CHAPTER 5

5. STRUCTURAL AND NON-STRUCTURAL METHODS

5.1 SECTION CONTENT

This chapter discusses key structural and non-structural methods for flood risk management (see fig. 5.1). The IFM approach in flood risk management (see chapter 3) goes beyond just implementing hard or soft methods; it includes the entire process of carefully selecting and carrying out the best combination of engineering and natural/nature-based structural and non-structural methods.

Floods happen in a watershed – an area with a variety of intrinsically connected geological, ecological and social components. The success of flood risk management methods depends on their suitability to the nature of the intended interventions, the scale of the intervention, and where in the watershed they are applied.

Table 5.1 (p. 118) gives a framework of selected flood risk management methods based on the type and level of the intended interventions.

Typically, flood risk management objectives broadly fall into three categories based on the nature of interventions:

- **REDUCE, RETAIN AND DETAIN FLOOD FLOWS**
- **IMPROVE CONVEYANCE AND ENHANCE RESISTANCE TO DAMAGE IN WATERWAYS**
- **ADAPT TO FLOODS**

Table 5.1 identifies which methods are applicable to these categories.

Flooding has consequences at multiple levels, including national/regional, watershed, floodplain, community and household. Therefore, methods should be selected based on the specific requirements at different scales (see fig. 5.2).

The Flood Green Guide recommends managers first apply IFM non-structural methods and then, if needed, include structural (hard and or soft) methods as part of an integrated approach. Guide users should note that rarely, if ever, will the use of a single flood management method be helpful. Managers should select methods that will enhance the efficacy of any existing flood risk management methods.

The remainder of this chapter is structured as follows:

Sections 5.2 and 5.3 introduce selected structural and non-structural flood risk management methods, briefly describing important design considerations. Section 5.4 discusses the applicability of different methods based on the flood type and location in the watershed. Sections 5.5 and 5.6 discuss the important considerations in implementation, operation and closure. Section 5.7 compares the benefits of combining different hard and soft methods. Section 5.8 provides guiding information for cost and resource requirements for different methods. Section 5.9 provides an overview of monitoring and evaluation of flood risk management projects.

The guide does not provide specific technical guidance on tasks required in the design and implementation of these methods, such as hydrological studies, feasibility studies, environmental assessment, comprehensive engineering/bioengineering design, cost analysis, project appraisal or construction management. These tasks are specific to the local context and follow established scientific methods; therefore, the guide user should involve a multidisciplinary team, as may be required for the local context, to plan a specific flood risk management project and acquire specialized expertise. The guide will assist the user to identify the expertise and resources required for some of these tasks.

GUIDANCE: Information provided in this chapter should always be used in conjunction with the Flood Green Guide Framework presented in chapter 2.

ADDITIONAL INFORMATION: This figure is used throughout the chapter to indicate whether methods are structural-hard, structural-soft, or non-structural. For example, upper watershed restoration AY1 is the first structural-soft method described.

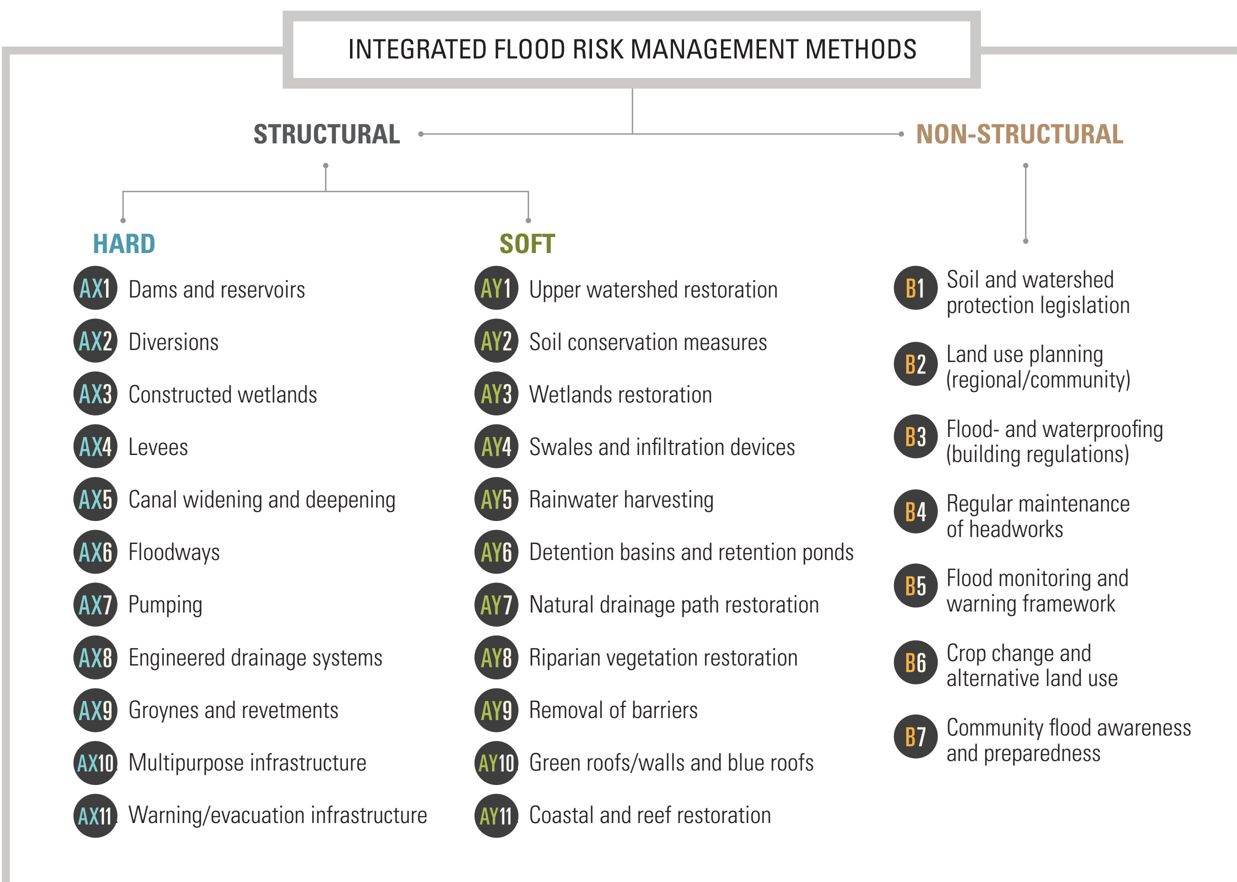
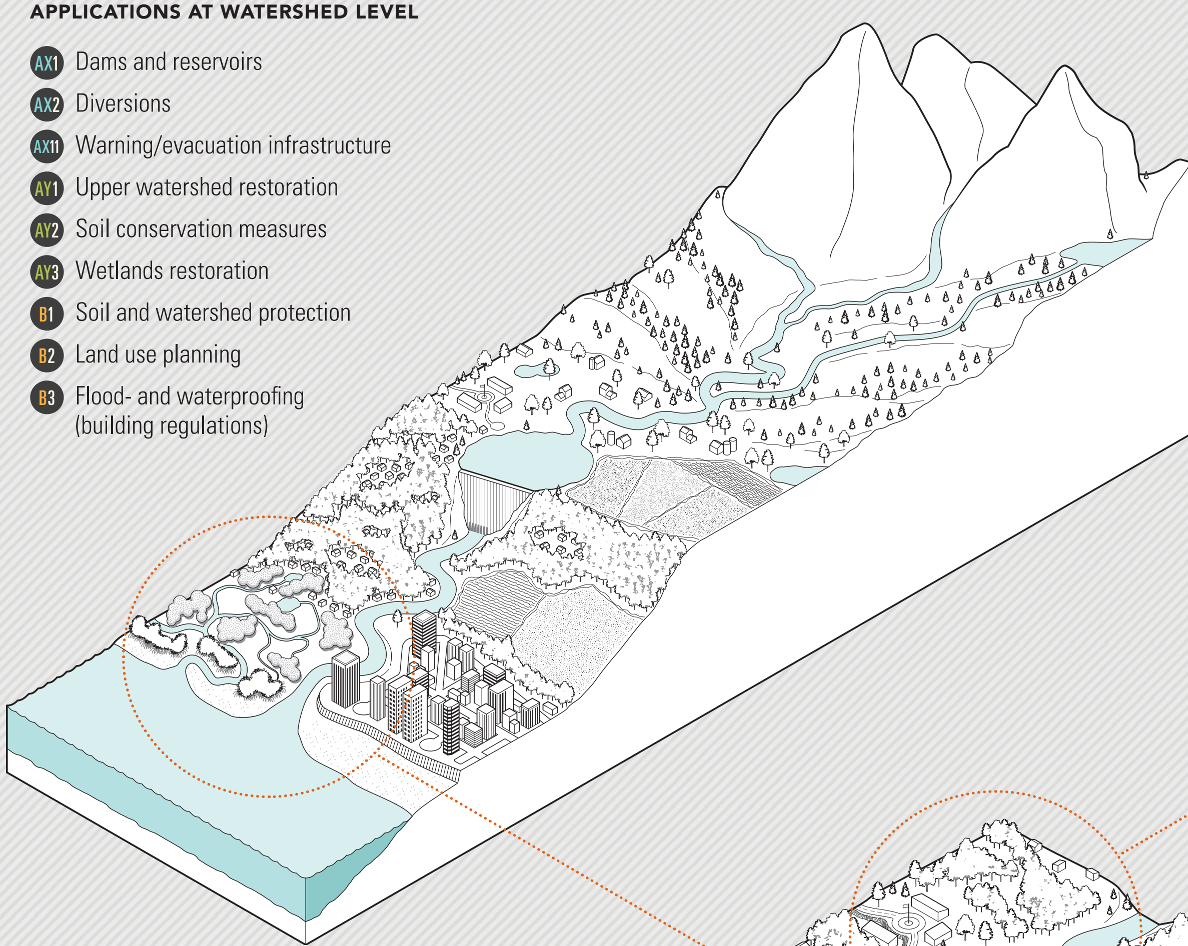
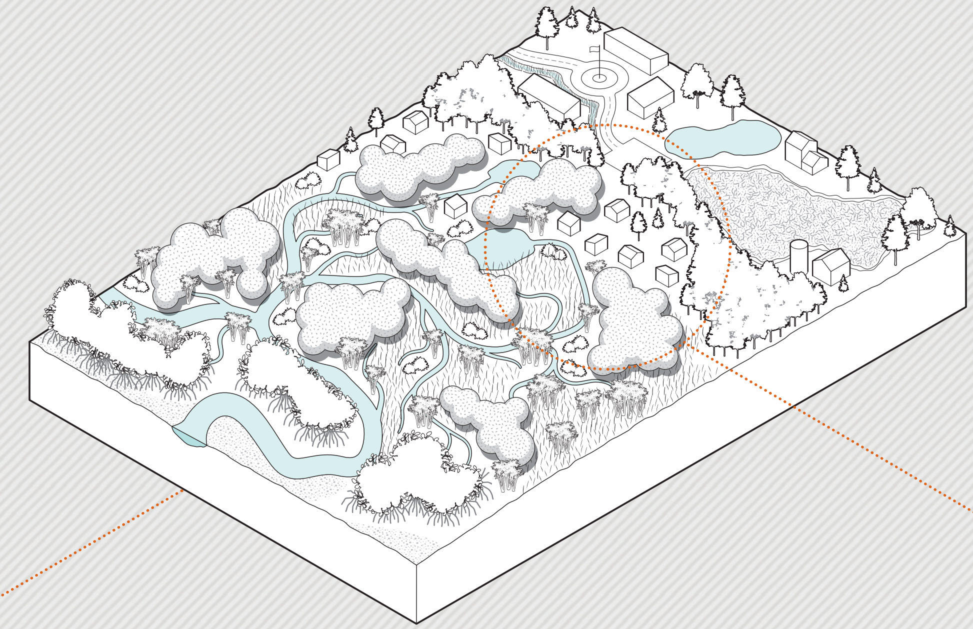


FIGURE 5.1 STRUCTURAL AND NON-STRUCTURAL FLOOD RISK MANAGEMENT METHODS

APPLICATIONS AT WATERSHED LEVEL

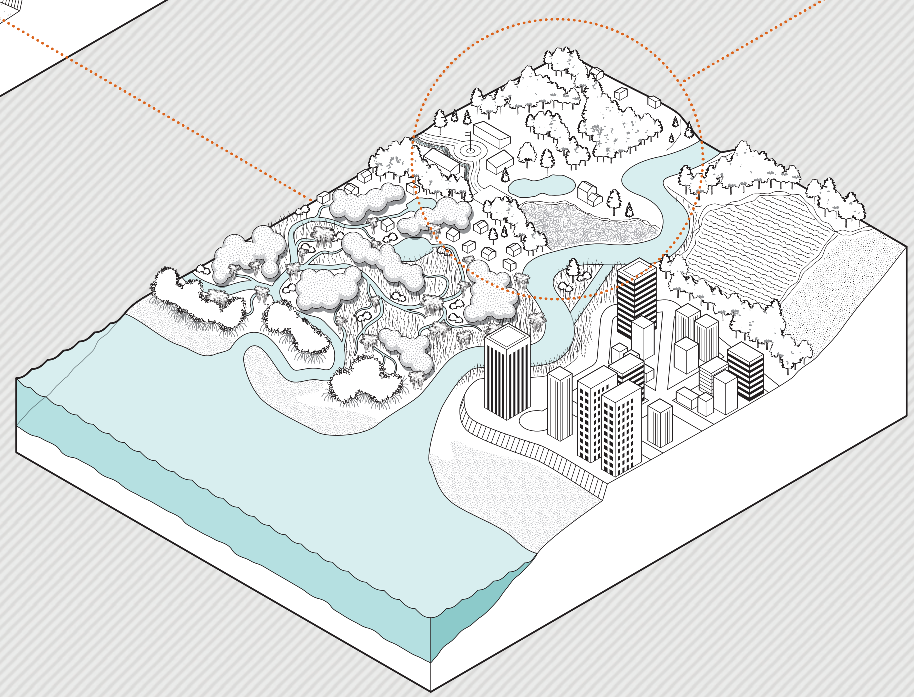
- AX1 Dams and reservoirs
- AX2 Diversions
- AX11 Warning/evacuation infrastructure
- AY1 Upper watershed restoration
- AY2 Soil conservation measures
- AY3 Wetlands restoration
- B1 Soil and watershed protection
- B2 Land use planning
- B3 Flood- and waterproofing (building regulations)





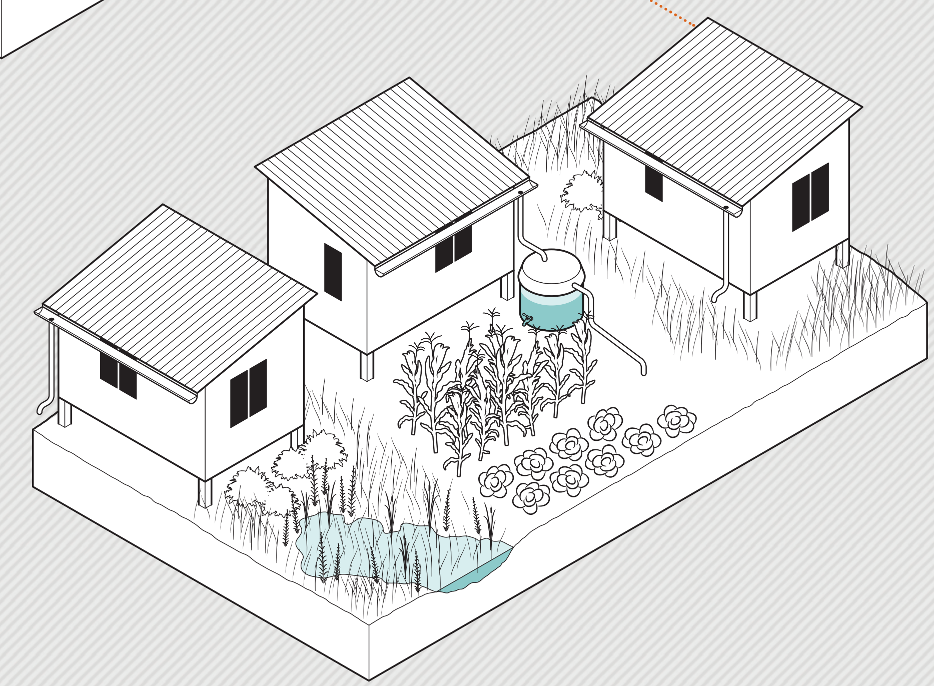
APPLICATIONS AT FLOODPLAIN LEVEL

- AX3 Constructed wetlands
- AX4 Levees
- AX5 Canal widening and deepening
- AX6 Floodways
- AX7 Pumping
- AX8 Engineered drainage systems
- AX9 Groynes and revetments
- AX10 Multipurpose infrastructure
- AY6 Detention basins and retention ponds
- AY7 Natural drainage path restoration
- AY8 Riparian vegetation restoration
- AY9 Removal of barriers
- B2 Land use planning
- B4 Regular maintenance of headworks
- B5 Flood monitoring and warning framework
- B7 Community flood awareness and preparedness



APPLICATIONS AT COMMUNITY LEVEL

- AX7 Pumping
- AX10 Multipurpose infrastructure
- AY4 Swales and infiltration devices
- AY5 Rainwater harvesting
- AY6 Detention basins and retention ponds
- AY7 Natural drainage path restoration
- AY8 Riparian vegetation restoration
- B2 Land use planning
- B3 Flood- and waterproofing (building regulations)
- B6 Crop change and alternative land use
- B7 Community flood awareness and preparedness



APPLICATIONS AT HOUSEHOLD LEVEL

- AY4 Swales and infiltration devices
- AY5 Rainwater harvesting
- B3 Flood- and waterproofing (building regulations)
- B7 Community flood awareness and preparedness

FIGURE 5.2 SCALE OF APPLICATION OF STRUCTURAL AND NON-STRUCTURAL METHODS

FLOOD GREEN GUIDE SCALE OF APPLICATION OF STRUCTURAL AND NON-STRUCTURAL METHODS

USAID FROM THE AMERICAN PEOPLE

WWF

World Wildlife Fund. 2016. Natural and Nature-based Flood Management: A Green Guide. Washington, DC: World Wildlife Fund. http://envirodm.org/flood-management

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5.2 STRUCTURAL METHODS

For thousands of years, civilizations have used structural methods for flood risk management. Ancient flood embankments dating from around 1000 BCE can be found in certain reaches of the Nile River.[1] The earliest settlers in the Indus and Ganges plains of India (2500 BCE) used such deterrents as ring bunds – or low walls along the contours of hills – to protect from flooding.[2] The agrarian revolutions and the expansion of urban settlements in the 19th century drove engineers to develop a systematic approach to structural flood risk management methods – commonly known as flood control and drainage engineering. Structural flood risk management involved both engineering interventions (hard engineering), such as flood embankments and dams, and ecological interventions (soft methods), such as soil conservation and wetland restoration (also known as natural and nature-based methods). Integrated flood management (IFM) gives equal attention to hard, soft and non-structural methods.

WARNING: Periodic inspection, maintenance, cleaning and repair of hard engineering structures are critical to stability of the structure. Significant functional and safety issues are possible if the integrity and proper functioning of these systems are compromised.

In this chapter, the structural methods are discussed under three flood risk management objectives (table 5.1):

- **REDUCE, RETAIN AND DETAIN FLOOD FLOWS**
- **IMPROVE CONVEYANCE AND ENHANCE RESISTANCE TO DAMAGE IN WATERWAYS**
- **ADAPT TO FLOODS**

5.2.1 METHODS FOR REDUCING, RETAINING, DETAINING FLOOD FLOWS

The first category of **structural flood risk management** interventions is reducing, holding (retaining) or delaying (detaining) the inflow (flood flow) of water. Conventionally, these methods are designed to handle a flood event of a given magnitude – normally referred to as **design flood** – statistically determined to occur once in a certain number of years, called the **return period**. However, managers should note that when uncertainties due to climate change and climate variability are considered, strictly abiding by such probabilistic norms (which assume a stationary climate) to select and design the methods may reduce their effectiveness. Therefore, provisions for uncertainties should be made, as discussed in chapters 3 and 4. In floods caused by precipitation (refer to appendix A, Flood Typology), a maximum flow, known as the **flood peak** (fig. 5.3), occurs during or after the precipitation event. The time between the start of the event and its peak is called **lag time** (also referred to as basin lag). Most of the methods described in sections 5.2.1.1 and 5.2.1.2 are designed to reduce the flood peak and increase the lag time.

