and tangible defence, they may even serve to encourage sustainable development within the coastal zone.

Dunes are naturally occurring features, and provided the construction/initiation of artificial dunes is completed in a sympathetic manner, they do not necessarily spoil the local landscape. Many sandy beaches would have had naturally occurring sand dune complexes prior to coastline development; as such, the initiation of artificial dunes may even restore a degree of natural character to the site.

Sand dunes also provide a valuable coastal habitat for many highly specialised plants and animals. As such, sand dunes may be considered important both ecologically and recreationally.

DISADVANTAGES

Despite being a natural feature of many sandy coastlines, dunes also represent a barrier to beach access. In many cases, dunes have been removed as a result of development and communities have grown used to direct access to beaches and views straight onto the sea. Reconstruction of dunes may receive local opposition if it affects these factors.

Land loss is another issue; dunes have a reasonable sized footprint. This space requirement increases further if dunes are to be given sufficient room to adapt to sea level rise, thus avoiding coastal squeeze. It could be controversial to use land with development potential for dune creation and rehabilitation if the full benefits are not made clear. Alternatively, sand dune construction may take place on an area of beach important for tourism and recreational purposes, therefore restricting its use by the public.

COSTS AND FINANCIAL REQUIREMENTS

Since the most basic sand dune construction projects consist simply of the deposit of dredged material onshore, followed by shaping using bulldozers, simple dune construction costs are not expected to be significantly different from beach nourishment costs in terms of cost per cubic metre of sediment used (see Section 1). Additional costs may however, be introduced through the requirement for dune grass planting and fencing.

Factors which are likely to influence the unit costs of dune construction are explored in Box 7.1.

- Whether dredged material is required for dune construction/restoration or whether fences or vegetation can be used to promote sand accumulation
- Availability and proximity of appropriate construction material from onshore or offshore sites
- Dredger type, size and availability
- Requirement to fence newly constructed dunes to prevent erosion
- Requirement for planting new dunes with vegetation
- Frequency with which the dune needs to be artificially replenished or whether the structure naturally accumulates sand
- Project size and resulting economies of scale

Box 7.1. *Factors affecting the unit costs of dune construction.*

INSTITUTIONAL AND ORGANIZATIONAL REQUIREMENTS

While dune construction using dredged sand may require specialised knowledge and equipment as detailed in Section 1, rehabilitation and maintenance of naturally occurring and artificially created dunes is accomplishable at a community level.

The application of fences to stabilise bare sand and encourage dune growth is possible using local, naturally occurring materials such as branches and reed sticks (Nordstrom & Arens 1998). The measure therefore requires very little external provision of materials or guidance. Fencing can also prevent dune erosion caused by human access.

As already mentioned, vegetation planting is frequently accomplished at the community level with subsequent maintenance also left to communities (Nordstrom & Arens 1998). The success of this approach has been found to vary considerably with local commitment (Nordstrom & Arens 1998). Local awareness raising campaigns could help local communities better understand the coastal protection role of dunes, which may promote local efforts to continue to preserve dunes.

Once sufficient material for the creation of dunes is available, dune creation either through naturally occurring processes or through artificial placement, movement and reshaping of the material is another task achievable with limited technology requirements. The use of a bulldozer or other earth moving equipment is sufficient to undertake ad-hoc operations to reshape or repair dunes. Sediment may even be bulldozed from dune crests and placed in lower areas if the dune crest height exceeds design specifications (Nordstrom & Arens 1998).

BARRIERS TO IMPLEMENTATION

Previous experience of artificial dune creation or rehabilitation projects has shown that one major barrier is the difficulty in convincing the public and municipal officials of the need for dune construction or heightening (Nordstrom et al. 2000).

Conflicts of interest may also arise, especially if dune construction takes place in an area primarily used for residential or tourism purposes, where local landowners may be concerned about maintaining sea views. In these cases it may be possible to keep new dunes relatively low and linear, although this could affect the level of protection offered. If the full coastal protection benefits of dunes are communicated, opposition may be kept to a minimum.

In the USA, coastal managers have sometimes constructed sub-optimal dunes to minimise public opposition and to familiarise local communities with the presence of dunes. By gaining acceptance in this way, it may be possible in the future to gain approval for dunes of larger dimensions, offering better levels of protection (Nordstrom et al. 2000).

Opposition may also be caused by the land-take requirements of dunes. Greater width on the ocean side could reduce beach space and on the landward side would bring dunes closer to human settlements such as housing.

Sand dunes are a dynamic form of coastal defence which respond to coastal processes such as the wave and wind climates. For example, in the summer months, dunes may grow as they accumulate sediments, while during winter storms, the sediment stored in the dunes may be accessed by the beach to satisfy erosion. Many communities are only familiar with static defences which do not react to the local conditions. The drastically different way in which dunes react to storm events may cause communities to object to their use, especially in communities where coastal *stabilization* has been the long-term goal (Nordstrom et al. 2000).

OPPORTUNITIES FOR IMPLEMENTATION

Dune restoration can be much more than mitigation or reparation, in that it can lead to increased understanding and appreciation of a threatened ecosystem (Nordstrom et al., 2000). Restoration programs can be linked to environmental education initiatives aimed at re-establishing an appreciation for naturally functioning coastal landscapes. This may increase the likelihood of implementing similar programs elsewhere (Nordstrom et al. 2000).

Due to factors such as urbanisation, development, trampling and conversion, sand dunes are becoming increasingly damaged and in decline (French 2001). With an improved understanding of the role of sand dunes in coastal defence and with greater awareness of the ecological importance of sand dunes for coastal species, dune construction and rehabilitation is likely to become more popular. This will bring advantages for coastal defence and nature.

Dune protection meets multiple management objectives, such as habitat protection, public access to environmental and recreational resources and hazard mitigation. Because of these benefits and the fact that they are less expensive and more aesthetically pleasing than some engineering solutions, dunes are likely to find broader public support in future (Moser 2000).

8 ECOSYSTEM BASED MANAGEMENT

DEFINITION

Ecosystem-based management (EBM) is an environmental management approach that recognizes the full array of interactions within an ecosystem, including humans, rather than considering single issues, species, or ecosystem services in isolation (McLeod et al. 2005; Christensen et al. 1996). This approach can constitute an important component of a broader coastal management scheme and incorporated in ICZM.

DESCRIPTION

EBM is a holistic and integrative management approach that goes beyond examining single issues, species or ecosystem functions in isolation. Instead, it recognizes ecological systems as a rich mix of elements that interact with each other in important ways (UNEP 2011). The terms 'ecosystem-based management' and 'ecosystem approach' are often used interchangeably, and they have basically the same meaning.

This multifaceted approach is particularly important for coasts, due to the multiple functions coastal areas provide to society and the range of pressures put on them. EBM in coastal environments aims to manage each of the human uses at a scale that encompasses its impacts on coastal ecosystem function, rather than scales defined by jurisdictional boundaries. Ecosystem-based management of terrestrial ecosystems began in the 1950s, but its application in coastal environments is relatively new. Two key dimensions of EBM of coastal hazards are (1) each human activity is managed in the context of all the ways it interacts with marine and coastal ecosystems, and (2) multiple activities are being managed for a common outcome (UNEP 2011).

> “EBM in coastal environments aims to manage each of the human uses at a scale that encompasses its impacts on coastal ecosystem function, rather than scales defined by jurisdictional boundaries.”

Key principles in applying Ecosystem-based management in coastal areas include:

1) Define clear and concise goals that move beyond exclusively science-based or science-defined objectives to include social and cultural importance.
2) Recognize connections among marine, coastal and terrestrial ecosystems, as well as between ecosystems and human societies.
3) Consider ecosystem service provision of both the basic goods they generate (e.g. food, raw materials, etc.), as well as the important services they provide (e.g. Protection from extreme weather, fishing spawning areas, carbon sequestration, etc.).
4) Address the cumulative impacts of different activities affecting an ecosystem.
5) Manage for and balancing multiple and sometimes conflicting objectives that are related to different benefits and ecosystem services.
6) Embrace change, learning from experience, and adapt policies throughout the management process (UNEP 2011).

Although application of EBM can and should vary according to local contexts, some basic steps or components it may include are:

- Scoping, including acquisition of data and knowledge from various sources in order to provide a thorough understanding of critical ecosystem components;
- Defining ecological, social and economic indicators;
- Setting thresholds or targets for each indicator and setting targets that would represent a desired level of health for the ecosystem;
- Risk analysis of the range of threats and disturbances, both natural and human, and their effects on the indicators;
- Monitoring and evaluating the effectiveness of the implemented EBM strategies (Tallis et al. 2010).

EBM is being put into practice in different ways in different contexts. EBM can for example, be achieved in a step-by-step incremental and adaptive process, often by combining with and building on coastal management practices that are already in place. Finally, it is important to note that EBM can be used in combination with many of the other coastal management practices outlines in this catalogue and would generally constitute a sub-component of ICZM.

ADVANTAGES

EBM is well suited to balancing the diversity of competing interests and functions placed on coastal areas, due to its holistic approach to consider use of, threats to, and services provides by, coastal ecosystems. EBM is also well suited to collaborative planning and decision making, due to active involvement of different stakeholders. Finally, EBM can effectively consider ecosystem health and incorporate options for sustaining the services ecosystems provide to human wellbeing into coastal management plans and actions.

DISADVANTAGES

Different ecosystems vary greatly and are each experiencing different degrees of vulnerability. Therefore, it is challenging to apply a functional framework that can be universally applied to all ecosystems. The steps or components of EBM outlined above can be applied to different ecological contexts and are only suggestions for improving or guiding the challenges involved with managing the complex issues. Furthermore, as a result of the numerous influences, impacts, and interactions to account for within EBM, a number of challenges to implementing EBM exist, which are discussed in the 'barriers to implementation' section below.

COSTS AND FINANCIAL REQUIREMENTS

Costs and financial requirements for implementing EBM, at a minimum, involve the fairly modest scale of expenses associated with coordination of meetings, participatory planning, stakeholder consultation, inter-agency collaboration, etc. Staff time, travel expenses and communication expenses, are likely to be higher for EBM than other approaches planned and implemented as single sector or single agency approaches. More substantial costs and financial requirements vary greatly, depending on the specific management activities that are implemented within an EBM approach.

INSTITUTIONAL AND ORGANIZATIONAL REQUIREMENTS

In order to successfully carry out these principles, it is essential that EBM practitioners must work in an integrated manner among a diversity of actors and sectors, striving for active collaboration and information sharing in decision making, planning, and implementation, monitoring and adaptive management.

BARRIERS TO IMPLEMENTATION

Because ecosystems differ greatly and express varying degrees of vulnerability, it is difficult to apply a functional framework that can be universally applied. The outlined components of ecosystem-based management can, for the most part, be applied to multiple situations and are only suggestions for improving or guiding the challenges involved with managing the complex issues. Because of the greater amount of influences, impacts, and interactions to account for, problems, obstacles and criticism often arise within ecosystem-based management.

One specific barrier to implementation is defining geographic management areas that are meaningful for both ecosystem dynamics and are feasible to plan and implement within, given legal and institutional arrangements that may not be consistent with ecosystem-based geographic parameters. One approach is to use 'bioregions' as management units, but these may not correspond with geopolitical, legal and administrative realities. Another approach is to use geopolitical or administrative units, but these may not correspond with ecosystem functionality. In cases when ecological and political geographic areas do not correspond, EBM practitioners must find ways to be creative and flexible in defining their management units (Slocombe 1998).

Another barrier to EBM implementation relates to limited foci and reach of different administrative bodies. For EBM to be fully effective, institutions should operate together seamlessly towards mutually agreed upon goals. However, this is not always reality. Competing objectives or priorities between management entities, overlapping jurisdictions or gaps in research can make it hard to define tangible and mutually shared goals and implement them effectively. Moreover, limited knowledge of ecosystem components and their functions can limit objectives to only those that can be addressed in the short-term (Tallis et al. 2010).

OPPORTUNITIES FOR IMPLEMENTATION

There is potential for EBM to be an effective approach to hazard management in virtually any context where ecosystems provide useful services to society. EBM can be an especially productive approach in contexts where ecosystems are relatively healthy and therefore particularly able to provide ecosystem services to local populations. However, it can be argued that EBM is perhaps even more useful when ecosystems are under substantial threat and active ecosystem restoration or protection is required to strengthen the capacity of ecosystems to deliver services. In order for EBM to be effective, it is important that there is a willingness to exchange information, plan and coordinate among sectors levels of government and institutions.

9 FLOATING AGRICULTURAL SYSTEM

DEFINITION

Floating agriculture is a way of utilising areas which are waterlogged for long periods of time in the production of food. The technology is mainly aimed at adapting to more regular or prolonged flooding.

The approach employs beds of rotting vegetation, which act as compost for crop growth. These beds are able to float on the surface of the water, thus creating areas of land suitable for agriculture within waterlogged regions. Scientifically, floating agriculture may be referred to as hydroponics. In Bangladesh, it has regional names such as baira, geto, dhap and bed.

DESCRIPTION

Floating agriculture can be used in areas where agricultural land is submerged for long periods; the approach is reasonably widespread in Bangladesh where agricultural land is inundated for extended periods during the monsoon season (APEIS & RIPSO 2004). The practice is similar to hydroponic agriculture whereby plants can be grown on the water on a floating bed of water hyacinth, algae or other plant residues (Saha 2010).

A typical example of floating agriculture in Bangladesh involves a floating layer of water hyacinth, straw or rice stubble to which is added upper layers of small and quick-rotting waterworts which make for good manure (APEIS & RIPSO 2004). The structure of the floating raft is strengthened with bamboo, while bamboo poles are used to fix it in position to avoid damage caused by wave action or drifting (Saha 2010). This floating raft can then be transferred to any submerged location for agricultural purposes (APEIS & RIPSO 2004). An example of a floating agricultural system is shown in Fig 9.1.

> “The practice helps mitigate land loss through flooding, by allowing cultivation of these areas to continue. In this way, the total cultivatable area can be increased and communities can become more self-sufficient.”

Fig. 9.1. *Floating agriculture at Lake Inle, Burma (Source: Wikimedia Commons).*

ADVANTAGES

The practice helps mitigate land loss through flooding, by allowing cultivation of these areas to continue. In this way, the total cultivatable area can be increased and communities can become more self-sufficient. In addition to this, the area under floating cultivation is up to 10 times more productive than traditionally farmed land (Haq et al. 2004) and no additional chemical fertilisers or manure is required. When the crops have been harvested and floating rafts are no longer required, they can be used as organic fertilisers in the fields or incorporated into the following years floating beds as a fertiliser (AEPIS & RIPSO 2004; Saha 2010).

The approach uses water hyacinth, a highly invasive weed with prolific growth rates, in a highly beneficial way. By harvesting water hyacinth, areas covered by the weed are cleared, with the beneficial side-effect of reducing breeding grounds for mosquitoes and improving conditions for open-water fishing (Saha 2010). By cultivating crops in water, it is also possible to simultaneously harvest fish populations which reside in the beds (APEIS & RIPSO 2004).

The practice of floating agriculture also helps supplement the income of local communities and contributes to alleviation of poverty (Saha 2010). It also provides greater food security by increasing the land output and supporting capacity for poor and landless people (Irfanullah et al. 2007). People practicing floating-bed cultivation are enjoying a better life economically, than those in other flood-affected areas who have not yet adopted this practice (Saha 2010).

Because the system is fairly labour intensive, it also has the capacity to provide employment opportunities within communities (Haq et al. 2004). As both men and women can carry out the floating agriculture practices, it can also lead to improvements in gender equity.

DISADVANTAGES

While this technology works well in some areas today, it is unclear how it may be affected by sea level rise and increases in salinity, which are likely to occur under scenarios of climate change. Additionally, while the technique is applicable in several mega-deltas such as the Ganges-Brahmaputra, the success of a more general application of this approach seems unlikely and we recommend caution in applying this approach more widely.

The methods used in floating agriculture have the drawback of encouraging insect and rodent infestation. This may cause health problems and damage to crops (Saha 2010).

The technology can also cause conflict within the community if common property areas are dedicated to the practice. Such an approach may lead to politically more powerful individuals attempting to acquire these areas for their own gains (Islam & Atkins 2007)

Although this technology provides the advantage of maintaining food production, it may be difficult to transport produce to market because the area remains waterlogged most of the time (APEIS & RIPSO 2004).

COSTS AND FINANCIAL REQUIREMENTS

Floating agriculture practices have minimal infrastructure and very little capital requirement (Saha, 2010). Costs can also be kept low because raw materials for the construction of floating beds are readily available from local waterways.

Haq et al. (2004) conducted an analysis of the costs of implementing floating agriculture in Bangladesh. Their findings are shown in Table 9.1.

Activity	**Duration**	**Total Cost (Tk)**	**Total cost converted to US$ (in 2009 US$)**
Construction of floating beds	60 man days	3000	63
Collection of raw materials (weeds)	20 man days	1000	21
Seed and/or seedling purchase		600	13
Bamboo, rope, crop harvesting and maintenance		1000	21
	Total	Tk 5600	US$ 118

Table 9.1. *Costs of implementing a floating agricultural system in Bangladesh (from Haq et al. 2004).*

The use of floating agriculture as an adaptive measure also provides direct economic benefits. Vegetables and spices produced on the floating beds can be sold at markets and since the approach is fully organic, the produce receives special attention from local buyers and consumers (Haq et al. 2004).

INSTITUTIONAL AND ORGANIZATIONAL REQUIREMENTS

Due to a lack of awareness of floating agriculture and its methods, it will be necessary to raise awareness and educate local communities. A recent scheme in Bangladesh was promoted by the Wetland Resource Development Society (an international research and development organization), which provides training and technical support to local communities.

Provided communities are furnished with the appropriate knowledge, implementation of floating agricultural systems should be achievable at the community scale. This is because raw materials are widely available and costs are low and offset by the production and sale of food stuffs.

In order to implement these schemes at the local level, communities are required to work together. It has been observed that in doing so, the local community and communal harmony can be strengthened (APEIS & RIPSO 2004).

Through a programme to encourage floating agriculture in Bangladesh, it was found that one of the most important aspects of implementation is to organize small-scale and poor farmers at grass-roots level and build up their entrepreneurial capacity for running small businesses (LEISA 2009). This builds the benefits to less well-off farmers and can be accomplished on a local level.

BARRIERS TO IMPLEMENTATION

The availability of high volumes of fast growing organic material may be limited in some areas and may be problematic if the uptake of this technology becomes widespread. As this is an essential material for floating agriculture, a limited supply will limit the uptake of this technology.

It is essential that knowledge of this technology be passed on to local communities in areas where floating agriculture is not carried out. To an extent, this has naturally occurred in Bangladesh where the practice has spread throughout the country (APEIS & RIPSO 2004), but on a global scale, the approach will require local awareness raising.

Poorer farmers can be prevented from participating in floating agriculture schemes if their rights to common property and ownership of technology are not protected. While many wetland areas with plentiful water hyacinth may exist, they are likely to be grabbed by the upper levels of the rural and urban society if extensive and persistent advocacy is not considered by the implementing bodies (LEISA 2009).

OPPORTUNITIES FOR IMPLEMENTATION

Floating agriculture is an environmentally-friendly option for increasing the land available for agriculture. As such, the practice could be sustainable and profitable in developing countries, helping to supplement incomes and to increase food security (APEIS & RIPSO 2004).

Regular, land-based agriculture requires farmland to be protected behind embankments or reclaimed from estuarine systems. Both of these activities can have detrimental side effects upon the local environment and economy. In contrast, floating agriculture can be conducted without land claim and hard defences. The procedure can even contribute toward maintaining healthy wetlands (Haq et al. 2004), which have coastal defence functions and also support a wide range of biodiversity.

Aquatic invasive species used in floating agriculture are considered to be the second largest reason for biodiversity loss worldwide (Haq et al. 2005). Clearing waterways to collect these plants is therefore beneficial to the health of wetland ecosystems and may contribute toward maintaining high biodiversity and associated benefits.

The practice is already widely applied in some developing countries such as Bangladesh, and the uptake of the technology is already increasing due to its sustainable, positive features (APEIS & RIPSO 2004).

10 FLOOD MAPPING

DEFINITION

Flood mapping is an exercise to define those coastal areas which are at risk of flooding under extreme conditions. As such, its primary objective is to reduce the impact of coastal flooding. However, mapping of erosion risk areas may serve to achieve erosion risk reduction. It acts as an information system to enhance our understanding and awareness of coastal risk.

DESCRIPTION

Flood Mapping is a vital component for appropriate land use planning in flood-prone areas. It creates easily-read, rapidly-accessible charts and maps which facilitate the identification of areas at risk of flooding and also helps prioritise mitigation and response efforts (Bapulu & Sinha 2005).

Flood maps are designed to increase awareness of the likelihood of flooding among the public, local authorities and other organizations. They also encourage people living and working in flood-prone areas to find out more about the local flood risk and to take appropriate action (Environment Agency 2010).

It is important to note here, that climate change must be carefully considered when implementing flood mapping. Flood mapping typically provides a ‘snapshot’ of flood risk at a given point in time. When considering the effects of climate change however, it is important to consider the *dynamic* nature of flood risks. For example, sea level rise and changes in storm intensity, occurring as a result of climate change, will causes changes in the areas susceptible to flooding. See, for example Fig 10.1.

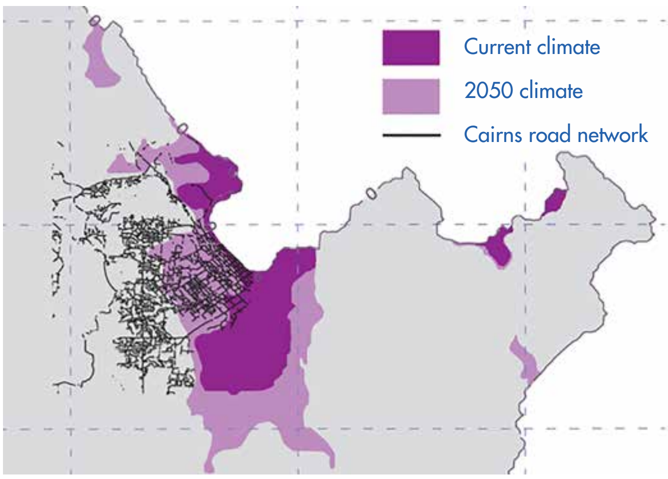

Fig. 10.1. *Flood map for the area around Cairns, Australia. The map shows both flood hazard under the present climate and under a projection of climate in 2050. It can be seen that under a scenario of climate change, developed areas that are presently not susceptible to flooding are likely to flood in future. The map also highlights currently undeveloped areas at flood risk (Source: IPCC 2007).*

> “Flood maps are designed to increase awareness of the likelihood of flooding among the public, local authorities and other organizations.”

Due to climate change and changes in relative sea level, it is important to note that flood maps will require periodic updates in order to reflect the changing risk of flooding. These updates should account for RSLR, erosion, changes in storm frequency and intensity, etc.

Flood maps can be used by developers to determine if an area is at risk of flooding, and by insurers to determine flood insurance premiums in areas where flood insurance exists.

Due to sparse empirical records and the statistical rarity of extreme coastal events, coastal flood prediction often relies on complex numerical models that approximate the processes and phenomena that lead to coastal floods (Water Science and Technology Board 2009). Coastal flood hazards are determined by the interaction of storm surges and waves with seabed bathymetry and coastal land cover. These factors determine the inland extent of flooding. Coastal flood models must therefore account for these features, as well as the processes associated with storm surges and waves (Water Science and Technology Board 2009).

The creation of flood maps usually combines topographic data with historic or modelled information on extreme sea levels and wave heights. This allows determination of the water level at the coast under extreme conditions and shows how this water could flood inland. This is likely to involve the deployment of storm surge and wave models.

The level of protection offered by existing coastal defences should also be accounted for. This helps to determine when overtopping of defences will occur, causing flooding of defended areas.

Geographic Information Systems (GIS) are frequently used to produce flood maps. They provide an effective way of assembling information from different maps and digital elevation models (Sanyal & Lu 2003). Using GIS, the extent of flooding can be calculated by comparing local elevations with extreme water levels.

ADVANTAGES

Identification of those areas at risk of flooding will help inform emergency responses. For example, areas that are likely to require evacuation can be identified, and evacuation routes can be planned and clearly signposted so local communities are made aware in advance of an emergency. The identification of flood risk areas will also help in the location of flood shelters for evacuees.

Identification of flood risk areas is likely to help in the planning of a more effective emergency response. It is essential that certain infrastructure, such as electricity supplies, sewage treatment, etc., and services, such as the emergency services, continue to function during a flood event. The creation of flood maps will therefore allow planners to locate these elements in low risk areas so that they can continue to serve during an extreme event. Alternatively, flood mapping may highlight a requirement to defend these elements from flooding.

Flood mapping will allow quantification of what is at risk of being flooded such as the number of houses or businesses. This will help identify the scale of emergency and clean-up operations.

The creation of flood maps should promote greater awareness of the risk of flooding. This can be beneficial in encouraging hazard zone residents to prepare for the occurrence of flooding. In order to achieve this however, local authorities must ensure that emergency procedures are established, and that information about what to do in the event of a flood is made available to the general public.