1 Douglas J. Brewer, *Ancient Egypt: Foundations of a Civilization* (New York: Routledge, 2014).

2 A. L. Basham, *The Wonder That Was India*, 3rd ed. (New Delhi: Pan McMillen, 2014).

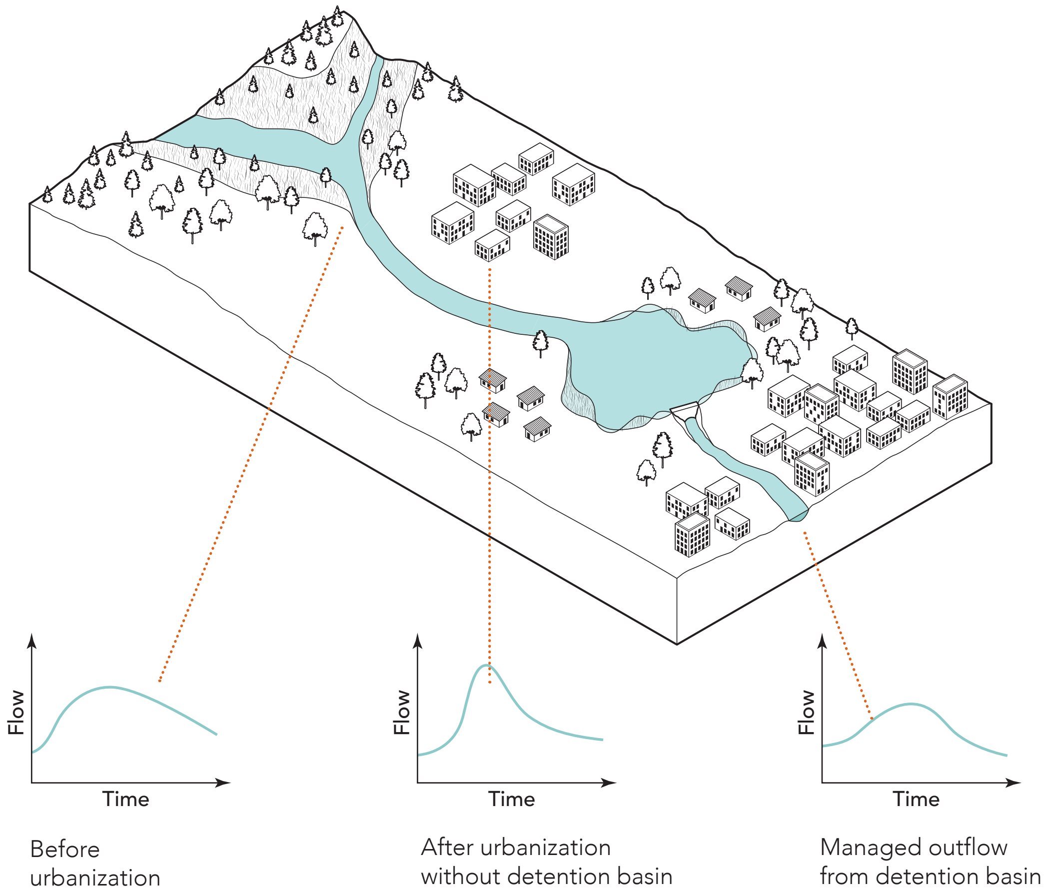

FIGURE 5.3 HOW THE FLOOD PEAK AND LAG TIME CHANGE WITH STRUCTURAL FLOOD RISK MANAGEMENT METHODS THAT REDUCE, RETAIN OR DETAIN THE FLOOD FLOWS

5.2.1.1 Hard Engineering Methods

DAMS AND RESERVOIRS AX1

A flood control reservoir is a widely used flood risk management method to retain floodwater by temporary storage. Water can be detained for a short period (a few days) or retained long term for other purposes, such as irrigation or hydroelectricity generation. Normally, a reservoir is created by building a dam across a main waterway. To manage riverine floods, managers can build watershed dams in lower, narrow points upstream of the floodplain or the target area. Dam types vary based on the structure and type of construction material (earth, concrete, rocks, wood, steel). The dam holds water up to a particular height, forcing an area upstream to be inundated, thus creating the reservoir. The stored water is then released by a pipe, tunnel or gate at the bottom of the dam (fig. 5.4).

WARNING: Dams only protect a small area within the given floodplain from frequent floods and carry the risk of dam failure, which can be catastrophic. Dams can increase the flood risk in other areas and can be extremely disruptive to the river ecosystem process. Thus the Flood Green Guide does not encourage dams to be considered as a viable solution in flood risk management. We include dam information here because they are commonly found in many countries and thus may need to be addressed.

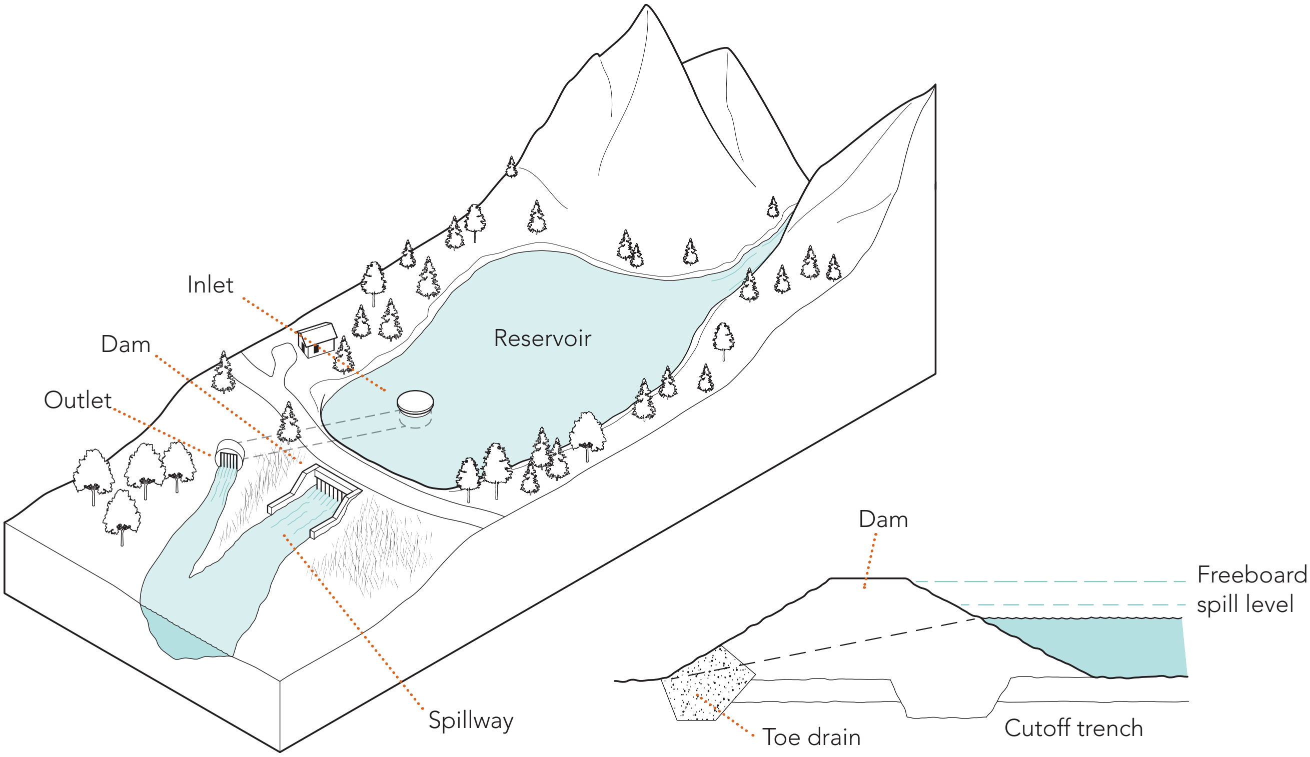

FIGURE 5.4 A GENERIC LAYOUT AND CROSS SECTION OF A SMALL DAM

IMPORTANT DESIGN CONSIDERATIONS

Design objectives: Reduce the flood peak and increase the lag time by storing water.

Main components: Dam, inlet, sluice/outlet, **spillway**, gates (optional).

Functionality: The size of a dam (and a reservoir) is determined by the volume of water (e.g., cubic meters or acre-feet) it stores during a storm event. The larger the storage, the more capable a reservoir will be in reducing the flood peak and increasing the lag time. This storage volume corresponds directly to the height (spill level) of the dam (fig. 5.4). In a storm event where inflow exceeds the designed storage volume, excess water has to be spilled from the dam using a spillway. A dam should have a carefully designed outlet structure (outlet pipe, sluice gate, tunnel) to regulate and release water regularly, and also to empty the reservoir if required. As the dam height increases, it puts massive pressure on the dam at its base. Therefore, structural design of the dam is very important for its functionality and safety. This includes selecting the proper foundation type and material for dam construction (soil, rock fill, concrete, steel, wood) and size. Regardless of the size, the dam foundation and construction materials should be carefully selected and designed to withstand the water pressure.

Safety: If the water **spills over** the dam or significantly seeps under it, the dam may fail. Therefore, three safety measures are advised in design. First, an additional height called the freeboard can be added to the spill level in determining the dam height (fig. 5.4). Second, the spillways should be carefully sized to allow effective spilling. Third, measures should be taken to prevent large quantities of water from seeping beneath the dam. There can be major safety issues and a dam breach due to inappropriate design, construction, and maintenance. Also, if design flow is exceeded, there can be catastrophic results. Periodic inspection and repair are required to ensure stability.

DIVERSIONS AX2

Diversion devices divert some of the flood flow away from a floodplain into a nearby floodplain or a watershed. For example, a weir or **barrage** built across a river can divert some of the water from its natural course, reducing the risk of downstream floods. A **weir** is a static structure that blocks the flow in a stream. Barrages are similar but have gates to control the flow. Diversion is useful in watersheds too small for reservoirs or when there is a nearby watershed with less flood intensity. Diversion devices are also useful in managing tidal floods and diverting rising tidal water away from human settlements to a nearby wetland or lowland.

IMPORTANT DESIGN CONSIDERATIONS

Design objective: Reduce the flood peak by diverting part of the inflow into a floodplain.

Main components: Weir, intake/inlet, diversion canal/tunnel, gates (optional).

Functionality: A diversion structure (for flood abatement) is designed based on the flow that has to be diverted from the floodplain (as a portion of the design flood). The diverted flow can be changed by changing the height of the weir and also by altering the size of the intake. A weir will reduce the velocity of the water and cause minor upstream impoundment, which should be considered in design. Weirs (or barrages) are designed to spill, but over the top or through the structure, and are sometimes controlled by gates built into the structure. Weir type and gate type (if applicable) have to be carefully selected and designed. Structural design of the weir is very important for both functionality and safety.

Safety: The strength of the foundation and durability of materials used for the weir/barrage are the main safety considerations in design. Breach of a weir/barrage may cause serious damage to communities.

CONSTRUCTED WETLANDS AX3

A **wetland** is an ecosystem in which the soil is permanently or intermittently saturated (or inundated) with water and has vegetation that tolerates high moisture levels.[3] Wetlands are often found as transitional ecosystems between terrestrial and aquatic ecosystems, and serve to regulate hydrological flows. They frequently retain and detain flood flows and stormwater. Wetlands gradually release water into the downstream ecosystems (sea, rivers and groundwater aquifers) and do not need sluices or spillways; wetlands can also handle more flow variability over time. The time that a unit volume of water is retained in a wetland before being released to downstream ecosystems is known as the **retention time**. In addition to detaining and retaining water, wetlands can improve the water quality. This is an added advantage in stormwater scenarios, where contaminated water from urban/agricultural areas is released to downstream aquatic ecosystems.

IMPORTANT DESIGN CONSIDERATIONS

Design objectives: Reduce the flood peak and increase lag time by detaining floodwater.

Main components: Controls (inlet, outlet, gates/valves), bunds, substrate, vegetation.

3 W. J. Mitsch and J. G. Gosselink, *Wetlands*, 4th ed. (Hoboken, NJ: John Wiley and Sons, 2007).

Functionality: Stormwater management wetlands are designed to provide the maximum retention time. The retention time corresponds to the area of the wetland and its water-holding capacity. Water-holding capacity is a complex function of the porosity of soil, vegetation and microtopography of the wetland. The flow pattern is also an important design parameter. In a wetland, water can flow above the soil substrate (surface flow wetlands), through the soil (subsurface flow wetlands), or both. In flood management, a mixed flow is important, as it allows more storage and a slow release. However, contaminants are more effectively retained by the soil substrate and the plant roots in subsurface flow wetlands.

Safety: To enhance safety, the design should incorporate an optimum retention time that will not allow stagnation, vector breeding or eutrophication.

In cases where the natural wetlands have been destroyed or damaged, managers can create wetlands (constructed wetlands) as a flood management method. **Polders** are similar to wetlands but are created by building dikes around subsided land. Wetlands and polders can be constructed to receive stormwater along a river, upstream of an estuary, or in an urban/agricultural area. It may take several years for a constructed wetland to become fully functional and able to provide ecosystem services such as flood management.[4]

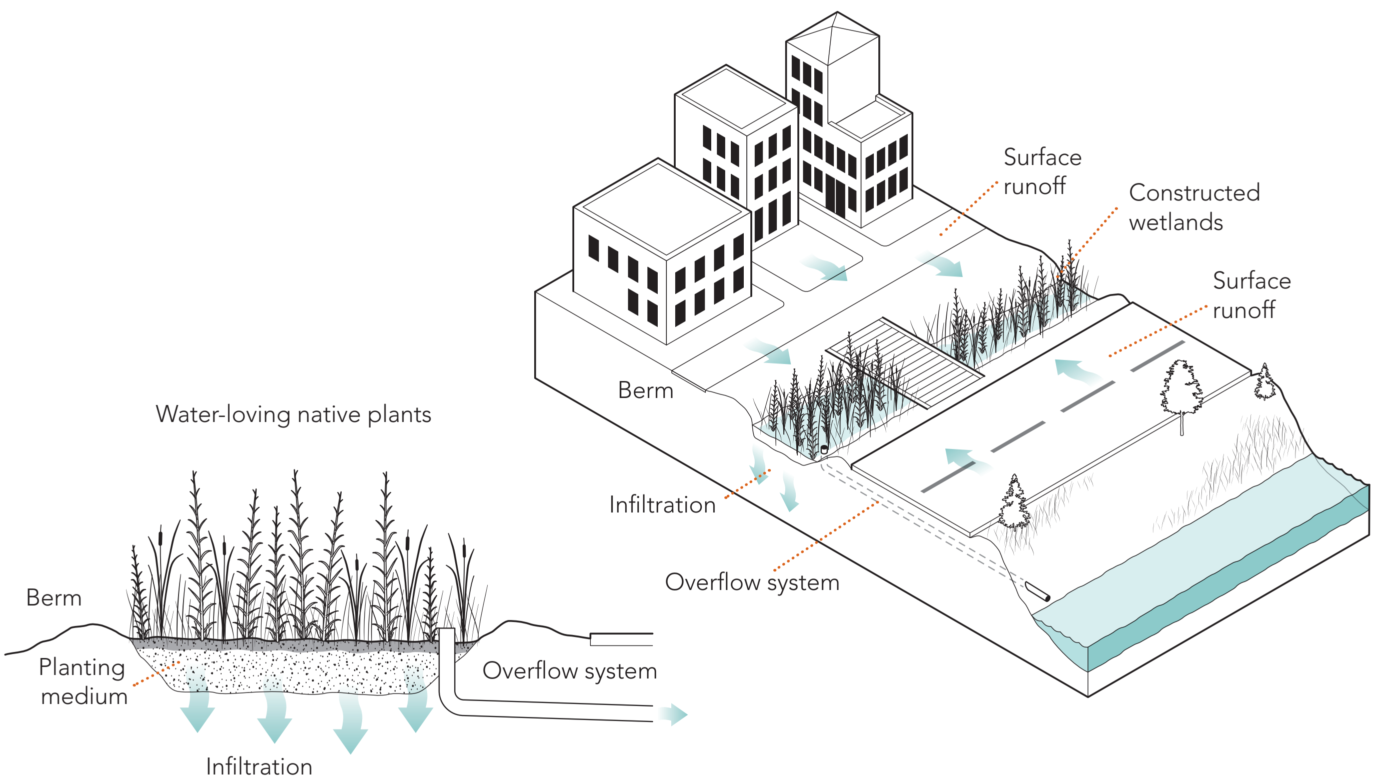

FIGURE 5.5 A TYPICAL CONSTRUCTED WETLAND DESIGN

4 Ibid.

5.2.1.2 Soft Measures

UPPER WATERSHED RESTORATION AND SOIL CONSERVATION MEASURES AY1 AY2

As discussed in chapter 3, when a watershed receives precipitation, a portion of that water will not reach the ground, due to evaporation and interception by vegetation. Another significant portion of water infiltrates the ground, without flowing as runoff to surface waterways. This infiltrated water is then released slowly to streams, lakes or wetlands as groundwater (**base flow**). Downstream flood risk can be reduced if managers can ensure optimum interception and infiltration are maintained in the upper part of a watershed and runoff is reduced.

Managers can use a number of techniques for climate-informed watershed restoration and **soil conservation**. These techniques include providing more leaf surface area for interception, enhancing ground infiltration, and reducing the velocity of water. The most common approach, **revegetation**, restores natural vegetation cover in the area and is especially effective where natural vegetation was at one time cleared for plantations – such as tea, coffee and oil palm. Restoration can encompass an entire area, like a decommissioned plantation, or strategic sections, like natural gullies, to achieve maximum infiltration or velocity reduction (fig. 5.6). Revegetation can be used in conjunction with soil erosion and slope stabilization solutions, such as terracing and erosion barriers (fig. 5.6), especially in hilly areas. These new plantings also might provide useful forest products, firewood, fodder or even timber. Tall trees with lush foliage increase interception of water; low plants help infiltration and reduce water velocity. The best approach is a natural combination of trees and undergrowth with species that will tolerate anticipated climate changes. (For more information on addressing climate change, see chapters 3 and 4).

Managers also can use soil bioengineering techniques for watershed restoration and soil conservation. Soil bioengineering is a sub-discipline of civil engineering in which living material (mainly plants) is used for near-natural construction and to complement conventional methods for slope and embankment stabilization and erosion control.[5] Several well-established soil bioengineering techniques, such as bush-layering, live crib walls and erosion control blankets, exist.[6]

IMPORTANT DESIGN CONSIDERATIONS

Design objectives: Reduce the runoff by increasing infiltration and base flow (fig. 5.6).

Main components: Vegetation, erosion control structures, bioengineering features, drainage.

Functionality: Watershed restoration projects (for flood management) are designed to achieve improved infiltration – for example, a proportion of a unit precipitation that infiltrates the ground without flowing as runoff. Decreasing the erosivity – measure of vulnerability of soil to erosion – is also often considered in the design. When physical features such as terraces or soil bioengineering features are used for erosion control, their spacing, sizing, structural design and construction material should be selected very carefully (fig. 5.6).

Revegetation should be carefully planned to avoid changing the natural habitat (e.g., grasslands to forest). Sections or strategic locations, however, may be converted with care. A well-designed revegetated area should not require extensive watering or fertilizer. Avoid using exotic, fast-growing ground-covering plants at all times (e.g., Wadelia [*Sphagneticola trilobata*], Guinea grass [*Megathyrsus maximus*]) because they can become invasive and ultimately interfere with flood risk

5 Donald H. Gray and Robbin B. Sotir, Biotechnical and Soil Bioengineering Slope Stabilization: A Practical Guide for Erosion Control, (New York: John Wiley and Sons, 1996).

6 L. Lewis, Soil Bioengineering an Alternative for Roadside Management: A Practical Guide, (San Dimas, CA: USDA, 2000).

management objectives. Though some exotic trees may be suitable, avoid revegetation with fast-growing timber-rich tree species like eucalyptus and pine in habitats where they are not native.

Safety: Safety parameters are not critical in revegetation. However, collapsing of physical features (e.g., benches, walls) can cause safety issues; therefore, proper structural design is essential.

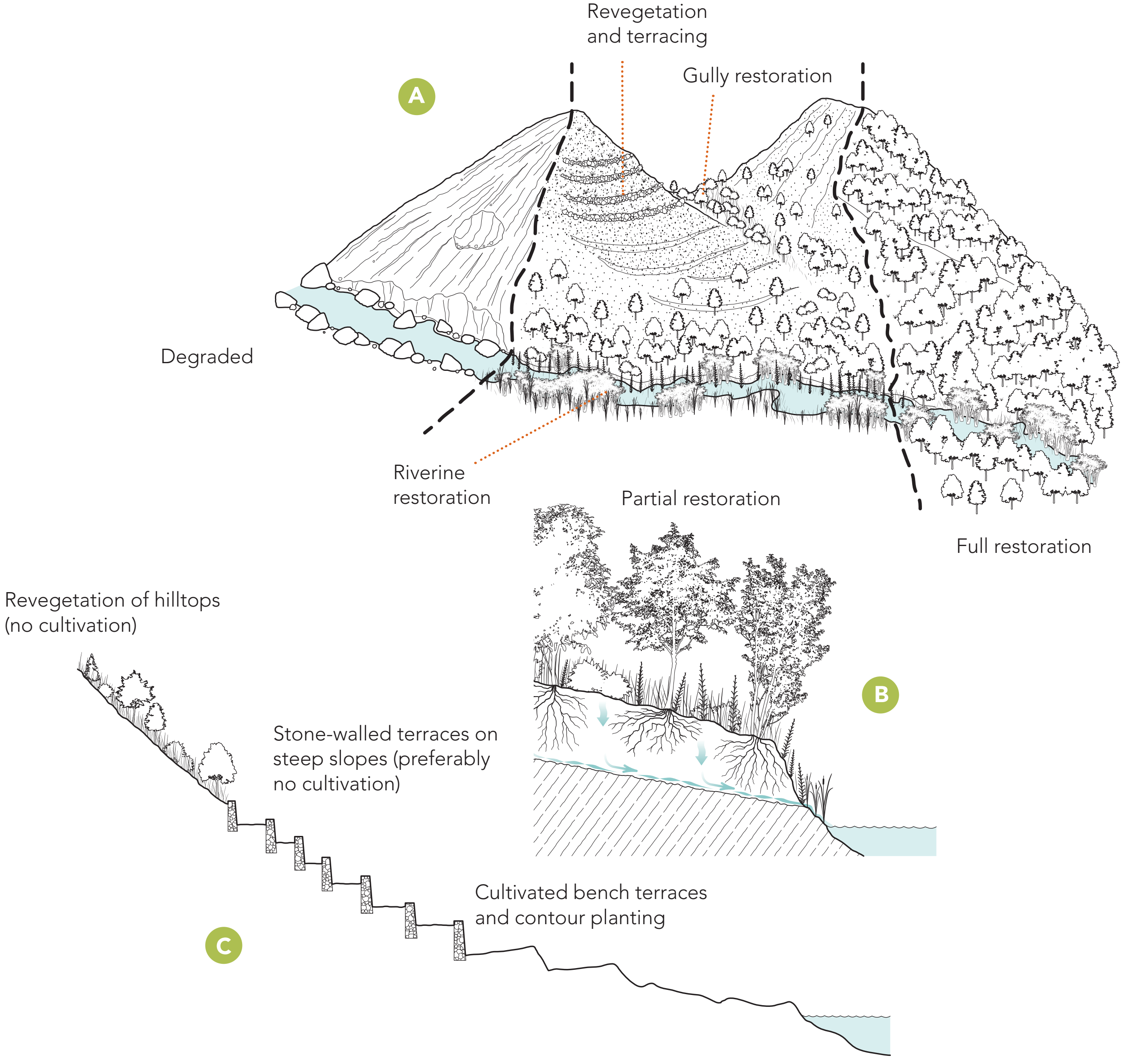

FIGURE 5.6 UPPER WATERSHED CONSERVATION: (A) TECHNIQUES APPLIED IN DIFFERENT SCALES AND LOCATIONS IN A TYPICAL UPPER WATERSHED LANDSCAPE, (B) CROSS SECTION OF A REVEGETATED AREA, (C) SOME LOW-COST SOIL CONSERVATION MEASURES

WETLAND RESTORATION AY3

As discussed in Constructed Wetlands AX3, natural wetlands in a floodplain can act as a sponge to store floodwaters and filter pollutants. Wetlands can reduce water velocity and detain runoff, thereby helping to reduce flash floods and storm surge. Especially in paved urban areas with low infiltration and higher-velocity runoff, wetlands can detain stormwater and minimize localized floods. A range of natural wetland types can be found in different parts of a watershed.[7] Some of these include the following:

- **Marshes:** Common in floodplain areas near the lower reaches of a river; characterized by low grassy vegetation and peaty soil that can hold very large amounts of water.
- **Estuarine or tidal wetlands:** Reed beds, salt marshes, mangroves or mudflats at a river mouth or landside of a lagoon; can provide protection from tidal floods.
- **Riverine wetlands and forested wetlands:** Wooded or shrub areas immediate to a river; can absorb small increases in flow and prevent localized floods.
- **Shallow lakes and ponds:** Occur in depression areas of a landscape; can act as a reservoir during a storm and release water slowly to the aquifer or natural waterways; important in urban or agricultural areas to regulate overland floods.

A wetland is degraded when it loses its characteristic vegetation and soil properties or when it is converted into non-wetland use (e.g., a built-up area or pasture). Vegetation and soil properties can change due to activities such as altering the water paths of a wetland (e.g., building canals or ditches), untreated **wastewater** disposal, excessive siltation, or clearing vegetation. When a wetland is degraded, water depth, vegetation and soil properties can change and may reduce its ability to absorb or detain water. The common symptoms of wetland degradation are

- transformation of vegetation patterns (e.g., marshes to shrubs)
- sediment buildup
- frequent and sudden water level change
- algal blooms
- proliferation of invasive or exotic species

Wetland restoration is the process of supporting the wetland to regain its health and function, thereby restoring its ability to contribute to flood management. Restoring a natural wetland involves reestablishing both its extent and ecological functions by removing the non-wetland features and recreating portions of the wetland that were lost. This may include excavation, removal of hydraulic structures, clearing of invasive and non-wetland vegetation, diversion of polluted runoff away from the wetland, and flooding some sections. Because wetlands are multifunctional ecosystems, their restoration can lead to multiple social benefits, including recreation, fishing, and the production of reeds, fodder and fruits that can be harvested.

IMPORTANT DESIGN CONSIDERATIONS

Design objectives: Enhance the water-holding capacity of the wetland and restore its ecological functions (fig. 5.7).

Main components: Restored wetland, fencing, bunds, hydraulic control structures, paths.

7 Definitions are adopted from the US Fish and Wildlife Service, Ramsar Convention and the US Army Corps of Engineers and simplified for the purpose of this guide.

Functionality: In wetland restoration, it is impossible to assign a simple set of denominators for water-holding capacity. Generally, qualitative improvement of the habitat as a whole is more important than a quantitative increase in water-holding capacity. Generally, wetland restoration planning is the first step to remove the causes of degradation (pollution sources, filled-up areas, invasive species) and let the wetland regenerate naturally. However, in highly degraded wetlands, carefully planned replanting and reintroduction of fauna might be required. Improvement is evaluated with a range of ecological indicators, including hydrological patterns, water quality, percentage of invasive species, percentage of obligate wetland species, and soil properties. Because the plant and animal species associated with wetlands help mitigate flood damage, wetland restoration design should include plans for reestablishing natural vegetation, animal paths, and spawning and nesting locations.

Safety: Safety parameters are not critical in wetland restoration. However, steps should be taken to manage vector breeding when applied in urban areas.

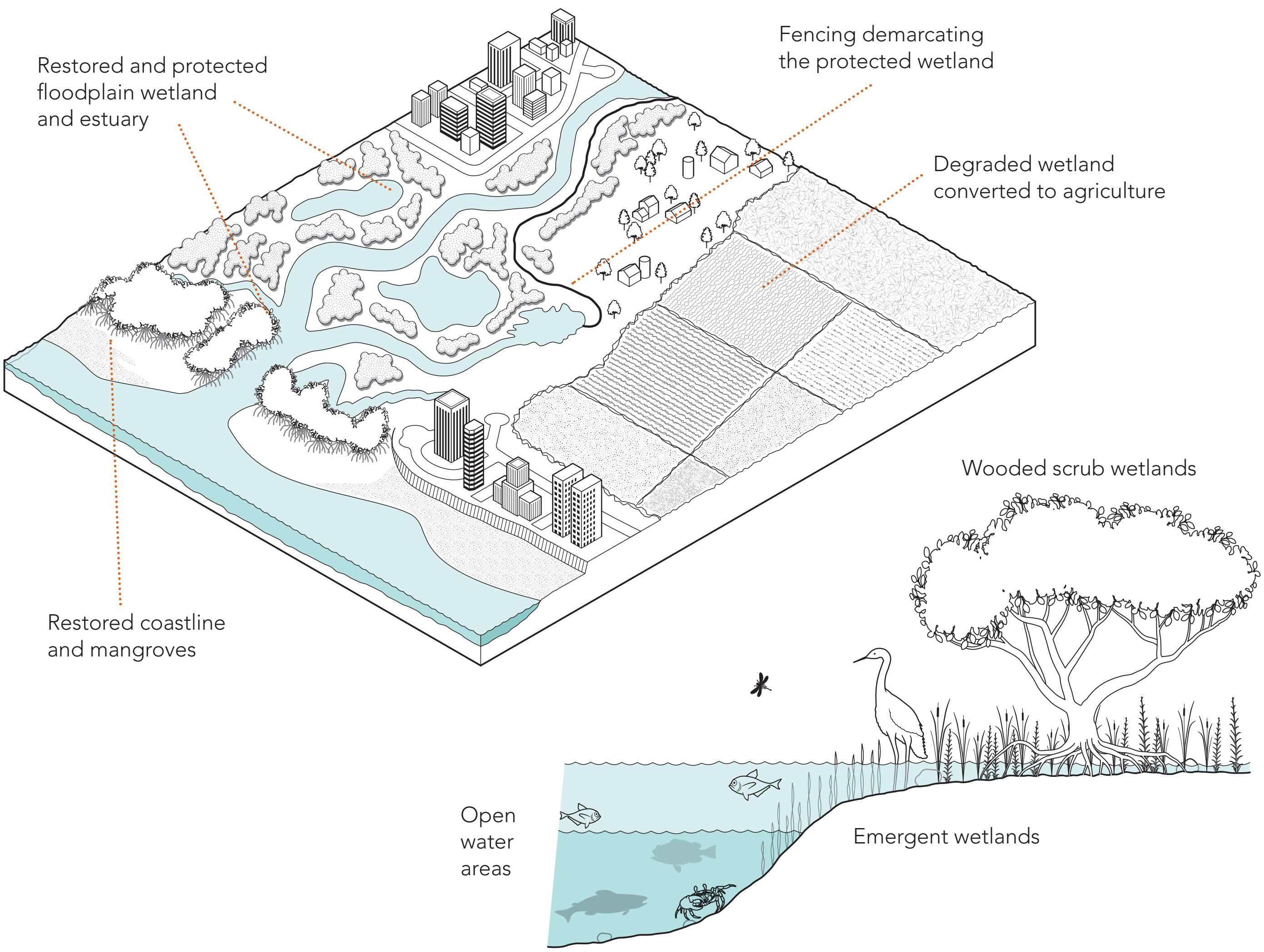

FIGURE 5.7 WETLANDS RESTORATION IN LOWER REACHES OF A WATERSHED AND CROSS SECTION OF WETLANDS

SWALES AND INFILTRATION DEVICES AY4

Swales and infiltration devices are used to increase infiltration of stormwater into the ground and slowly release it into drainage systems. These methods can also filter stormwater by trapping pollutants.

Infiltration devices: Soakways, infiltration trenches, filter drains and infiltration basins receive water from impermeable surfaces such as roofs and car parks. They help maximize the infiltration of water into the ground before it reaches engineered drainage systems. These devices can be designed and constructed with minimal technical expertise.

Permeable pavements: Any type of pavement that allows partial infiltration of water through a porous paving material or gaps between paving blocks (fig. 5.8) is designated permeable. Managers can use this method in car parks, driveways and lightly trafficked roads. The water can either infiltrate the ground or be collected in a sand bed beneath the pavement and allowed to flow very slowly into the drains (fig. 5.8).

Rain gardens, swales and filter strips: Vegetated channels or strips that allow infiltration, conveyance and storage of stormwater (fig. 5.8). Managers generally use rain gardens in household plots, swales on roadsides, and filter strips in more open landscapes.

IMPORTANT DESIGN CONSIDERATIONS

Design objectives: Enhance infiltration and detain water from a storm event to reduce flood peak and increase lag time.

Main components: Vegetation, permeable surface or pavement, porous substrate, underdrains, geotextiles.

Functionality: All these devices are designed to enhance the infiltration rate and achieve optimum temporary storage capacity to reduce stormwater flowing into drainage systems as runoff. Sizing and choice of materials for these devices should be selected to optimize temporary retention/storage, infiltration and controlled conveyance to drainage systems. Where vegetation is used, plants also should be selected to increase infiltration, **evapotranspiration** and bioretention of pollutants. Plants should be selected carefully to avoid invasive species or species that require extensive watering, fertilizer or frequent pruning and weeding.

Safety: Since all these features are constructed in open or public spaces, managing vector breeding is an important safety measure in design.

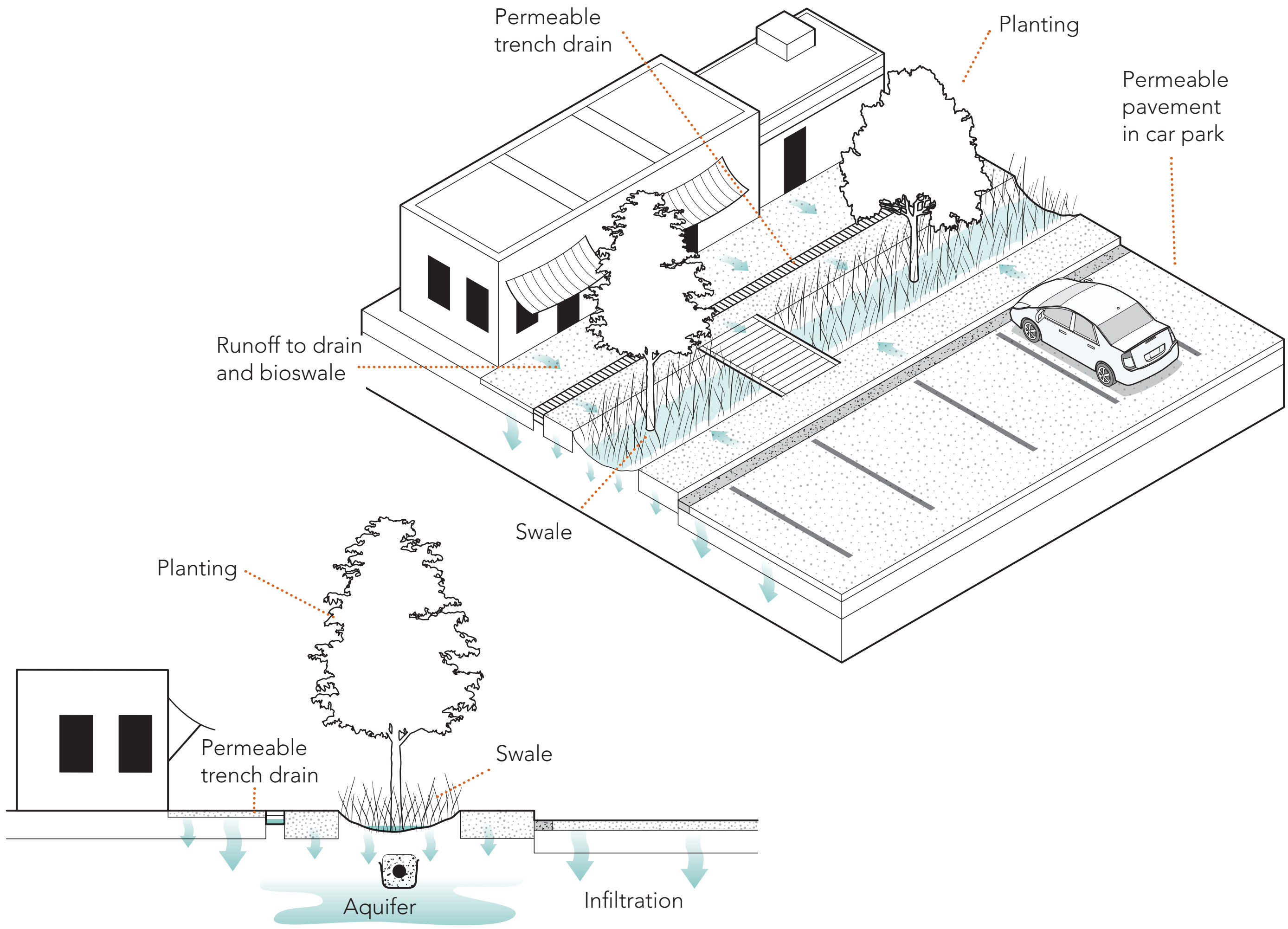

FIGURE 5.8 SWALES, PERMEABLE PAVEMENTS AND INFILTRATION DEVICES

RAINWATER HARVESTING AY5

Rainwater harvesting can be used to reduce flood peak (stormwater peak) and lag time. Rainwater collected from the roof of a building is stored in a tank and used for regular household purposes (fig. 5.9). Usually a gutter or rooftop gully collects the rainwater and conveys it to an above-ground or underground tank. An above-ground tank allows water to be easily distributed by pipes, while an underground tank saves space in small household compounds.

IMPORTANT DESIGN CONSIDERATIONS

Design objectives: Reduce runoff from household plots by temporary storage and use.

Main components: Roof collection system, rainwater tank, distribution system.

Functionality: In designing rainwater harvesting systems, the storage capacity of the rainwater tank is the most important design consideration (fig. 5.9). Capacity should be decided based on the volume of water to be retained in a given storm event and the amount of rainwater required for household use. To ensure good functionality, systems should be designed with a proper roof collection system (roof plumbing), use proper materials for the tank (plastic, ferro-cement, concrete, brick), and include plumbing for distribution.

Safety: Tank strength and stability are important safety concerns with a rainwater harvesting system. Collapse of an above-ground or underground tank may cause serious damage to humans as well as adjacent structures. Furthermore, it is important to ensure the quality of captured water if it is meant to be used for household purposes. Some systems use nets and filter to prevent solids from getting into the tank. Some designs allow diversion of the first flush (water from the first few minutes of a rainfall) to ensure better water quality. Steps should be taken to manage vector breeding in above-ground collection systems.