By identifying buildings at flood risk, awareness raising campaigns can also be targeted at high risk properties. This may include raising awareness of emergency flood procedures and may also promote the implementation of flood-proofing measures (see Section 11).

In the longer-term, flood maps can support planning and development by identifying high risk locations and steering development away from these areas. This will help to keep future flood risk down and also encourages sustainable development. In order for this to occur, the consideration of flood maps must be integrated into planning procedures.

DISADVANTAGES

In itself, flood mapping does not cause a reduction in flood risk, it must be integrated into other procedures, such as emergency response planning and town planning, before the full benefits can be realised.

More advanced, accurate flood maps are likely to rely on complex numerical models due to the lack of observed extreme event data. This requires a degree of expertise to implement. The collection of topographic and bathymetric data to complement extreme water level and wave height information could also be expensive to collect.

To realise the full benefits of flood mapping, it is important to provide people in the hazard zone with information about emergency procedures and ways of reducing flood risk. If information on what to do in the event of an emergency is not provided, flood maps may serve only to increase fear and anxiety as residents are more aware of the risk of flooding.

COSTS AND FINANCIAL REQUIREMENTS

The costs of flood mapping are not widely known. Therefore it is not possible to provide likely cost estimates here. However, Box 10.1. provides a number of factors which are likely to contribute toward the cost of flood mapping.

- External expertise on numerical modelling of flood risk brought in from academic institutions or commercial organizations
- Topographic surveys (LiDAR or remote sensing) to provide information on land elevation which will feed back into the flood risk model
- Historic costs of collecting extreme event data such as water levels, wave heights, etc.
- Cost of employing a Geographic Information System (GIS)

Box 10.1. *Factors contributing toward the cost of flood risk mapping exercises.*

INSTITUTIONAL AND ORGANIZATIONAL REQUIREMENTS

Flood mapping may be difficult to undertake at the community level due to the need for complex numerical modelling for the forecast of extreme water levels, storm surges and wave heights. The required expertise and modelling capacity is unlikely to be locally available, especially in developing countries. As such, it may be necessary to enlist the help of external organizations. Following developed country examples, this type of mapping has been accomplished via national programmes.

BARRIERS TO IMPLEMENTATION

Flood mapping relies on the availability of topographic, and long-term extreme event data and complex numerical modelling techniques. This requires specific modelling capabilities and expertise which may not be readily available.

A lack of public understanding about the benefits of flood mapping may also provide a barrier to implementation. If the public is unaware of the benefits of flood mapping, they may prefer to see public money spent on more tangible flood and erosion protection measures.

OPPORTUNITIES FOR IMPLEMENTATION

Flood mapping complements and strengthens other adaptation options, such as flood-proofing measures (Section 11), emergency planning, provision of flood shelters (Section 12) and evacuation planning. As such, this approach could be applied almost universally, irrespective of the other adaptation technologies that are used.

11 FLOOD PROOFING

DEFINITION

The primary objective of flood-proofing is to reduce or avoid the impacts of coastal flooding upon structures. This may include elevating structures above the floodplain, employing designs and building materials which make structures more resilient to flood damage and preventing floodwaters from entering structures in the flood zone, amongst other measures.

DESCRIPTION

Flood-proofing measures are widely applied in the USA where two types of flood-proofing are widely recognized: wet and dry. Wet flood-proofing reduces damage from flooding in three ways; (1) allowing flood waters to easily enter and exit a structure in order to minimise structural damage; (2) use of flood damage resistant materials; and (3) elevating important utilities. On the other hand, dry flood-proofing is the practice of making a building watertight or substantially impermeable to floodwaters up to the expected flood height (FEMA 2008).

Wet flood-proofing measures typically include structural measures, such as properly anchoring structures against flood flows, using flood resistant materials below the expected flood depth, protection of mechanical and utility equipment and use of openings or breakaway walls to allow passage of flood waters without causing major structural damage (FEMA 2010). A typical example of wet flood-proofing is shown in Fig 11.1.

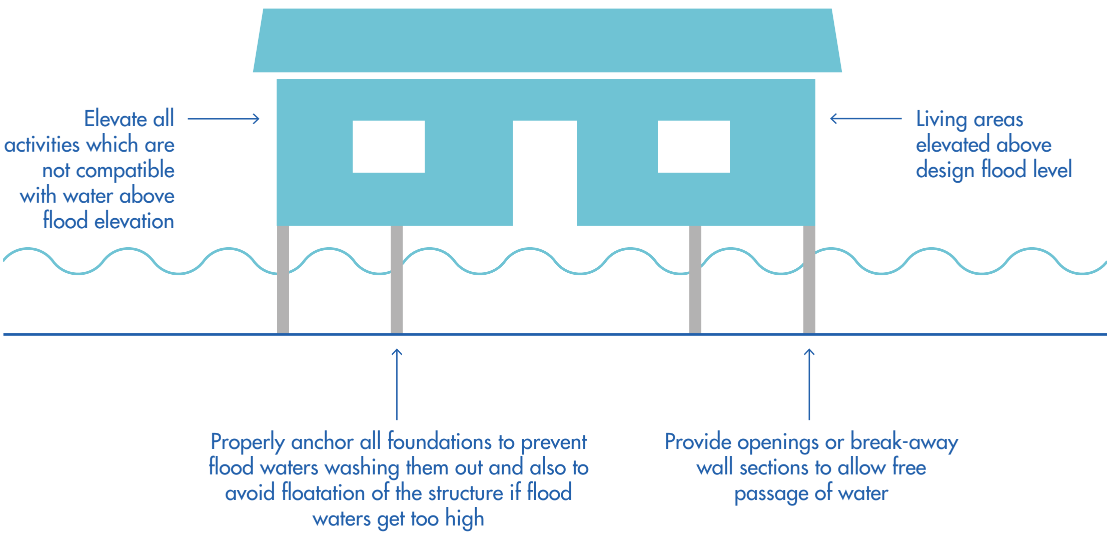

Fig. 11.1. *Basic wet flood-proofing measures for a residential structure (Source: Redrawn by the authors).*

> “Flood-proofing can also be undertaken by individuals, rather than requiring funding from central or local government bodies.”

A dry flood-proofed structure is made watertight below the expected flood level in order to prevent floodwaters from entering in the first place. Making the structure watertight requires sealing the walls with waterproof coatings, impermeable membranes, or a supplemental layer of masonry or concrete, installing watertight shields on openings and fitting measures to prevent sewer backup (FEMA 2007). A typical example of dry flood-proofing is shown in Fig 11.2.

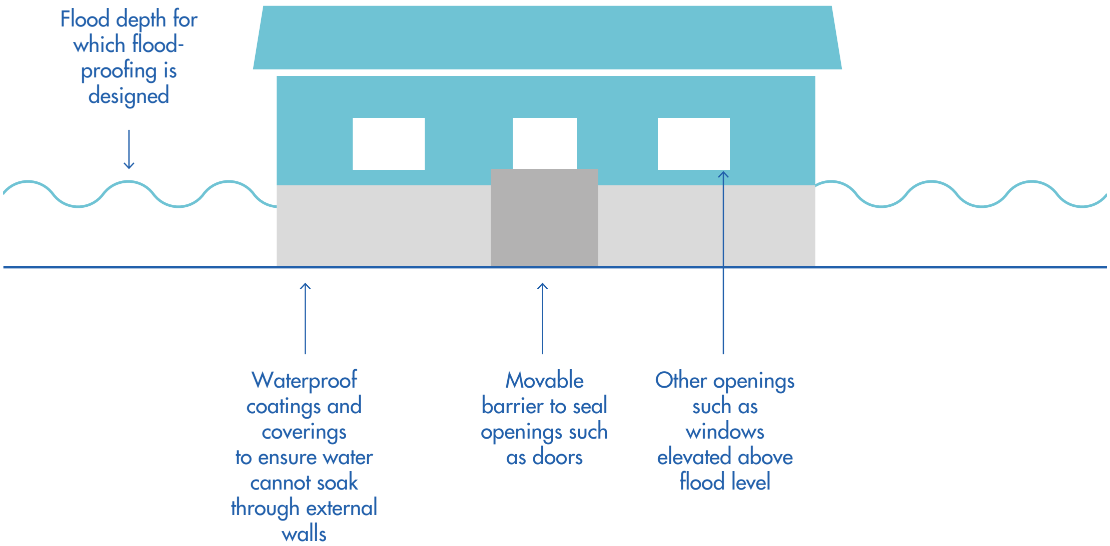

Fig. 11.2. *Basic dry flood-proofing measures for a residential structure (Source: Redrawn by the authors).*

Flood-proofing can be applied in residential *and* non-residential buildings and the principles of flood-proof design can also be applied to other important infrastructure such as electricity substations and sewage treatment works.

Obviously, the decision to choose wet or dry flood-proofing should be influenced by the use of the structure being protected and the compatibility with flood waters.

ADVANTAGES

One of the main advantages of flood-proofing is that it avoids the need to elevate, demolish or relocate structures and as a result, is often a much more cost effective approach to reducing flood risk (Powell & Ringler 2009). Flood-proofing measures are also much more affordable than the construction of elaborate flood protection works such as sea walls and dike systems (FEMA 2007).

Flood-proofing is also advantageous because it does not require the additional land that would be needed to offer the same degree of flood protection through sea walls or dikes.

Wet flood-proofing measures are beneficial because they allow internal and external hydrostatic pressures[1] to equalise during a flood therefore lessening the loads on walls and floors (FEMA 2007). This means structures are less likely to fail during floods.

Although flood-proofing will not allow residents to continue living in their house during flooding, flood-proofing measures will make it much quicker and easier to clean up and repair flood damage (FEMA 1992).

Flood-proofing can also be undertaken by individuals, rather than requiring funding from central or local government bodies. Even small, inexpensive flood-proofing efforts are likely to result in worthwhile reductions in flood damage. Availability of funds to undertake more expensive flood-proofing measures will no doubt encourage the uptake of flood-proofing however.

[1] Relating to fluids which are *not* in motion (for example, the maximum still water level caused by extreme events).

DISADVANTAGES

Flood-proofing measures require the current risk of flooding to be known and communicated to the public through flood mapping studies and flood warning systems (see Sections 10 and 13 for further information). This will allow flood-proofing measures to be appropriately applied and will allow time for residents to vacate flood-proofed buildings in the event of an emergency. In the case of dry flood-proofing, it will also allow residents to close barriers in a timely fashion. Although the provision of flood hazard maps and flood warnings bring benefits themselves, it is an additional cost that must be borne when implementing flood-proofing measures.

Since residents are not able to continue living in flood-proofed houses during flooding, amenities for accommodating evacuated people must also be provided. These facilities may be required for some period after a flood event, as wet flood-proofing may leave the structure uninhabitable for a small period following flooding.

Flood-proofing measures are most effective when applied in areas where flood depth is low. The application of flood-proofing measures does little to minimise damage caused by high velocity flood flow and wave action (FEMA 2007). If a flood larger than the design specification occurs, the effect will be as if there was no protection at all (FEMA 2001).

Another disadvantage is that in the case of dry flood-proofing, flood shields are not aesthetically pleasing (FEMA 2007). Shields for doors and windows are left in place in most circumstances, so that they can be quickly closed when required. However, this means that these measures are permanently on display. Ongoing maintenance of flood-proofing measures is also required to ensure they continue to provide appropriate protection (FEMA 2007).

When wet flood-proofing measures are applied, flood waters still enter the structure. Therefore significant clean up may be required following floods to remove water borne materials such as sediments, sewage or chemicals (FEMA 2007). The choices of materials used in these structures will still enable clean up to progress much more quickly than in non-flood-proofed structures.

In the case of dry flood-proofing, if design loads are exceeded, walls may collapse, floors buckle and homes may even float. This has the potential to cause more damage than if the home were just allowed to flood (FEMA 2009).

COSTS AND FINANCIAL REQUIREMENTS

In the absence of cost information from developing countries, cost estimates for a number of flood-proofing measures in the US are provided. The US is one country which widely applies flood-proofing measures.

In the US, the cost of elevating a structure above flood depth is likely to be between US$29 and US$96 per square foot of house footprint (FEMA 2009). The range in cost is due to the construction and foundation type and the required elevation.

Wet flood-proofing measures are likely to include the addition of wall openings for the entry and exit of floodwaters, installing pumps, rearranging or relocating utility systems, moving large appliances and coating surfaces in coverings which make it easier to clean up after flood waters recede. According to FEMA (2009), the cost of wet flood-proofing in the US is likely to be between US $2.20 and US $17.00 per square foot of house footprint when considering basement flood-proofing up to a depth of approximately 2.4 m.

Dry flood-proofing measures in the US include sealing walls with waterproof coatings, impermeable membranes or supplemental layers of masonry or concrete and equipping doors, windows and other openings below the flood elevation with permanent or removable shields. Installation of backflow valves on sewer lines and drains is also likely to be required (FEMA 2009). US cost estimates for these measures are given in Table 11.1.

Component	Cost	Per
Sprayed on cement	$55.10	Linear metre of wall covered
Waterproof membrane	$18.70	Linear metre of wall covered
Asphalt	$39.36	Linear metre of wall covered
Drainage line around perimeter of house	$101.68	Linear metre
Plumbing check valve	$1060	Each
Sump and sump pump	$1710	Lump sum
Metal flood shield	$1230	Linear metre of shield surface
Wood flood shield	$383.76	Linear metre of shield surface

Table 11.1. *Approximate costs of dry flood-proofing measures in the USA. Costs are relevant for flood proofing to a depth of approx. 0.9 m. Costs are presented in 2009 US$ (from FEMA 2009).*

Wet flood-proofing is generally less expensive than dry flood-proofing since any action to reduce the number of items that are exposed to flood damage is considered a wet flood-proofing measure (FEMA 2007). For example, moving valuable items to an upper story is a wet flood-proofing measure that can be undertaken at negligible cost.

The costs of dry flood-proofing a structure will depend on the following factors (FEMA 2007):

- The size of the structure;
- The height of the flood protection elevation;
- Types of sealant and shield materials used;
- Number of openings that have to be covered by shields;
- Plumbing measures required to prevent water back-up.

At the community level, flood-proofing costs will depend largely on the number of properties in the flood hazard zone and associated costs such as flood mapping and modelling exercises to determine properties at risk.

INSTITUTIONAL AND ORGANIZATIONAL REQUIREMENTS

Flood-proofing measures are very much possible at the community level. At its simplest, wet flood-proofing involves moving valuable objects to higher ground in order to avoid the effects of flooding. Since this can be undertaken at negligible cost, wet flood-proofing is highly achievable on a local level provided sufficient warning time is provided.

More advanced flood-proofing measures are not as capital intensive as the construction or realignment of coastal defences and therefore should also be achievable at the community scale. Implementation of this technology will however, require a proactive planning approach.

It may even be possible for individual households to finance basic flood-proofing measures themselves. This may include elevating valuable items and utilities above the expected level of flooding. This will be possible if households are given adequate information on the likely level of flooding. However, more advanced
flood-proofing measures are likely to require the assistance of specialists. For example, the construction of houses within the flood zone will require experienced, professional engineers or architects to develop and/or review structure designs to ensure that structures are capable of functioning as designed.

Although flood-proofing is achievable at the community level, its effectiveness depends on community uptake and the standard to which measures are implemented. Few benefits will be gained from flood-proofing if the uptake is low or if measures are completed to a low standard. Potential unwillingness to undertake flood-proofing has been highlighted by Mathis and Nicholson (2006) who found that only 63% of new buildings are in compliance with flood regulations in the US. Due to reluctance to undertake flood-proofing measures on an individual basis, it may be necessary to inspect properties in the hazard zone to ensure that flood-proofing measures have been employed and to an acceptable standard.

Funding may be provided to local communities in order to increase uptake of flood-proofing projects. This may increase uptake in poorer communities and may help to protect those at risk rather than just those who can afford such measures. A similar outcome may be achieved if flood insurance is regionally important. Reduced premiums for flood-proofed properties will encourage the uptake of flood-proofing.

Before communities can go ahead with flood-proofing measures, it will be necessary to undertake some form of flood mapping (see Section 10). This will inform decision-makers on which buildings require flood-proofing and to what depth. It can also support the appropriate design of flood-proofing measures.

BARRIERS TO IMPLEMENTATION

Although basic flood-proofing measures can be undertaken at negligible cost, the cost of implementing more advanced flood-proofing may be prohibitive in poorer communities. This may prevent implementation but could be addressed by providing funding opportunities.

For more advanced flood-proofing measures, such as anchoring structures and installing breakaway walls, specialist knowledge is likely to be required. This may require the input of experienced architects or engineers.

In areas where flood hazard maps do not currently exist, the uptake of flood-proofing measures may be problematic. Non-availability of flood hazard maps will make identification of properties at risk and the minimum specification of flood-proofing measures difficult to define.

OPPORTUNITIES FOR IMPLEMENTATION

The main opportunity for the implementation of flood-proofing lies in the capacity to allow development in the flood hazard zone to go ahead albeit, with explicit limitations. Where there is high demand for coastal land, flood-proofing measures present an opportunity to utilise this land. This is in contrast to policies such as building setbacks (see Section 4) which prevent coastal development.

12 FLOOD SHELTERS

DEFINITION

Flood shelters are robust elevated structures that can be used as refuge by local residents during an extreme weather event. It is important that such structures are complemented by flood forecasting and warning systems to enable a timely response.

DESCRIPTION

Flood shelters are generally made of solid concrete, for ease of design and construction as well as robustness and cost efficiency. Such structures are elevated from the ground on strong pillars with a deep foundation designed to withstand high winds, water levels and potentially scour in high flow environments. Flood shelters may sometimes also incorporate a bending aerodynamic facade and protected entrance area. Structures often have metal shutters to protect against strong wind, rain and debris.

Possible design features of newly developed shelters include separate floors for livestock, separate rooms for pregnant women, gender marked toilets, enhanced toilet facilities with soak pits and septic tanks, store rooms, emergency water supply (tube wells), first aid facilities, solar lights and rain water harvesting (World Bank 2015). When not used as shelter, the structure can be used for other public purposes such as school, community centre, etc.

Construction of flood shelters should always be accompanied by an early warning system (see Section 13) to allow residents to be informed about possible adverse conditions in due course. This would include weather and water level forecasting systems and local alerts by radio, mobile phone and personnel.

> “Construction of flood shelters is a relative simple way of protecting local residents against adverse coastal conditions. When constructed, they can last for decades with a basic level of maintenance.”

Fig. 12.1. *Flood shelter structure (Photo: Helena Wright 2013, CC BY 2.0).*

ADVANTAGES

Construction of flood shelters is a relative simple way of protecting local residents against adverse coastal conditions. When constructed, they can last for decades with a basic level of maintenance. Flood shelters have saved many lives over the last decades, especially in areas frequently hit by tropical cyclones.

When appropriately designed, flood shelters also allow refuge for important possessions such as livestock. Preserving these assets is of obvious benefit in aiding coastal communities to return to normal life as quickly as possible and for enabling a greater degree of self-sufficiency in the aftermath of an extreme event.

Such structures are fairly low cost and have significant payback in terms of the number of lives preserved in extreme events.

DISADVANTAGES

Alone, flood shelters will not contribute significantly to adapting to coastal flood hazards. Instead, these structures must be implemented alongside warning systems and awareness raising campaigns to inform local residents on how and when to use such shelters.

Because flood shelters can accommodate only a limited number of people and because local residents require a shelter within reasonable travel distance in order to be effective, a high number of shelters are needed to protect larger coastal populations. Ensuring full coverage of coastal areas therefore requires significant investments and construction work.

COSTS AND FINANCIAL REQUIREMENTS

The cost of flood shelters can vary significantly between different locations depending on design conditions, local labor cost, material cost etc. As one example, a flood/cyclone shelter in Bangladesh costs approximately £ 45,000 to build (Oxfam 2015). It must also be borne in mind that such structures must be implemented alongside reliable flood warning systems, with their associated costs, to achieve their maximum potential.

INSTITUTIONAL AND ORGANIZATIONAL REQUIREMENTS

Implementation of a flood shelter protection scheme requires the development of a well-functioning early warning system and often a large number of shelter structures. It is therefore likely to involve some level of central planning, although even an isolated local shelter can save lives.

Awareness raising campaigns are also likely to be required alongside flood shelter construction. This will serve to inform local residents of the flood warning procedure and necessary response at an individual level.

BARRIERS TO IMPLEMENTATION

Barriers to implementation mainly relate to the development of a functional early warning system for maximum effectiveness. Centrally coordinated shelter coverage for the coastal population is also beneficial.

While flood shelters may be of simple design, such structures must be constructed with the extreme loadings of wind, water levels and potential flow on the structure in mind. This will serve to reduce the risk of failure which could endanger more lives.

Even once a warning system has been implemented, significant barriers to the effectiveness of this approach may still exist. Haque (1995) found that despite receiving flood warnings, a large proportion of the population took no deliberate emergency action. Three main factors were cited as reasons for failing to take action: Fear of losing household assets through looting if the house is abandoned, fatalism and disbelief of warnings. As such, despite receiving warnings, a large segment of the population remained vulnerable. These factors are dealt with in more detail in Section 13.

Additional reasons noted by Haque (1995) for failing to take action include disbelief that floods would occur in that area due to a lack of experience within living memory, over-filled shelters, the fact that shelters were crowded by men which discouraged females users and finally, a lack of awareness of the limited amount of protection that homes would provide. Sympathetically designed shelters and awareness raising campaigns have the potential to address many of these issues.

OPPORTUNITIES FOR IMPLEMENTATION

The simple nature of flood shelters offers great potential for large-scale implementation and although it does not protect farmland and property it is an efficient life-saving facility.

13 FLOOD WARNING SYSTEM

DEFINITION

A flood warning system is a way of detecting threatening events in advance. This enables the public to be warned en masse so that actions can be taken to reduce the adverse effects of the event. As such, the primary objective of a flood warning system is to reduce exposure to coastal flooding.

DESCRIPTION

The purpose of a flood warning service is to detect and forecast threatening flood events so that the public can be alerted in advance and can undertake appropriate responses to minimise the impact of the event. This is a particularly important technology in developing countries, where flooding results in massive loss of life and property.

Flood warnings are a highly important adaptive measure where protection through large scale, hard defences, is not desirable or possible. This may be the case if defences would cause adverse environmental or social problems, or where the cost of defence construction would be prohibitive.

A flood warning process has two distinct stages: (1) flood warning and (2) response. These stages are composed of a number of sub-stages and are linked through the dissemination of warnings as shown in Fig 13.1.

> “Flood warning technologies are relatively low-cost and have been successfully employed in a diverse range of countries from developed countries, such as the USA, to developing ones, like Bangladesh (IOC 2009).”

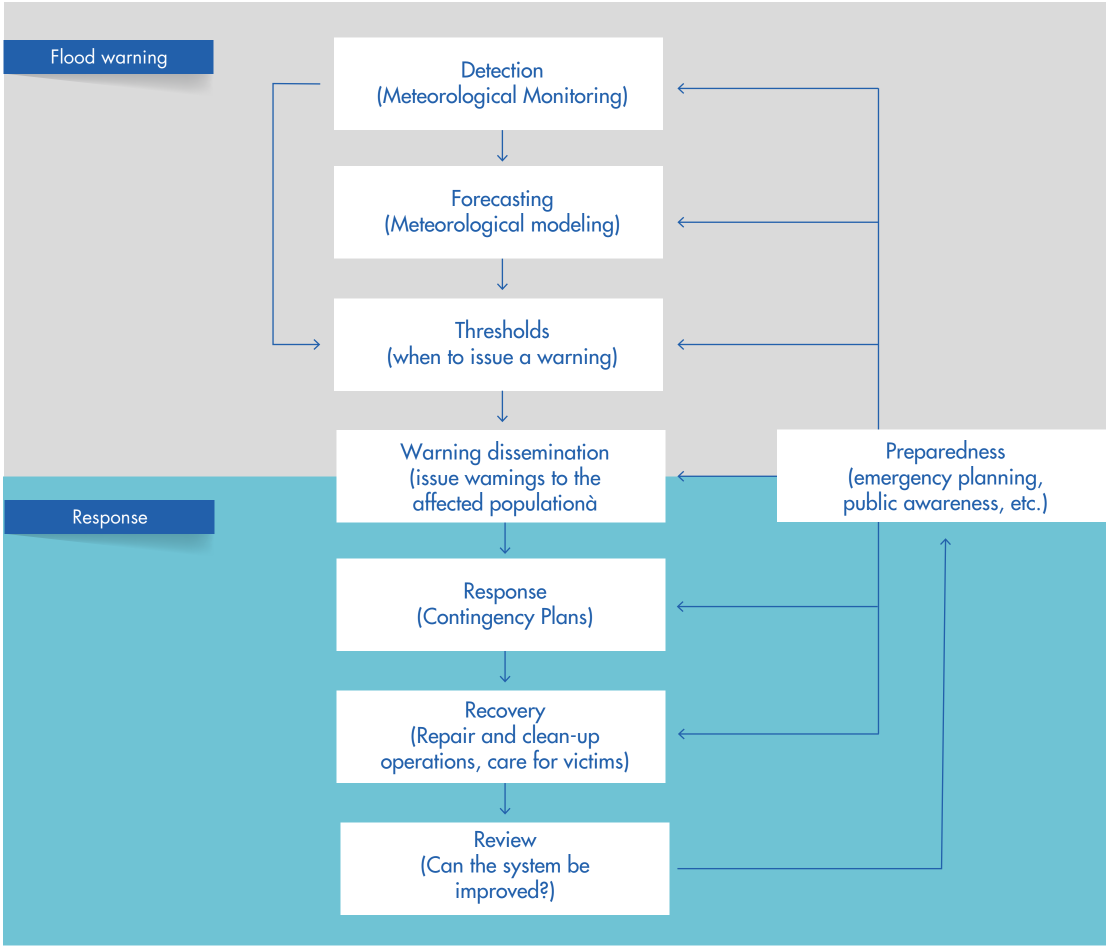

Fig. 13.1. *Components of a flood warning system (Source: Redrawn by the authors, based on Sene, 2008).*

The flood warning stage requires constant monitoring of meteorological conditions. This allows detection and assessment of threatening events to take place before it hits a community. Forecasts may also be made to help decision-makers model how an event is likely to develop, how significant it will be upon arrival, and what sections of the population are likely to be at risk. This is necessary because simple detection of an event will not provide enough time to undertake appropriate responses. To achieve monitoring and forecasting, it is likely that a flood warning system will include meteorological and tidal detection systems and river and coastal flood forecasting models.