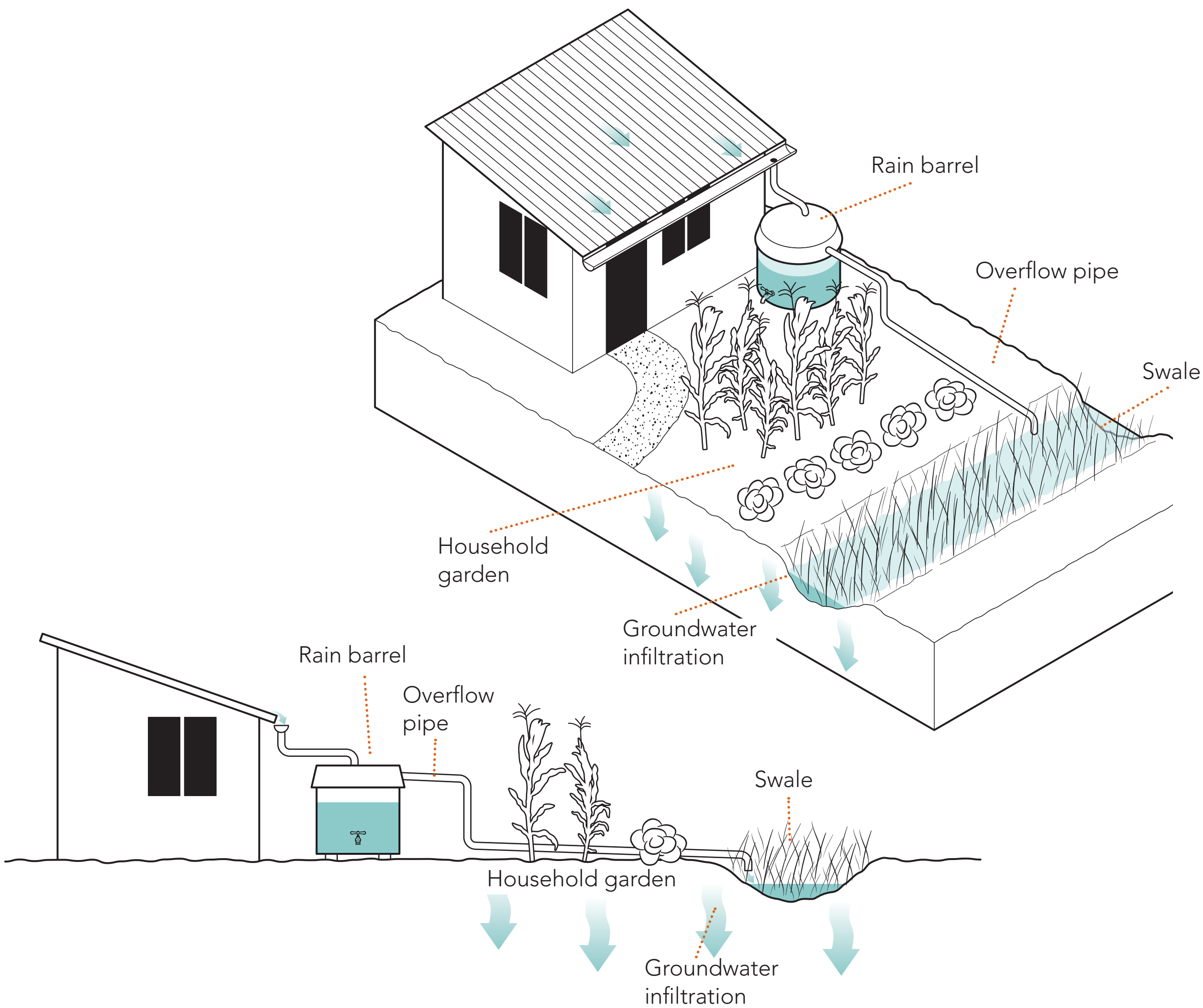

FIGURE 5.9 RAINWATER HARVESTING AND RAIN GARDENS AT THE HOUSEHOLD LEVEL

DETENTION BASINS AND RETENTION PONDS AY6

Detention basins are natural depressions or developed open spaces (e.g., car parks) in the landscape that can temporarily hold stormwater and then release it slowly through a controlled outflow (fig. 5.10). This will control runoff into downstream drains or waterways and reduce the flood risk. Detention basins are not meant for permanent impoundment.

Retention ponds, on the other hand, hold water permanently and detain additional flows during a storm. Typically, the water level in the ponds will drop during dry periods due to evaporation. The ponds also have the added advantage of trapping silt. In urban catchments, retention ponds can also be used for recreation.

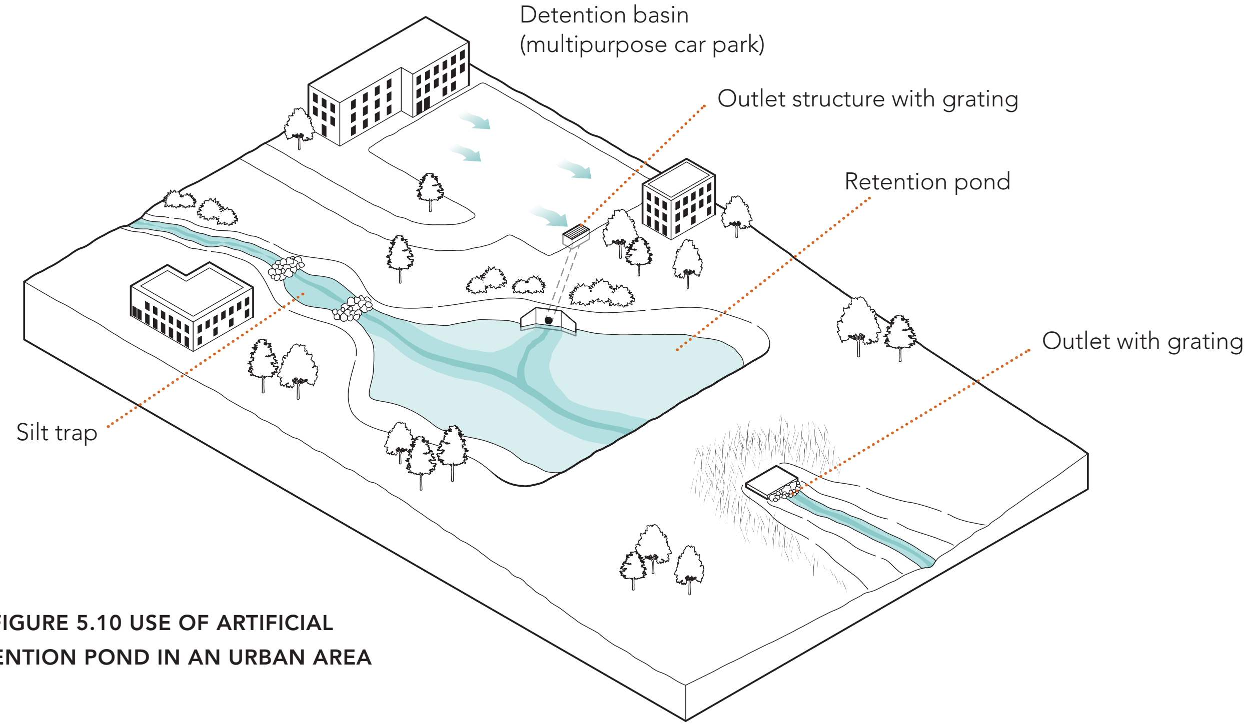

FIGURE 5.10 USE OF ARTIFICIAL RETENTION POND IN AN URBAN AREA

IMPORTANT DESIGN CONSIDERATIONS

Design objectives: Temporary storage of stormwater to reduce stormwater peak and lag time.

Main components: Pond/basin, outlet structure and pipe, grill, bund/weir (retention ponds only), silt trap (retention ponds only).

Functionality: Both detention basins and retention ponds are designed to have adequate storage volume and to substantially reduce the flood peak based on runoff generated in the sub-catchment during a design storm and the discharge rate from the pond or basin. Most basins and ponds are designed to be fully discharged within less than one day. A retention pond should have a gate or a valve to let out water from the bottom. Ponds should be periodically emptied for cleaning and desilting.

Safety: The main safety concern in ponds and basins is the risk of localized flooding. Because they hold stormwater in one place in order to reduce flood risk in another, they may **overflow** and cause unanticipated local floods if not properly designed and managed. The possibility of vector breeding is a safety issue in retention ponds.

A green roof in Western Cape, South Africa.

A vertical garden, or green wall, also known as a biowall.

GREEN ROOFS/WALLS AND BLUE ROOFS AY10

Green roofs and walls, and blue roofs, are designed to temporarily retain water from local storm events and reduce **stormwater runoff**. Green roofs and walls can improve local air quality, improve a building's energy efficiency, and reduce the **urban heat island** (UHI) effect through **evapotranspiration**.

Green roofs: Green roofs consist of vegetation, a growing medium, drainage materials, and a waterproof membrane on top of a roof system.[8] The two main types of green roof systems in common use are extensive and intensive. An extensive green roof has a soil depth of 7-15 cm (3-6 inches), is lightweight at 73-244 kg/m² (15-50 lb/ft²), consists of only 10%–20% organic matter in soil, has limited plant species options, and requires few, if any, structural adjustments to the roof.[9] Green roofs require lower maintenance, nutrients and irrigation.

Intensive green roofs require greater soil depths, usually 15 cm or more, and additional structural support, which increases their cost. They are heavier but offer more plant options, including trees and shrubs. Intensive green roofs require irrigation, fertilization and maintenance.[10]

Container or modular gardens can be placed on structurally sound flat roofs to enhance stormwater retention.

Green walls: Green walls, or vertical gardens, are typically constructed using modular containers to hold a growing medium, the growing medium itself and vegetation. Typical green wall systems are constructed using panels, felt, and containers or trellis systems.[11] Pre-planted panels or felt pockets can be attached to the exterior of a building, along with some type of irrigation system, or constructed using containers or trellis systems to direct plants grown at the base of the building.

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8 EPA, "Urban Heat Island Basics," in *Reducing Urban Heat Islands: Compendium of Strategies*, October 2008, accessed March 21, 2016. http://www.epa.gov/heatisland/resources/pdf/GreenRoofsCompendium.pdf.

9 Ibid.

10 Ibid.

11 Susan Loh, "Living Walls: A Way to Green the Built Environment," August 2008, http://math.unife.it/lm.ecologia/Insegnamenti/management-degli-ecosistemi/materiale-didattico/Loh%202008%20living%20walls.pdf.

Blue roofs: Blue roofs are non-vegetated rooftop detention systems designed to temporarily store and slowly drain water through the use of waterproofing membranes and weirs on roof drains.[12] They are typically cheaper to construct than green roofs.

© New York City Department of Environmental Protection

A water retention or "blue" roof in New York City. The roof is designed to temporarily retain water and gradually release it through weirs on roof drains.

IMPORTANT DESIGN CONSIDERATIONS

Design objective: Temporarily detain water from a localized storm event and increase lag time.

Main components: Vegetation, growing media, and/or containers or rooftop detention system.

Functionality: The main design parameters of green and blue roofs are the slope of the roof and how much water needs to be detained. Steeper roofs retain less water and may not be suitable for a blue roof. The load-bearing capacity of the building, or how much weight the roof can handle, will determine which type of green or blue roof is appropriate or whether retrofitting is an option.

Safety: Green roofs and walls, and blue roofs, should be carefully designed to prevent water damage to the structure and fit within its load-bearing abilities. Before adding these features, the building should be assessed for structural soundness and ability to accommodate the extra weight of a green or blue roof. Fire safety is another consideration when using these techniques. Fire risk can be reduced by avoiding plants that dry out during hot months and by including firebreaks on the roof or irrigation systems.

12 NYC Environmental Protection, "Blue Roof and Green Roof," accessed December 30, 2015, http://www.nyc.gov/html/dep/html/stormwater/green_pilot_project_ps118.shtml.

5.2.2 METHODS FOR IMPROVING CONVEYANCE AND RESISTANCE TO DAMAGE IN WATERWAYS

The second category of flood risk management methods includes effective conveyance of flood flows and stormwater and enhancing the resistance of waterways (streams, rivers, canals, drains) to flood-related damage (e.g., bank erosion, scouring).

Conveyance improvements should enhance the carrying capacity of major water bodies and provide effective drainage of runoff in a floodplain.

Deeping/widening a waterway, increasing bank heights, or providing alternative flow paths can improve the carrying capacity, or discharge capacity, of major waterways. Providing effective drainage in a floodplain can include improving conveyance in defined drainage pathways (natural gullies, engineered drains, canals, pipes), so they can effectively carry the maximum runoff produced in a storm (stormwater peak). These defined pathways ultimately connect to the main water bodies, such as streams, rivers, lakes or the sea.

In addition to improving conveyance, the waterways should also be protected against flood damage (e.g., erosion and scouring of banks). Protecting the banks and beds of waterways (such as rivers, canals, streams) from damage will enhance their ability to function properly and reduce the potential for flooding.

5.2.2.1 Hard Engineering Methods

LEVEES AX4

A riverine flood occurs when the water level of the waterway (river, stream) rises above the height of the banks and flows over. One method used to manage such a flood is to raise the bank height along a given stretch of the waterway. Structures built to raise bank levels are commonly known as **levees**.

Levees are typically made from soil (or rock-filled) structures built along riverbanks. In certain cases, levees are built only along one side (bank) of the waterway to protect a certain area along that bank; in other cases, both banks are raised. Levees are often used as roads, railway tracks or footpaths.

Most levees are massive engineering structures and will invariably hinder the natural drainage of the areas they protect. Therefore, hydraulic features such as **culverts** and lock gates should be included to allow drainage from the landward side to the waterside through the levee (internal drainage). Pumping over the levee might be necessary in certain cases. In stream stretches with high-velocity flows, levees should be protected using lining, vegetation or revetments (see AX9).

> **WARNING:** Levees can only protect a small area within the given floodplain from frequent floods, and they are not effective against extreme events. Levees can increase the flood risk in other areas and are extremely disruptive to the river ecosystem process. Thus the Flood Green Guide does not encourage levees to be considered as a viable solution in flood risk management. We include levee information here because they are commonly found in many countries and thus may need to be addressed.

There are also smaller-scale flood bunds, which are usually designed to protect a particular village or agricultural field from floods. Similar to the way levees function, a flood bund can be constructed along the banks of a waterway, or, similar to a dam, a bund can be constructed at a strategic point of a floodplain. Bunds are structures significantly smaller in scale than a levee or a dam, and are usually constructed using earth or earth reinforced with timber, bamboo or other vegetation. It should be noted, however, that small flood bunds are engineering structures and thus should be designed by qualified professionals using the same design principles as levees or dams.

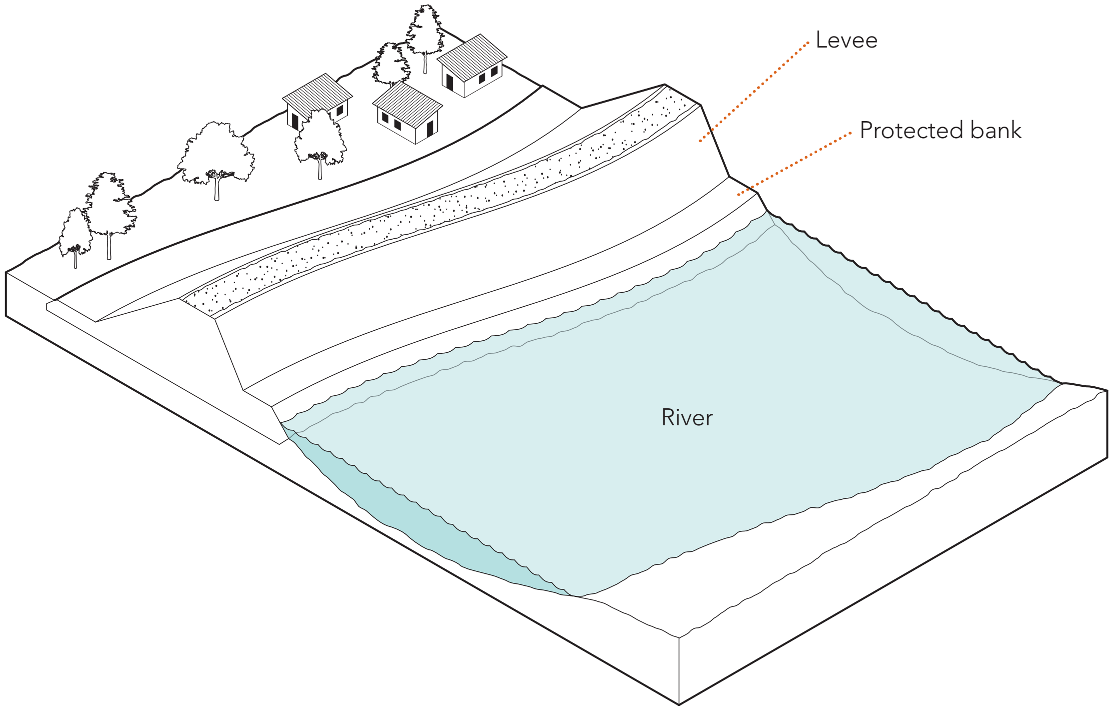

FIGURE 5.11 A LEVEE BETWEEN A WATER BODY AND DEVELOPED AREA

IMPORTANT DESIGN CONSIDERATIONS

Design objectives: Increase the carrying capacity of a main waterway by raising the bank height using artificial structures to prevent overbank flooding.

Main components: Levees, banks protection (lining, vegetation, revetments), lock gates, pumps.

Functionality: Levees are designed based on the water level that corresponds to the design flood in the waterway. Levee height (bank height) should exceed this water level. A standard freeboard height is also added to the design flood water level for operational safety. Sizing and structural strength of the levee are also determined to withstand the water pressure of design flood water level. If the levee is used for other purposes, such as roads and rail tracks, the load stress on the system should be considered. Structures and devices included in levees to facilitate internal drainage (lock gates, pumps) need careful hydraulic design.

Safety: There are two safety concerns with regard to levees. One is the stability of the structure and its ability to withstand water pressure, scouring and erosion without sudden breach. Sudden breach of a levee can cause disastrous flash floods. In addition, other levee concerns include the possibility of **overtopping** if a flood exceeds the design flood; the upstream and downstream impacts of altered river characteristics; risk associated with a false sense of security that can encourage settlement near the structure; and eliminating potential flood benefits. Spillways to allow safe spilling of excess water should be incorporated into levee designs to minimize unexpected damages due to overtopping. Breach or leaking of a levee or damage to accessory structures, such as lock gates, can cause catastrophic harm to both human communities and the environment; thus, periodic inspection, maintenance, cleaning and repair of these structures are very important.

CANAL WIDENING AND DEEPENING AX5

The amount of water that can be carried by a natural or manufactured waterway is a function of the width, depth, slope and smoothness of the canal bed. Enhancing any of these variables will increase the waterway's carrying capacity and reduce the risk of overflow and flooding. This process is also known as channel improvement.

Widening – increasing the width by cutting the banks – is the most common and usually the cheapest way to increase a waterway's flow. Because the depth and slope of a canal are usually constrained by the nature of the terrain, deepening is only used in special conditions. Lining the natural bed and banks of a canal with cement, **gabions**, or geotextiles makes the surface smoother and increases the flow velocity. Lining is costlier than widening and is usually done to control bank erosion. Changes to any of these canal parameters can have serious effects on upstream and downstream flow, and environmental effects on the waterway.

IMPORTANT DESIGN CONSIDERATIONS

Design objectives: Enhancing the carrying capacity (also known as discharge capacity) of a channel by changing width, depth, slope and smoothness.

Main components: N/A

Functionality: Channel improvement projects are designed to gain the maximum discharge capacity by changing the width, depth, slope and/or bed smoothness of the waterway. The velocity of water in the channel is maintained at around 2 m/s to control sedimentation or scouring of the banks. The channel banks should be designed with proper slopes or lined to minimize erosion.

Safety: The main safety concern in design is the stability of the banks after modification. If the bank collapses under the weight of adjacent structures or due to erosion, it may cause serious damage to people and property.

FLOODWAYS AX6

Another approach to increasing the carrying capacity of a waterway is to provide an alternate path for part of the flow. A **floodway** is a parallel canal or an enclave or reservoir that receives overflow when the flood flow exceeds the waterway's carrying capacity (fig. 5.12). The floodway is expected to be dry in normal conditions and can be used for other purposes, such as cultivation. The floodway's inlet and outlet should be carefully designed and constructed to prevent localized flooding. Managers can either use existing natural depressions and drainage paths in the area or construct an entirely new engineered channel.