Once an event exceeds a given threshold, a warning will be issued. This message is likely to be disseminated to the 'at risk' population via a number of channels. The media, services such as the police and fire departments and basic signals such as sirens and flags all have important roles to play.

After the at risk population have been warned, the second stage of the flood warning service is initiated; the response. Communities in the hazard zone are required to take action to minimise their exposure to the hazard and to reduce the consequences of flooding. It is important that appropriate actions are communicated to the public through awareness raising campaigns, prior to an emergency. Doing so, will mean actions can be quickly taken, helping to mitigate the consequence of flooding to the greatest degree.

An effective flood warning service requires cooperation between different agencies, such as the government, relief agencies and local communities. As such, this approach not only provides technical challenges but also, organizational ones.

At its simplest, the task of flood warning consists of answering the following five questions (EMA, 1999):

1) How high will the flood reach and when?
2) Where will the water go at that predicted height?
3) Who will be affected by flooding?
4) What information and advice do the people affected by flooding need to respond effectively?
5) What is the best way of giving the people affected by flooding the appropriate information?

Some of the essential components required in an effective coastal flood warning system are shown in Table 13.1.

Item	Component	Examples
Flood Warning	Detection	Monitoring meteorological, river & tidal conditions Meteorological forecasting (e.g. weather prediction)
	Thresholds	The meteorological, river & coastal conditions under which decisions are taken to issue flood warnings
	Dissemination	Procedures and techniques for issuing warnings to the public, local authorities, emergency services, etc.
Flood Forecasting	Rivers/Coasts	Models for forecasting future river and coastal conditions
Response	Response	Emergency works. E.g. temporary barriers, flow control, evacuation, rescue, incident management, decision support
	Recovery	Repair, debris removal, reuniting families, emergency funding arrangements Providing shelter, food, water, medical care, counselling
	Review	Review performance of all components of the system Recommendations for improvements
	Preparedness	Emergency planning, public awareness campaigns, training, systems improvements, flood risk mitigation

Table 13.1. *Typical components of a flood warning, forecasting and emergency response process (from Sene 2008).*

It is important to note that a flood warning system is not a standalone response to minimisation of the impacts of coastal flooding. An early warning system should be coupled with emergency planning measures, such as the provision of evacuation routes and flood shelters, and should also contain an awareness raising element. These systems are only useful when everybody knows what the system of warning means, what the stages of warning are and what to do when the warnings are given (Tompkins et al. 2005).

Coupling this measure with technologies, such as flood mapping (see Section 10), will improve the effectiveness of flood warnings and will help to further raise awareness of the local risk of flooding.

ADVANTAGES

HR Wallingford (2006) state that flood warning systems provide advance warning of flood events which can potentially allow:

- The risk to life to be minimised;
- Evacuation of vulnerable groups;
- Residents to move assets (e.g. food, livestock, personal effects) to safer locations;
- Timely operation of flood control structures (e.g. storm surge barriers, temporary flood defences, etc.) to prevent inundation of property and land;
- Installation of flood resilience measures (e.g. sandbags, property flood barriers);
- Pre-event maintenance operations to ensure free channel conveyance.

If warnings can be disseminated to the public, it will also be possible to give communities advice on what to do in the event of a flood, as well as providing further information to limit losses. This may include areas to be evacuated, evacuation routes and the location of refuges for evacuees. It is likely that advice and guidance can be issued through the same channels used to notify communities of the flood risk as well as being made available prior to flood events.

Flood warning technologies are relatively low-cost and have been successfully employed in a diverse range of countries from developed countries, such as the USA, to developing ones, like Bangladesh (IOC 2009).

DISADVANTAGES

As stressed above, a flood warning system is not sufficient on its own to reduce risk; people's reactions to warnings – their attitude and the nature of their response – has an important bearing upon the effectiveness of a warning system (Haque 1995). Flood warnings must be disseminated to local communities and responses must be made to minimise risks. Without these elements, the effectiveness of flood warning systems is compromised. It is therefore highly important that warnings can be communicated effectively to the public and that emergency responses are implemented. It is thus essential that the public are educated about appropriate responses to flood warnings, in advance of a flood emergency.

It is also essential that the flood warning system is accurate – system inaccuracies may lead to complacency if previous warnings were unfounded, or fear by causing unnecessary anxiety (UNFCCC 1999). In order for a flood warning system to be successful, it is essential that communities heed the warnings issued – this requires the public to trust the agency providing the warning.

COSTS AND FINANCIAL REQUIREMENTS

The costs of implementing flood warning systems are expected to differ widely, depending on the level of sophistication of monitoring and forecasting technologies.

In developing countries, meteorological observations are frequently made using basic methods, which may include ground-based methods and weather balloon observations, coupled with limited computing. In these cases, annual running costs are expected to be in the hundreds of thousands of pounds. It is also not unusual for flood warning schemes in developing countries to be heavily funded by international civil society organizations (UK POST 2005).

In more developed countries, where more sophisticated meteorological observations are made, and where computing power is more advanced, annual running costs are expected to be in the hundreds of millions of pounds (UK POST 2005).

It is not necessarily the case that lower technology systems offer less effective protection against flooding. Community-based, early warning systems such as those frequently applied in developing countries can sometimes be more effective than top-down, centralised systems. This is attributed to the fact that they can be more directly integrated into local response and risk reduction strategies (DFID 2004).

The effectiveness of flood warnings can even be improved by involving local communities, for example, in the creation of flood hazard maps, scientific monitoring and contingency planning, because these activities help to increase awareness and understanding of the impacts of natural hazards (UKPOST 2005). People-centred strategies which increase access to, and understanding of, information can even help to provide a more robust defence against a number of stresses, not just those related to climate change (Hay 2009).

Because of their ability to drastically reduce property losses and loss of life, flood warning services may be seen as a cost-effective means of mitigating flood hazards.
This is especially the case when compared against hard technologies, such as sea walls and dikes, which are often prohibitively expensive to construct.

Some of the key factors which contribute to variations in the cost of flood warning systems are provided in Box 13.1.

- Extent of meteorological monitoring network
- Cost of sourcing meteorological data
- Set up costs of warning dissemination system and its degree of sophistication
- Training and employment costs of meteorological data analysts
- Cost of associated measures:
  - Provision of flood shelters
  - Creation of evacuation routes
  - Awareness raising
  - Training of emergency services

Box 13.1. *Factors influencing the cost of implementing a flood warning system.*

INSTITUTIONAL AND ORGANIZATIONAL REQUIREMENTS

The organization of a flood warning service varies widely between countries and depending on the scale of the overall system. Sene (2008) indicates that it may include some, or all, of the following activities:

- Detection: design, installation and operation of rainfall, river level, tidal level, wind, wave and other monitoring equipment;
- Design: design of flood warning schemes, including contributing to decisions on who should receive warnings, setting flood warning thresholds, deciding how flood warnings should be disseminated and under what circumstances;
- Dissemination: monitoring measurements and forecasts against thresholds and issuing warnings following agreed procedures and public awareness activities;
- Operation: suggesting actions which should be taken to mitigate flooding risks/losses;
- Management: general management activities, including defining staff rotas, procurement, performance monitoring and reporting, research and development, etc;
- Forecasting: development and operation of flood forecasting models to provide estimates of river levels, river flows, tide levels, wave overtopping, etc.

Some of these tasks may be unnecessary for a small-scale, community-based warning system where the primary needs are for detection and dissemination of warnings. However, for a regional or national programme, most of the tasks will be necessary, although some may be shared with other organizations (Sene 2008).

It is possible to employ low technology methods in warning systems. For example, in Bangladesh, warnings are disseminated by local trained volunteers or alternatively, through channels such as newspapers, television and radio. The use of volunteer messengers has been very successful in Bangladesh, since warnings may even be viewed as more relevant and person-specific when delivered by other members of the community. This demonstrates real potential for flood warnings in developing countries.

Responses to flood warnings can also be conditioned at the community level. This may include the provision of sandbags, designing and implementing evacuation procedures, or distributing relief goods, amongst other activities. In Bangladesh, this is undertaken by local volunteers. Education may also be offered to communities at risk in advance of a significant event. This is likely to make people more aware of the severity of hazards and of the precautionary options available (Haque 1995).

It may also prove beneficial to teach coping strategies at a community level. Strategies may include swimming lessons or providing information on evacuation. Haque (1995) found that the majority of communities in Bangladesh had *not* received information from government departments regarding coping strategies for cyclones.

It can be seen that to be effective, warning systems require the development, implementation and coordination of quite diverse flood responding technologies (IOC 2009). This may prove challenging for local communities to achieve, especially given the involvement of multiple organizations in flood warning.

Despite the fact that these actions *can* take place on a local level, involving larger organizations, with superior resources, knowledge and know-how may still prove beneficial in improving the quality of warning messages from the warning systems. Better still, by working together with neighbouring countries that may also operate flood warning systems, it may be possible to obtain more complete and timely meteorological data, better dissemination of warnings and improved responses.

BARRIERS TO IMPLEMENTATION

One of the main barriers to implementation of flood warning systems in developing countries is the availability of communication channels, through which warnings can be disseminated to the public. In developed countries this can be achieved through radio and television channels and the internet. These resources are less widely available in developing countries therefore sending out the warning messages in a timely manner to the targeted audience can be problematic.

The approach also requires significant volumes of detailed information to be collected and analysed in order to detect flood threats. It needs significant investment in equipment and training. This has, however, been achieved in developing countries such as Bangladesh (Haque 1995; Mirza et al. 2005) and Vietnam (Pilarczyk & Nuoi 2010) with the help of foreign organizations who can supply information and real-time data on weather patterns (Haque 1995). Locally recognized indicators may also be important when developed by coastal communities with a close relationship with the land and sea.

Even once a warning system has been implemented, significant barriers to the effectiveness of this approach may still exist. In a field study following the April 1991 cyclone in Bangladesh, Haque (1995) found that despite receiving flood warnings, a large proportion of the population took no deliberate emergency action. Therefore, a large segment of the population remained vulnerable. Three main factors were cited as reasons for failing to take action:

1) Fear of losing household assets through looting if the house is abandoned
2) Fatalism
3) Disbelief of flood warnings

Fear of looting may be addressed by providing a denser network of smaller shelters to reduce the distance between homes and shelters and to allow better protection of property (Haque, 1995). Improved law enforcement is also needed for better protection of private property during disaster events.

Fatalism typically stems from a sense of powerlessness to influence events. It has been suggested that some individuals believe flooding is God's will and that individuals must instead just learn to live with the consequences (Haque 1995).

Disbelief of flood warnings may be due to past false warnings. It can be hard to forecast significant flood events due to their unpredictable nature. Therefore, it may be wise to implement a trade-off between the gains of advance warning when the hazard probability is low, and gains resulting from enhanced responses when the incidence of false alarms is reduced (Haque 1995).

Additional reasons noted by Haque (1995) for failing to take action include disbelief that floods would occur in that area due to a lack of experience within living memory, over-filled shelters, the fact that shelters were crowded by men, which discouraged females users and finally, a lack of awareness of the limited amount of protection that homes would provide.

OPPORTUNITIES FOR IMPLEMENTATION

It is possible to implement flood warning systems together with other adaptation measures , as part of an integrated flood risk management plan. Complementary actions could be part of a protect, accommodate or retreat approach. In London, flood warnings inform operation of a storm surge barrier and embankments have also been constructed along the majority of the riverside.

The costs involved in implementation of a flood warning system could be offset through the construction of multi-purpose shelters which could also serve as schools, health facilities and agricultural extension centres (Haque 1995). This has already proven successful in Indian communities (Mishra & Prakash 1982).

Technology used for detecting flood risk may also be used for forecasting rainfall when flood risk is low. This could benefit agricultural practices in these regions.

14 FLUVIAL SEDIMENT MANAGEMENT

DEFINITION

Fluvial sediment management is the holistic management of sediment supply from rivers to the coast, taking the full range of human activities at river basin level into account.

DESCRIPTION

Sediment transported by rivers contributes with 95% of the sediment entering the ocean and annually rivers discharge about 15-20 billion tonnes of sediment of which a large part comes from rivers in Southern Asia and Oceania (Syvitski et al. 2003; Milliman and Mei-e 1995).

The sediment supply from a river is a first-order function of river basin size and topography. Yet, smaller river basins tend to have a relatively higher sediment supply to the coast as they have a smaller flood plain where the sediment can be deposited. A large river such as the Amazon therefore only supplies a small percentage of its sediment load to the ocean, whereas smaller rivers can supply a higher percentage of their total sediment load (Milliman and Mei-e 1995).

Human activities can both increase and reduce the fluvial sediment supply to the coast. The key drivers of increased sediment load include land clearance for agriculture and other land surface disturbances such as logging and mining. The key drivers of reduced sediment supply include soil conservation and, most importantly, sediment trapping by dams and reservoirs (Walling 2006). In many large river basins, several of these drivers are present together and hence it is a complex exercise to determine the impact from human activities.

There are some examples of rivers having increased their coastal sediment supply, such as Rio Magdalena in Colombia that has increased its sediment supply by more than 40% in response to forest clearance, land use intensification and mining. This can be damaging to sensitive coastal habitats which cannot cope with high levels of sedimentation e.g. coral reefs.

Generally, however, a reduction in fluvial sediment supply is a greater and more pressing matter for coastal inundation, erosion and flooding. A large number of the world's rivers have experienced a dramatic decrease in sediment supply to the coast due to human activities in the past decades (Walling 2006). More than 40% of the global river discharge is currently being intercepted by large reservoirs and since 1950, the number of dams globally has increased more than sevenfold, with the number of dams in China alone increasing from 8 to 18,595 between 1950 and 1982 (Vörösmarty et al. 2003; Milliman and Mei-e 1995).

Examples of rivers with dramatically reduced sediment supply include the Nile River in Egypt that had its sediment supply reduced to almost zero after the construction of the Aswan High Dam compared to 100 Mt/year prior to dam construction; the Yellow River in China that had its sediment

> “In Ghana, where the construction of the Akosombo dam has resulted in a reduction of the sediment supply to the coast by about 90%, it has become necessary to undertake an $83 mill coastal protection project to stabilize the coastline of Keta (Boateng et al. 2011).”

supply reduced by over 60% since the 1980s mainly due to water abstraction, agricultural soil water conservation and damming; and the Sao Francisco river in Brazil that had its sediment output reduced by 80% after the construction of the Sobradinho Dam and related reservoirs (Walling 2006).

Consequently, downstream coastal areas often suffer major sediment deficits as a result of dam construction and management actions become increasingly necessary to protect people and property. In Ghana, where the construction of the Akosombo dam has resulted in a reduction of the sediment supply to the coast by about 90%, it has become necessary to undertake an $83 mill coastal protection project to stabilize the coastline of Keta (Boateng et al. 2011).

Fig. 14.1. *The Akosombo dam in Ghana has dramatically reduced the sediment supply to the coast from the Volta River.*

Quantifying the sediment supply to the coast faces a number of challenges, including availability and reliability of sediment load data, absence of information on bed load transport and uncertainties on how much sediment is deposited in the flood plain before it reaches the coast (Walling 2006). As many world regions suffer from problems with insufficient data for sediment supply, one has to reply on different approximation methods (Boateng et al. 2011). Advanced modelling systems, however, offer possibilities for making reliable estimates of the coastal sediment supply (DHI 2015a).

Generally, there is no standard approach for fluvial sediment management, but a clear understanding of the factors affecting the coastal sediment supply for a river basin is a key prerequisite. In some cases, subsidence of larger coastal areas due to decreasing fluvial sediment supply and geological sediment compaction can have much greater impact than the global sea level rise, and hence awareness of this coastal management component is of vital importance (Milliman and Mei-e 1995).

Often coastal areas are suffering from earlier river management decisions that are difficult to reverse and various damage control measures such as hard-engineering structures or beach nourishment may therefore be needed. However, fluvial sediment management should be taken into account in all new management decisions at river basin level, encompassing a holistic view of the whole river basin and downstream coastline. Construction of modern dams with sluicing designs that improve sediment through-flow, allowing continued sediment deposition in delta areas to minimize subsidence, should also be encouraged.

ADVANTAGES

There are far reaching advantages of implementing a fluvial sediment management scheme including minimizing coastal erosion and land subsidence. As fluvial sediment is a vital source of sediment to the coastal sediment balance, it is of general relevance for maintaining stable coasts at all sedimentary coastlines and essential for delta areas.

In many areas, fluvial sediment supply is also highly important in maintaining ground elevations in the face of compaction of relatively young and weak sediments. The importance of fluvial sediment supply becomes even more so when considering its importance in maintaining fertile lands, often in delta areas for agricultural purposes.

By addressing sediment entrapment behind dams, it also becomes possible to increase the longevity of such structures in the face of upstream sedimentation. If sediment through-flow measures can be incorporated in such structures, it clearly offers a win-win scenario for both dam developers and coastal communities.

DISADVANTAGES

The main disadvantage of fluvial sediment management relates to the resources required to determine the sediment flows at basin level and balance the different societal interests. River damming can provide great benefits to society through hydropower production, agricultural irrigation, flood and drought control, but at the same time have major impacts on coastal areas downstream, and it can therefore be a political issue to prioritise the different goals.

COSTS AND FINANCIAL REQUIREMENTS

The cost of fluvial sediment management is highly dependent on the scope and scale of the activity and the human resources and equipment requirements to implement it. As such, costs and financial requirements are highly variable from scheme to scheme.

INSTITUTIONAL AND ORGANIZATIONAL REQUIREMENTS

Fluvial sediment management requires highly specialized expertise and collaboration between a range of different institutions at river basin level. In some cases this can involve cross-border coordination and can therefore be a complex and sensitive exercise. In some locations, institutions have already been established to deal with river basin management and in these cases coastal managers can often work directly with them.

BARRIERS TO IMPLEMENTATION

The complexity of fluvial sediment management means that it requires significant scientific and administrative resources and in many cases, coordination at political level. Coastal managers may therefore need to find an appropriate balance between engaging in activities at river basin level and implementing local management actions.

Because river basins are large geographical features, effective fluvial sediment management is likely to require the cooperation of neighbouring cities, states, provinces or countries with different objectives and priorities. Without cooperation between these users, effective management of the resource is likely to be troublesome.

OPPORTUNITIES FOR IMPLEMENTATION

Improving the understanding of sediment flows at river basin level can be of great benefit to many actors in the river basin. Enhancing the data collection systems and improving the scientific understanding of the sediment dynamics can therefore be a valuable first step towards proper long term sediment management. Internationally, there is an increasing focus on a holistic approach to sediment management and efforts such as UNESCO's International Sediment Initiative aims at improving the sediment management at global scale (UNESCO 2015a).

15 GROUNDWATER MANAGEMENT

DEFINITION

Groundwater management refers to a range of measures to ensure sustainable groundwater availability, limit saltwater intrusion and limit land subsidence. Related activities include proper management of surface waters, flood management and alternative water supplies.

DESCRIPTION

Coastal aquifers are the main freshwater supply source for most urbanised coastal areas around the world. Such aquifers are sensitive to disturbances such as land use changes and groundwater pumping (Dogan and Fares 2008). With global population growth and increasing per-capita water demand, these resources are under increasing pressure from overuse.

One of the primary problems faced is that of saltwater intrusion into fresh groundwater reserves. Under healthy groundwater conditions, the seaward movement of freshwater in coastal areas prevents saltwater from encroaching on coastal aquifers and maintains the interface between freshwater and saltwater near the coast or far below the land surface. This interface is generally a diffuse zone in which freshwater and saltwater mix and is referred to as the zone of dispersion. However, human groundwater extraction and increased evaporation due to higher temperatures can reduce the freshwater flow toward the coast and cause saltwater to be drawn toward the freshwater zones of the aquifer; this can further be exacerbated by sea level rise (NOAA 2015a; USGS 2015; Schwartz 2005). Saltwater intrusion can thereby decrease freshwater storage in the coastal aquifers and in extreme cases result in the abandonment of supply wells.

> “The city of Bangkok has subsided up to 2 metres over the last 100 years and parts of Tokyo have subsided up to 5 metres mainly as a result of excessive ground water extraction (Nicholls 2014).”

Saltwater intrusion can occur by many mechanisms, including lateral encroachment from coastal waters, vertical upconing near discharging wells and coastal flooding (USGS 2015; IPCC 2014). The time it takes for saltwater to move through an aquifer and reach a pumping well can vary significantly depending on the location and lateral width of the transition zone and in some cases, many years can pass before a well that is unaffected by saltwater intrusion suddenly becomes contaminated (Kumar 2006). When saltwater intrudes into a groundwater aquifer, its recovery is very difficult, even in the longer term. This means that water may have to be supplied from other groundwater or surface water bodies, often over long distances, transferring and increasing the water stress to distant areas. In Europe, the main cause of saltwater intrusion is groundwater over-abstraction for public water supply, followed by agricultural water demand mainly for irrigation (Scheidleder 2003).

Extensive groundwater extraction can also lead to severe land subsidence of larger areas. This has been experienced in many populated areas worldwide, including major coastal cities. For example the city of Bangkok has subsided up to 2 metres over the last 100 years and parts of Tokyo have subsided up to 5 metres mainly as a result of excessive ground water extraction (Nicholls 2014). Proper groundwater management is therefore also a prerequisite for maintaining a stable land elevation.

Groundwater management encompasses both monitoring and assessment of the groundwater conditions and direct management interventions. For monitoring and assessment, a range of models have been developed over the past years that can be used for determining the groundwater flow. This can be combined with different geochemical and geophysical assessment techniques for assessing groundwater chemistry, geology and aquifer properties (DHI 2015b; Kumar 2006). Management interventions should therefore be based on a robust decision-base and address two main components (Kumar 2006):

- The present groundwater conditions related to groundwater tables, piezometric levels and salinity distribution and the current exploitation, i.e. location and rates of abstraction;
- The desired state after the intervention in terms of sustainable rates of abstraction and the means and locations thereof, groundwater tables and piezometric levels and the volume of groundwater that should be permanently present in the aquifers as a strategic reserve for emergencies and to cope with fluctuations in the rates of recharge and abstraction.

Once the present state is sufficiently known and the desired state defined within the natural, technical and economic boundaries of the hydrological system, the necessary actions can be taken. From Armstrong et al. (2015) and Kumar (2006), these could include:

- Reduction of the abstraction rates in order not to exceed the sustainable yield;
- Relocation of the abstraction works to reduce the losses of fresh groundwater by outflow;
- Increase the natural recharge and thereby the sustainable yield;
- Artificially recharge and thereby increase the sustainable yield;
- Abstraction of saline groundwater – this measure aims at increasing the volume of fresh groundwater and at reducing the losses of fresh groundwater by outflow. The abstracted saline groundwater can under certain conditions be used as a source for desalting;
- Construction of protected wells that are resilient to flooding. Protected wells can include tubewells, boreholes and dug wells and hand pumps can be fitted to most wells to improve convenience and decrease the likelihood of contamination.

In addition to these interventions, alternative water sources could be exploited, including rainwater and fog harvesting and surface water storage (ADB 2014), as well as making greater use of grey water for uses such as toilet flushing. Rainwater harvesting can be highly effective in supplementing or augmenting household and community water supplies and can also function as a supplement to public water supply disruptions during extreme events.

Desalination provides another alternative option for making saltwater or brackish water suitable for human consumption, irrigation, and other uses. The most common desalination technology makes use of reverse osmosis or nanofiltration membranes, but thermal distillation is also still applied in some desalination facilities. Desalination is generally more expensive and energy intensive than other water supply options, but if combined with renewable energy technologies it may be more viable, especially in remote locations such as oceanic islands (ADB 2014).

ADVANTAGES

Proactive groundwater management has a wealth of benefits. Primarily, this approach helps to ensure sustainable groundwater supply for essential human needs such as consumption and irrigation. Forcing planning authorities to consider long term supply issues will help to maintain consistency of supply over a wide range of climate and other scenarios. Through careful monitoring of groundwater supplies, it also helps to ensure consistency and quality of supply whilst taking hydrological changes into account in due course.