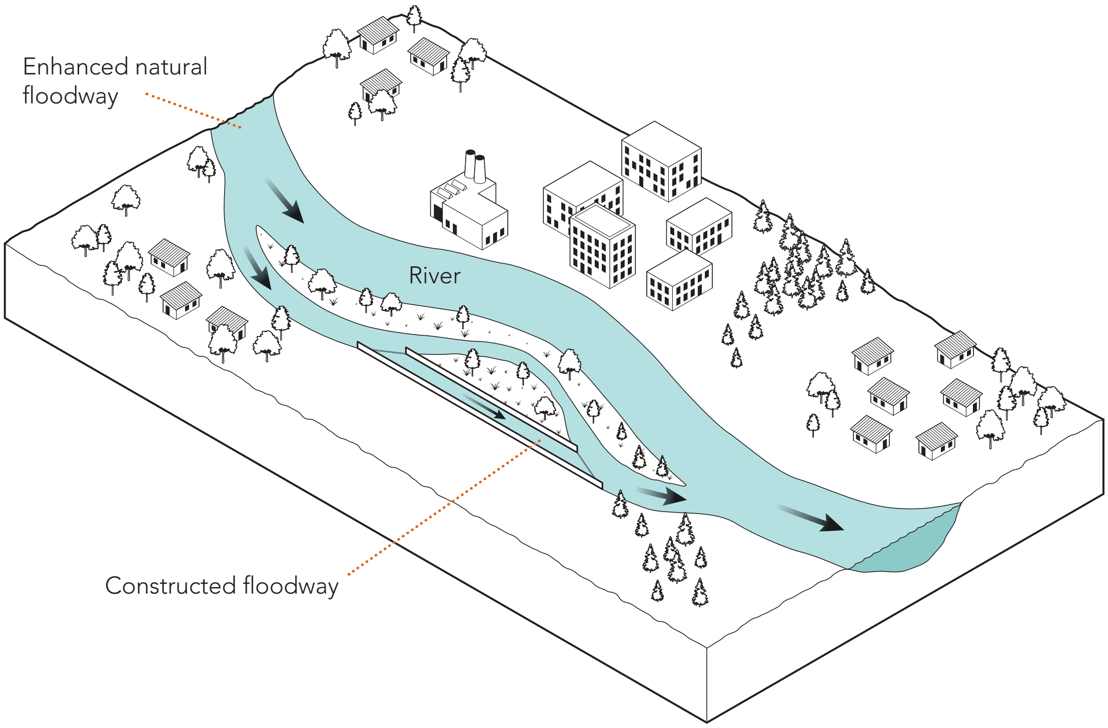

FIGURE 5.12 FLOODWAYS IN A RIVER SYSTEM

IMPORTANT DESIGN CONSIDERATIONS

Design objectives: Enhancing the carrying capacity (discharge capacity) of a channel by providing an auxiliary path.

Main components: Existing channel, auxiliary channel (floodway), inlet, outlet.

Functionality: Floodways are designed in a way that combined discharge capacity of the existing and auxiliary pathways can safely accommodate the design flow. As in any channel design, the discharge capacity is determined by the width, depth, slope and bed smoothness of the auxiliary path/channel. It is always economical to have auxiliary pathways that can be used for other purposes during dry periods (agriculture, for example). However, these land uses may affect the surface roughness of the channel bed and significantly slow the water flow.

Safety: The most important safety concern in floodways is the risk of secondary floods along the auxiliary pathway. The stability of the channel and the banks is also critical for safety.

PUMPING AX7

Another method of providing an alternate pathway to reduce flood risk is to mechanically shift part of the flow downstream using pumps. Pumping can be used to increase conveyance along a channel or improve drainage in a floodplain. However, pumping requires energy and costly infrastructure; typically, it is used only in specific conditions and as a last resort. Pumping can also be used to

- convey a large flow quickly away from a concerned stretch of the river, managing rapid-onset floods, such as urban flash floods;
- remove water from a small, localized floodplain to prevent urban flash floods;
- create drainage when the floodplain is lower than the sea level and natural drainage is not possible;
- avoid salinity intrusion in cases where there are lock gates along streams; and
- drain groundwater floods that can't be naturally drained.

Usually the pumps are installed in a structure called a pump station upstream of the area where managers want to reduce the flood risk. Water is pumped through pipes to downstream locations. Since the water is pumped at a faster rate than the natural flow of the source (stream, river, tidal flow), the pipes require far less capacity than an auxiliary channel. Pumps can also transport water to a higher elevation (if required).

IMPORTANT DESIGN CONSIDERATIONS

Design objectives: Mechanically shifting part of the flow in a water body to a location with less flood risk.

Main components: Inlet, pump station, conduits, fittings and fixtures (e.g., valves, anchors), outlet.

Functionality: Pumps should be selected according to the flow that has to be diverted and the elevation or distance that the water needs to be conveyed. The capacity of a pump is the flow that a given pump can deliver to a given elevation with maximum energy efficiency. If you use a large-capacity pump to carry a small flow, a lot of energy will be wasted. The sizes of pipelines should be carefully calibrated to provide minimal resistance to the flow and reduce energy loss.

Safety: Breach of a conveyance pipeline can cause localized flooding. Large electrical or fuel-operated pump stations may cause a fire hazard.

ENGINEERED DRAINAGE SYSTEMS AX8

Manufactured infrastructure built to effectively collect and convey runoff away from a given area is called an **engineered drainage** system. Drainage systems include collection drains (surface or underdrains) that connect water from sub-watersheds, a main stormwater canal or underground sewer, and an outfall into a main water body (fig. 5.13). Surface drains are generally rectangular or semicircular channels made of earth, concrete or brick; under drains are submerged PVC, clay or concrete pipes that have been perforated along the bottom or have gaps in their connections (fig. 5.13). Circular or ovoid underground sewers are used in urban areas when there is no open space for surface canals or when greater depths are needed. In some cases, stormwater mixes with human waste in sewers (known commonly as combined sewers), but this can cause serious pollution and water management issues, so it is largely avoided in new designs.

IMPORTANT DESIGN CONSIDERATIONS

Design objectives: Effectively collect the runoff generated in a design storm from a landscape and convey it to major waterways to prevent localized floods.

Main components: Surface drains, under drains, gully boxes, manholes, silt traps, tunnels, outfalls.

Functionality: The most important design concern in an engineered drainage system is to have sufficient carrying capacity in all the devices (e.g., drains, pipes, canals, tunnels, manholes and outfalls), effectively conveying a flow corresponding to the stormwater peak. Each device should be sized carefully with precise calculation of flow; failure to do so will cause overflow and local flooding. Moderately sized drains can carry large amounts of water. For example, a drain that is 30 cm wide and 20 cm deep can carry a flow of 50-80 liters per second. The speed of water is also a very important design factor. If the speed is excessive (>2 m/sec), the drains tend to erode or scour; very low speeds allow sediment deposition and blockage. Where the speeds are high, drains should be lined with concrete. The designs should ensure that roadside drains are strong enough to withstand the impact of moving traffic. Where the speeds are low and stormwater tends to carry large amounts of silt or dirt, silt traps should be included in appropriate locations, with a plan in place to have them cleaned regularly (typically 2-3 times per year). Drainage outfalls to water bodies should be carefully designed. If the water level in the water body exceeds the water level in the drains, water flows upward, causing back-flushing and floods. This can also happen if the outfalls are too narrow and the water builds up rapidly in an intense storm event. All underground systems should include manholes for maintenance purposes; these are generally spaced in 100-200 m intervals.

Safety: Covering deep surface drains properly (>50 cm covers) in urban areas is an essential safety measure. The same applies to manholes in underground systems. Leaking underground sewers can cause subsurface erosion and create hazardous sinkholes. Keep in mind that stormwater can have many contaminants and connecting a stormwater drain to a water body used for drinking may create serious health risks. If absolutely necessary, combined sewers (sewage and stormwater) should be designed very carefully to prevent contaminating water bodies and introducing health and environmental risks.

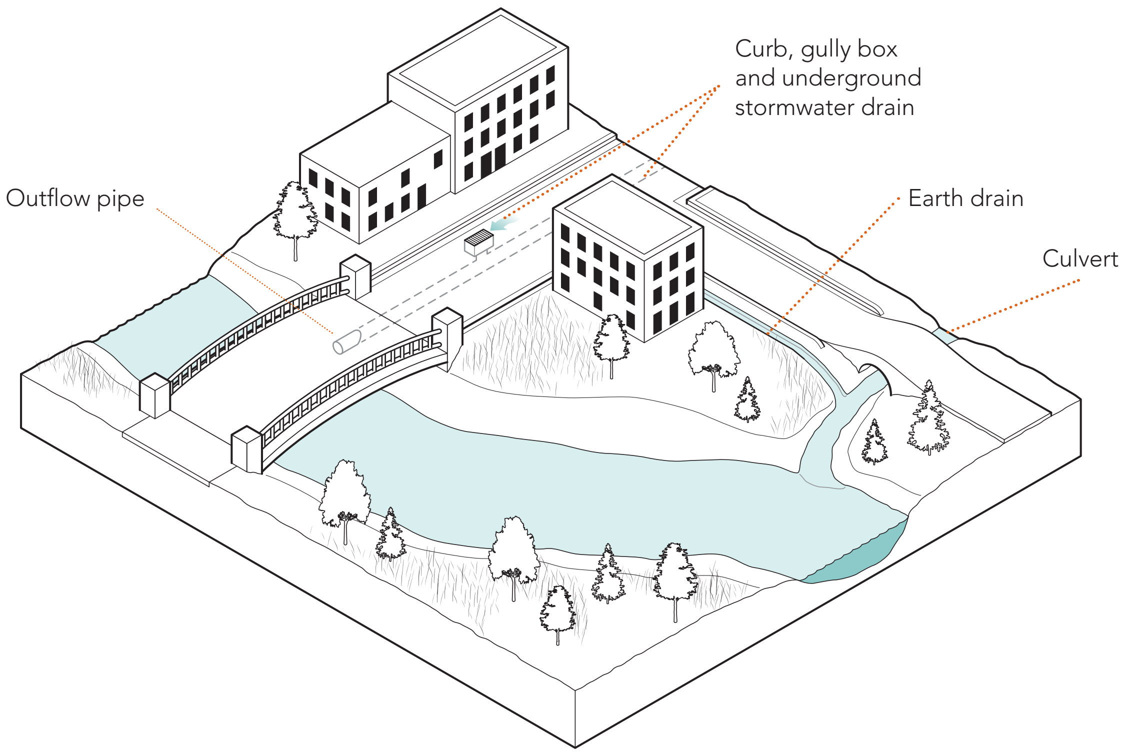

FIGURE 5.13 ENGINEERED DRAINAGE SYSTEMS

GROYNES AND REVETMENTS AX9

In addition to enhancing flow conditions, engineering measures are commonly used to artificially strengthen the banks of waterways against erosion. This is achieved by either building structures that will reduce the velocity of the water at the edges (groynes) or altering the structural properties of the bank material to make it less erodible (revetments and bank stabilization). Methods commonly used include the following:

Groynes: Groynes are built against movement of the water flow along the banks of a waterway. They break the flow, reduce velocity, and allow time for bank material carried by the flow to resettle. These structures usually have a simple, linear shape and are constructed at right angles (90 degrees) to the bank. Groynes are effective in preventing erosion in the lower reaches of a river with moderate velocities. They are usually constructed using heavy material such as rock or concrete; smaller groynes can be constructed with wooden piles and soil. Groynes were originally designed to manage coastal erosion and are not generally suitable for river systems. However, they have been introduced in some river systems to protect levees from heavy erosion. Groynes can significantly change the river hydrology, constrict flow and cause excessive silt accumulation. Thus the Flood Green Guide does not encourage groynes to be considered as a viable solution in flood risk management.

Revetments and bank stabilization: Revetments are structures built as a cover or apron to protect a stream/lake bank with loose material. They are usually constructed by packing boulders, using gabion walls or concrete lining, which cannot be carried by the force of water along the waterway. The other option is to improve the strength of the existing material in the bank by compaction, slope alteration, or introducing chemical binders or other soil stabilization methods. Revetments are very effective in sections with high velocity and in protecting other constructed flood defense structures, such as levees. Bank stabilization is useful in places where velocities are low and where space prohibits construction of groynes or revetments. However, both revetments and bank stabilization will affect the hydraulics of the river and other ecological processes. They cause significant damage to ecosystems along the banks (e.g., riverine vegetation, mangroves) and also destroy the habitat for fauna like water birds, otters and crabs. Therefore, both options should be carefully designed by a team of hydraulic/geotechnical engineers and aquatic ecologists. Groynes and revetments will also restrict access to the waterway and potentially impact its uses (e.g., fishing, recreation); therefore, it's important to provide proper access structures.

IMPORTANT DESIGN CONSIDERATIONS

Design objectives: Reduce bank erosion in a water body by dissipating the energy of the flow or enhancing resistance to erosion.

Main components: Groynes, protected bank (revetments or bank stabilization), access structures.

Main design parameters: Groynes are designed to dissipate the energy carried by the flow (or waves) before it reaches the bank and causes erosion. In revetments and bank stabilization, the energy calculations are used to determine the structural strength and stability required. In most cases, the velocity of the water is proportional to the energy it carries. The structural strength and stability are a function of material selected for construction, size and shape.

Safety: Structural strength and stability are the most important safety concerns. Breach can cause serious hazards. Groynes and revetments should be designed to ensure safety in other uses of the river (fishing, boating, recreation).

5.2.2.2 Soft Measures

NATURAL DRAINAGE PATH RESTORATION AY7

Often natural drainage paths (gullies, small streams, sloping land strips) in a landscape are modified or eliminated with urbanization and agriculture. However, these drainage paths require little or no maintenance and are the most stable conveyance paths in the landscape. Most of these drainage paths are not perennial and barely distinguishable as waterways during dry periods. Thus, when their surroundings are modified, these paths may get blocked with debris, silted, overgrown with weeds, or intentionally cut or filled. A manager can often improve stormwater drainage by identifying such natural drainage paths and monitoring, maintaining and restoring them (fig. 5.14). Often culverts are also installed where drainage paths cross roads, pathways, or pipelines, which are often undersized due to the complexity of calculating natural flows. Flows may increase over time, especially in growing urban areas. In such cases, culvert opening has to be done (culverts widened or replaced with bridges or low-water crossings that allow overflow), and the managers must continue to maintain them to prevent blockage.

IMPORTANT DESIGN CONSIDERATIONS

Design objectives: Identify and restore the original carrying capacity of natural drainage pathways in a landscape.

Main components: N/A

Functionality: The main design task in natural drainage restoration is to identify natural drainage paths and calculate the discharge capacity (both width and depth) that must be restored. Identification is a challenging task in most modified landscapes because no water will be flowing in dry conditions. Both expert and community knowledge will be useful in identifying discharge requirements and restoring the original conditions. Remote sensing and GIS can be very useful in identifying the natural drainage paths.

Safety: Safety issues are not critical unless removal of large engineered structures is required.

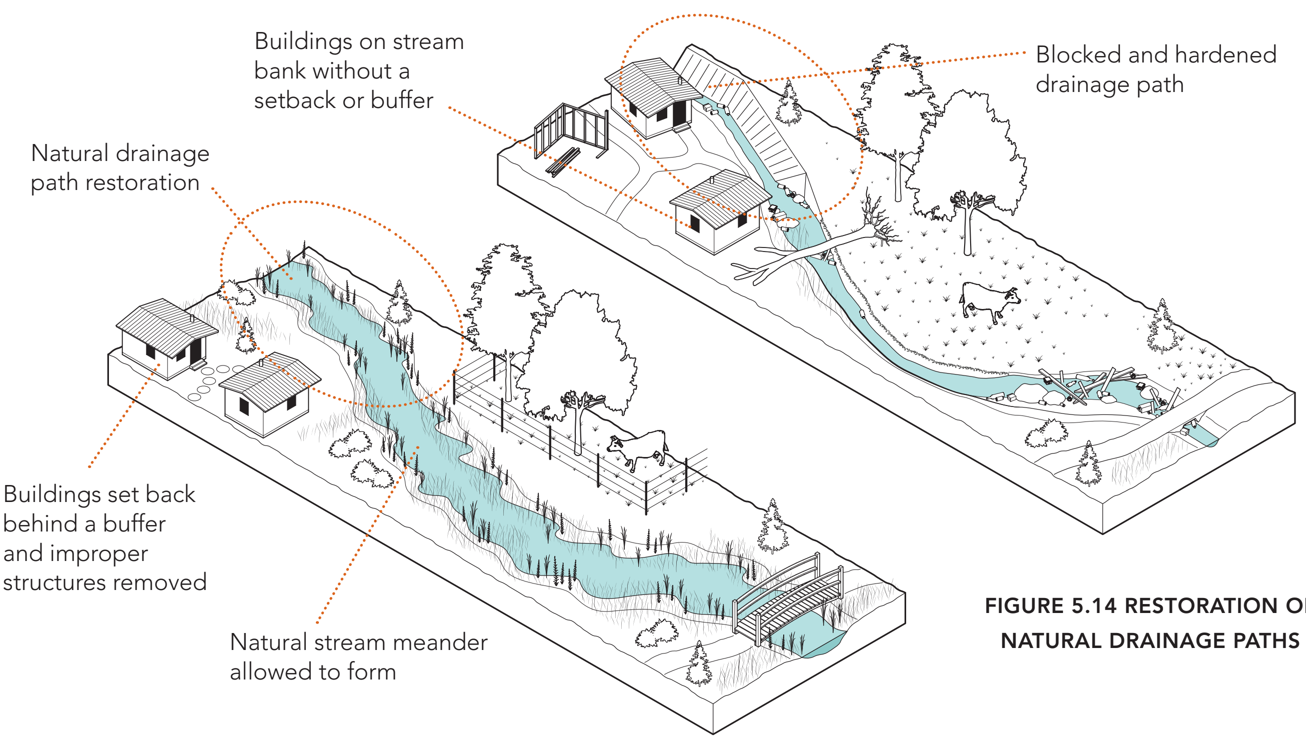

FIGURE 5.14 RESTORATION OF NATURAL DRAINAGE PATHS

RIPARIAN VEGETATION RESTORATION AY8

Most **riparian** ecosystems (habitats that exist adjacent to or along streams) are naturally resistant to erosion and scouring from high-velocity flows and floods. When riparian ecosystems are modified or damaged, they lose their ability to protect waterways, and the waterways experience excessive erosion. Most riparian plant species have adapted to withstand high water velocities and fluctuating water levels. Formations such as buttresses and adventitious roots stabilize the plants and firmly hold root-zone soil (fig. 5.15). Riparian habitats provide a barrier to sudden surge in water level. In upper watershed streams, riparian habitats also break the energy in high-velocity flows and reduce the flash flood or erosion threat downstream. Fallen trees and organic litter in the banks help break water velocity and provide extra cover for the soil. A number of other processes are carried out by microorganisms in the root zone and larger animals in the habitat (e.g., crabs, ants) that continually stabilize the soils. Restoration of riparian habitats will contribute to reducing erosion and protecting the banks.

Degraded riparian habitat can usually be reestablished through restoration and revitalization of riparian vegetation. The restoration projects should be carefully planned and the correct plant species selected. It is also important to recreate conditions for animal habitats – such as roosting and nesting sites, hideouts, shades and dens – and it is recommended to include aquatic or wetland expertise in the design and planning. Riparian restoration projects can affect the existing community uses of waterways, such as fishing, water collection and recreation. Restoration projects should take these uses into account and try to preserve them with community consultation.

IMPORTANT DESIGN CONSIDERATIONS

Design objectives: Enhancing the natural resistance in streams to withstand high-velocity and high-flow conditions.

Main components: Restored vegetation, restored habitats, access structures (pathways, pears), fences.

Functionality: The most important design tasks in riparian restoration are to identify the areas to restore and to select the correct plant species for revegetation. Most plants won't grow in highly moist riparian conditions, and introducing the wrong plant species might cause excessive silt trapping and filling up of the banks. The selected plants should support the other ecological processes of the ecosystem and provide for nesting, breeding and feeding of fauna. Small artificial structures like hideouts, shades or caves may have to be designed for habitat restoration. Depending on the existing level of human modification and erosion damage, supplementary measures like artificial bank stabilization or revetments may have to be designed.