In geologically young areas, well-considered groundwater management can also help to prevent significant land subsidence. Addressing this issue proactively helps to minimise the problems associated with relative sea level rise which are likely to include land loss due to erosion and submergence, inland habitat migration and/or loss caused by coastal squeeze and increased flood damage through extreme sea level events (see IPCC 2014; IPCC 2007).

Furthermore, forward-thinking actions to sustainably manage groundwater resources are also likely to have beneficial impacts on local ecosystems which are reliant on these resources. As such, a positive management strategy is likely to have beneficial ecological outcomes.

DISADVANTAGES

Groundwater management is generally viewed as a positive and proactive measure. As such, there are few direct disadvantages of this approach. However, in order to fully implement and enforce, such strategies require allocation of significant dedicated human and financial resources.

COSTS AND FINANCIAL REQUIREMENTS

The cost of groundwater management is highly dependent on the scope and scale of activity and the human resources and equipment requirements to implement it. As such, costs and financial requirements are highly variable from scheme to scheme.

Factors which are likely to affect the cost of implementing such a scheme include:

- Baseline assessment to establish current groundwater levels, quality and sustainable abstraction rates;
- Groundwater monitoring to ensure sustainable use;
- Alternative water sources in the event of over abstraction; likely to be a factor of availability, transport distance and additional energy requirements (such as desalinization requirements);
- Protection measures against saline intrusion.

INSTITUTIONAL AND ORGANIZATIONAL REQUIREMENTS

Groundwater management should be implemented as an integrated approach comprising both surface water and groundwater, addressing both water quality and quantity. It should take a catchment area perspective and encompass data collection, hydrological projections and broader collaboration between stakeholders. Furthermore, it should address relevant regulatory frameworks. As such, proper groundwater management generally requires specialized expertise and therefore needs allocation of resources for human capacity and equipment.

In addition, groundwater management is likely to require centralised oversight by an independent body to ensure that groundwater users comply with requirements. As such, mutual agreement and understanding between stakeholders is required.

BARRIERS TO IMPLEMENTATION

The main barrier to groundwater management is the need for specialized expertise and equipment. This pertains specifically to the establishment of baseline conditions and ongoing monitoring of groundwater levels and quality. Such information must be communicated to central regulators and water abstractors to ensure that proactive action is taken when necessary.

Groundwater resources do not abide by human geographical delineations; such resources may be shared by populations in neighbouring cities, states, provinces or countries with different objectives and priorities. Without cooperation between these users, effective management of the resource is likely to be troublesome.

OPPORTUNITIES FOR IMPLEMENTATION

Proper groundwater management generates long term benefits as it can ensure predictable and sustainable freshwater supply to human activities and for growing populations. It can therefore be of great value to coastal communities to set up groundwater management schemes in due course, and well before actual salinity or subsidence problems occurs.

There is also potential for improved groundwater management through improved urban planning and design.

With increasing human populations, greater areas of land are typically covered by impermeable surfaces such as concrete, tarmac and buildings. This has the capacity to negatively impact on groundwater recharge as well as contributing to localised flooding in extreme events. Through the implementation of more sustainable drainage systems and incorporation of more open and/or green spaces through proactive town planning, groundwater recharge can be aided.

16 GROYNES

DEFINITION

Groynes are narrow, shore-perpendicular, hard structures designed to interrupt longshore sediment transport thereby trapping a portion of the sediment which is otherwise transported alongshore. By doing so, groynes help to build and stabilize the beach environment. These are generally solid, durable structures and are considered a hard-engineering protection measure to address coastal erosion.

DESCRIPTION

Groynes are normally built on *exposed* and *moderately exposed* sedimentary coastlines to address erosion hazards (Rosendahl Appelquist and Halsnæs 2015). They can be constructed from a wide variety of materials including rock armour, concrete, dolos, tetrapods, steel piling and hardwood timber.

In the UK, groynes are traditionally constructed of hardwood timber but in more recent years, rubble rock groynes have become more widely applied. This is attributed to the greater energy dissipation characteristics of rubble groynes and the fact that they are more aesthetically sympathetic; the cost differential between these options is often small though (Smith 1999). Timber groynes are generally narrower, allowing for greater recreational beach use compared to wider, rock groynes.

Groynes are often constructed in series, as part of a groyne field which allows transmission of a certain proportion of the longshore drift while continuing to retain a sufficient volume to minimise the erosion hazard.

> “If groynes are designed and maintained properly, they are robust structures that can be used for long-term stabilization of coastlines used for societal activities.”

The dimensions between groyne length and groyne spacing generally varies from 1:4 on sandy beaches to 1:2 on gravel beaches, and conventional practice is that groyne length should be approximate 40-60% of the average surf zone width. This allows the groynes to trap some, but not all, of the littoral drift (Masselink and Hughes 2003). Clearly, sediment characteristics also play a part in groyne design with longer groynes typically employed where sediments are smaller. This is because smaller sediments are typically mobile at greater water depths; consequently groynes are less effective at retaining finer material (Brampton 2002).

The ideally designed groyne field allows sediment to accumulate and eventually bypass the buried groyne, without causing significant down-drift erosion. However, the ideal design is rarely achieved due to lack of detailed data on wave climate and long-shore sediment transport rates (Davis Jr and Fitzgerald 2004).

Fig. 16.1. *Groyne field in Denmark.*

ADVANTAGES

The advantages of groynes are mainly related to their ability to trap sediment, thereby leading to beach widening with the consequent benefits of reduced erosion and greater wave energy dissipation. As such, groynes also complement other adaptation responses such as seawalls, revetments and dune construction by reducing the wave energy arriving at these structures.

However, while groynes effectively trap sediment, this can have a negative impact on downdrift coastlines through sediment starvation. Using groynes in conjunction with artificial nourishment however, acts as a sediment source to fill the beach area between groynes whilst reducing the impact on downdrift coastlines.

By fostering beach widening, groynes have the benefit of maintaining an attractive beach environment which can be valuable for recreation and tourism. This is particularly the case when applied alongside measures such as beach nourishment.

While groyne field construction requires a good degree of know-how, the measure has been widely applied around the world for decades. Consequently, there is broad global experience with groyne design and construction.

As stated above, groynes may be constructed of a wide variety of materials. To a certain degree, this allows for material selection to be tailored to local availability. In practice however, construction and maintenance costs should be carefully evaluated during the design phase to ensure that selected materials truly offer value for money. While local materials may be available, imports of quarried stone or hardwood may offer better value for money in the long term due to their greater longevity.

DISADVANTAGES

The primary disadvantage of groynes is that interruption of longshore drift to promote beach widening on one section of coastline is likely to cause sediment starvation and erosion further downstream. This is because groynes do not add sediment to the shoreface but instead distribute the available materials differently. As such, groyne construction is perhaps most effective when complemented by beach nourishment as discussed above.

By promoting sediment build up on the updrift side of the groyne, there is a consequent sediment deficit on the downdrift side, requiring the construction of further groynes to maintain beach width. At the most downdrift extent of a groyne field, a symptom known as 'terminal groyne syndrome' often exists, whereby sediment starvation causes accelerated erosion of the unprotected coastline. This has obvious negative implications.

While groynes promote recreational beach use through beach widening, another problem with their use is related to the formation of rip currents adjacent to groynes. These can present a hazard to bathers and furthermore, may also lead to sediment being transported to deep water and lost from the coastal system during storm events (Masselink and Hughes 2003).

While beach widening is typically viewed positively, groynes affect the visual appearance of the coastline by introducing unnatural, shore perpendicular structures. Groynes may also reduce accessibility of the beach to those less mobile.

COSTS AND FINANCIAL REQUIREMENTS

The cost of groynes generally consists of a large construction cost, followed by some varying O&M costs, largely dependent on the materials utilised.

Costs are dependent on a range of parameters including type of material, availability of material, labour costs, equipment cost and the related socioeconomic and geographical context. As groynes are often constructed from rock amour, data has been collected on the cost components for structures using this material, if constructed by international dredging companies. It should be noted that the cost numbers may differ if the groynes are built by local material and contractors.

Table 16.1. provides an overview of the magnitude of the different cost components in 2012 for rock armour structures constructed by the dredging company Boskalis (Rosendahl Appelquist and Halsnæs 2015). The costs are broken down into cost of rock quarrying and delivery on large pontoon at the shipment site, long distance transport by pontoon, short distance transport by pontoons at the project site and placement by grab-dredger. The numbers shown are realistic examples of the magnitude of costs for standard projects and the costs are expected to increase by 10-50% for projects with higher business risks such as projects in developing countries (Paulsen 2012).

Cost of rock armour structures (Boskalis example)	
Rock quarry & delivery on large pontoon at shipment site	
Large rocks bigger than 1 ton	40 USD/ton
Mixed size rocks	25 USD/ton
Long distance transport with large pontoon	
Cost for pontoon	13,000 USD/ day
Capacity	10,000 ton
Approximate cost for long distance rock transport	1.3 USD/ton/ day
Pontoon speed	5 knots
Shuttle pontoons for short distances to placement site	
Cost for pontoon loading	1.5 USD/ton
Cost for pontoons (with two pontoon shift)	2.5 USD/ton
Cost for tugboat	1.5 USD/ton
Placement ship - grab dredger	
Operation cost	130,000 USD/ week
Capacity	100 ton/hour
Approximate weekly capacity	10,000 ton
Approximate cost for placement	13 USD/ton

Table 16.1. *Realistic example of cost components for rock armour structures by Boskalis in 2012 prices (Rosendahl Appelquist and Halsnæs 2015; Paulsen 2012).*

In order to provide data from two independent sources, Table 16.2 shows an example of the different cost components for rock amour structures by the dredging company Van Oord in 2012 (Rosendahl Appelquist and Halsnæs 2015). The table is less detailed than Table 16.1. and shows the cost of purchase and transport of rocks, assuming a transport distance of 50 km and the cost of combined dry and waterborne placing. It should be mentioned that these costs are rough examples and can vary significantly depending on the quality of the rock/quarry, transport conditions, physical conditions at the project site and other business risks, but it can be seen that the cost levels for the two data sources listed in Table 16.1. and Table 16.2. are relatively similar.

Cost of rock armour structures (Van Oord example)	
Breakwaters/Groynes/Jetties/Revetments	
Purchase and transport of rocks based on transport distance of 50 km	25 USD/ton
Placing (combination of dry and waterborne placing)	40 USD/ton

Table 16.2. *Realistic example of cost components for rock armour structures by Van Oord in 2012 prices (Rosendahl Appelquist and Halsnæs 2015; Lindo 2012).*

In the UK, estimates of groyne construction costs vary from £10,000 (Scottish Natural Heritage 2000) to £220,000 per structure (SCOPAC 2010), not accounting for price fluctuations to the present day. These costs are largely dependent on environmental conditions for construction works, e.g. tidal restrictions limit workable construction windows, thus increasing unit costs.

Groynes of rock armour can be constructed using both large and small rocks depending on the wave exposure and environmental conditions of the project site. Typical groyne lengths are described earlier in this section. Groynes of rock armour often have the form of a trapeze, but the specific groyne dimensions depend on the local coastal profile and physical conditions.

The availability of suitable and hardwearing construction materials will be one key factor in construction cost. During the design phase, a balance should be sought between construction and maintenance costs. Furthermore, the cost of employing complementary approaches such as beach nourishment and construction of hard defences should also be considered at an early stage.

While costs are likely to vary between projects, factors which are likely to affect the unit costs of implementing such a scheme include:

- Requirement for localised data collection to inform scheme design;
- Selected construction material and availability of such;
- Anticipated wave loadings and the requirement to source large construction units to prevent movement in extreme wave conditions;
- Requirement for and/or availability and proximity of marine equipment for the purposes of construction;
- Structure length and crest height required to perform effectively;
- Environmental conditions on site including tidal restrictions, wave conditions, etc. which will impact on workable construction window;
- The need for supplementary defence schemes such as beach nourishment, revetments, seawalls, etc.;
- Availability and cost of human resources including expertise.

INSTITUTIONAL AND ORGANIZATIONAL REQUIREMENTS

The construction of a groyne field requires detailed initial design studies including analysis of wave conditions and sediment transport by specialized institutions. This will inform the length, height and spacing of a groyne field. Doing so will ensure effective design which considers the likely coastal response to these structures. Furthermore, the impacts on adjacent coastlines must also be considered so as not to simply transfer problems alongshore. To do so, at least basic design guidance must be afforded.

It is likely that groyne construction will require at least a degree of heavy construction work. Such works are likely to require large machinery and will often be carried out by a specialized contractor. If the construction material is rock armour, it is necessary to have a quarry in the vicinity of the construction site or rely on shipment of rock material from other locations. Should timber be selected, a suitable, hardwearing source must be identified, often requiring the utilisation of tropical hardwoods for the purposes of longevity.

In addition to the actual design and construction phase, it is necessary to establish a monitoring and maintenance scheme to make sure the groynes are kept in functional condition. This is particularly important when structures are constructed of degradable materials such as timber or when undermining is a possibility. Monitoring and maintenance is also central to maintaining effectiveness of these structures in hostile environments where damage is likely.

BARRIERS TO IMPLEMENTATION

Barriers to construction of groynes mainly relates to the significant construction costs, availability of suitable construction material and availability of data for the initial design phase. As groynes are long-lasting structures that have a great impact on the natural coastal environment, it is important that the design process is properly prioritized and that monitoring and maintenance are arranged.

OPPORTUNITIES FOR IMPLEMENTATION

If groynes are designed and maintained properly, they are robust structures that can be used for long-term stabilization of coastlines used for societal activities. The structures provide benefits for recreation and potentially also tourism, maintaining a good recreational beach environment.

Furthermore, opportunities exist for employing this approach alongside a number of other adaptation approaches including beach nourishment and hard engineering measures.

17 JETTIES

DEFINITION

Jetties are hard structures constructed at the banks of tidal inlets and river mouths to trap a portion of the longshore sediment transport, thereby stabilizing the inlet and preventing siltation of the channel. Jetties are solid, durable structures and are considered a hard-engineering protection measure.

DESCRIPTION

Jetties serve very much the same purpose as groynes; their distinction comes in that they are constructed at *tidal inlets* and *river mouths*, they are typically larger and also extend to greater offshore distances (Davis Jr and Fitzgerald 2004).

These structures are built to line the banks of *tidal inlets* or *river mouths*, aiming to stabilize one or both sides from shifting position. They are also employed to prevent large volumes of sand from filling the inlet, thus maintaining an open and navigable channel.

Jetties may also be used to prevent spit growth into a *tidal inlet*, thus maintaining water exchange with the open sea as well as commercial and recreational navigation.

These structures may be constructed from a wide variety of materials including rock armour, concrete, dolos, tetrapods and steel piling.

> “Since jetties can be very long, tremendous amounts of sediment can be trapped on the updrift side. This can lead to major setbacks of the coastline on the down-drift side (Davis Jr and Fitzgerald 2004).”

Fig. 17.1. *Jetty structures in California (Photo: U.S. Army Corps of Engineers Digital Visual Library 2007, CC BY-SA 3.0).*

ADVANTAGES

Jetties can provide robust and reliable stabilization of *tidal inlets* or *river mouths*, controlling the development of unwanted features which interfere with the open channel to the sea. *Tidal inlets* and *river mouths* are otherwise highly dynamic and unstable environments which can create issues for societal development.

Jetties are long term solutions to coastal protection in these locations and can be very beneficial if the coastline is developed with infrastructure and property. Their principle advantage is to ensure continuous passage of ships through a *tidal inlet* or *river mouth* which is of significant benefit for development and commerce.

DISADVANTAGES

Like groynes, jetties are designed to interrupt long-shore sediment transport, preventing sediment accumulation in an inlet or river mouth. Consequently, sediment accumulation typically occurs on their updrift side and sediment starvation on their down-drift side (Masselink and Hughes 2003).

Since jetties can be very long, tremendous amounts of sediment can be trapped on the updrift side. This can lead to major setbacks of the coastline on the down-drift side (Davis Jr and Fitzgerald 2004). Furthermore, as with groynes, the formation of rip currents in the adjacent area should be expected. With jetties typically longer than groynes it may be expected that this would lead to greater sediment loss to deep water during storm events (c.f. Masselink and Hughes 2003).

When implementing jetties, long-shore sediment transport is therefore a critical design parameter. Considering this, it may be necessary to combine jetty construction with a sediment bypassing scheme, where sediment trapped by the jetty is dredged from its updrift side and deposited on the downdrift side of the tidal inlet/river mouth. This would maintain a degree of longshore sediment supply and could be implemented alongside channel dredging which is likely to be required for the maintenance of a navigable channel.

COSTS AND FINANCIAL REQUIREMENTS

As with groynes and breakwaters, the cost of jetties generally consists of a large construction cost, followed by some varying O&M costs. The cost is depending on a range of parameters including type of material, availability of material, labour costs, equipment cost and the related socioeconomic and geographical context.

As jetties often are constructed from rock amour, data has been collected on the cost components for structures using this material, if constructed by international dredging companies. It should be noted that the cost numbers may differ if the jetties are built by local material and contractors.

Table 17.1. provides an overview of the magnitude of the different cost components in 2012 for rock armour structures constructed by the dredging company Boskalis (Rosendahl Appelquist and Halsnæs 2015). The costs are broken down into cost of rock quarrying and delivery on large pontoon at the shipment site, long distance transport by pontoon, short distance transport by pontoons at the project site and placement by grab-dredger. The numbers shown are realistic examples of the magnitude of costs for standard projects and the costs are expected to increase by 10-50% for projects with higher business risks such as projects in developing countries (Paulsen 2012).

Cost of rock armour structures (Boskalis example)	
Rock quarry & delivery on large pontoon at shipment site	
Large rocks bigger than 1 ton	40 USD/ton
Mixed size rocks	25 USD/ton
Long distance transport with large pontoon	
Cost for pontoon	13,000 USD/day
Capacity	10,000 ton
Approximate cost for long distance rock transport	1.3 USD/ton/day
Pontoon speed	5 knots
Shuttle pontoons for short distances to placement site	
Cost for pontoon loading	1.5 USD/ton
Cost for pontoons (with two pontoon shift)	2.5 USD/ton
Cost for tugboat	1.5 USD/ton
Placement ship - grab dredger	
Operation cost	130,000 USD/week
Capacity	100 ton/hour
Approximate weekly capacity	10,000 ton
Approximate cost for placement	13 USD/ton

Table 17.1. *Realistic example of cost components for rock armour structures by Boskalis in 2012 prices (Rosendahl Appelquist and Halsnæs 2015; Paulsen 2012).*

In order to provide data from two independent sources, Table 17.2. shows an example of the different cost components for rock armour structures by the dredging company Van Oord in 2012 (Rosendahl Appelquist and Halsnæs 2015). The table is less detailed than Table 17.1. and shows the cost of purchase and transport of rocks, assuming a transport distance of 50 km and the cost of combined dry and waterborne placing. It should be mentioned that these costs are rough examples and can vary significantly depending on the quality of the rock/quarry, transport conditions, physical conditions at the project site and other business risks, but it can be seen that the cost levels for the two data sources listed in Table 17.1. and Table 17.2. are relatively similar.

Cost of rock armour structures (Van Oord example)	
Breakwaters/Groynes/Jetties/ Revetments	
Purchase and transport of rocks based on transport distance of 50 km	25 USD/ton
Placing (combination of dry and waterborne placing)	40 USD/ton

Table 17.2. *Realistic example of cost components for rock armour structures by Van Oord in 2012 prices (Rosendahl Appelquist and Halsnæs 2015; Lindo 2012).*

While costs vary between projects, factors that affect the unit costs of implementing such a scheme are likely to include:

- Requirement for localized data collection to inform scheme design;
- Selected construction material and availability of such;
- Anticipated wave loadings and the requirement to source large construction units to prevent movement in extreme wave conditions;
- Requirement for and/or availability and proximity of marine equipment for the purposes of construction;
- Structure length and crest height required to perform effectively;
- Environmental conditions on site including tidal restrictions, wave conditions, etc. which will impact on workable construction window;
- The need for supplementary defence schemes such as dredging and sediment bypassing;
- Availability and cost of human resources including expertise.

INSTITUTIONAL AND ORGANIZATIONAL REQUIREMENTS

The construction of jetties requires detailed initial design studies including analysis of wave conditions and sediment transport by specialized institutions. This will inform the length, crest height and construction design of the structure for optimum effectiveness. The design phase should also consider the likely response of the adjacent coastlines to this construction. To do so, at least basic design guidance must be afforded.

For the construction phase, heavy construction work will be required for the placement of large construction elements such as rock armour or steel piling. Such work will require large machinery and is likely to be carried out by a specialized contractor. If the construction material is rock armour, it is necessary to have a quarry in the vicinity of the construction site or rely on shipment of rock material from other locations.

In addition to the actual design and construction phase, it is necessary to establish a monitoring and maintenance scheme to make sure the jetty is kept in functional condition and to monitor downdrift effects of the scheme. Sediment bypassing is likely to require specialist dredging contractors unless sediment can be collected by land-based equipment and transported by road for deposition at downdrift locations. Clearly this will be dependent on the accessibility of such environments.

Monitoring and maintenance will also be central to maintaining the effectiveness of these structures in hostile environments where damage is likely.

BARRIERS TO IMPLEMENTATION

Barriers to construction of jetties mainly relates to the significant construction costs, availability of construction material and availability of data for the initial design. The construction of such structures is often a significant engineering undertaking, working in challenging environmental conditions. As jetties are long-lasting structures that have a great impact on the natural coastal environment, it is very important that the design process is properly prioritized.

OPPORTUNITIES FOR IMPLEMENTATION

If jetties are designed and maintained properly, they are robust structures that can be used for long-term stabilization of coastlines used for societal activities. However, they can have a major impact on the adjacent coastal environment and therefore requires continuous monitoring.

A key benefit of jetties is to maintain navigable shipping channels to inland areas. As such, their construction can yield benefits in terms of developing shipping, commerce, industry and trade.

18 LAND CLAIM

DEFINITION

The main objective of land claim is neither erosion nor storm reduction. The aim of land claim is instead, to create new land from areas that were previously below high tide. However, if land claim is designed with the potential impacts of climate change in mind, measures can be taken to reduce the exposure of these areas to coastal flooding. For example, in Singapore and Hong Kong, there are enforced minimum reclamation levels to account for future sea level rise.

Land claim is likely to be accomplished by enclosing or filling shore or nearshore areas (Bird 2005). Several alternative terms may be used when referring to land claim; these may include land reclamation, reclamation fill and advance the line.

DESCRIPTION

This is a more aggressive form of coastal protection which may more accurately be termed 'attack' or 'advance the line' under the shoreline management typology. Land claim is typically undertaken to gain land, for agricultural or development purposes (French 1997). It is particularly common around coastal cities, such as Singapore and Hong Kong, where land values are very high, therefore justifying the costs. In recent years, large-scale land claims have also been conducted in Dubai, for residential, leisure and entertainment purposes. These developments include the Isle of Palms and the World.

By shortening the coastal length, land claim can contribute to coastal defence, as has been accomplished on the North Sea coast of Germany (Sterr 2008). In the future, the main benefit of land claim will remain the additional land, but under a rising sea level, coastal defence benefits will also be considered.

Coastal land claim is most frequently employed in estuaries or deltas due to the shelter afforded to potential industrial developments, such as ports and due to the availability of large areas of cheap, flat land, accessible from both land and sea (French 1997). In areas such as deltas, with positive sediment budgets, land claim has often been facilitated by steady accretion (e.g. Li et al. 2004), but this is likely to be increasingly less common through the 21st century, as sediment supplies fail (e.g. Syvitski et al., 2009). However, engineered land claim will continue, such as the Isle of Palms, Dubai and the implications of sea level rise will still need to be considered.

> "Land claim is typically undertaken to gain land, for agricultural or development purposes (French 1997)."

In order to enclose areas for land claim, hard coastal defences must be constructed seaward of the existing shoreline. Dikes (Section 6) and sea walls (Section 21) are typically constructed to protect the claimed land from flooding by the sea (Burgess et al. 2007).

Land claim generally takes place on the higher areas of the intertidal zone. This is because the higher elevation means wave energy will be reduced through interaction with lower intertidal habitats, and because less material will be required to build up the claimed land in relation to sea level. Higher elevation areas are also selected because the required defences will not need to be as high in order to prevent overtopping. Finally, if required for agriculture, the upper intertidal zone presents the most mature soil and will be more suited to farming than lower areas (French 1997).

Lower elevation intertidal areas and sub-tidal areas can also be used for land claim, although these projects will require greater engineering and investment. If low-elevation areas are to be claimed, it is necessary either to heavily protect these areas from inundation or significantly increase their elevation through the deposit of sediments. The latter can be achieved in a similar way to the deposition of sediments during beach nourishment (see Section 1). Ambitious land claim projects have been implemented in both Singapore and Hong Kong where both intertidal and sub-tidal areas have been reclaimed by elevation raising, for development purposes.

As mentioned above, the two main methods of land claim are: (1) enclosing and defending shore or nearshore areas; and (2) filling shore or nearshore areas, often using the same techniques used in beach nourishment. These approaches are illustrated in Fig 18.1. When considering adaptation to climate change, land claim using fill methods is perhaps more appropriate as it does not carry such a great flood risk.

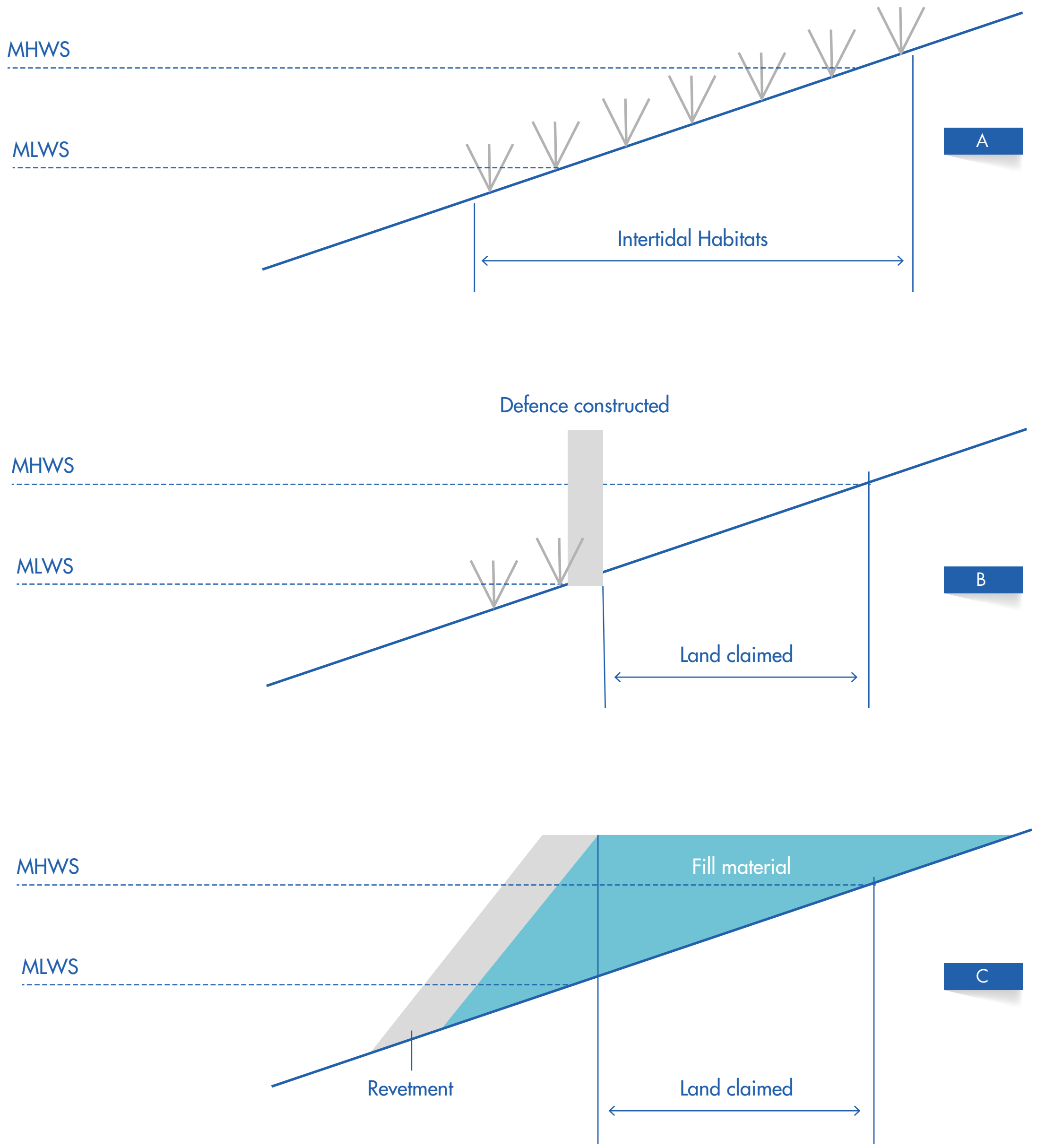

Fig. 18.1. *The main methods of land claim. There are two main methods of land claim: (A) shows the initial situation while (B) claims land by enclosing shore or nearshore areas to create a low-lying 'polder', most suitable for agriculture and (C) uses fill material to raise the elevation of shore and nearshore areas and is suitable for development purposes (Source: The authors).*

ADVANTAGES

The key advantage of land claim is the gain of additional coastal land for uses such as agriculture or development. In terms of development, coastal land can be very valuable due to accessibility by both land and sea which is essential for port development and due to its highly desirable location for housing and leisure facilities.

DISADVANTAGES

Land claim can be traced back approximately 2000 years. Early on, land claim was carried out largely to provide agricultural land, particularly in areas where the hinterland was unsuitable for cultivation. More recently, land has been claimed for port and harbour facilities and for the construction of industrial sites (French 1997). Although the physical gain of land is beneficial, it is now understood that land claim can also generate a number of negative impacts.

The process of land claim requires either the enclosure of intertidal habitats by hard defences, or the raising of their elevation above that of sea level to prevent inundation. This causes the direct loss of intertidal habitats such as saltmarshes, intertidal flats and sand dunes (French 1997). This is significant because many bird and plant species have specifically adapted to life in these zones. Furthermore, these areas are largely in decline due to coastal squeeze and human development.

Another disadvantage is dewatering. By draining reclaimed land which has a high water content, land is caused to dry out, compact and shrink (French 1997), thus reducing its elevation in relation to sea level. This causes a difference between land elevations inside the flood defences, where compaction and shrinkage has occurred and outside, where natural intertidal environments continue to naturally accrete sediments. This difference in elevation is also exacerbated by sea level rise and results in an ever increasing requirement for flood defences (Burgess et al., 2007). It also requires an ongoing commitment to defend these areas (French 1997).

The use of hard defences to claim low-lying land, as shown in Fig 18.1, can be detrimental because these structures cause erosion and scour of the shoreline. Hard defences also prevent habitat adjustment in response to changing factors such as sea level rise (French 1997).

Any type of land claim will cause the displacement of water during a natural tidal cycle. This is illustrated by Fig 18.2. Because of this displacement, incoming tides have a smaller area to inundate. This will cause water depths to increase and will mean intertidal areas are submerged for longer – this has the potential to cause negative biological consequences and can also increase the tidal range upstream (French 1997).

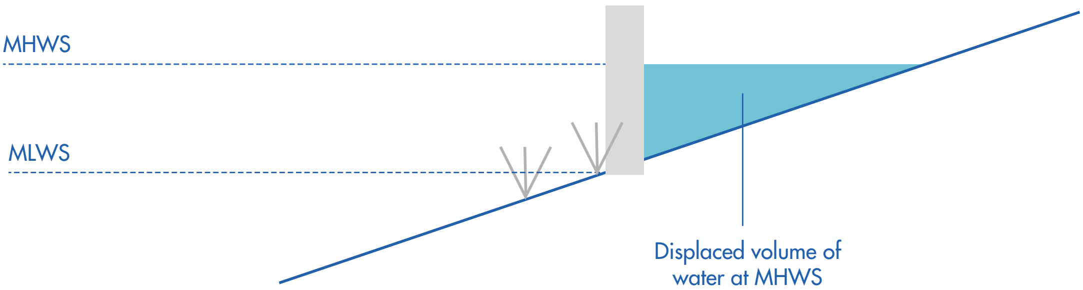

Fig. 18.2. *Illustration of the displaced volume of water at MHWS caused by land claim (Source: The authors).*

By displacing large volumes of water, land claim can also alter the basic erosional/accretional characteristics of an estuary. An estuary's erosional/accretional characteristics are closely linked to the magnitude of incoming and outgoing tides. Estuaries naturally accrete sediment when they are flood-dominant, i.e. when the incoming tide is greater in magnitude than the outgoing tide. However, by displacing water on the incoming tide, land claim can cause estuaries to switch to ebb-dominance, thus enhancing seaward sediment transport, erosion and increases in depth (Friedrichs et al. 1992). This can cause a previously stable estuary to develop erosion problems if the volume of land claim is sufficient.

The construction of hard defences prevents interactions between the sea and the hinterland. If coastal deposits such as sand dunes, mudflats or saltmarshes are located behind these defences, they are prevented from contributing to the local sediment budget. This can be problematic because these sediment deposits are required during times of erosion. Without them, a future sediment deficit and consequent erosion problems are likely to occur (French 1997).

Land claim can also introduce contamination to the coastal zone and acidification of coastal waters. This can be problematic if claimed land is to be used for agriculture or when coastal waters are important for fishing. Contaminants may be introduced through the use of dredged sediments for land elevation raising – caused by the input of hazardous chemicals from industries located on the coast, from ships or from upstream river sources. Acidification on the other hand, has been linked to the action of bacteria in estuarine sediments which create sulphuric acid when exposed to air (Anderson 1991).

COSTS AND FINANCIAL REQUIREMENTS

Work by Linham et al. (2010) into coastal defence unit costs, found that the cost of land claim by elevation raising in South-East Asia varies from US$3-5 per cubic metre of material used, at 2009 price levels. For land claim in Hong Kong Harbour, Yim (1995) stated the costs of land claim per square metre of claim are US$3.9 when utilising marine fill and US$6.4 when using land-based fill material (prices normalised to 2009 levels).

While these costs may be representative of South-East Asia, global unit costs for land reclamation are not widely available. The financial costs of land reclamation are dependent on a number of factors (see Box 18.1.).

- Chosen method of reclaim (enclosing previously intertidal areas using hard defences or raising the elevation of previously submerged land)
- Availability and proximity of fill material from onshore or offshore sites
- Number, type, size and availability of dredgers
- Requirement for hard protection measures to defend reclaimed land from coastal flooding and erosion
- Project size and resulting economies of scale
- Estimated material losses

Box 18.1. *Factors affecting the cost of land reclamation projects.*

If land claim is conducted by enclosing previously intertidal areas, the additional costs of providing hard protective measures, such as dikes and sea walls to prevent flooding and erosion of these areas is important. The cost of providing these measures has been described in Sections 6 and 21 respectively. Ongoing maintenance costs for these structures must also be considered.

If land claim is achieved by raising the elevation of previously submerged land, the cost of fill material is likely to be the main determinant of project cost. In turn, this cost will be influenced by the availability of appropriate materials, their proximity to the construction site and the characteristics of the reclaim site – this influences the type of dredging equipment which can be used. Changes in the cost of fill material are likely to occur in the future due to increased demand and greater restrictions on dredging.

INSTITUTIONAL AND ORGANIZATIONAL REQUIREMENTS

The institutional and organizational requirements of land claim projects are likely to depend on the scale and ambition of the project. Small-scale land claim for agricultural uses is more likely to be achievable at the community level than large-scale island enlargement and creation as seen in Singapore or Dubai. These large-scale projects will require the involvement of large organizations and large amounts of funding.

Land claim on the upper intertidal margins will be the easiest to accomplish at a local level, due to the presence of a lower energy wave climate and reduced fill material requirements. Land claim in greater water depths will require the construction of significant defensive measures and will call for significant quantities of fill material.

Small-scale land claim projects have been undertaken for centuries and as such, the technological requirements of these schemes appear minimal. Historic projects tended to consist of dike construction to exclude the sea, followed by drainage measures. However, historic land claims have led to significant environmental problems which were not foreseen. These problems are discussed under the disadvantages of land claim. Therefore, while land claim may be *possible* at a local level, the impacts must be borne in mind and weighed carefully against the benefits. If a project goes ahead, involvement of organizations with a good scientific and technology base could serve to reduce negative impacts.

BARRIERS TO IMPLEMENTATION

One barrier to the use of land claim is potential long-term costs. Land claim creates land which *will require* protection from coastal flooding and/or erosion. This requires construction of defences such as dikes and sea walls (discussed in Sections 6 and 21 respectively) with associated construction and ongoing maintenance costs.

Environmental concerns may provide another barrier to implementation. Land claim is most frequently undertaken in estuaries, due to the shelter afforded and availability of large areas of cheap, flat land, accessible from both land and sea (French 1997). However, a number of bird, plant and animal species have specifically adapted to life in these zones. By reclaiming land in these areas, environmentally important intertidal habitats are lost, and knock-on impacts such as alterations to ebb/flood dominance may also occur. As a result, environmental opposition to land claim may mount. In the EU, compensation for lost habitats is required; this is likely to become more widespread in other countries throughout the 21st century.

As outlined in the disadvantages section, the detrimental impacts of land claim are now better understood than in the past. Our knowledge of these impacts is likely to reduce the uptake of land claim projects based on the precautionary principle.

OPPORTUNITIES FOR IMPLEMENTATION

Opportunities for land claim exist where demand for land in the coastal zone is high. Coastal land is required for three main uses; (1) transport – mainly ports and airports; (2) leisure; and (3) residential. Due to these uses, land claim mainly takes place around cities. With projected increases in coastal zone populations, land claim may provide a highly valuable source of land. The creation of high value coastal land may also have beneficial developmental impacts.

Land claim through elevation raising may also be a cost-effective method of disposing of dredged material from ports, harbours and navigation channels. This could reduce the overall cost and eliminate the need to identify offshore disposal sites for dredge material. As with beach nourishment, pollutant levels in the dredge material should be carefully monitored.

19 MANAGED REALIGNMENT

DEFINITION

Managed realignment is able to reduce both coastal flooding and erosion. It is the deliberate process of altering flood defences to allow flooding of a presently defended area. Managing this process helps to avoid uncertain outcomes and negative impacts. It also helps to maximise the potential benefits (Leggett et al. 2004). A number of terms may be used as an alternative to managed realignment. These include managed retreat, dike realignment, dike (re)opening, de-embankment and de-polderisation.

DESCRIPTION

Managed realignment generally involves setting back the line of actively maintained defences to a new line, inland of the original or preferably, to rising ground. Doing so should promote the creation of intertidal habitat between the old and new defences, as shown in Fig 19.1. In most cases, the objective of realignment is to create saltmarshes. Saltmarshes develop between mean high water springs (MHWS) and mean low water springs (MLWS), in areas shaped predominantly by tidal processes and where silts and mud are predominant (French 1997).

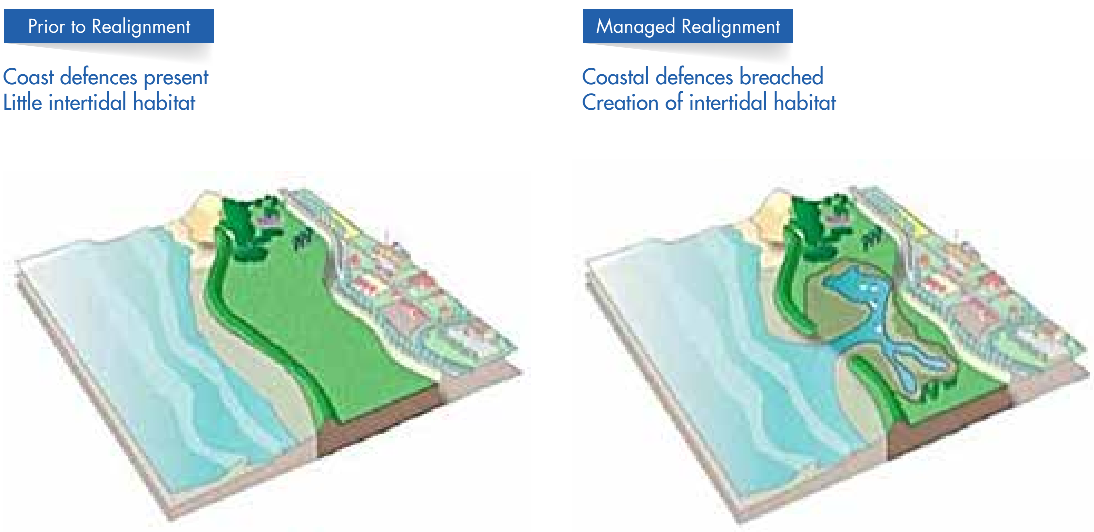

Fig. 19.1. *The process of managed realignment (Source: Adapted from ComCoast 2006).*

> Managed realignment can be part of a 'strategic' shoreline management plan. These plans typically consider tens of kilometres of coastline in a holistic sense, and address a variety of needs within the targeted area.

The benefit of creating intertidal habitats lies in the fact that they are highly effective at attenuating wave energy. This helps to reduce offshore sediment transport and therefore erosion. Intertidal habitats also form dense root mats which increase the stability of intertidal sediments, helping to reduce erosion rates (USACE 1989).

This section uses the creation of saltmarshes through managed realignment as an example because, to date, the managed realignment approach has only been applied in North-West Europe and North America, where saltmarshes are the dominant intertidal habitat. There appears to be no reason why creation of other wetland habitats, such as mangroves, should not be possible through realignment, although such an approach has not been undertaken to date.

Studies on saltmarshes have shown they are capable of attenuating up to 97% of incoming wave energy depending on the width of the marsh (Doody 2008). This can have highly beneficial implications for coastal protection. For example, if defences are realigned to an inland location, the presence of intertidal habitats can greatly reduce the cost of installing and maintaining protective measures (Doody 2008). This is illustrated in Fig 19.2. Alternatively, if realignment to higher ground is undertaken, defences may not be required at all.

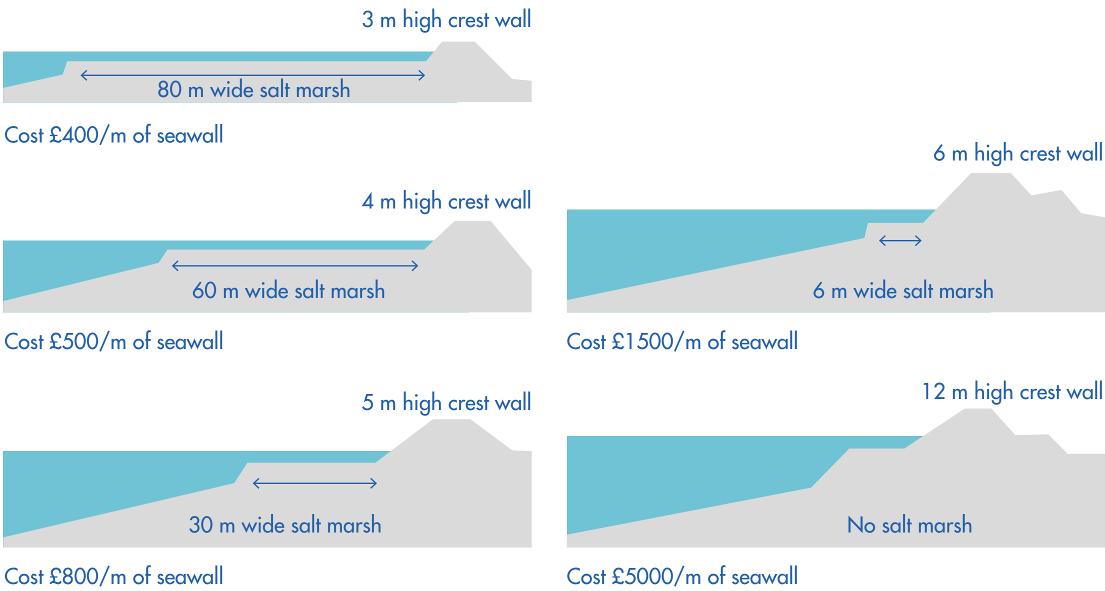

Fig. 19.2. *Effect of saltmarshes on required sea wall standards and consequent costs. Indicative costs and heights of sea defences with different widths of saltmarsh fronting. Costs presented in early 1990s prices. Information drawn from south east England (Source: Adapted from Doody 2008).*

Managed realignment may involve deliberate breaching or the complete removal of a current coastal defence. The process can be planned through abandonment or relocation of existing defences or unplanned through abandonment of defences if, for example, financial resources for maintaining defences are not available (Nicholls et al. 2007).

In order to undertake managed realignment, a number of conditions must be present. Six of the most important conditions are given below (Gardiner et al. 2007; Rupp-Armstrong and Nicholls, forthcoming):

1) presence of coastal defences
2) availability of low-lying land
3) desire or need to improve flood or coastal defence systems
4) presence of a sustainability-oriented coastal management attitude
5) desire or need to create intertidal habitats
6) societal awareness about the benefits of managed realignment

ADVANTAGES

As already mentioned, managed realignment can significantly reduce the cost of providing a given level of protection against coastal flooding and erosion. Intertidal habitats attenuate incoming wave energy, meaning that waves reaching the shore are smaller in height and less powerful. This is advantageous as it may mean hard defences are not required, or if they are necessary, that they can be of reduced height and strength. Reduced incident wave energy is also likely to result in reduced defence maintenance costs. Further cost savings can be made if realignment allows the defensive line to be shortened or completely abandoned (Nicholls et al. 2007).

The effectiveness of saltmarshes at attenuating wave energy means that the coastal zone is less reliant on engineered hard defences for reducing coastal flood and erosion risk. By increasing the coastal zone's natural flood and storm buffering capacity, the long-term sustainability is also improved (Leggett et al., 2004). The widespread application of managed retreat could significantly reduce the need for coastal defences in the future (Nicholls et al. 2007). In addition, the approach is highly robust against unexpected climate change futures and generally enhances resilience to unexpected changes (Nicholls et al. 2007).

As well as helping us respond to unexpected futures, this approach helps to mitigate carbon dioxide and methane emissions because the gases are stored within the sediment deposits. Another major benefit of managed realignment is that intertidal habitats are encouraged to return on surrendered land. This is a real benefit because coastal squeeze and human development have caused a marked decline in these habitats in many areas in recent years. Managed realignment contributes toward the reinstatement of intertidal habitats which are important to specialised birds, plants and commercially exploited fish and shellfish (Leggett et al. 2004; UK POST 2009). A beneficial by-product of intertidal habitat creation is that these areas can then be used to promote recreation and ecotourism (Nicholls et al. 2007). In the UK and elsewhere, intertidal habitats are popular areas for walking, sailing and bird watching.

As well as habitat benefits, the creation of new intertidal areas would also help to maintain water quality and avoid saltwater intrusion due to inappropriate land use. This is achieved by reducing the undesirable effects of eutrophication[1] (Leggett et al. 2004). This would be of benefit in locations where drinking water supply is threatened by sea level rise, in highly populated locations where water availability is limited, and in areas where water bodies are required to meet a certain standard.

[1] The process whereby a water body becomes hyper-enriched by plant nutrients, therefore resulting in excessive plant growth which eventually leads to oxygen depletion which is detrimental to aquatic life

DISADVANTAGES

One of the biggest drawbacks of managed realignment is that the option requires land to be yielded to the sea. This may require the relocation of important infrastructure or buildings, potentially at significant cost. Alternatively, the land may be able to be used in other ways, such as for recreation. In both instances, valuable land on the seafront is required to be relinquished.

For this reason, the managed realignment option is often of high political and social controversy. The schemes frequently suffer from a lack of public acceptance, perhaps because of a perceived threat from the sea coming closer or because of a reluctance to lose land which forefathers fought hard to (re)claim from the sea (Rupp-Armstrong & Nicholls, forthcoming).

Managed realignment is further complicated by the frequent involvement of numerous land owners. It is important to involve those affected in the planning and decision making process in order to increase acceptability.

Managed realignment is also likely to be highly disruptive and expensive if relocation of coastal infrastructure is required (Nicholls et al. 2007). Care should be taken to ensure that if infrastructure is abandoned rather than relocated, that nearby areas do not become isolated, thus leading to increased poverty (Nicholls et al. 2007). As a result, managed realignment must be strategically planned to minimise problems and avoid detrimental local impacts. If a scheme is well planned, it may even be possible to improve local opportunities.

Another disadvantage of this approach which may become more significant in the future is the conflict between the need for wetland creation and the need to retain valuable agricultural and historical sites (UK POST 2009). At present, a significant portion of realignment projects are carried out on agricultural land, largely because these sites do not require such significant relocation of infrastructure. However, inundating agricultural land may lead to reductions in local agricultural production. This is likely to become a more significant issue in the future as the issue of food security becomes more pertinent and may be particularly problematic in some developing countries.

Although experience in the application of managed realignment is growing, the approach is still relatively young and uncertainties still exist. For example, it is not fully understood how long it will take to create typical intertidal habitats that deliver the full benefits of naturally occurring systems (UK POST 2009). In addition, the approach is not necessarily conducive to all environments; wetlands and saltmarshes tend to occur in locations where wave energy is low and where high volumes of sediment are available. It is therefore important to carefully evaluate the feasibility and effects of this approach in specific locations.

COSTS AND FINANCIAL REQUIREMENTS

As no reference on the application of managed realignment in any developing countries has been found, the authors are unable to present cost information for the developing world. Developed country costs are instead presented to give some indication of costs and how they are likely to vary.

Rupp-Armstrong and Nicholls (forthcoming) state that the average cost of managed realignment in Britain is approximately US$97,000 per hectare (at 2009 prices), where construction of a new defence was also required. However, the costs of managed realignment schemes can vary widely as a result of numerous factors outlined in Box 19.1.

- Cost of the land where managed realignment will be performed
- Requirement for compensation to land owners/occupiers
- The need to dismantle human-made structures present on the site to prevent marine pollution
- Requirement for and size of sea defences to protect the hinterland
- Availability and cost of human resources including expertise
- Scale and frequency of monitoring

Box 19.1. *Factors affecting unit costs of managed realignment.*

In developed countries, where experience of managed realignment is greatest, the main cost of managed realignment is usually the cost of purchasing the land to be flooded. This may differ in developing countries where land prices are not so high and may already be owned by the state. Land costs can vary widely depending on the current land use and as such, so too will realignment costs. As an example, agricultural land is usually less costly than land used for housing or industry, largely due to the presence of infrastructure. If land is used for housing or industry it may also be necessary to provide additional compensation for relocation.