Safety: Safety concerns are not critical in riparian restoration unless supplementary methods such as revetments are involved.

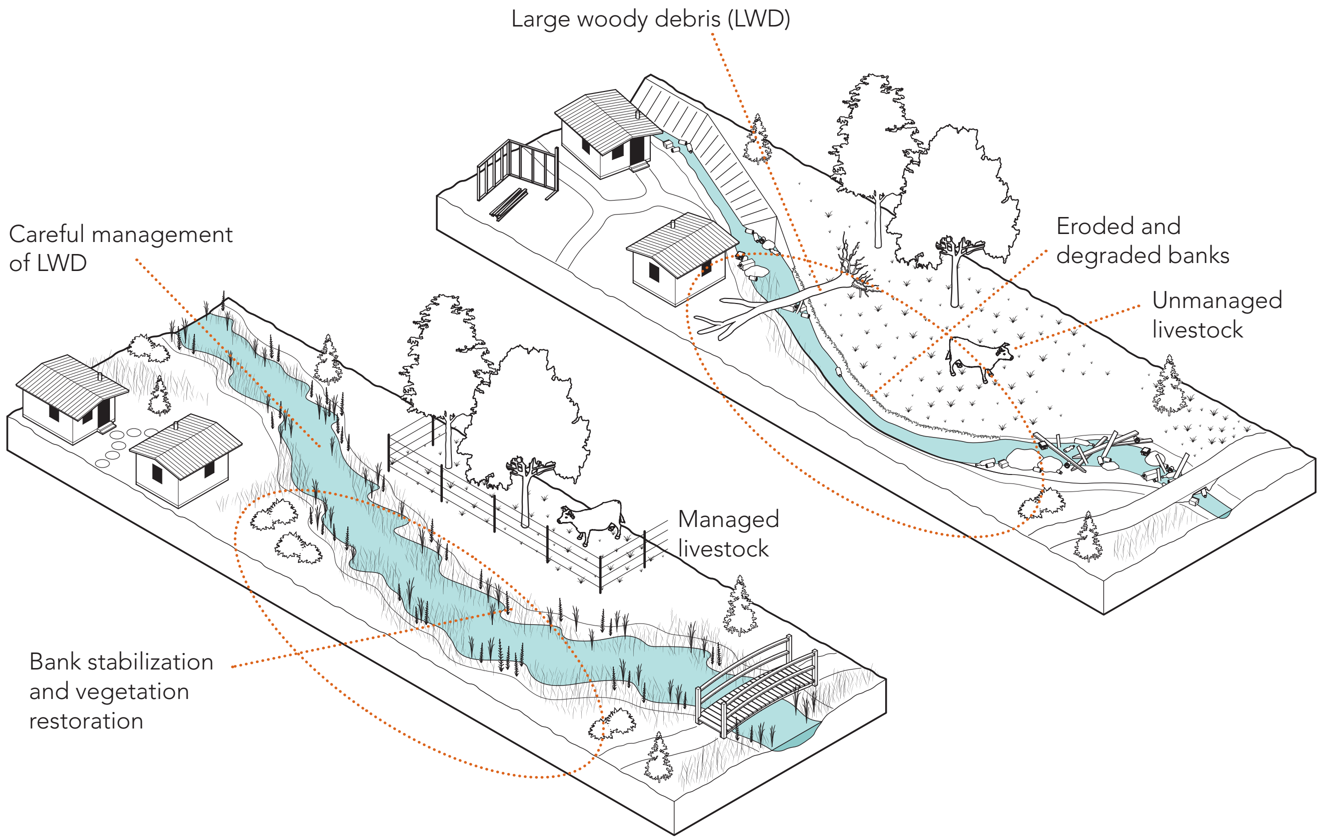

FIGURE 5.15 RESTORATION OF RIPARIAN VEGETATION AND HABITATS

REMOVAL OF BARRIERS AY9

Another way to improve conveyance capacity of waterways (especially small and medium streams) is by removing the barriers to flow. In natural systems this involves removal of boulders, vegetation and debris on the streambed that hinder flow (fig. 5.16). In small streams with habitual high velocities, regular removal of large woody debris can substantially reduce the local flood risk, especially for flash floods. Removing weeds in streams is also an effective way to restore flows. Streams in urbanized or agricultural areas are often overgrown with weeds that block the natural flows, and regular weeding is required. Floating weeds can be removed by mechanical collectors, and emergent and submerged weeds can be removed by volunteer weeding groups.

Regular removal of large trash (plastic items, rags, cardboard) is also important in urban streams. Large trash may include polythene/plastic bags, discarded household items (containers, furniture, electrical items), packaging material and rags. Such items accumulate in streambeds, bends or narrow points in channels, and culverts or control structures (sluices, weirs), and they block water flow. Trash also interferes with the functioning of natural streams and can decrease water quality. Trash removal is usually done manually by municipal workers, environmental volunteers or community groups in periodic stream cleaning programs. To restore highly degraded streams, machinery and vehicles may be necessary to remove and transport trash. In these cases, careful project planning and substantial investments are essential. Large trash removal programs should be accompanied by

- local government-level solid waste collection and disposal;
- public awareness programs on solid waste management (reducing, separation for recycling, composting);
- public awareness programs on stream health and ecology; and
- strict enforcement of solid waste management regulations.

In human-modified systems, removing obsolete structures like old bridges and narrow culverts is also required. The process of carefully removing (replacing with bridges) or widening narrow culverts is also known as culvert opening. Removing such barriers can be particularly useful in areas undergoing urbanization, where the runoff (overland flow) has increased over time. Many structures that block urban streams were built without considering buffer distance regulations for the existing stream. Removing these structures is an effective way to increase or restore the conveyance capacity of a waterway. However, certain unauthorized structures are common in low-income settlements and are essential to everyday life. Removing them should be done with extreme care and with community participation.

Conveyance capacity also can be improved by moving levees further away from the edges of the waterway (also known as levee setback). Levee setbacks increase conveyance and reconnect the waterway to portions of the floodplain. Widening the boundaries of the waterway slows the velocity of water during flooding, which can reduce downstream bottlenecks and back-flushing. This approach also helps to restore riverine habitats and reduces operations and maintenance costs associated with levees, which degrade more quickly under pressure from high-velocity water.

A more intrusive approach to removing barriers in waterways is to eliminate natural features, such as sandbars and rocks, in river mouths to prevent back-flushing during high flows. This method can interfere with the stream's natural flows and functions, including fish migration, and should be carefully planned by professionals working with the communities using the waterways.

IMPORTANT DESIGN CONSIDERATIONS

Design objectives: Restore or enhance the carrying capacity of a waterway by removing features that reduce the cross-sectional area or increase the roughness of the channel.

Main components: N/A

Functionality: Barrier removal projects are designed to optimize the carrying capacity (discharge capacity) and reduce the surface roughness of waterways. However, it is extremely difficult to accurately calculate the increase in flow after a barrier is removed in a natural stream. The general rule is that any barrier that alters the natural flow conditions of a waterway is worth removing. When it comes to removing natural barriers in order to artificially enhance discharge capacity, precise hydrological design and environmental assessment is critically important.

Safety: Safety issues are not paramount in regular weeding or debris clearance operations. However, dismantling old engineered structures, demolishing unauthorized buildings, or removing natural barriers (e.g., large boulders) may cause serious hazards to people and property and should be planned by a safety team.

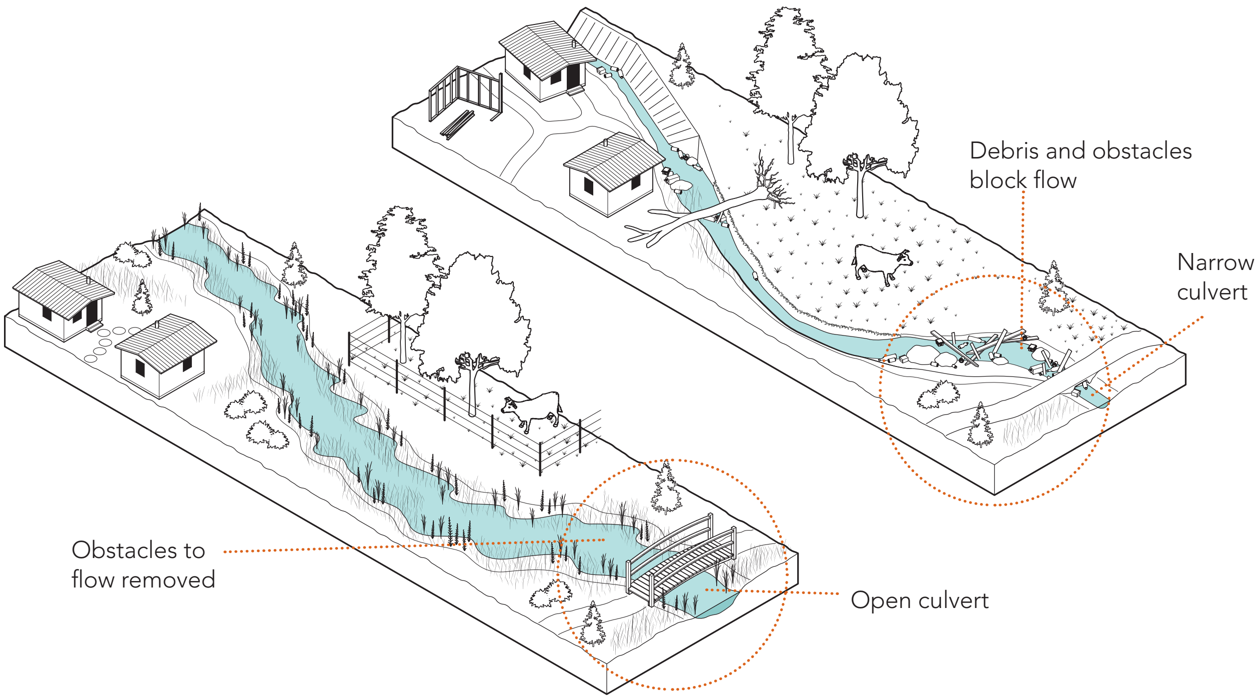

FIGURE 5.16 REMOVING BARRIERS TO FLOW

COASTAL AND REEF RESTORATION AY11

Coastal ecosystems can provide natural protection from coastal and tidal flooding and can significantly dissipate wave energy, break offshore waves, and reduce inland flooding. When mangroves, dunes, beaches, seagrass beds, and coral or shellfish reefs are damaged or degraded by, for example, development or climate change, their ability to provide protective services is greatly reduced. (See wetland restoration AY3).

Along some coastlines, beaches and sand dunes may be at a higher elevation than the land behind them, and they can provide a barrier to flooding and dissipate wave energy. Naturally occurring sand dunes are sand deposits formed by the wind. Dunes can provide a natural supply of sediment to replenish the surrounding beaches based on winds and tides and reduce coastal erosion. Sand dunes are often degraded by human activity and development, thereby diminishing their potential to serve as a buffer against coastal storms and flooding. Dunes and beaches, however, can be restored by trapping sand with fences – for example, constructed with branches or reed stakes – or can be stabilized by planting vegetation. Native vegetation can be transplanted from intact dune systems or acquired from nurseries, and artificial dunes can be created to buffer coastlines. It is important that dune restoration projects consider the source of sand and the types of vegetation species used. Coastal projects should also consider the relationship between the coastal area and the back bay or lagoon to ensure that dune restoration does not impede sand replenishment or increase the risk of flooding elsewhere. It's also important to allow the restored or managed ecosystem to adapt to climate change.

Coral reefs are underwater ecosystems that provide habitat for a multitude of marine species with rigid structures built by coral. These underwater structures can act as natural breakwaters and break up waves, reducing their velocity and force. Coral reefs are degraded by human activities like coral mining, pollution and sedimentation from coastal development. Warming ocean temperatures and ocean acidification – results of climate change – further degrade coral reefs, reducing their effectiveness as a buffer against coastal storms.

Shellfish reefs, such as those colonized by oysters and mussels, provide similar benefits to coral reefs, but since shellfish reefs are typically smaller, they have less impact on wave dampening.

Coral nurseries are used to grow coral for reef restoration.

In some cases, degraded reefs can be restored to some level of function, while artificial reefs can in some places be created to carry out similar functions. Although technically challenging and potentially costly, it is sometimes possible to transplant coral or shellfish to appropriate substrates, or construct artificial barriers to colonize damaged sites. During restoration, particular attention should be given to the types of species used in colonization, the environmental conditions, the type of substrate used for attachment and, for coral, the type and shape of the transplant. In most cases, restoring or creating reefs will be more expensive and time consuming, and less successful, in returning reef functioning than protecting and managing existing reefs. Reefs should be protected from human threats. Protection and management include allowing for climate change adaptation as ecosystems will respond and/or adapt.

Coastal restoration projects should be undertaken with planning and technical expertise. Depending on the scope and context, it is highly recommended that coastal managers and aquatic ecologists be consulted during the planning and design stages of the project.

IMPORTANT DESIGN CONSIDERATIONS

Design objectives: To enhance the natural ability of coastlines to withstand high-velocity and high-flow conditions.

Main components: Restored vegetation, substrate and habitat.

Functionality: Identify areas to restore, and select the correct species and substrates for restoration. The existing level of human modification, erosion damage, and degradation will affect the types of restoration projects possible and may require the use of artificial reefs or dunes. Coastal and reef restoration projects are similar to wetland and riparian restoration in that a primary concern is that they restore the preexisting habitat in addition to creating an extra buffer or breakwater along the coastline. Projects should allow for adaptation to a changing climate.

Safety: Safety concerns are not typically critical in coastal restoration unless supplementary methods, such as revetments, are involved.

5.2.3 METHODS FOR ADAPTING TO FLOODS

The third category of flood risk management methods is **adaptation** to floods. These methods focus on helping communities adapt to floods, rather than on preventing or mitigating floods (or flood damage). Instead of managing the hazard, these methods strive to reduce the vulnerability and increase the capacity of communities to live with floods.

5.2.3.1 Hard Engineering Methods

MULTIPURPOSE INFRASTRUCTURE AX10

Public infrastructure that can be used for flood conveyance or detention during the wet season and for other purposes in the dry season is generally referred to as multipurpose infrastructure. Some examples are

- multilevel traffic tunnels that serve as drainage tunnels during the wet season
- playgrounds that can serve as detention basins
- tennis courts/basketball courts constructed below ground level to serve as detention ponds during rain
- parks and recreation areas designed to accommodate temporary flooding during heavy rains

Designers should plan such infrastructure based on a location's specific needs and to provide maximum benefits to all constituents. Multipurpose infrastructure should provide the required hydraulic conveyance and/or storage capacity for flood management and be structurally and functionally suitable for its other purposes. For example, a multipurpose park should be designed so that several days of flooding will not damage its paths, benches or open areas.

IMPORTANT DESIGN CONSIDERATIONS

Design objectives: To incorporate hydraulic functions (storage, conveyance, infiltration) into common infrastructure.

Main components: N/A

Functionality: There are three essential points to designing multipurpose infrastructure:

1. It should be structurally and functionally designed to fit primary purpose (car park, tunnel).
2. It should be hydraulically designed for the secondary flood-related purpose (storage, conveyance, detention).
3. It should be ensured that the structure is safe under exposure to water and additional loads/pressure exerted in the secondary flood-related purpose.

Safety: All the safety concerns that apply to designing the corresponding hydraulic structure (detention basin/pond, infiltration device, stormwater tunnel) apply here. Strict design measures should be taken to avoid exposing infrastructure users to any hazard during flooding. For example, in a multipurpose traffic-drainage tunnel, there should be a safe and reliable closing mechanism to prevent traffic from entering during flooding. In addition, consideration should be given to risks of water contamination, vector breeding, and post-flood physical hazards in a public place. Safety concerns that apply to the infrastructure's other uses (e.g., playground, traffic tunnel) should be considered separately by the relevant experts.

5.3 NON-STRUCTURAL METHODS

Non-structural flood risk management methods do not involve any physical interventions (engineering or ecological). Non-structural methods can be categorized mainly into two categories, depending on the nature of the interventions:

1. Governance changes
2. Changes in community and household practices

Governance changes include modification or introduction of laws, regulations or organizational procedures to induce practices (at different levels) that will contribute to prevention, **mitigation** or adaptation to floods.

Changing community and household practices includes approaches that will actively engage the community and households to induce behaviors that contribute to prevention, mitigation or adaptation to floods.

5.3.1 GOVERNANCE CHANGE

SOIL AND WATERSHED PROTECTION LEGISLATION B1

Most countries have legislation and policies in place to prevent environmental degradation, deforestation and soil erosion in upper watershed areas. These laws or procedures are important in flood risk management, as they regulate human activities that may increase soil erosion and cause hydrological changes, thereby exacerbating flood risk. The specifics of flood protection are different from country to country. Soil conservation in many places is regulated by national or state-level parliamentary acts. These laws outline conservation measures, permitted and prohibited activities, and compensation procedures for landowners. Some countries form exclusive agencies to enforce soil and watershed conservation regulations, while others use agriculture departments or regional administration offices for enforcement. Where national legislation has been enacted for soil and watershed protection, regulations and procedures may be enforced at local government levels. In some cases, watershed and river basin development agencies may have specialized approaches to watershed conservation.

Regardless of their technical effectiveness or legal enforceability, such laws, regulations and procedures should be considered at all stages and scales of flood risk management planning. Legislation and procedures may have weaknesses that a specialized flood risk management project can address. An integrated flood risk management project can, as a secondary goal, strive to improve the soil and watershed conservation regulations and procedures. Changing national legislation can be challenging, and improving local soil conservation regulations can be accomplished with local advocacy.

LAND USE PLANNING (REGIONAL) B2

Land use planning can influence the causes and consequences of floods. A country's land use planning is carried out at different administration and policy levels and is determined by a range of legislations and procedures, including land-use and urban development acts, national physical plans, environmental laws, and long-term development plans. Decisions begin at the level of national planning commissions, moving down to the level of local council offices. Proper land use planning is an essential element in any flood risk management project.

Although land use planning is transdisciplinary, zoning is the most critical aspect for flood risk management:

- **Zoning** identifies the geographical distribution of different land uses and what should be permitted or barred in specific locations.
- Careful planning of permissible land-cover and development in different sections of a landscape can help a manager manage hydrological flows and is central for soil conservation.

- In urban areas, zoning can help minimize flood damage (e.g., allowing flood buffer zones free of buildings along a river) and enable efficient flood evacuation.

A flood risk management project of any scale must incorporate land use planning. Moreover, land use planning should involve all relevant stakeholders, including government agencies and community organizations, while encouraging public participation. Details of integrated decision-making and public participation are discussed in chapter 3, and land use planning in urban areas is discussed in chapter 6.

FLOOD- AND WATERPROOFING (BUILDING REGULATIONS) B3

Improved building designs can minimize flood damage at household and neighborhood scales. There is a global trend to formally incorporate **flood-proofing** features into building designs. Some municipalities have made this mandatory. Such design concepts have several objectives:

- to make the buildings more flood tolerant (e.g., use of moisture-tolerant material)
- to improve the functionality of the building during the floods (e.g., elevated buildings and pathways)
- to improve drainage, infiltration and temporary water storage in the compound (e.g., domestic rain gardens)

Designs that combine traditional knowledge with modern technology and recent innovations can help achieve flood risk reduction objectives.

Building standards can be adopted at different administrative levels. The most common way is to prepare a technical document describing preferred approaches to be incorporated into building requirements at local government (city or village council) levels. Such standards may change from place to place according to the intensity and types of floods. For example, protecting buildings from groundwater floods may require a different approach than protecting against river floods.

Environmental implications should be carefully considered when preparing building codes. This applies to both materials and construction practices. For example, toxic or environmentally harmful construction chemicals are not recommended for flood-proofing. Building codes should take local environmental issues into consideration, guiding builders to sustainably source material, and recommending environmentally certified material when importing (e.g., certified timber).