Costs may increase further if it is necessary to dismantle human-made infrastructure present in the realignment zone. This may include structures such as buildings and roads, underground pipes for gas delivery or wires for electricity, internet or television, to name but a few.

Costs are likely to be lowest if existing defences are left to breach naturally. This saves money which would have been spent on the creation of artificial breaches. In Germany, the cost of realignment is seen as a major barrier to implementation of managed realignment, since the majority of the North Sea defences are in excellent condition (Rupp & Nicholls 2002).

The scale of monitoring operations post-realignment will also influence costs. The more rigorous the monitoring schedule, the higher the likely costs.

INSTITUTIONAL AND ORGANIZATIONAL REQUIREMENTS

Both planned and unplanned managed realignment could be achieved at the community level. Breaching or abandonment of defences is inexpensive and straightforward and is therefore unlikely to require the involvement of external organizations. However, in order to obtain the greatest benefits from managed realignment, implementation must be more carefully planned. Pre-implementation monitoring and modelling will help to determine the effect of managed realignment and will help to maximise the benefits.

To avoid unwanted consequences of managed realignment, detailed planning and pre-implementation modelling studies will be required. These studies will furnish decision makers with information on how the scheme is likely to function and whether the full range of benefits will be realised. Managed realignment schemes completed to date have used modelling to determine if alterations to the site before defence breaching, such as creek excavation or elevation raising, can encourage formation of beneficial features. Additionally, pre-implementation modelling will provide information on environmental changes caused by the scheme, such as changes to estuarine ebb/flood dominance. A higher degree of certainty regarding the behaviour of managed realignment sites can be gained through modelling but this activity is likely to require the involvement of external organizations.

It is essential that coastal managers involve stakeholders including local communities in the realignment planning process. Leggett et al. (2004) claim that effective stakeholder and local community engagement is essential to successful implementation of managed realignment schemes. They also claim participation can help to:

- Understand legitimate concerns and interests;
- Explain and convince the local community of a scheme's merits;
- Manage expectations;
- Develop stakeholder ownership.

BARRIERS TO IMPLEMENTATION

Barriers to implementation have only been investigated in developed countries; to date, managed realignment has only been applied in North-West Europe and North America. However, barriers which are relevant to developed countries will also have relevance in the developing world.

Rupp-Armstrong and Nicholls (forthcoming) investigated the main barriers to implementation of managed realignment in England, Scotland, the Netherlands and Germany. Their findings are summarised below:

A lack of public acceptance is the main barrier. It is thought that opposition is caused by the perception that loss of land is a retrograde step. Concerns over loss of land with high perceived property value and development potential may also contribute to a lack of acceptance (Leggett et al. 2004). Public acceptance may also be reduced by peoples' understanding of how the technology mitigates coastal flooding and erosion. In order to overcome this barrier, it is important to communicate the true advantages and disadvantages of the approach and fully engage stakeholders in the process of managed realignment.

The second most important barrier in the studied countries relates to farming communities. These groups are frequently affected by managed realignment which is mainly implemented on agricultural land. The main barrier in this case is a lack of adequate compensation for the loss of land. If sufficient compensation were available, many farmers would be more willing to sell their land (Rupp-Armstrong & Nicholls, forthcoming).

The potentially high cost of managed realignment also poses a barrier. An analysis of existing British schemes has shown an average cost of approximately US$97,000 per hectare, for schemes involving the construction of a substantial new defence line. In addition, the relocation of infrastructure located in the managed realignment zone is potentially costly.

In other studies, legal and financial difficulties have been identified as a barrier to implementation. As previously stated, it is frequently the case that the process of managed realignment must deal with numerous coastal land owners who will be affected by the scheme. As a result there can be difficulties concerning the responsibilities and liabilities of certain land owners or authorities.

Availability of land is another significant barrier to implementation. The relocation of any infrastructure present in the realigned area requires land elsewhere. In densely populated coastal areas this may be very difficult.

As stated at the beginning of this chapter, managed realignment is not necessarily an option that can be applied in any location. Rupp-Armstrong and Nicholls (forthcoming) identified a number of criteria which are required in order to implement managed realignment. Firstly, the presence of low-lying land sheltered by existing coastal defences is an essential requirement. Without low-lying land, intertidal habitats will not be created and the full benefits of managed realignment will therefore not be realised. This must be coupled with the presence of a sustainability-oriented coastal management attitude and a societal willingness to entertain the notion of managed realignment. Without these conditions, managed realignment is either prevented from going ahead, or is likely to encounter further, significant barriers.

An extra barrier to implementation may be related to the existence of important or protected habitats behind existing coastal defences. Managed realignment can bring about detrimental impacts on such areas through tidal inundation. In the UK, coastal grazing marsh frequently occurs behind coastal defences. This environment is important for many plants, animals and endangered aquatic invertebrates. As such, coastal grazing marshes are of national and international importance for nature conservation. Managed realignment can lead to the destruction of such important habitats, causing negative impacts on the local environment.

OPPORTUNITIES FOR IMPLEMENTATION

Managed realignment can be part of a 'strategic' shoreline management plan. These plans typically consider tens of kilometres of coastline in a holistic sense, and address a variety of needs within the targeted area. This approach is often seen as a desirable way to maximise benefits and overcome potential constraints (Leggett et al. 2004).

Managed realignment can also help recreate intertidal habitats lost through human development and sea level rise. In this way, provision for coastal defence may be made but not at the expense of important intertidal habitats. In some cases, legal obligations to offset previous and predicted losses of these habitats may exist – the managed realignment response could play a role in meeting these requirements.

Opportunities for the implementation of managed realignment may also occur as a result of more site-specific factors (Leggett et al. 2004). These may include, the opportunity to reduce defence maintenance costs, opportunity to create a new nature reserve and the availability of funding for realignment.

20 REVETMENTS

DEFINITION

Revetments are shore-parallel, sloping structures, constructed landwards of the beach to dissipate and reduce wave action at the boundary between the sea and land. These structures typically protect a soft landform such as a dune area or coastal slope or provide supplementary protection to existing defences such as a dike or sea wall. They are generally very solid, durable structures and are considered a hard-engineering protection measure to address mainly erosion hazards.

DESCRIPTION

Revetments are mainly built on *exposed* and *moderately exposed* sedimentary coastlines to address erosion hazards, but can also have secondary effects on flooding and gradual inundation hazards, depending on what they are designed to protect (Rosendahl Appelquist and Halsnæs 2015). These structures fix the location of the shoreline, helping to limit damage to vulnerable back-beach environments. However, revetments do not address the root cause of erosion.

Structures are typically employed on the seaward edge of coastal sections vulnerable to erosion, such as dunes, soft cliffs or other defence measures. They are typically built from rock armour, dolos, tetrapods, asphalt blankets or gabions and designed as sloping, permeable structures to encourage wave breaking on their seaward face and to maximize energy dissipation in the interstices between construction units (Masselink and Hughes 2003).

Revetments are often constructed in combination with other protection measures including breakwaters, groynes, beach nourishment, dikes, etc.

> “Revetments are robust, long-lasting structures that fix the location of the shoreline in a similar way to the use of seawalls. By encouraging wave energy dissipation revetments are associated with fewer negative impacts.”

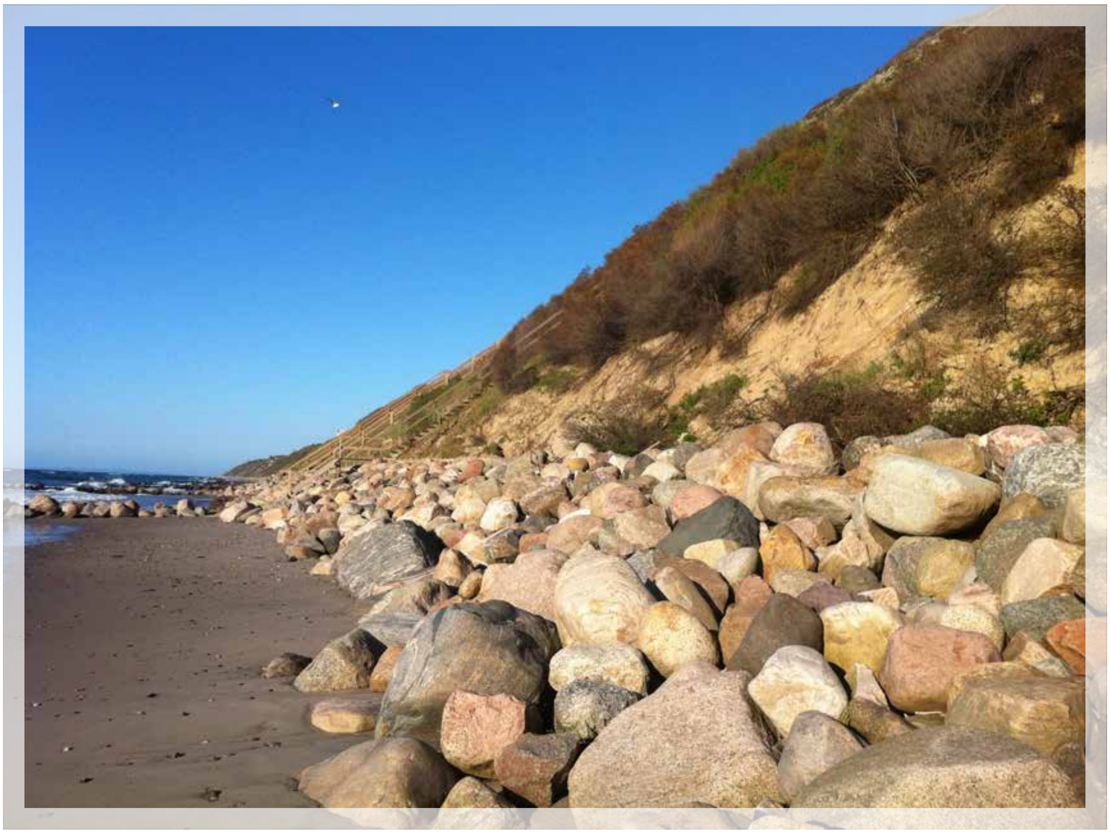

Fig. 20.1. *Revetment on a sloping soft rock coast in Denmark.*

ADVANTAGES

Revetments are robust, long-lasting structures that fix the location of the shoreline in a similar way to the use of seawalls. Their use can be critical for the protection of dunes, cliffs, dikes or seawalls from wave action. Large rock revetments will typically have a greater design life than revetments constructed of gabions and are also likely to have lower maintenance requirements.

The structures are relatively simple to construct and do not cause major interference with the longshore sediment transport. Furthermore, by encouraging wave energy dissipation revetments are associated with fewer negative impacts such as scour and toe erosion and are therefore also less susceptible to catastrophic instability.

Revetments are frequently applied alongside other adaptation responses such as seawalls and dikes as toe protection and to minimise wave reflection at the seaward side. These structures have also been shown to work effectively with beach nourishment which addresses the root cause of shoreline erosion.

While well considered design is clearly beneficial, the potentially simple construction of revetments mean that lower cost and more ad-hoc implementation is possible, to protect shorter, vulnerable sections of a coastline from wave attack, for example through the placement of riprap or gabions.

While revetments, particularly those constructed of large rock or concrete elements, can impair beach access, it is possible to incorporate a promenade into these structures in order to improve amenity value. Access points may also be built into the structures to allow recreational beach use without impairing the function of the structure significantly.

DISADVANTAGES

While revetments are effective at dissipating wave energy and therefore reducing erosion at the coast, these structures do not address the root cause of coastal erosion. As such, this phenomenon will continue to act on the coast. Only supply of sediment, for example through beach nourishment, can address this issue.

Because revetments are static structures, they conflict with the natural coastal dynamics and may cause accelerated erosion of adjacent unprotected coastlines due to their effect on the dynamic processes. In a similar way to seawalls, the coast will remain free to respond to natural conditions at the unprotected ends. This can cause undefended adjacent stretches of coastline to move inland, causing a stepped appearance to the coastline (French 2001). Despite this, they do not cause the same level of interference with the longshore sediment transport as breakwaters, groynes and jetties.

It is possible to construct revetments from lower cost construction elements such as gabions. This can help to avoid costly import of suitably large rock armour. Clearly this is beneficial in areas where coastal protection budgets are limited. However, such lower cost solutions are susceptible to abrasion and damage, requiring more thorough maintenance to preserve effectiveness.

The use of large rock armour units is frequently employed in the construction of revetments to facilitate wave energy dissipation in the interstices. However, the presence of large voids between these units can create a public health hazard if the public are permitted access to the structure. Restricting access to the structure and beach may be seen as negative although this may be addressed through the construction of a promenade and access points along the structure as discussed above.

COSTS AND FINANCIAL REQUIREMENTS

The cost of revetments generally consists of a large construction cost, followed by some varying O&M costs. The cost is dependent on a range of parameters including type of material, availability of material, labour costs, equipment cost and the related socioeconomic and geographical context. As revetments often are constructed from rock amour, data has been collected on the cost components for structures using this material, if constructed by international dredging companies. It should be noted that the cost numbers may differ if the revetment is built using local material and contractors.

Table 20.1. provides an overview of the magnitude of the different cost components in 2012 for rock armour structures constructed by the dredging company Boskalis (Rosendahl Appelquist and Halsnæs 2015). The costs are broken down into cost of rock quarrying and delivery on large pontoon at the shipment site, long distance transport by pontoon, short distance transport by pontoons at the project site and placement by grab-dredger. The numbers shown are realistic examples of the magnitude of costs for standard projects and the costs are expected to increase by 10-50% for projects with higher business risks such as projects in developing countries (Paulsen 2012).

Cost of rock armour structures (Boskalis example)	
Rock quarry & delivery on large pontoon at shipment site	
Large rocks bigger than 1 ton	40 USD/ton
Mixed size rocks	25 USD/ton
Long distance transport with large pontoon	
Cost for pontoon	13,000 USD/day
Capacity	10,000 ton
Approximate cost for long distance rock transport	1.3 USD/ton/day
Pontoon speed	5 knots
Shuttle pontoons for short distances to placement site	
Cost for pontoon loading	1.5 USD/ton
Cost for pontoons (with two pontoon shift)	2.5 USD/ton
Cost for tugboat	1.5 USD/ton
Placement ship - grab dredger	
Operation cost	130,000 USD/week
Capacity	100 ton/hour
Approximate weekly capacity	10,000 ton
Approximate cost for placement	13 USD/ton

Table 20.1. *Realistic example of cost components for rock armour structures by Boskalis in 2012 prices (Rosendahl Appelquist and Halsnæs 2015; Paulsen 2012).*

In order to provide data from two independent sources, Table 20.2. shows an example of the different cost components for rock armour structures by the dredging company Van Oord in 2012 (Rosendahl Appelquist and Halsnæs 2015). The table is less detailed than Table 20.1. and shows the cost of purchase and transport of rocks, assuming a transport distance of 50 km and the cost of combined dry and waterborne placing.

It should be mentioned that these costs are rough examples and can vary significantly depending on the quality of the rock/quarry, transport conditions, physical conditions at the project site and other business risks, but it can be seen that the cost levels for the two data sources listed in Table 20.1. and Table 20.2. are relatively similar.

Cost of rock armour structures (Van Oord example)	
Breakwaters/Groynes/Jetties/Revetments	
Purchase and transport of rocks based on transport distance of 50 km	25 USD/ton
Placing (combination of dry and waterborne placing)	40 USD/ton

Table 20.2. *Realistic example of cost components for rock armour structures by Van Oord in 2012 prices (Rosendahl Appelquist and Halsnæs 2015; Lindo 2012).*

Revetments are usually constructed from smaller rocks of < 1 ton, although larger rocks can be used in more *exposed* conditions. In *exposed* locations, revetments can have a thickness in the order of 3 metres, while they tend to be 2 metres thick at *moderately exposed* locations.

It is likely that large rock revetments will have greater lifespan than those constructed of riprap or gabions due to their greater durability. They are also likely to require less maintenance due to lower susceptibility to abrasion and damage to steel or plastic wires used to contain the smaller rocks.

As opposed to groynes, breakwaters and jetties, the location of revetments is often less challenging in terms of a building environment since these structures are typically located at or above the high water mark. If construction elements are able to be transported to the location by road and placed by land-based equipment as opposed to by vessel, costs may be reduced somewhat due to the greater availability of such equipment.

Costs estimates for UK revetment construction are available from Scottish Natural Heritage (2000) and are outlined below:

- Gabion revetments £5,000 to £50,000/100m of frontage;
- Rock armour revetments £100,000 to £300,000/100m length;
- Timber revetments £2,000 to £50,000/100 m frontage length.

While costs are likely to vary between projects, factors which are likely to affect the unit costs of implementing such a scheme include:

- Requirement for localised data collection to inform scheme design;
- Selected construction material and availability of such;
- Anticipated wave loadings and the requirement to source large construction units to prevent movement in extreme wave conditions;
- Requirement for and/or availability and proximity of marine equipment for the purposes of construction;
- Structure length and crest height required to perform effectively;
- Environmental conditions on site including tidal restrictions, wave conditions, etc. which will impact on workable construction window;
- The need for supplementary defence schemes such as beach nourishment, breakwaters, groynes, seawalls, etc.;
- Availability and cost of human resources including expertise.

INSTITUTIONAL AND ORGANIZATIONAL REQUIREMENTS

The construction of revetments requires some initial design studies including analysis of wave conditions and appropriate design dimensions. This is often performed by a specialized contractor. Design must account for anticipated wave climate and loadings on the structure which will inform size selection of construction units to prevent shifting and damage and also crest height of the structure to cope with anticipated wave run up at the location. Determination these factors requires knowledge of the wave climate to ensure suitability and resistance to damage (Brampton 2002).

During construction, heavy equipment is likely to be required, although the location of revetments is often a less challenging building environment than groynes, breakwaters and jetties for example because they are typically located at or above the high water mark. As such, construction is likely to be less demanding than for the aforementioned structures.

If the construction material is rock armour, it is necessary to have a quarry in the vicinity of the construction site or rely on shipment of rock material from other locations. Such material should have sufficient mass to prohibit movement or damage of the structure. It is possible to construct revetments of concrete elements as opposed to natural stone but this is often less aesthetically pleasing and may be opposed by local stakeholders.

In addition to the actual design and construction phase, it is necessary to establish a monitoring and maintenance scheme to make sure the revetments are kept in functional condition.

BARRIERS TO IMPLEMENTATION

Barriers to construction of revetments mainly relates to the significant construction costs, availability of construction material and availability of data for the initial design. The construction of such structures is often a significant engineering undertaking, working in challenging environmental conditions, although perhaps less so than structures which extend below the low water mark.

The availability of experience in the design of such structures may be a barrier in some less developed countries. However, design guidance does exist and extensive experience of revetment construction is available in many developed countries with long histories of coastal engineering. More challenging may be the availability of sufficient data, including wave data, on which to base structural designs.

As revetments are long-lasting structures that have a great impact on the natural coastal environment, it is important that the design process is properly prioritized.

OPPORTUNITIES FOR IMPLEMENTATION

Provided revetments are constructed and maintained properly, they are robust structures that can be used for long-term stabilization of coastlines used for societal activities. They may be combined with a range of other hazard management measures either at the time of construction or at a later stage.

As outlined above, effective revetments can be of simple construction, employing locally available materials such as large quarried stones, concrete or smaller rocks contained within plastic or steel gabions. This extends the opportunity for application in less developed countries where resources and budgets are potentially more limited.

21 SEA WALL

DEFINITION

Sea walls are hard engineered structures with a primary function to prevent further erosion of the shoreline. They are built parallel to the shore and aim to hold or prevent sliding of the soil, while providing protection from wave action (UNFCCC 1999). Although their primary function is erosion reduction, they have a secondary function as coastal flood defences.

The physical form of these structures is highly variable; sea walls can be vertical or sloping and constructed from a wide variety of materials. They may also be referred to as revetments.

DESCRIPTION

Sea walls are very widespread around the world's coasts and many ad-hoc sea walls are found in developing countries. Here, we emphasise best practice guidance, although these principles could be used for more ad-hoc structures.

Sea walls form a defining line between sea and land. They are frequently used in locations where further shore erosion will result in excessive damage, e.g. when roads and buildings are about to fall into the sea. However, while they prevent further shoreline erosion, they do not deal with the *causes* of erosion (French 2001).

Sea walls range in type and may include steel sheetpile walls, monolithic concrete barriers, rubble mound structures, brick or block walls or gabions[1] (Kamphuis 2000). Some typical sea wall designs are shown in Fig 21.1. Sea walls are typically, heavily engineered, inflexible structures and are generally expensive to construct and require proper design and construction supervision (UNFCCC 1999).

> “The sea wall in Galveston, Texas was constructed in 1903 and continues to provide coastal flood and erosion protection to the city to this day (Dean & Dalrymple 2002).”

[1] Wire baskets filled with rocks

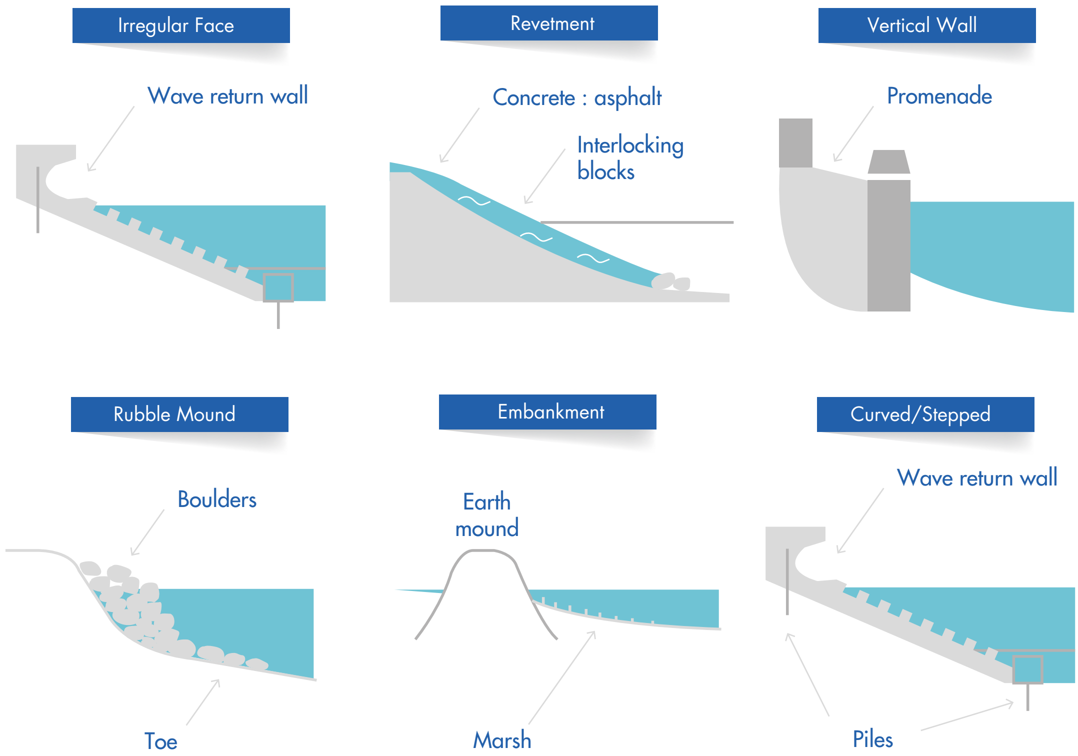

Figure 21.1. Variation in design type of sea walls. Hard, concrete structures are typically replaced by revetments and embankment-type structures in more sheltered environments (Source: Adapted from French 2001).

The shape of the seaward face is important in the deflection of incoming wave energy; smooth surfaces reflect wave energy while irregular surfaces scatter the direction of wave reflection (French 2001). Waves are likely to impact the structure with high forces and are also likely to move sand off- and along-shore, away from the structure (Kamphuis 2000).

Since sea walls are often built as a last resort, most are continually under severe wave stress.

Sea walls usually have a deep foundation for stability. Also, to overcome the earth pressure on the landward side of the structure, 'deadmen' or earth anchors can be buried upland and connected to the wall by rods (Dean & Dalrymple 2002).

ADVANTAGES

The main advantage of a sea wall is that it provides a high degree of protection against coastal flooding and erosion. A well maintained and appropriately designed sea wall will also fix the boundary between the sea and land to ensure no further erosion will occur – this is beneficial if the shoreline is home to important infrastructure or other buildings of importance.

As well as fixing the boundary between land and sea, sea walls also provide coastal flood protection against extreme water levels. Provided they are appropriately designed to withstand the additional forces, sea walls will provide protection against water levels up to the sea wall design height. In the past the design height of many sea walls was based on the highest known flood level (van der Meer 1998).