REGULAR MAINTENANCE OF HEADWORKS B4

As discussed in the previous sections, flood risk management often involves physical structures (**headworks**) such as dams, canals, drainage systems and pumping systems. Once built, most of these structures need some level of regular maintenance. Certain headworks, including pumping stations or barrages with mechanical gates, may require daily maintenance and a regular operating staff. Others, such as open drainage systems or small watershed dams, may need occasional maintenance – to clean debris and silt that accumulate over time. Lack of maintenance will invariably lead to reduced capacity or malfunctions that will trigger floods.

Headworks maintained by large state agencies like irrigation departments or municipal councils generally have written maintenance protocols. However, maintenance of projects at the local government or neighborhood level is often neglected. It is important to document the maintenance needs for any project and establish a mechanism for regular monitoring. Community organizations, local flood committees and council representatives should be educated about the importance of regular maintenance so they can demand, allocate and monitor funds for the work.

FLOOD MONITORING AND WARNING FRAMEWORK B5

Monitoring, predicting floods and issuing flood warnings are vital components of flood risk management. Flood patterns can be observed over time, enabling predictions about flood likelihood and potential damage. Once predictions are made, vulnerable communities should be warned about dangers.

Flood monitoring and warning involve a range of activities at different levels and must be organized and scientific, regardless of the scale. Without proper coordination, an operation can lose efficacy, and false warnings may create unnecessary public chaos.

Most countries have established a flood monitoring and warning process as part of the national disaster management framework. The World Meteorological Organization (WMO) supports meteorological agencies at the national level through the Global Observing System. Individual national meteorological agencies work with irrigation departments and river basin agencies to gather weather and hydrological data and make predictions. Other international and regional networks, such as International Flood Network (IFNet) and Asian Disaster Preparedness Centre (ADPC), work directly with national-level agencies to issue flood warnings. As a result, predictions and warnings in certain flood-prone areas can be made before a storm or rainy season. While national disaster management authorities can issue warnings, effective communication to communities should involve local government and village leaders, local flood committees and community-based organizations. The local government in any flood-prone area should have its own flood monitoring and warning framework to work with the national disaster management agencies to communicate reliable information and issue warnings to the public. National agencies can partner with community-based organizations to form local flood committees. Media and cellular technology offer effective ways to issue flood warnings to individuals. Local television, radio channels and mobile text messages can inform the community promptly about flood situations. However, care should be taken to ensure that consistent warnings to the media come from a single source.

5.3.2 CHANGING COMMUNITY AND HOUSEHOLD PRACTICES

CROP CHANGE AND ALTERNATIVE LAND USE B6

Soil and watershed protection laws can sometimes discourage harmful land management practices, but most intense land degradation occurs where it is difficult to enforce national-level laws. For example, communities – especially those engaged in agriculture – might depend on the land for their livelihoods, and some of their practices may be environmentally destructive. In such situations, pragmatic approaches can improve a community's planting, harvesting and management practices to ensure the land's long-term viability. Rather than structural measures, these changes involve community training, building awareness, and, in some cases, reviving indigenous technology.

On the other hand, certain traditional land management practices can be environmentally beneficial–such as terraced farming and forest garden systems that may reduce soil erosion, reduce runoff, and prevent silting and blocking of streams and flood-control headworks.

© Chris Reij/WRI

Traditional and community land practices include stone terrace walls in Ethiopia for rainwater infiltration.

However, such traditional practices frequently disappear when intensive agriculture, cash cropping and animal husbandry are introduced. Likewise, community-maintained infrastructure is often neglected as more residents are employed in salaried jobs and agriculture becomes market oriented. A flood risk management project should take specific steps to reintroduce some of these lapsed good practices with communities. It is important to carefully identify which traditional practices should be encouraged and which should be replaced by alternative methods, both with expert advice and community consultation.

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Terraced farm and fields in Kyumnu, Nepal. Terracing and stone walls help rainwater infiltrate steep slopes and recharge groundwater sources.

The first step in sustainable community land management practices is to build community awareness on the issues of soil erosion and land degradation. This should be done at all levels, from households to farmers' and women's organizations. It may also be necessary to build awareness among local agricultural extension officers. Changes in community practices may come at a cost to both the community and individuals, so it's important to create incentives for adopting new practices.

5.4 APPLICATION OF METHODS ACCORDING TO TYPE OF INTERVENTION, LOCATION (IN THE WATERSHED) AND SCALE

Suitability and applicability of different flood risk management methods to a given flooding problem depend on a number of factors. The selected methods should suit the desired type/category of intervention (objective). Different methods are effective at different geographical scales (i.e., watershed, floodplain, community and household). In addition, the effectiveness of methods varies depending on the geographic location in a watershed at which they are applied. Finally, the selected methods should be suitable for the type of floods experienced in the given case. Tables 5.1 and 5.2 categorize the flood risk management methods discussed in sections 5.2 and 5.3 according to these factors.

TABLE 5.1 FLOOD RISK MANAGEMENT METHODS AND SCALES OF APPLICATION

OBJECTIVE		STRUCTURAL METHODS		NON-STRUCTURAL METHODS	
Type of intervention	Intervention scales	Hard methods	Natural and nature-based methods	Governance change	Community and household practices
Reduce, retain, detain and divert flood flows	Transnational/ national	AX1 Dams and reservoirs AX2 Diversions	AY1 Upper watershed restoration	B1 Soil and watershed protection legislation (national level)	*Not applicable*
	Watershed	AX1 Dams and reservoirs AX2 Diversions	AY1 Upper watershed restoration AY2 Soil conservation measures AY3 Wetlands restoration	B1 Soil and watershed protection legislation B2 Land use planning B4 Regular maintenance of headworks	*Not applicable*
	Floodplain	AX3 Constructed wetlands and polders	AY6 Detention basins and retention ponds	B2 Land use planning B4 Regular maintenance of head-works	*Not applicable*
	Community	*Not applicable*	AY4 Swales and infiltration devices	*Not applicable*	B6 Crop change and alternative land use
	Household	*Not applicable*	AY5 Rainwater harvesting AY10 Green roofs/ walls and blue roofs	*Not applicable*	*Not applicable*

OBJECTIVE		STRUCTURAL METHODS		NON-STRUCTURAL METHODS	
Type of intervention	**Intervention scales**	**Hard methods**	**Natural and nature-based methods**	**Governance change**	**Community and household practices**
Improve drainage and enhance resistance to damage	Transnational/ national	*Not applicable*	*Not applicable*	*Not applicable*	*Not applicable*
Improve drainage and enhance resistance to damage	Watershed	*Not applicable*	*Not applicable*	*Not applicable*	*Not applicable*
Improve drainage and enhance resistance to damage	Floodplain	AX4 Levees AX5 Canal widening and deepening AX9 Groynes and revetments AX6 Floodways AX7 Pumping AX8 Engineered drainage systems	AY4 Swales and infiltration devices AY7 Natural drainage path restoration AY8 Riparian vegetation restoration AY9 Removal of barriers AY11 Coastal and reef restoration	B4 Regular maintenance of headworks B2 Land use planning	*Not applicable*
Improve drainage and enhance resistance to damage	Community	AX7 Pumping	AY8 Riparian vegetation restoration AY9 Removal of barriers	*Not applicable*	*Not applicable*
Improve drainage and enhance resistance to damage	Household	*Not applicable*	*Not applicable*	*Not applicable*	*Not applicable*
Adapt to floods	Transnational/ national	*Not applicable*	*Not applicable*	B5 Flood monitoring and warning framework B3 Flood- and water-proofing (building regulations)	*Not applicable*
Adapt to floods	Watershed	AX11 Warning/evacuation infrastructure	*Not applicable*	B3 Flood- and water-proofing (building regulations)	*Not applicable*
Adapt to floods	Floodplain	AX10 Multipurpose infrastructure AX11 Warning/evacuation infrastructure	*Not applicable*	*Not applicable*	*Not applicable*
Adapt to floods	Community	AX9 Removal of barriers AX10 Multipurpose infrastructure AX11 Warning/evacuation infrastructure	AY7 Natural drainage path restoration AY11 Coastal and reef restoration	*Not applicable*	B3 Flood- and waterproofing (building regulations)
Adapt to floods	Household	*Not applicable*	*Not applicable*	*Not applicable*	B3 Flood- and waterproofing (building regulations)

TABLE 5.2 APPLICABILITY OF STRUCTURAL METHODS TO DIFFERENT FLOOD TYPES AND LOCATIONS IN THE WATERSHED

FLOOD TYPE	HARD ENGINEERING METHODS	SOFT METHODS
Riverine floods	AX1 Dams and reservoirs AX2 Diversions AX4 Levees AX5 Canal widening and deepening AX6 Floodways AX7 Pumping AX9 Groynes and revetments AX10 Multipurpose infrastructure AX11 Warning/evacuation infrastructure	AY1 Upper watershed restoration AY2 Soil conservation methods AY3 Wetland restoration AY8 Riparian vegetation restoration AY9 Removal of barriers
Overland floods	AX1 Dams and reservoirs AX8 Engineered drainage systems AX10 Multipurpose infrastructure AX11 Warning/evacuation infrastructure	AY1 Upper watershed restoration AY2 Soil conservation methods AY3 Wetland restoration AY4 Swales and infiltration devices AY6 Detention basins and retention ponds AY7 Natural drainage path restoration
Flash floods	AX1 Dams and reservoirs AX2 Diversions AX3 Constructed wetlands AX4 Levees AX5 Canal widening and deepening AX6 Floodways AX7 Pumping AX8 Engineered drainage systems AX10 Multipurpose infrastructure AX11 Warning/evacuation infrastructure	AY1 Upper watershed restoration AY2 Soil conservation methods AY3 Wetland restoration AY4 Swales and infiltration devices AY5 Rainwater harvesting AY6 Detention basins and retention ponds AY7 Natural drainage path restoration AY8 Riparian vegetation restoration AY9 Removal of barriers AY10 Green roofs/walls and blue roofs
Coastal floods	AX7 Pumping AX10 Multipurpose infrastructure AX11 Warning/evacuation infrastructure	AY3 Wetland restoration AY11 Coastal and reef restoration
Lake floods	AX10 Multipurpose infrastructure AX11 Warning/evacuation infrastructure	AY3 Wetland restoration
High groundwater floods	AX7 Pumping AX8 Engineered drainage systems AX10 Multipurpose infrastructure	AY3 Wetland restoration AY6 Detention basins and retention ponds AY7 Natural drainage path restoration
Rain on ice floods	AX5 Canal widening and deepening AX8 Engineered drainage systems AX10 Multipurpose infrastructure AX11 Warning/evacuation infrastructure	AY3 Wetland restoration AY5 Rainwater harvesting AY6 Detention basins and retention ponds AY7 Natural drainage path restoration

LOCATION IN THE WATERSHED	HARD ENGINEERING METHODS	SOFT METHODS
Upper watershed	AX1 Dams and reservoirs AX2 Diversions AX5 Canal widening and deepening AX8 Engineered drainage systems AX10 Multipurpose infrastructure AX11 Warning/evacuation infrastructure	AY1 Upper watershed restoration AY2 Soil conservation methods AY4 Swales and infiltration devices AY5 Rainwater harvesting AY7 Natural drainage path restoration AY8 Riparian vegetation restoration AY9 Removal of barriers
Middle watershed	AX1 Dams and reservoirs AX4 Levees AX5 Canal widening and deepening AX8 Engineered drainage systems AX10 Multipurpose infrastructure AX11 Warning/evacuation infrastructure	AY1 Upper watershed restoration AY2 Soil conservation methods AY3 Wetland restoration AY4 Swales and infiltration devices AY5 Rainwater harvesting AY6 Detention basins and retention ponds AY7 Natural drainage path restoration AY8 Riparian vegetation restoration AY9 Removal of barriers
Lower watershed	AX3 Constructed wetlands AX4 Levees AX5 Canal widening and deepening AX6 Floodways AX7 Pumping AX8 Engineered drainage systems AX9 Groynes and revetments AX10 Multipurpose infrastructure AX11 Warning/evacuation infrastructure	AY3 Wetland restoration AY4 Swales and infiltration devices AY5 Rainwater harvesting AY6 Detention basins and retention ponds AY7 Natural drainage path restoration AY8 Riparian vegetation restoration AY9 Removal of barriers
Coast and estuaries	AX2 Diversions AX4 Levees AX9 Groynes and revetments AX10 Multipurpose infrastructure AX11 Warning/evacuation infrastructure	AY3 Wetland restoration AY9 Removal of barriers AY11 Coastal and reef restoration
Urban areas	AX3 Constructed wetlands AX4 Levees AX5 Canal widening and deepening AX6 Floodways AX7 Pumping AX8 Engineered drainage systems AX9 Groynes and revetments AX10 Multipurpose infrastructure AX11 Warning/evacuation infrastructure	AY3 Wetland restoration AY4 Swales and infiltration devices AY5 Rainwater harvesting AY6 Detention basins and retention ponds AY7 Natural drainage path restoration AY8 Riparian vegetation restoration AY9 Removal of barriers AY10 Green roofs/walls and blue roofs

5.5 FACTORS AFFECTING SUCCESSFUL IMPLEMENTATION OF STRUCTURAL METHODS

A given structural method may be technically appropriate for an intended objective, flood type or scale of application. However, there are a number of factors (economic, operational, social and environmental) that may affect its successful implementation. All of these factors should be considered during the method selection process. Table 5.3 describes key advantages and disadvantages of economic, operational, social, and environmental issues.

TABLE 5.3 FACTORS CRITICAL TO SUCCESSFUL IMPLEMENTATION OF STRUCTURAL METHODS

METHOD(S)	ECONOMIC AND OPERATIONAL		SOCIAL AND ENVIRONMENTAL	
	DISADVANTAGES	ADVANTAGES	DISADVANTAGES	ADVANTAGES
AX1 Dams and reservoirs AX2 Diversions	• High capital and maintenance costs	• High flood peak reduction • More predictable management of regular floods • Moderate construction time • Effective with high and fluctuating flows	• Inundation, habitat loss, geological issues • High toll on natural resources for construction • Community displacement and impacts on traditional livelihoods • Danger of dam breach	• Potential livelihood development through multipurpose schemes
AX3 Constructed wetlands	• High capital cost • May consume significant land extents in high-property-value areas	• Low maintenance costs • Co-benefits include uses for recreational areas or farming • Long-term resilience	• Vector breeding • May introduce fire hazards	• Low environmental impact (if properly designed) • Bioretention of contaminants
AX4 Levees	• High capital and maintenance cost • Highly technical design and construction • Blocks local drainage and increases local flooding when design storm exceeded, leading to catastrophic losses	• More predictable management of regular floods • Reduces small-scale floods	• Blocking of natural flow paths and animal migration • High toll on natural resources for construction • Danger of levee breach • Property acquisition and impacts on livelihoods • Up- and downstream flood impacts • False sense of security, which promotes increased floodplain activities • River access cut off, which reduces benefits for agricultural land	

METHOD(S)	ECONOMIC AND OPERATIONAL		SOCIAL AND ENVIRONMENTAL	
	DISADVANTAGES	ADVANTAGES	DISADVANTAGES	ADVANTAGES
AX5 Canal widening and deepening	• High capital cost • Needs regular maintenance	• More predictable management of regular floods • Quick implementation	• Intense hydrological modification • Disturbance of streambed and changes in sedimentation • Property procurement and impacts on livelihoods	• Potential recreational co-benefits in urban areas
AX6 Floodways	• High capital cost • May consume significant land extents in high-property-value areas	• Low maintenance cost • More predictable management of regular floods	• Potential habitat loss, seasonal inundation • Community displacement and impacts on traditional livelihoods • May introduce new flood risks	• Potential livelihood development through multipurpose schemes
AX7 Pumping	• High capital and maintenance costs • High energy consumption	• More predictable management of regular floods • Effective with high and fluctuating flows • Quick implementation	• Changes in sedimentation patterns, downstream bed erosion	
AX8 Engineered drainage systems	• High capital and maintenance costs	• More predictable management of regular floods	• May change natural drainage patterns	• If properly designed, can reduce water stagnation, reducing waterborne diseases and vector breeding
AX9 Groynes and revetments	• High construction cost	• Can withstand high flood flows	• Changes in sediment patterns, habitat disturbance • May conflict with fishing and other community uses	
AX10 Multipurpose infrastructure	• Advantages and disadvantages may vary significantly based on the type of infrastructure. Combining flood management infrastructure with other infrastructure needs will generally save cost, but can be operationally complex.		• Advantages and disadvantages may vary significantly based on the type of infrastructure. However, combining two types of infrastructure generally gives environmental and social benefits.	
AX11 Warning/ evacuation infrastructure		• Effective in saving lives • Quick implementation	• Some communities may not be receptive	• Significant lifesaving benefits

METHOD(S)	ECONOMIC AND OPERATIONAL		SOCIAL AND ENVIRONMENTAL	
	DISADVANTAGES	ADVANTAGES	DISADVANTAGES	ADVANTAGES
AY1 Upper watershed restoration AY2 Soil conservation methods	• Longer time needed for implementation • Difficult to quantitatively predict attenuation effect	• Moderate cost • Extends life of downstream infrastructure • Long-term resilience	• May impact livelihoods such as livestock grazing	• Positive ecological impacts • Reduced sediment transport • Groundwater recharge • May create new livelihood opportunities
AY3 Wetland restoration AY11 Coastal and reef restoration	• Longer time needed for implementation • Difficult to quantitatively predict attenuation effect	• Moderate cost • Long-term resilience	• May result in community relocation • May impact livelihoods such as livestock grazing, fishing	• Positive ecological impacts • May create new livelihood opportunities • Recreational benefits
AY4 Swales and infiltration devices AY5 Rainwater harvesting	• Only applicable in small scale	• Low cost • Quick implementation	• May increase vector breeding	• Groundwater recharge • Bioretention of contaminants • Reduced sediment transport • Recreational benefits
AY6 Detention basins and retention ponds	• Only applicable in medium scale • May consume significant land extents in high-property-value areas	• Moderate cost • Quick implementation	• Modification of drainage paths and stagnation • Vector breeding • Property procurement • May create polluted water bodies	• Reduced sediment transport • Helps groundwater recharge • Recreational benefits
AY7 Natural drainage path restoration	• Less applicability under changed flow conditions • Difficult to quantitatively predict attenuation effect	• Low implementation cost • Less complex design • Long-term resilience	• May trigger social resistance in highly modified areas	• Reduced sediment transport • Cleaner and healthier environment

METHOD(S)	ECONOMIC AND OPERATIONAL		SOCIAL AND ENVIRONMENTAL	
	DISADVANTAGES	ADVANTAGES	DISADVANTAGES	ADVANTAGES
AY8 Riparian vegetation restoration	• Not effective in high-velocity conditions • Difficult to quantitatively predict attenuation effect	• Low cost	• May constrain some existing uses of streams or lakes	• Positive ecological impacts • Recreational benefits
AY9 Removal of barriers	• Mostly applicable in medium scale • Difficult to quantitatively predict attenuation effect	• Low cost	• Removal of natural features (rocks, sandbars, beaver mounds) may cause environmental damage • May trigger social resistance in highly modified areas	• Cleaner and healthier environment
AY10 Green roofs/ walls and blue roofs	• Only applicable in small scale • May need additional structural strengthening of the building	• Low cost • Fast implementation	• May increase vector breeding • May cause fire hazard in dry season	• Improves aesthetic appeal and thermal comfort of buildings • Increases urban agriculture and park space • Reduces urban heat island effect

5.6 IMPORTANT CONSIDERATIONS FOR DESIGN, IMPLEMENTATION, MAINTENANCE AND CLOSURE OF STRUCTURAL METHODS

There are a number of design and implementation considerations for any structural flood risk management method that should be considered at the method selection stage and integrated into planning. Table 5.4 provides managers with information about common issues raised by experts during design and implementation, and highlights potential challenges at each stage.