Sea walls also have a much lower space requirement than other coastal defences such as dikes (Section 6), especially if vertical sea wall designs are selected. In many areas land in the coastal zone is highly sought-after; by reducing the space requirements for coastal defence the overall costs of construction may fall. The increased security provided by sea wall construction also maintains hinterland values and may promote investment and development of the area (Nicholls et al. 2007). Moreover, if appropriately designed, sea walls have a high amenity value – in many countries, sea walls incorporate promenades which encourage recreation and tourism.

When considering adaptation to climate change, another advantage of sea walls is that it is possible to progressively upgrade these structures by increasing the structure height in response to sea level rise. It is important however, that sea wall upgrade does not compromise the integrity of the structure. Upgrading defences will leave a 'construction joint' between the new section and the pre-existing sea wall. Upgrades need to account for this weakened section and reinforce it appropriately.

Provided they are adequately maintained, sea walls are potentially long-lived structures. The sea wall in Galveston, Texas was constructed in 1903 and continues to provide coastal flood and erosion protection to the city to this day (Dean & Dalrymple 2002).

DISADVANTAGES

Sea walls are subjected to significant loadings, as a result of wave impact. These loadings increase with water depth in front of the structure because this enables larger waves close to the shoreline. Sea walls are designed to dissipate or reflect incoming wave energy and as such, must be designed to remain stable under extreme wave loadings. The effects of sea level rise, increased wave heights and increased storminess caused by climate change must all be taken into account.

Smooth, vertical sea walls are the least effective at dissipating wave energy; instead, the structures reflect wave energy seawards. Reflection creates turbulence, capable of suspending sediments (Bush et al. 2004), thus making them more susceptible to erosion. In a worst-case scenario, reflected energy can interact with incoming waves to set up a standing wave which causes intense scouring of the shoreline (French 2001).

Scour at the foot of a sea wall is a particular problem with vertical sea wall designs. This phenomenon is caused by the process shown in Fig 21.2. Incoming waves impact the structure, causing water to shoot upwards. When the water falls back down, the force on the seabed causes a scour hole to develop *in front of* the structure. This can cause structural instability and is an important factor leading to the failure of many sea walls. As a result, sea wall maintenance costs can be high (Pilarczyk 1990). A similar process occurs on inclined sea walls but in this case scour will occur *away* from the foot of the structure.

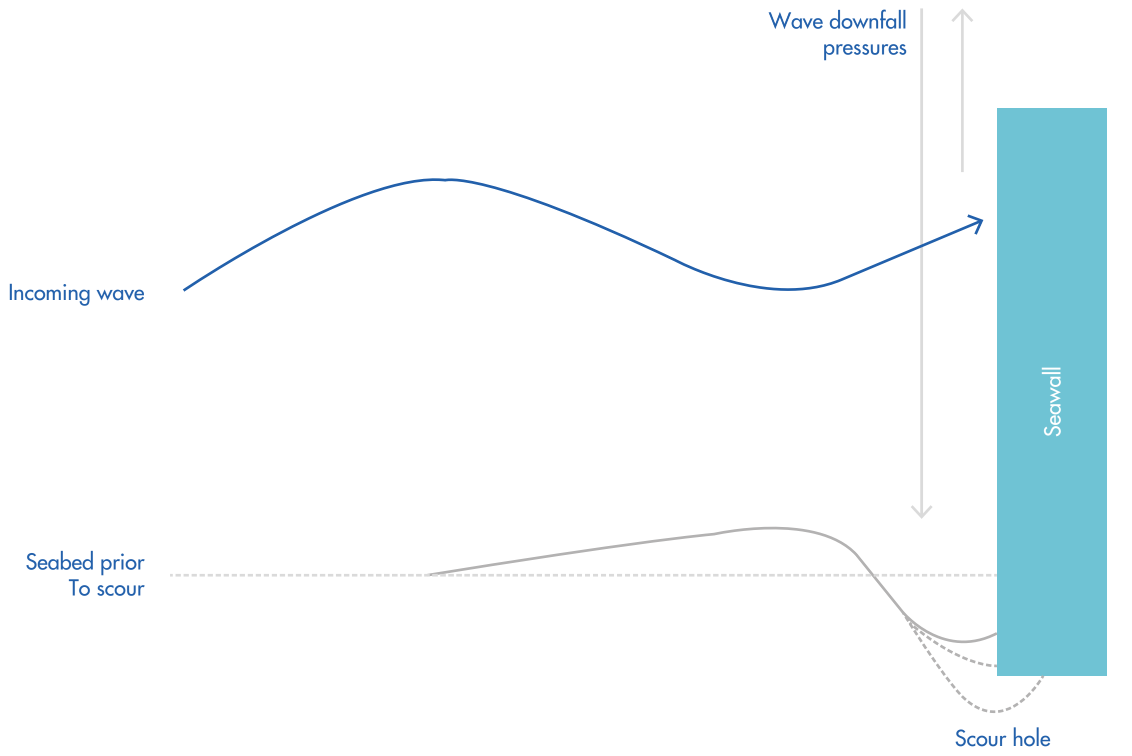

Fig. 21.2. *Schematic illustration of sea wall scour. Scour occurs at the foot of a sea wall as a result of wave impact. Dashed lines at the base of the wall indicate potential future scenarios with sea wall undermining (Source: The authors).*

The problems of wave reflection and scour can be reduced to some degree by incorporating slopes and irregular surfaces into the structure design. Slopes encourage wave breaking and therefore energy dissipation while irregular surfaces scatter the direction of wave reflection (French 2001). Pilarczyk (1990) recommends the use of *maximum sea wall slopes of 1:3* to minimise scour due to wave reflection.

Sediment availability is also affected by sea wall construction. The problem is caused by replacing soft, erodible shorelines with hard, non-erodible ones. While this protects the valuable hinterland, it causes problems in terms of sediment starvation; erosion in front of the sea wall will continue at historic or faster rates but the sediment is not replaced through the erosion of the hinterland (French 2001). This can cause beach lowering, which reduces beach amenity value and increases wave loadings on the sea wall by allowing larger waves close to the shore.

In the absence of a sea wall, natural shoreline erosion would supply adjacent stretches of coastline with sediment, through a process known as longshore drift. Once a sea wall is constructed however, the shoreline is protected from erosion and the supply of sediment is halted. This causes sediment starvation at sites located alongshore, in the direction of longshore drift and this has the capacity to induce erosion at these sites.

Although sea walls prevent erosion of protected shorelines, where the sea wall ends, the coast remains free to respond to natural conditions. This means that undefended areas adjacent to the wall could move inland causing a stepped appearance to the coast (French 2001). The downdrift end of the sea wall is also typically subjected to increased erosion as a result of natural processes (see Fig 21.3). This flanking effect can cause undermining and instability of the wall in extreme cases.

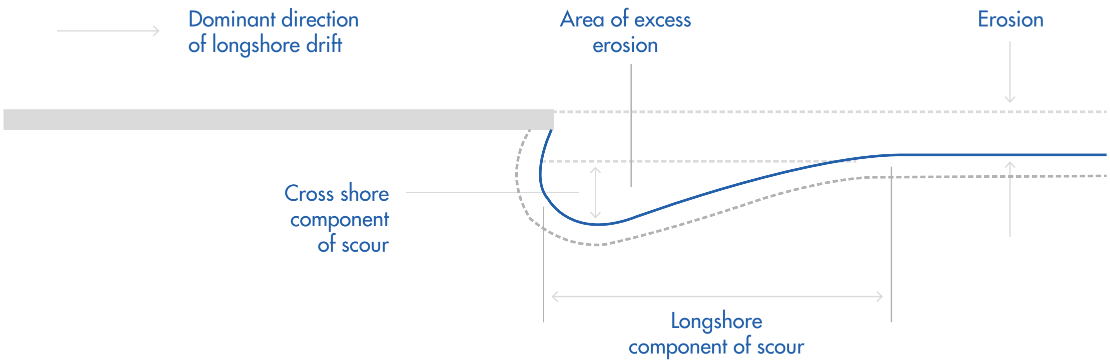

Fig. 21.3. *A sea wall as viewed from above, showing typical end effects associated with the structure. The dotted line indicates possible future shoreline position, with outflanking behind the barrier and undermining of the structure (Source: Adapted from McDougal et al. 1987).*

Because sea walls are immovable defences, they can also interfere with natural processes such as habitat migration which is naturally induced by sea level change. Sea walls obstruct the natural inland migration of coastal systems in response to sea level rise, therefore causing coastal squeeze. This process causes a reduction in the area of intertidal habitats such as sandy beaches and saltmarshes because these environments are trapped between a rising sea level and unmoving, hard defences.

In estuaries, sea walls also cause changes to the area inundated by the tides thus, reducing the available area for occupation by water on a high tide. With the same volume of water flowing into the estuary, the level of the water after sea wall construction will be higher. This may mean areas in front of the defence remain submerged longer and by greater depths. In turn, this is likely to affect the distribution of vegetation and could increase tidal range upstream of the defence (French 2001).

Another potential problem is overtopping. This occurs when water levels exceed the height of the sea wall, resulting in water flow into areas behind the structure. Overtopping is not a continuous process but usually occurs when individual high waves attack the sea wall, causing a temporary increase in water level which exceeds the structure height (Goda 2000). If the structure is too low, excessive overtopping can remove considerable amounts of soil or sand from behind the wall, thus weakening it. Further, overtopping water saturates and weakens the soil, increasing pressures from the landward side, which can cause the foot of the structure to 'kick out' and collapse (Dean & Dalrymple 2002). Overtopping will become increasingly problematic with sea level rise, increased wave heights and increased storminess.

As mentioned in the advantages section, sea walls increase security by reducing the risk of flooding and erosion. However, the coastal zone remains a high risk location not least due to the presence of residual risk. To combat unwise development of the coastal zone, future developments need to be carefully planned.

Additionally, by encouraging development, hard defences necessitate continued investment in maintenance and upgrades, effectively limiting future coastal management options. Although authorities may not have a responsibility to continue providing protection, the removal of defences is likely to be both costly and politically controversial (Nicholls et al. 2007).

Sea walls also reduce beach access for handicapped people and for emergency services. This can be problematic if the beach fronting such structures is to be used for recreation. The appearance of sea walls can be aesthetically displeasing which can further negatively affect beaches dependent upon a tourist economy.

COSTS AND FINANCIAL REQUIREMENTS

A study by Linham et al. (2010) indicates that the unit cost of constructing 1 km of vertical sea wall is in the range of US$0.4 to 27.5 million. The study found sea wall costs for around ten countries. Most were developed country examples, although a number of newly developed and developing countries, such as Egypt, Singapore and South Africa were also found. Problems arise in the reporting of unit costs for vertical sea walls as the effect of height on unit costs is rarely considered. As such, these costs are likely to relate to sea walls of various heights; this explains some of the significant variation in costs between projects.

Some of the best unit cost information is given by the English Environment Agency (2007), for unit costs relevant to the UK. This source gives an average construction cost for sea walls of US$2.65 million (at 2009 price levels). This cost includes direct construction costs, direct overheads, costs of associated construction works, minor associated work, temporary works, compensation events and delay costs. This does not include Value Added Tax (VAT) or external costs such as consultants, land and compensation payments. Variation in costs between projects is a result of numerous factors, detailed in Box 21.1.

- Design height is a major factor affecting costs per unit length of sea wall. Height affects the volume of materials required for construction and the build time
- Anticipated wave loadings will affect how resilient the structure needs to be; deeper waters and exposed coasts cause higher wave loadings which will mean the structure needs to be more robust, thus higher costs
- Single or multi stage construction; costs are lower for single stage (Nicholls & Leatherman 1995)
- Selected sea wall design and the standard of protection desired. Certain design features will increase costs and more robust sea walls will be more costly
- Construction materials (e.g. rubble blocks, pre-cast concrete elements, metal, soil, etc.)
- Proximity to and availability of raw construction materials
- Availability and cost of human resources including expertise

Box 21.1. *Factors affecting unit costs of sea wall construction.*

Maintenance costs are another significant and ongoing expense when a hard defence is selected. These costs are ongoing for the life of the structure and are therefore likely to result in significant levels of investment through a project's lifetime. Continued investment in maintenance is highly recommended to ensure defences continue to provide design levels of protection (Linham et al. 2010).

It has been noted that construction and maintenance costs are likely to increase into the future in response to sea level rise (Burgess & Townend 2004; Townend & Burgess 2004). This is caused by increases in water depth in front of the structure which, in turn cause increased wave heights and wave loadings on the structure.

Maintenance costs are also likely to be higher when sea walls are poorly designed or constructed of inappropriate materials. In many cases, design can be of secondary importance to the availability of raw materials, especially in locations where appropriate construction materials are scare. This was found to be the case in a study of shoreline protection in rural Fiji by Mimura and Nunn (1998). Their study highlights the problem that inappropriate design often leads to unfavourable effects, such as wave reflection and toe scour. In the absence of proper design, it is not unusual for designs from one location to be blindly copied at another. Such an approach is likely to result in exaggerated socio-economic and environmental costs (UNFCCC 1999). The provision of even, basic design guidance would improve project performance in many cases.

INSTITUTIONAL AND ORGANIZATIONAL REQUIREMENTS

Sea wall construction is possible on a community scale. There are many examples of ad-hoc construction to protect individual properties and communities. However, ad-hoc sea walls are likely to give much less consideration to the water levels, wave heights and wave loadings during an extreme event. This is largely because these events are hard to foresee without a well-developed science and technology base. For example, traditional sea wall construction methods in Fiji involved poking sticks into the ground to create a fence, behind which logs, sand and refuse would be piled to pose a barrier to the sea. This type of traditional construction has shown to have low effectiveness against significant events, however, and in many cases, these defences are washed away during extreme events (Mimura & Nunn 1998).

A degree of technical guidance would be of benefit in the design and construction of effective sea walls. This would improve their effectiveness during extreme events and would also help to reduce adverse impacts on adjacent coastlines.

Although it is clearly *possible* to construct ad-hoc, or traditional, low technology sea walls at a community level, these structures have been shown to afford lower levels of protection against extreme events than designs with a solid science and technology base. They have also been known to exacerbate existing problems.

At present, the advice given in developing countries for modern sea wall construction appears to be informal, if given at all. If effective design and construction is to occur, local communities must be given at least basic design guidance. This may come from government or voluntary organizations.

Sea wall maintenance is likely to be possible at a community level when given appropriate training. This may include educating maintenance engineers on the likely failure mechanisms, how often to survey the structure, what to look for and how to identify weaknesses in the design. If major weaknesses are found, it may be necessary to employ a professional organization to repair the structure in the most effective manner.

BARRIERS TO IMPLEMENTATION

One of the main barriers to the implementation of a well-designed sea wall is cost. The design of an effective sea wall requires good quality, long-term environmental data such as wave heights and extreme sea levels. This is frequently unavailable in developing countries and can be costly to collect. Secondly, because sea walls are frequently exposed to high wave loadings, their design must be highly robust, requiring good design, significant quantities of raw materials and potentially complicated construction methods. In locations of high energy waves, additional cost must be expended on protective measures such as rip-rap[2] to protect the structure's toe.

A case study from the Pacific island of Fiji (Mimura & Nunn 1998) shows sea wall construction to be very costly even when local materials were utilised in conjunction with other materials supplied by the government. Sea wall construction in Fiji consumed the villagers' time and also required significant time and money to be spent on the provision of catering services for workers.

The availability of experience, materials, labour and specialised machinery for the construction of sea walls may also pose a barrier to the implementation of this technology.

French (2001) recommends proactive construction of sea walls at some distance inland. This reduces interference with coastal processes and creates a buffer zone to protect against coastal flooding and erosion. A key barrier to this type of approach lies in convincing and educating landowners of the necessity for, and benefits of, these measures (Mimura & Nunn 1998).

[2] Wide-graded quarry stone normally used as a protective layer to prevent erosion (Coastal Research, 2010).

OPPORTUNITIES FOR IMPLEMENTATION

Sea wall construction is one of several options available when high value land cannot be protected in other ways. The approach provides a high level of protection to valuable coastal areas although the long-term sustainability of the approach should also be taken into account.

Less technologically advanced designs can be implemented at local levels, utilising local knowledge and craftsmanship. This requires less investment and a reduced need for involvement of large organizational bodies such as national or sub-national government or non-governmental organizations (NGOs). While ad-hoc implementation is possible, technological guidance from expert organizations is desirable to ensure sufficient levels of protection.

Sea walls can also be implemented as part of a wider coastal zone management plan which employs other technologies such as beach nourishment (see Section 1) and managed realignment (see Section 19). Placement of sea walls inland, following managed retreat, reduces interference with coastal zone processes and creates a buffer zone to protect against coastal flooding and erosion (French 2001). The sea wall therefore acts as a last line of defence. Use of sea walls in conjunction with beach nourishment can also address some of the negative impacts of sea wall construction, such as beach lowering and downdrift erosion.

22 STORM SURGE BARRIER/ CLOSURE DAM

DEFINITION

Storm surge barriers and closure dams are hard engineered structures with a primary function of preventing coastal flooding. Their secondary role is to shorten the required length of defences behind the barrier. This reduces the risk of defence failure and reduces the cost of providing the additional defences. Surge barriers are movable or fixed barriers or gates which are closed when an extreme water level is forecast in order to prevent flooding. Closure dams are fixed structures that permanently close off a river mouth or estuary. For these and fixed barriers, water is discharged through, or pumped over the barrier (IOC 2009).

DESCRIPTION

Storm surge barriers and closure dams are large-scale coastal defence projects, capable of protecting tidal inlets, rivers and estuaries from occasional storm surge events (UNFCCC 1999). They provide a physical barrier which prevents storm surges travelling upstream. This helps to keep upstream water levels low and therefore minimises coastal flooding. The two solutions are most frequently applied at narrow tidal inlets, where the length of the structure is not required to be so great and where defences behind the barrier can be reduced in height or length. An example of a movable storm surge barrier is shown in Fig 22.1

> “Surge barriers and closure dams can be easily integrated into larger, overall flood prevention systems.”

Fig. 22.1. *The Thames Barrier is a movable storm surge barrier constructed in 1982 to protect London (Photo: Rui Saraiva/Shutterstock).*

Storm surge barriers most commonly consist of a physical, movable barrier across the mouth of a tidal inlet or estuary. While there are no known examples in the developing world, a number of projects have been completed in developed countries, mainly in Europe. For example, the Thames Barrier, London, the Maeslantkering Barrier, Rotterdam and the St. Petersburg Flood Protection Barrier, while the MOSE project in Venice is scheduled for completion in 2018. Although each of these projects has roughly the same objective, the design of these structures varies significantly.

Fixed barriers and closure dams are a lower technology option which may be more appropriate in developing countries. These are non-movable barriers across tidal inlets or estuaries. They are constructed through gradual or sudden closure of an inlet. Gradual closure can be accomplished through land-based construction which gradually narrows the inlet, or by water-based construction which builds a barrier up, layer by layer, from the seabed. Alternatively, sudden closure blocks an inlet in a single operation, using pre-installed gates or by the placement of a caisson[1].

Examples of completed closure dams include the Feni closure dam in Bangladesh, constructed mainly to provide a freshwater reservoir for irrigation purposes, several projects in Korea to close tidal basins, mainly for land claim (van Houweninge & de Graauw 1982) and the Afsluitdijk, in the Netherlands, which separates what is now Lake IJsselmeer from the North Sea.

Movable barriers will require the simultaneous implementation of a storm surge monitoring and flood warning system (an adaptation option in its own right and discussed in Section 13). This will allow the barrier to be moved into position before a storm surge arrives. Because closure dams are fixed structures, they do not require these systems.

While there are clear differences between storm surge barriers and closure dams, the coastal defence purpose of the structures is the same; to prevent extreme water levels penetrating an estuary. The method, by which this is achieved, is illustrated in Fig 22.2.

[1] A retaining, watertight structure

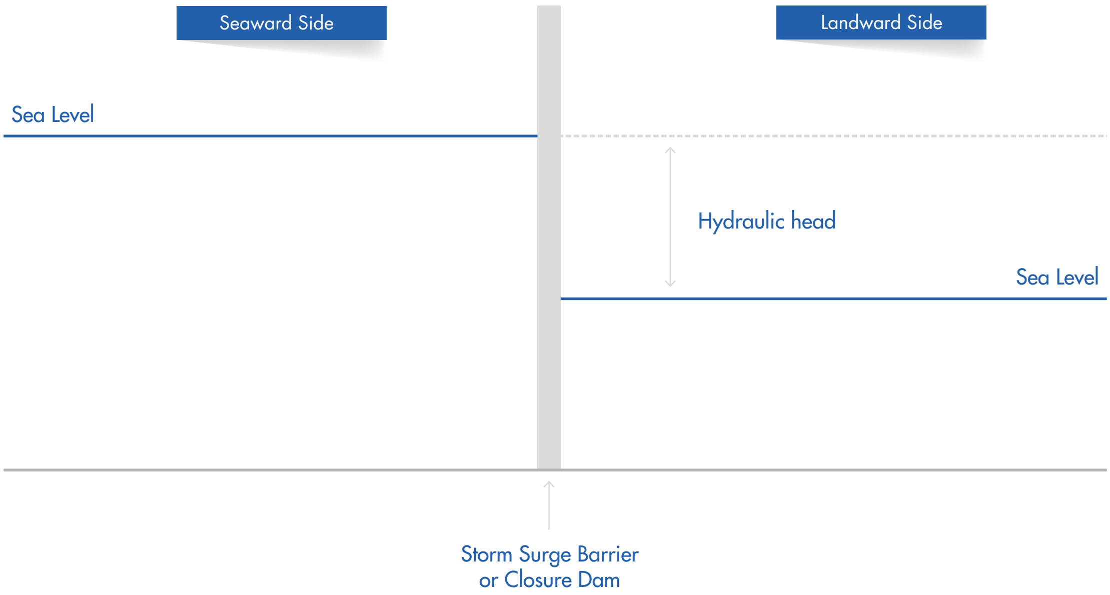

Fig. 22.2. *Schematic illustration of how storm surge barriers and closure dams prevent coastal flooding. During an extreme event, a storm surge will cause a rise in sea level on the seaward side of the barrier. The presence of a physical barrier such as a closure dam or storm surge barrier prevents high waters from penetrating the estuary. As a result, the water level on the landward side remains low (Source: The authors).*

Surge barriers and closure dams can be easily integrated into larger, overall flood prevention systems. For example, barriers may be present alongside additional flood prevention works such as dikes and flood warning systems (Sections 6 and 13).

An important characteristic of surge barriers is that they are movable. As such, they are often partly opened during normal conditions. This will allow tides and saltwater to enter the areas behind the barrier (Hillen et al. 2010) and allows continued use of waterways for shipping and transport. Conversely, closure dams permanently close off estuarine areas. This prevents interactions between freshwater and the sea and also prevents use of the waterway for shipping and transport.

ADVANTAGES

Storm surge barriers and closure dams provide a high degree of protection against coastal flooding by preventing storm surges from entering low-lying estuarine areas. Although permanently closing off the estuary mouth using a closure dam, would achieve the same outcome, the use of a movable barrier allows waterways to remain open during normal conditions. This can be beneficial to trade if the estuary also acts as a trading port and is also valuable for estuarine species reliant on brackish water[2] conditions.

The two technologies effectively reduce the height of extreme water levels in the area behind the barrier, if closed in a timely fashion. Doing so may allow the strength of existing defences behind the barrier to be reduced (Hillen et al. 2010). This will reduce both construction and maintenance costs for defences on the landward side of these structures.

By reducing the height of extreme water levels inside of the barrier, the length of a coastal flood defence system may also be shortened (Hillen et al. 2010). This too, would have the effect of reducing maintenance and construction costs of defences on the landward side of the barrier.

More than one barrier may be constructed to close off narrow inlets into a tidal system, such as a lagoon. This is the case in Venice under the MOSE project where three barriers are under construction to close three of the lagoon's narrow tidal inlets. Through the construction of multiple barriers, the scheme offers the additional benefit of enhancing the lagoon's natural capacity to clean itself. This is achieved by independently opening and closing selected barriers, depending on wind direction. By closing barriers it enhances the ability of the wind to drive water out of the lagoon, therefore increasing the turnover of water, dispersing pollutants.

Closure dams can provide additional benefits by forming a permanent barrier between freshwater and the sea. For example, in Bangladesh, the Feni closure dam was constructed primarily to provide a reservoir of freshwater for irrigation purposes. Closure dams may also be used in conjunction with land claim (see Section 18) and may even be used for the production of tidal energy (van Houweninge & de Graauw 1982).

[2] A mixture of salt and fresh water – brackish water is salty but not as salty as sea water.

DISADVANTAGES

One of the key disadvantages of the storm surge barrier is the high capital and maintenance costs. Significant investment is required to construct these structures and to continually maintain them. In addition, movable barriers also require simultaneous investment in flood warning systems which provides information on when to close the barrier. This cost is avoided through the use of a closure dam, which also has lower capital and maintenance costs.

A potential disadvantage of both surge barriers and closure dams is they can cause flooding on the landward side of the barrier when river levels are high and, in the case of movable barriers, if the defence remains closed for an extended period. Landward flooding occurs as a result of water backing up on the landward side of the barrier due to the obstruction of continued river discharge by the barrier. This should not present a problem, provided closure dams are designed to cope with extreme river discharges and that studies to determine the maximum duration of closure have been undertaken in the case of movable barriers.