TABLE 5.4 STRUCTURAL METHOD DESIGN, IMPLEMENTATION, MAINTENANCE AND CLOSURE CONSIDERATIONS

METHOD	DESIGN AND IMPLEMENTATION	OPERATION AND CLOSURE
AX1 Dams and reservoirs AX2 Diversions	• Should be designed by qualified professionals • Should be designed for multiple community uses • Poor designs can be costly and cause hazards • Community consultations and pre-feasibility studies are essential before site selection • Environmental impact study, feasibility study and community consultations are essential before design • Should minimize community relocation • Comprehensive relocation program should be developed if community relocation is required • Professional safety plans for construction are essential: heavy machinery movement, excavation, rock blasting	• Requires specifically dedicated trained staff for operation and monitoring; large dams need full-time staff • Frequent (e.g., once in three months) monitoring by a professional team is essential; may need advanced monitoring systems • Needs dedicated professional staff and a documented protocol to operate sluices and gates • Some reservoirs may need desilting every few years • Closure and removal are extremely expensive • If discontinued, a careful closure, decommissioning and restoration plan should be prepared; neglected structures can cause serious hazards and environmental issues
AX3 Constructed wetlands	• Should be designed by qualified professionals • Should be designed for multiple community uses • Environmental study and community consultations are essential before design	• Occasional (e.g., once in two years) monitoring/ inspection by an environmental engineer is required • Maintenance is generally low; however, some weeding may be necessary • Community volunteers can be involved in maintenance • Community awareness programs are essential where community use of wetlands is involved
AX4 Levees	• Should be designed by qualified professionals • Poor design can be costly, and mishaps and malfunctions can be dangerous • Environmental impact study, hydrological study, feasibility study, and community consultations are essential before design • Should not interfere with existing community uses (e.g., fishing, navigation) • Professional safety plans for construction are essential: heavy machinery movement, excavation, rock blasting	• Frequent monitoring by a team of professionals is essential • May need advanced monitoring systems • Dedicated operators needed if design includes lock gates • Removal is expensive • If discontinued, a comprehensive decommission plan should be prepared to remove the levees and restore the ecology; if the levees are entirely removed, regular safety inspections are required even after decommissioning the project
AX5 Canal widening and deepening	• Should be designed by qualified professionals • Environmental impact study, hydrological study, feasibility study, and community consultations are essential before design • Should minimize property acquisitions in urban areas • Professional safety plans for construction are essential (e.g., heavy machinery movement, excavation, rock blasting)	• Moderate (e.g., once a year) monitoring/ safety inspection by an engineer is required • May need desilting and bank stabilization every few years • Community volunteers can be involved in maintenance

METHOD	DESIGN AND IMPLEMENTATION	OPERATION AND CLOSURE
AX6 Floodways	• Should be designed by qualified professionals • Environmental impact study, hydrological study, feasibility study and community consultations are essential before design • Should be designed for multiple uses if possible • Design should keep property damage and land acquisition at a minimum • Comprehensive relocation program should be developed if community relocation is required	• Moderate (e.g., once a year) monitoring/safety inspection by a professional team is required • Seasonal cleaning, desilting and removal of large vegetation may be necessary • Community volunteers can be involved in maintenance • If discontinued, a comprehensive decommission and restoration plan should be prepared and implemented
AX7 Pumping	• Should be designed by qualified professionals • Poor designs can be energy inefficient • Environmental impact study, hydrological study, feasibility study and community consultations are essential before design • Pumping rate (flow) should be carefully selected when pumping groundwater floods – excessive pumping may cause ground subsidence	• Dedicated full-time operators required in pumping stations • Frequent monitoring by a professional team is essential; may need advanced monitoring systems • Replacement or overhaul of pumps necessary at regular intervals • If discontinued, machinery, electrical connections and structure must be carefully removed and the ecology of the site restored
AX8 Engineered drainage systems	• Can be constructed following standard guidelines, but larger systems require expert inputs • For larger systems, hydrological study and community consultations are essential before design • Combine with infiltration devices and sustainable urban drainage systems (SUDS) to minimize flow • Proper culvert design is very important; external professional inputs may be necessary	• Maintenance requirements are moderate; however, inspection for blockages and damage (by an engineer/technician) essential at least twice a year • Regular removal of silt and vegetation from drains and culverts required in most systems • Underground sewers/stormwater tunnels should be inspected annually by professional staff • May need advanced electronic monitoring systems • Community volunteers can be involved in maintenance
AX9 Groynes and revetments	• Should be designed by qualified professionals; poor design can exacerbate problems • Environmental impact study, hydrological study, feasibility study, and community consultations are essential before design • Should not interfere with existing community uses (e.g., fishing, navigation) • Professional safety plans for construction are essential (e.g., heavy machinery movement, excavation, rock blasting)	• Low maintenance requirements • Moderate monitoring/safety inspection by an engineer required • Removal is expensive • If discontinued, a comprehensive decommission plan should be prepared to remove the structures and restore the ecology
AX10 Multipurpose infrastructure	• May vary according to the type of structure	• May vary according to the type of structure
AX11 Warning/ evacuation infrastructure	• Larger structures should be designed by qualified professionals • Community consultations are essential • Considerations vary according to the type of structure	• Low maintenance requirements; however, regular (e.g., once a year) inspections are essential • Where electronic warning systems are used, frequent inspection by professionals is required • Community awareness programs for proper use and protection of the warning infrastructure are required

METHOD	DESIGN AND IMPLEMENTATION	OPERATION AND CLOSURE
AY1 Upper watershed restoration AY2 Soil conservation methods AY3 Wetland restoration AY11 Coastal and reef restoration	• Should be designed with both expert and local knowledge • Environmental impact study and community consultations are essential before design • Use only native plants and animals in restoration • Never change ecosystem or wetland type to gain better infiltration • Plan to maximize multiple community benefits	• Low maintenance requirements once restoration has matured • Occasional monitoring and inspection by a restoration ecologist are required • Weed management necessary in some cases • Combine with community use to minimize maintenance • Community awareness programs essential (on importance of restoration, protection and maintenance of restored areas)
AY4 Swales and infiltration devices AY5 Rainwater harvesting	• Can be designed with little expertise; best to use established guidelines and maximize multiple uses • Maximize recreational benefits • Never use for wastewater disposal	• Moderate maintenance once features have matured; annual inspections, weeding, and pruning required • Occasional monitoring and inspection by a trained professional are required • Vector management required • Community volunteers can be involved in maintenance • Volunteer training and awareness building about features helpful in user communities
AY6 Detention basins and retention ponds	• Should be designed by qualified professionals • Hydrological study and community consultations are essential before design • Avoid unnecessary water impoundment • Maximize recreational benefits	• Desilting required every few years • Vector management required • If discontinued, efforts required to prevent further impoundment/stagnation • Community volunteers can be trained in maintenance; if a retention is closed, it should be fully restored to avoid unintended water collection
AY7 Natural drainage path restoration	• Community consultations are essential and should be carried out with maximum community participation • Consult experts if the historical drainage paths are unclear • If culverts are required, culvert design should be done by professionals	• Annual maintenance and inspection programs are essential • Community volunteers can be involved in maintenance • Training and awareness building about restoration programs can involve volunteers in target communities
AY8 Riparian vegetation restoration	• Should be designed with both expert and local knowledge • Environmental assessments and community consultations are essential before design	• Annual inspection and weeding programs are necessary • Involve community volunteers in maintenance • Training and awareness building about restoration programs can involve volunteers in target communities
AY9 Removal of barriers	• Community consultations are essential and should be carried out with maximum community participation • Consult experts if removal of large natural features or unauthorized structures is required • Environmental assessments and hydrological studies are essential before design if removal of large natural features is involved	• Removal of weeds, large woody debris and silt has to be carried out in regular intervals (every one to two years) • Involve community volunteers in maintenance • Training and awareness building about restoration programs can involve volunteers in target communities
AY10 Green roofs/ walls and blue roofs	• A qualified civil engineer should check whether the building is fit for the modification and for the additional weight load, or in the case of a blue roof design, the water retention system • Waterproofing should be properly designed • Plants and soils should be selected carefully by a specialist knowledgeable about green roof/wall technology	• Green roofs/walls require regular weeding, watering and fertilizing • Yearly inspection (by professionals) of the roof for damage to the structure is necessary • Removal of a green roof/wall can be costly

5.7 USING THE OPTIMUM COMBINATIONS OF HARD AND SOFT STRUCTURAL METHODS

Managers should strive to use hard engineering and soft methods (natural and nature-based) in combination to meet objectives. The appropriate combination of methods will optimize the project's flood risk management, as well as its social and environmental benefits. A structural method's effectiveness can be substantially enhanced by pairing it with other structural and non-structural methods. Doing so will help managers reduce the capacity/size/area of such hard methods as dams, diversions or levees, which can be costly structures. For example, lower dam heights or levee heights will be possible if runoff from the upper catchment has been reduced by watershed conservation. The Flood Green Guide also recommends exploring options for enhancing the effectiveness of existing hard methods with soft methods. For example, upper watershed conservation in existing dam or levee systems can minimize the need for future dam and levee expansion. Since hard structural methods can lead to negative social and environmental impacts, it is better for the community to use complementary hard and soft methods. For example, a mix of revetments and riparian restoration can be used in high-risk areas, and areas exposed to lower risk of flooding can be protected only with riparian restoration. The combined-method approach will minimize disturbance to the ecological functioning of the riparian system and, therefore, potentially provide enhancement to livelihoods and recreation benefits of the waterway. On the other hand, riparian restoration should also further strengthen the risk reduction function of revetments by reducing amount and flow of floodwaters. Table 5.5 illustrates options for combining soft methods with specific hard structural methods.

5.8 RESOURCE AND COST PLANNING IN SELECTION AND IMPLEMENTATION OF STRUCTURAL METHODS

Planning, regulatory, resource (both human resources and material inputs), and cost requirements are all important feasibility parameters of a flood risk management project. Planning and execution of any flood risk management method will require human, financial and material resources, beginning with the design stage. Structural and non-structural methods that are technically applicable to a given flood risk management problem may not be practical in certain contexts due to their multiple requirements. This section provides guiding information for cost and resource requirements in a table for each structural method. However, in flood warning and evacuation infrastructure/multipurpose infrastructure (AX10, AX11), costs and inputs will vary significantly depending on the type of infrastructure (e.g., multipurpose tunnels, developing evacuation paths, flood warning signs). Therefore, the section will not provide cost and resource requirement guidelines for these two methods.

5.8.1 PLANNING AND REGULATORY REQUIREMENTS

National and/or local government regulations influence the feasibility of flood risk management methods in a given area. Regulations related to flood risk management projects might include

- land use and land tenure-related laws and land use plans
- environmental laws and Environmental Impact Assessment (EIA) regulations
- local government bylaws on building permits, land subdivision and drainage
- national or provincial development plans and policies
- national or provincial disaster management regulations and action plans

5.8.2 HUMAN RESOURCES

From the start of any flood management project, appropriate human resources are essential. Acquiring the proper expertise to undertake feasibility studies and design of structural and non-structural methods is key. For example, engineers, hydrologists, ecologists, conservation specialists, surveyors and sociologists might all be part of the team. Most projects also will need the services of community organizers or mobilizers.

HARD ENGINEERING METHODS	SOFT METHODS							
	AY1 Upper watershed restoration AY2 Soil conservation methods	AY3 Wetland restoration	AY4 Swales and infiltration devices AY5 Rainwater harvesting AY10 Green roofs/walls and blue roofs	AY6 Detention basins and retention ponds	AY7 Natural drainage path restoration	AY8 Riparian vegetation restoration	AY9 Removal of barriers	AY11 Coastal restoration
AX1 Dams and reservoirs AX2 Diversions	• Reduces runoff • Less dam/diversion capacity required	• Increase downstream retention • Less dam/diversion capacity required	Not applicable	Not applicable	Not applicable	Increases downstream resilience to high velocity and flow conditions	Not applicable	Capacity of tidal flood barriers/diversions can be reduced
AX3 Constructed wetlands	Not applicable	• Complements the retention capacity • Less constructed wetland area required	• Detains runoff and improves water quality • Enhances endurance of wetland	Not applicable	• Better flow conditions • Less siltation	Not applicable	Not applicable	
AX4 Levees	• Reduces runoff and velocity • Lower levee heights required • Reduced threat of breach due to scouring	Not applicable	Not applicable	Not applicable	Not applicable	Complements bank strengthening	Not applicable	Lower levee heights required (in the case of tidal floods and storm surges)
AX5 Canal widening and deepening	Not applicable	Not applicable	• Detains runoff • Reduced widening required	• Detains runoff • Reduced widening required	Not applicable	Complements bank strengthening	Improves flow conditions	
AX6 Floodways	• Reduces runoff • Less floodway capacity required	• Retains overflow • Less floodway capacity required	Not applicable	Not applicable	Not applicable	Increases downstream resilience to high velocity and flow conditions	Not applicable	
AX7 Pumping	• Reduces runoff • Less pump capacity required	• Retains overflow • Lower pump capacity and pumping frequency required	• Retains runoff and controls silt • Lower pump capacity and pumping frequency required • Long pump life	• Retains runoff and controls silt • Lower pump capacity and pumping frequency required • Long pump life	Not applicable	Not applicable	• Improves flow conditions • Lower pump capacity and pumping frequency required	
AX8 Engineered drainage systems	Not applicable	• Retains overflow • Small drain size can be used	• Retains runoff and controls silt • Small drain size can be used • Less maintenance	• Retains runoff and controls silt • Small drain size can be used • Less maintenance	Improves flow conditions	Not applicable		
AX9 Groynes and revetments	• Reduces runoff, flow fluctuations and velocity • Reduces erosion	Not applicable	Not applicable	Not applicable	Not applicable	Complements bank strengthening	Not applicable	Complements groynes and revetments by dissipating the energy of storm surges and tidal waves

TABLE 5.5 COMBINATIONS OF HARD AND SOFT STRUCTURAL METHODS TO ENSURE OPTIMUM FUNCTIONALITY, COST, AND SOCIAL AND ENVIRONMENTAL BENEFITS

COMBINATIONS OF HARD AND SOFT STRUCTURAL METHODS TO ENSURE OPTIMUM FUNCTIONALITY, COST, AND SOCIAL AND ENVIRONMENTAL BENEFITS

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Regardless of the scale of the project, it is important to have a dedicated project manager or coordinator and an accountant involved from the initial stage. Field-level staff (field assistant, survey assistants, drivers) and labor are also important human resource requirements. Managers should plan well in advance on how to acquire these human resources and prepare a plan of recruitment. Care should be taken to ensure that recruiting for skilled or unskilled tasks is done locally, thereby supporting the local community and economy. Managers should plan training for personnel and develop a training plan from the design stage of the project.

5.8.3 MATERIAL SOURCING

Most structural methods (hard and soft) will involve significant sourcing of materials. Though material requirements invariably affect a project's cost, other factors should also be considered in sourcing materials. Flood risk management projects often require a wide range of materials, including construction material (sand, gravel, cement, timber, soil, seeds and seedlings, and synthetic material like geotextiles). Managers should consider the following criteria in addition to cost-effectiveness:

- Material should be environmentally and responsibly sourced without depleting or damaging ecosystems.
- Any material that carries a human health or environmental risk should not be used.
- Procurement of any biological material (plants, seeds, animals) should be done with expert consultations.
- Imported material should conform to existing environmental certification.
- Local material sourcing should not adversely affect traditional livelihoods, but instead should strive to support them where possible.
- Material transport and storage should be done with no adverse impacts on local communities and their livelihoods.

5.8.4 COST ANALYSIS

Cost is often a limiting factor in flood risk management projects, as finances are often limited and, in many cases, inadequate. Therefore, cost analysis, budgeting and cost management are crucial for the success of a project.

First, the managers should work out preliminary cost estimates for the potential combination of methods. Costs involved in planning, design, construction/implementation, operation, maintenance and monitoring should be included in these preliminary estimates. For hard engineering works, the services of a qualified engineer and a budget consultant should be enlisted to prepare initial estimates. Some guidelines for preparing preliminary estimates are provided in appendix D. Based on preliminary cost estimates, some options may need to be ruled out. When an economically feasible set of methods is selected, detailed budgeting of the project should be completed, in consultation with an accountant or finance officer. Based on these detailed budgets, the project design should be carried out with the participation of managers, technical experts, communities, donors and finance officers.

The cost of structural methods is scale dependent. For example, a project that covers larger areas or handles a bigger flood flow will cost more. However, it should be noted that while certain cost components, such as materials or construction labor, will be directly proportional to the scale of the project, other components, such as preparation of designs, community consultations or building access to roads, will vary only marginally between different scales. Different cost components for different types of projects are discussed in appendix D. The cost of a project also may increase with qualitative changes. For example, in an engineered drainage system, installing underground drains is significantly more expensive than constructing surface drains.

For all construction work, detailed bills of quantities should be prepared by a qualified expert (quantity surveyor, cost engineer, civil engineer, civil engineering technician) based on the measurement standards followed in the country or locality. Detailed budgets should be prepared for each phase of the project, even for nonengineering works such as replanting and wetland restoration. During project implementation, costs should be monitored and managed according to bills of quantities or budgets.

All works entrusted to another party (other than the manager's organization) should be agreed upon by a standard written contract clearly stating the nature and value of the work. Most countries have standard formats for construction contracts. See appendix D for resource and cost planning guidance.

5.9 MONITORING AND EVALUATION

Managers should carefully plan and implement monitoring and evaluation as an essential part of the planning process for flood risk management projects. The following are general requirements for effective monitoring of a flood risk management project:

1. Monitoring should cover both the project as a whole and individual methods separately.

2. Monitoring parameters should be carefully selected. They should cover all aspects of the project and methods – technical, ecological, social, financial, and program management issues.

3. Selecting too few parameters will make the monitoring program ineffective. Too many parameters will make it too time consuming and costly.

4. Different types of monitoring are used for different parameters, mainly based on who's involved in monitoring and what resources are required: (a) official monitoring conducted by the responsible agencies and organizations, (b) monitoring conducted by external experts, or (c) community monitoring done in conjunction with responsible agencies. A good monitoring program will have a combination of official, expert and community monitoring.

5. Different parameters will require different monitoring frequencies: short-term, intermediate and long-term. Selecting the proper monitoring frequency for each parameter will be vital for effective maintenance and evaluation of the project.

Table E1 in appendix E provides a detailed guide for selection of parameters, types and frequencies for monitoring and evaluation programs.

5.10 ADDITIONAL RESOURCES

1. Steve Adair et al., *Management and Techniques for Riparian Restorations: Roads Field Guide*, (Fort Collins, CO: US Dept. of Agriculture, Forest Service, Rocky Mountain Research Station, 2002), http://www.fs.fed.us/rm/pubs/rmrs_gtr102_1.pdf.

2. Philip Roni and Tim Beechie (eds.), *Stream and Watershed Restoration: A Guide to Restoring Riverine Processes and Habitats* (West Sussex, UK: Wiley-Blackwell, 2012).

3. US Environmental Protection Agency (EPA), *A Handbook of Constructed Wetlands, vol. 1*, https://www.epa.gov/sites/production/files/2015-10/documents/constructed-wetlands-handbook.pdf.

4. W.J. Mitsch and J.G Gosselink, *Wetlands* (Hoboken, NJ, USA: John Wiley and Sons, 2007).

5. W.J. Mitsch and S.E. Jorgensen, *Ecological Engineering and Ecosystem Restoration* (Hoboken, NJ: John Wiley and Sons, 2004).

6. D. Butler and J.W. Davies, *Urban Drainage*. 2nd ed. (New York, London: Spon Press, 2004), https://vannpiseth.files.wordpress.com/2015/07/urban-drainage-butler.pdf (Also see the third edition published in 2011).

7. D.H. Gray and R.B Sotir, *Biotechnical and Soil Bioengineering Slope Stabilization: A Practical Guide for Erosion Control* (New York: John Wiley and Sons, 1996).

8. Lewis L., *Soil Bioengineering, an Alternative for Roadside Management: A Practical Guide* (San Dimas, California: USDA, 2000).

9. Water by Design, *Concept Design for Water Sensitive Urban Design*, version 1. (Brisbane: South East Queensland Waterways Partnership, 2009), http://waterbydesign.com.au/conceptguide/.

10. H.C. Pereira, *Policy and Practice in the Management of Tropical Watersheds* (London: Westview Press, 1989).