Both surge barriers and closure dams have the capacity to change the chemical, physical and biological properties of estuarine systems by altering the inflow and outflow of water from the estuary. This may include alterations to water salinity, temperature, suspended matter, nutrients which all have the potential to affect local communities of organisms (Elgershuizen 1981). These changes will be more significant in the case of a closure dam as the barrier is permanent. The application of movable rather than fixed gates can mitigate these impacts (IOC 2009).

COSTS AND FINANCIAL REQUIREMENTS

Table 22.1 shows the costs for storm surge barrier construction of both completed projects and projects near completion. Since there are no known examples of movable surge barriers in the developing world, it has unfortunately, not been possible to include costs estimates for developing countries.

Storm surge barrier construction costs are highly variable, as shown in Table 22.1. Influential factors in the cost of these structures include the design and hydraulic head over the barrier.

Barrier and Location	Barrier Type	Hydraulic Head (m)	Construction Costs (2009 price level) (US$ mil.)
Ems Germany	Sector gates	3.8	519
Thames Barrier, London, UK	Sector gates	7.2	2043
IHNC Barrier, New Orleans, USA	Sector gates	4	730
Seabrook Barrier, New Orleans, USA	Vertical lifting gates/ sector gates	4	162
Hartel Barrier, Hartel Channel, NL	Vertical lifting gates	5.5	202
Eastern Scheldt Barrier, NL	Vertical lifting gates	5	5670
Maeslantkering Rotterdam, NL	Floating sector gate	5	925
MOSE Project, Venice, IT	Flap gates	3	6596
Ramspol, Near IJssellake, NL	Bellow barrier	4.4	186

Table 22.1. *Overview of storm surge barriers, types and costs (from Hillen et al. 2010).*

Hillen et al. (2010) investigated the unit costs of storm surge barriers and found that the hydraulic head will be an important determinant for the forces on the barrier and the required construction properties and costs. They also found that there is a weak relationship between the head and the unit costs, although the factors determining unit costs still need to be investigated further. They concluded that unit costs for storm surge barrier construction range between US$0.7 and 3.5 million per unit metre width, at 2009 price levels. Maintenance costs are an ongoing expense which must also be accounted for; annual costs have been estimated at approximately 5-10% of the capital, for movable barriers (Nicholls et al. 2007).

The costs of constructing closure dams in Bangladesh are given in Table 22.2. The three projects for which cost data is available, were constructed largely of traditional materials but with the guidance of experienced coastal engineering consultancies. Traditional Dutch construction methods were used in all three projects.

Project	Year Completed	Barrier width x depth (m)	Construction Materials	Cost (2009 value)
Feni River	1985	1200 m width Unknown depth	Clay filled sacks Bamboo Reed rolls Steel beams Bricks & blocks	US$38 million
Chaka Maya Khal	1979	210 x 5.5	Bamboo Palm leaves Reed bundles Timber piles Jute	US$1.3 million
Amtali Khal	1982	130 x 8	Reed bundles Golpata leaves Clay filled sacks Timber piles	Tk 16 million

Table 22.2. *Costs of completed closure dams in Bangladesh (from DHV Haskoning 2007).*

As shown in Table 22.1. and 22.2. the costs of surge barrier and closure dam construction are highly variable with project costs likely to be influenced by the factors shown in Box 22.1.

- Type of barrier
- Local soil characteristics
- Desired height of the barrier
- Required hydraulic head for the structure
- Anticipated wave loadings; higher wave loadings require more robust and expensive structures
- Single or multi stage construction; costs are lower for single stage construction (Nicholls & Leatherman, 1995)
- Proximity to and availability of raw construction materials
- Availability and cost of human resources including expertise

Box 22.1. *Factors affecting unit costs of storm surge barrier and closure dam construction.*

It has been noted that construction and maintenance costs are likely to increase into the future in response to sea level rise (Burgess & Townend 2004; Townend & Burgess 2004). This is caused by increases in water depth in front of the structure which in turn, cause increased wave heights and wave loadings on the structure.

INSTITUTIONAL AND ORGANIZATIONAL REQUIREMENTS

Effective implementation of storm surge barriers always requires considerable engineering studies to design and install these structures (IOC 2009). Barrier design is likely to be technologically challenging and almost impossible to undertake at the community level. Additionally, as seen under the costs and financial requirements section, surge barriers can be highly expensive and funds may be lacking at a local level. As such, technical assistance may be sought from coastal engineering consultancies or other experienced organizations, while funding may be obtained from external organizations such as NGOs or local government and enterprises which benefit from the structure.

In addition to the hardware, effective forecast and warning systems are required when implementing a movable storm surge barrier (see Section 13 for more information on flood warning services). This may require significant institutional capacity (IOC 2009). Implementation of a flood warning system requires some or all of the following tasks to be conducted: system design, management and forecasting of floods, operation, detection of storms and warning dissemination (Sene 2008).

Closure dams and non-movable barriers are lower technology alternatives to movable surge barriers. A number of such projects have been successfully constructed in countries such as Bangladesh and Korea. To make these projects more feasible at a local level, construction methods may employ local materials and labour, although guidance from experienced contractors would also prove beneficial (e.g. DHV Haskoning 2007).

BARRIERS TO IMPLEMENTATION

The high cost of surge barrier construction and the requirement for specialist knowledge in the design and implementation phases may prove a barrier to implementation of storm surge barriers.

Additionally, surge barriers and closure dams are not suitable for all locations. They are most appropriate in locations where a narrow river mouth or inlet can be closed. Alternatively, they are appropriate where the length behind the barrier that would otherwise require defending can be substantially reduced; in the case of a short defensive length, it may be more effective to upgrade defences than to construct a barrier.

Although barrier construction across narrow channels is cheaper, it is apparent that surge barriers *can* be implemented where narrow inlets are absent, provided sufficient funds for construction are available and the political will exists. For example, the St. Petersburg Flood Protection Barrier employs two movable storm surge barriers within a man-made 25.4 km long barrier, across the mouth of the Neva Bay on the Gulf of Finland.

OPPORTUNITIES FOR IMPLEMENTATION

Opportunities for the implementation of storm surge barriers are numerous. The MOSE project in Venice, Italy, has demonstrated the capacity for surge barriers to offer co-benefits alongside flood protection. For example, opening and closing specific barriers depending on the wind direction can facilitate dispersion of pollutants thus helping to improve coastal water quality. This is beneficial for both recreation and tourism.

Storm surge barriers can also provide additional services such as recreation, amenity and water supply when appropriately designed. The Marina Barrage in Singapore was completed in 2008 and provides an excellent example of the additional benefits which can be gained from a well-designed surge barrier. As well as providing protection against coastal flooding, construction of the barrier has also provided a large reservoir which will help meet water demand in one of the island's most urbanised catchments (Moh & Su 2009). By eliminating tidal influence inside the reservoir the area is now an ideal venue for recreational activities such as boating, windsurfing and water skiing (Moh & Su 2009). By integrating an art gallery and retail outlets into the barrier design, the defence is also now a significant tourist attraction.

Storm surge barrier projects have also been seen to act as a catalyst for development of newly protected areas. This was observed following construction of the Thames Barrier, when London's derelict docklands were regenerated with new transport links, homes, businesses and the important financial district around Canary Wharf (Nicholls 2006).

In the future there could even be opportunities to integrate storm surge barrier or closure barrier design with the production of renewable hydroelectricity. This will provide long-term, sustainable energy as well as security of energy supply for local communities.

23 TSUNAMI WARNING SYSTEM

DEFINITION

Since 1850, tsunamis have been responsible for the loss of over 420,000 lives and billions of dollars of damage to coastal structures and habitats (NOAA 2015b). Today advanced monitoring, modelling and communication technologies allow for the development of robust tsunami warning systems that can be implemented at ocean basin level to provide early warning to coastal populations of many nation states.

DESCRIPTION

A tsunami warning system is a complex monitoring and alert system that contains a seismic data collection network, a range of tsunami detection buoys, a tsunami modelling system, a public communication and warning scheme and educational activities (Australian Government 2015c; NOAA 2015b).

The most established tsunami warning system is the Pacific Tsunami Warning System which was commenced in 1946 (NOAA 2015b). It is designed with a network of seismographic monitoring stations throughout the pacific basin that provide data on Pacific earthquakes which have the potential to generate tsunamis.

When a possible tsunami-generating earthquake has taken place, a 'tsunami watch' is issued to a network of tide-gauges and monitoring stations. A possible tsunami will be automatically recorded by the monitoring stations closest to the epicentre.

If a tsunami is detected, the tsunami watch is upgraded to a 'tsunami warning' and at this stage, the estimated arrival time for the first waves are computed for all stations across the basin. Once a tsunami warning is issued and provides the arrival time of the first waves for the different locations, it is the responsibility of the local police, military and authorities to decide on possible evacuation plans for a particular area (Schwartz 2005).

The prediction of the arrival of the first tsunami wave can be determined with an accuracy of minutes, even when the tsunami travels across large ocean basins. Due to the very high speed of tsunami waves, however, areas close to the epicentre have very short reaction times and warnings can reach the public too late, unless a fast and efficient communication system has been developed (Schwartz 2005).

Similar to flood warning systems, tsunami warnings have two distinct phases: (1) tsunami detection and warning; (2) response. As part of this second phase, it must be

“Due to the very high speed of tsunami waves, however, areas close to the epicentre have very short reaction times and warnings can reach the public too late, unless a fast and efficient communication system has been developed (Schwartz 2005).”

ensured that local residents are aware of the warning system and are informed of the best course of response. This will require a level of preparedness planning at local and/or regional levels as well as awareness raising and possible provision of safe refuge from these events.

As part of tsunami warning systems, some high risk locations have commissioned special escape paths or elevated platforms for refuge. In Japan, many coastal towns have constructed walls and gates around inhabited areas and sensitive infrastructure, such as nuclear power plants to protect against tsunami waves (Haslett 2009). The failure of the tsunami protection wall for the Fukushima Daiichi nuclear power plant in 2011 highlighted the importance of design considerations for such structures (IAEA 2012).

Outside the very seismically active ocean basins of the Pacific and Indian Oceans, it is difficult for non-specialists to determine the need for advanced tsunami warning systems. It should therefore be a task for seismic and oceanographic experts to provide recommendations on the need for a tsunami warning system. In ocean basins with already established warning systems, it is generally relevant for all coastal nations to participate in data collection, warning and response activities.

ADVANTAGES

In locations with possible tsunami occurrence, a well-developed tsunami warning system can potentially save thousands of lives. As advanced tsunami warning systems are already in place for most of the world's seismically active ocean basins (IOC 2015; UNESCO 2015b) it is in many cases just a question of full participation of the individual coastal nation states.

By providing early warning, tsunami warning systems allow affected areas to protect some property and assets. In the case of tsunami warnings however, lead time are often short due to the speed with which tsunami waves travel; as such only minimal measures are likely to be able to be taken before a tsunami hits. Proactive awareness raising campaigns will however, also serve to inform local residents of what improvements may be made to property and assets to best cope with a tsunami situation.

DISADVANTAGES

Since a tsunami warning system requires advanced technology and scientific knowledge, it can be challenging for some countries to participate fully in the international tsunami warning arrangements. Such warning systems rely on scientifically advanced instrumentation to detect, communicate and forewarn of tsunami events. On a more positive note however, a significant amount of tsunami detection instrumentation is already deployed and maintained with warnings communicated to participating nations.

It often requires significant resources to develop a proper public communication and alert system at national level, including appropriate preparedness planning at local and/or regional levels. In developing nations where communication channels are less readily available, it may also be difficult to communicate warnings in sufficient time for residents to take action.

While tsunami detection systems are generally fairly accurate, a certain level of false readings would be expected. These cases can be detrimental to the overall effectiveness of a warning system since false warnings can foster complacency and disregard.

Due to the speed with which tsunami waves travel, there is often little response time between warnings and impact at sites close to the epicentre. This can mean that residents have insufficient time to prepare and seek refuge before the impact. Without improved earthquake prediction, to calculate earthquake events before they actually occur, this is unlikely to improve.

COSTS AND FINANCIAL REQUIREMENTS

No cost estimates are provided for this management option.

INSTITUTIONAL AND ORGANIZATIONAL REQUIREMENTS

A well-functioning tsunami warning system requires state of the art instrumentation, clearly established institutional structures and response procedures and a high degree of collaboration between different authorities at national and international level.

Due to the very short time for action during tsunami events, fast and efficient information pathways need to be established between national tsunami focal points and international tsunami centres. Furthermore, when the information reaches the national focal points, fast and efficient public communication procedures and emergency plans need to be in place and ready to activate.

BARRIERS TO IMPLEMENTATION

Due to the complexity of a tsunami warning system, it requires full commitment of the involved institutions and a reliable resource allocation. This includes communication between tsunami monitoring stations, warning centres and the population at risk.

While a large amount of equipment is already deployed for the purposes of tsunami monitoring (c.f. Pacific Tsunami Warning System, Australian Tsunami Warning System, Indian Ocean Tsunami Warning System and Sea Level Station Monitoring Facility), continued operation and maintenance of such devices is costly and is likely to require international cooperation to ensure continued funding. Furthermore, in developing nations where communication channels are less readily available, it may also be difficult to communicate warnings in sufficient time for residents to take action.

OPPORTUNITIES FOR IMPLEMENTATION

Although the implementation of a tsunami warning system may be hampered by limited resources and human capacity at national level, it is of general interest for the broader international tsunami warning community to have all countries on board and have a fully functional warning system for the whole ocean basin. Since extensive practical experience with tsunami warning systems is available at international level, it can be copied in locations currently lacking a fully functioning warning system.

24 WETLAND RESTORATION

DEFINITION

The primary objective of wetland restoration can be three-fold. These projects can serve to reduce coastal flooding and erosion and can also provide new habitats and environmental benefits.

The term ‘wetland’ refers to a diverse range of shallow water and intertidal habitats, which occur in various locations around the world. Wetland restoration relates to the rehabilitation of previously existing wetland functions from a more impaired to a less impaired or unimpaired state of overall function.

Although similar to managed realignment (Section 19), wetland restoration can be distinguished by the goal to maintain the present position of the coastline as opposed to realigning landward, as occurs under managed realignment.

DESCRIPTION

The most commonly restored wetland ecosystems for coastal protection are saltmarshes and mangroves. Seagrasses may also be employed as a coastal defence, to dampen waves but on their own they are seldom considered an adequate shore protection alternative (USACE 1989).

Wetland habitats are important because they perform essential functions in terms of coastal flood and erosion management. They induce wave and tidal energy dissipation (Brampton 1992) and act as a sediment trap for materials, thus helping to build land seawards. The dense root mats of wetland plants also help to stabilise shore sediments, thus reducing erosion (USACE 1989). Wetland restoration re-establishes these advantageous functions for the benefits of coastal flood and erosion protection.

> “Observations indicate that a mature mangrove stand will reduce the costs of dike maintenance by 25-30% assuming a stand width at least comparable to the characteristic wavelength of incident waves (Tri et al. 1998).”

Restoration is required because many of the world’s wetlands have become increasingly degraded through both natural and human activities.

Techniques have been developed to reintroduce coastal wetlands to areas where they previously existed and to areas where they did not, but conditions will allow. The diversity of wetland types means there are numerous methods for restoring wetlands. The method adopted will depend on the habitat which is being restored.

Saltmarshes are widely re-established through managed realignment schemes (see Section 19). However, this involves retreating the present line of defence. Saltmarshes can also be re-established whilst maintaining the present coastline position through vegetative transplants from healthy marshes. Transplant types often include sprigs, stems with leaves or pot-grown seedlings; seeding is not likely to be effective on sites subject to erosion (USACE 1989). Re-establishment of saltmarshes may require the site’s elevation to be raised using appropriate fill material.

For mangrove restoration, it is necessary to collect plant propagules[1] from a sustainable source, prepare the restoration site for planting and directly plant propagules at regular intervals at an appropriate time of year (de Lacerda 2002). In re-establishing mangroves, it may also be desirable to establish nurseries to stockpile seedlings for future planting (de Lacerda 2002). Mangrove re-establishment can also be achieved by planting dune grasses. These grasses provide a stable, protective substrate for mangroves to establish their root systems in. However, as the mangroves grow, they will eventually overshadow the dune grasses, causing them to die. Thereafter, the mangrove becomes the dominant species (USACE 1989).

[1] A structure, such as a cutting, seed or spore that propagates a plant.

ADVANTAGES

In terms of climate change adaptation in the coastal zone, the main benefit of wetland restoration is the reduction of incoming wave and tidal energy by enhancing energy dissipation in the intertidal zone. This is achieved by increasing the roughness of the surface over which incoming waves and tides travel (Nicholls et al. 2007). This reduces the erosive power of waves and helps to reduce coastal flood risk by diminishing the height of storm surges.

A reduction in installation and maintenance costs of sea defences may occur when such structures are located behind large areas of saltmarsh. A similar effect exists for mangroves which absorb the energy and slow the water flow of storm surges (Barbier 2008). Evidence from the 12 Indian Ocean countries affected by the 2004 tsunami disaster suggested that coastal areas with dense and healthy mangrove forests suffered fewer losses and less damage to property than those areas in which mangroves had been degraded or converted to other land use (Kathiresan & Rajendran 2005). Observations indicate that a mature mangrove stand will reduce the costs of dike maintenance by 25-30% assuming a stand width at least comparable to the characteristic wavelength of incident waves (Tri et al. 1998).

In contrast to hard defences, wetlands are capable of undergoing 'autonomous' adaptation to sea level rise, through increased accumulation of sediments to allow the elevation of the wetland to keep pace with changes in sea level (Nicholls & Klein 2005). Provided wetlands are not subjected to coastal squeeze, and the rate of sea level rise is not too rapid to keep pace, wetlands are capable of adapting to sea level rise without further investments.

Coastal wetlands also provide a number of important ecosystem services including water quality and climate regulation, they are valuable accumulation sites for sediment, contaminants, carbon and nutrients and they also provide vital breeding and nursery ground for a variety of birds, fish, shellfish and mammals. They are also a sustainable source of timber, fuel and fibre (White et al. 2010).

The restoration and recreation of wetlands can also reduce or even reverse wetland loss as a result of coastal development. This is important in terms of maintaining the global area of wetlands and in sustaining wetlands in the face of climate change. Wetland creation may also fulfil legal obligations for the compensation of habitats lost through development.

DISADVANTAGES

The disadvantages of wetland restoration are minimal. The restoration of natural ecosystem services, including flood and erosion protection benefits, largely outweighs any disadvantages.

One possible disadvantage is the space requirement in locations which are often of high development potential. This must be carefully weighed against the range of benefits accrued.

Wetland restoration is also likely to require a degree of expertise, especially in locations where wetland re-colonisation has to be encouraged by transplanting wetland plants. Some wetland habitats will no doubt be more difficult to recreate than others and could require greater expertise.

COSTS AND FINANCIAL REQUIREMENTS

Tri et al. (1998) studied the costs and benefits of mangrove restoration in Vietnam. The project involved the expansion of an existing mangrove forest on the seaward side of a dike system. The study estimates planting, capital and recurrent costs at approximately US$41 per hectare of mangrove planted, at 2009 price levels. This estimate includes planting costs and the cost of thinning from year six onwards (Tri et al. 1998).

Because the term 'wetland' refers to a diverse range of habitats, it is difficult to give accurate cost estimates. Different types of wetland will require different restorative measures with varying costs and labour requirements. A number of factors which are likely to contribute toward variations in costs are given in Box 24.1.

- Type of wetland to be restored, expertise availability, and consequent chances of success
- Degree of wetland degradation and consequent restoration requirements
- Intended degree of restoration (for example, it may not be possible to restore all the ecosystem functions of a wetland if it is located in a highly industrialised/urbanised environment and the planned restoration measures may be less ambitious)
- Land costs if land purchase is required to convert to wetlands
- Labour costs
- Transportation distance between seedling source and planting site
- Seedling mortality rate between collection and planting
- Cost of raising specific species in nurseries before transplantation because they cannot be directly planted on mud flats due to strong wind and wave forces
- Scale of post-implementation monitoring operations

Box 24.1. *Factors affecting costs for wetland restoration (adapted from Tri et al. 1998).*

Clearly, estimating the costs of wetland restoration is complex and depends on a large number of factors. The cost of individual projects should be calculated on a case-by-case basis.

INSTITUTIONAL AND ORGANIZATIONAL REQUIREMENTS

At a local level, proactive measures can be implemented to ensure wetland habitats are maintained and used in a sustainable manner. This will preserve habitats into the future *and reduce or even avoid* the cost of restoration and planting schemes. By preventing wetland loss or degradation, it is also possible to avoid the many potential problems encountered in the course of wetland restoration efforts (NRC 1992).

It is important that the multiple agencies involved in shoreline management avoid providing conflicting guidance. In the Pacific islands, many communities were advised to clear mangroves on medical advice in the 1930s and 1940s because these areas were seen as a breeding ground for malaria-transmitting mosquitoes. Today however, the ecosystem services provided by mangroves, including their coastal protection function, is valued. As such, many communities have been encouraged to replant mangroves to prevent shoreline erosion (Mimura & Nunn 1998).

Past wetland restoration projects have been conducted on an experimental basis through ‘learning by doing’ with limited technological experience (e.g. Saenger & Siddiqi 1993). Using this approach, it is foreseeable that communities could implement wetland restoration on a local scale, although with improved understanding, failures could be minimised and costs reduced.

At a larger scale, it is useful for governments to adopt proactive coastal management plans to protect, enhance, restore and create marine habitats. Without such a framework, action to restore wetlands is likely to be fragmented and uncoordinated (NRC 1994). This is compounded by the involvement of multiple agencies with overlapping responsibilities and different policies (NRC 1994).

BARRIERS TO IMPLEMENTATION

One of the most significant barriers to the use of wetlands as a measure to combat coastal flooding and erosion is a lack of public awareness of the flood and erosion protection benefits offered by these ecosystems. Unless the public is educated on the benefits that wetlands provide, the link between coastal flood and erosion protection and wetland restoration is likely to be unclear. This will hinder the uptake of these projects as communities press for more tangible, hard defence options, for which the protective benefits are more widely understood.

Another barrier to successful implementation is an incomplete understanding of the ability of a degraded wetland to recover, and of the success rates of wetland creation. We still do not fully understand the needs of wetland plants and animals. As such, uncertainty also surrounds the effectiveness of wetland restoration activities and whether the full range of ecosystem functions will be restored during wetland repair. Monitoring of completed schemes will enhance our understanding of wetland restoration.

The adoption of wetland restoration and (re)creation as a response to coastal flooding and erosion requires a sustainability-focussed and anticipatory coastal management plan. The establishment of wetlands which provide full coastal flood and erosion protection takes time, and the approach does not offer immediate benefits. As such, wetland recreation may not be practicable where coastal management is reactive and focussed on hard defences. A desire to improve wetland habitats also needs to exist before the strategy can go ahead. This may involve raising public awareness of the benefits of wetland restoration and (re)creation.

Wetlands only exist under specific conditions and it is not always clear if habitat restoration will be achievable or successful, especially when coastal managers have limited predictive capabilities for shoreline change (NRC 1994). Although studies have shown that it *is* possible to create wetlands in areas where they did not previously exist (Platong 1998), sites with the potential for wetland restoration or creation should be identified on a case-by-case basis.

Identifying individuals and organizations qualified to undertake wetland restoration and recreation work can also prove a barrier to implementation. The qualifications and know-how of the implementing organizations directly influence the effective application of scientific knowledge and engineering capabilities and ultimately, project performance (NRC 1994). To address problems associated with limitations in knowledge and capabilities, it is advisable to seek direct involvement or guidance by experienced and qualified organizations.

OPPORTUNITIES FOR IMPLEMENTATION

One of the biggest opportunities that exists to aid implementation of wetland restoration programmes is a growing concern regarding wetland loss and the associated loss of ecosystem functions such as habitat provision, food production and water quality improvement. The implementation of wetland restoration projects not only compensates for wetlands lost through development and natural processes but also provides the additional benefits of coastal flood and erosion protection. This option also helps reduce wetlands losses as a result of climate change.

Wetland creation can bring about various economic, social, and environmental benefits to local communities. For example, it has the capacity to improve the productivity of coastal waters for fishing. Given the importance of the fishing sector in many coastal communities in developing countries, this is likely to be highly beneficial. Such an effect may increase incomes of local communities and contribute toward local sustainable development. Other goods and services provided by wetlands, such as the provision of wood and fibres could also prove highly beneficial to local communities, especially in developing countries. Wetland recreation can also create opportunities for eco-tourism and increase recreational opportunities. Creation of wetlands, especially in or in close proximity to urban areas can even serve to increase awareness of the important functions performed by these habitats.

Because wetland restoration meets multiple management objectives – such as habitat protection, public access to environmental and recreational resources and hazard mitigation – and is less expensive and more aesthetically pleasing than some engineering solutions, the approach is likely to find broader public support in the future (Moser 2000).

There is also the opportunity to implement wetland restoration or creation together with hard defences such as dikes or seawalls. In such a case, the presence of wetlands on the seaward side of the defence leads to lower maintenance costs over the lifetime of the structure (Tri et al. 1998).

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P.O. Box 30552 - 00100 Nairobi, Kenya
Tel.: +254 20 762 1234
e-mail: publications@unep.org
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