



# MAHARASHTRA STATE BOARD OF TECHNICAL EDUCATION MUMBAI.

## “FLOOD-RESISTANT URBAN INFRASTRUCTURE” UNDER THE GUIDANCE OF Mrs. Aishwarya A. Patil

### 1. Introduction

#### 1. Background

Floods are the most frequent and among the costliest natural hazards worldwide. Cities are especially exposed because they concentrate people, property, economic activity and critical services in relatively small areas, many of which were historically built beside rivers, estuaries and coasts for trade, transport and water supply. As of the mid-2020s, more than half of the world's population lives in urban areas, and the United Nations projects that this share will approach 70 per cent by 2050. Much of this growth is happening in low- and middle-income countries in Asia and Africa, often in low-lying deltas and floodplains.

Urbanization changes how water behaves in a landscape. In natural catchments, rainfall is intercepted by vegetation, infiltrates into soil, is stored in depressions and wetlands, and flows slowly toward rivers. In cities, roofs, roads, pavements and compacted ground are impermeable. Rain that once soaked into the ground now runs off quickly, reaching drains and streams in minutes rather than hours. Peak flows rise, flood timing shortens and the volume of runoff increases. Drainage systems designed decades ago for smaller populations and milder rainfall are frequently overwhelmed.

At the same time, climate change is intensifying the problem. A warmer atmosphere holds more moisture (roughly 7 per cent more per degree Celsius of warming), which raises the potential for extreme rainfall. Sea level rise increases coastal flood risk and reduces the ability of urban drainage to discharge by gravity. Together, rapid urban growth and a changing climate mean that the flood risk in many cities is increasing faster than the capacity of existing infrastructure.

#### 2. What Is Flood-Resistant Urban Infrastructure?

Flood-resistant urban infrastructure refers to the physical systems, structures, designs and supporting policies that help a city prevent, withstand, manage and recover from flooding. It includes:

- **Structural defenses** such as levees, flood walls, embankments, storm surge barriers and flood gates.
- **Drainage and conveyance systems** such as storm sewers, culverts, canals, pumping stations and underground tunnels.
- **Storage and attenuation systems** such as detention basins, retention ponds, underground tanks and flood plains.
- **Nature-based and green-blue infrastructure** such as wetlands, parks, green roofs, rain gardens,

bioswales and permeable pavements.

- **Flood-proofed buildings and utilities** designed to reduce damage when water enters or surrounds them.
- **Resilient transport and energy networks** that continue to operate or recover quickly during and after floods.
- **Soft infrastructure** such as early warning systems, flood forecasting, land-use regulation, building codes and emergency response.

The word "resistant" is often used together with "resilient". Strictly, **resistance** means keeping water out or preventing damage, while **resilience** means the ability to absorb the shock, continue functioning and recover quickly. Modern flood management recognises that complete flood prevention is neither technically possible nor economically viable everywhere. The modern goal is therefore a combination of both: resist where it makes sense, and design the city to cope and recover where flooding cannot be prevented.

### 3. Objectives of This Report

This report aims to:

- 1 Explain the types, causes and consequences of urban floods.
- 2 Describe the main engineering, ecological and planning approaches used to reduce urban flood risk.
- 3 Present international case studies to illustrate what has worked in practice.
- 4 Discuss economics, governance, equity and climate change in the context of flood management.
- 5 Provide a practical set of design principles and a checklist that can be applied in project work.

### 4. Scope and Structure

The report moves from understanding the hazard (Chapters 2 and 3), to the principles of design (Chapter 4), to specific infrastructure types (Chapters 5 to 8), to the enabling environment of policy, technology and finance (Chapters 9, 10 and 12), supported by case studies (Chapter 11), and finally to future challenges, equity, practical guidance and conclusions.

## 2. Objectives

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### 1. Objectives of Flood Resistant Urban Infrastructure Project

1. To reduce flood damage to buildings, roads, bridges and other urban infrastructure.
2. To improve stormwater drainage and provide efficient water-flow systems.
3. To prevent waterlogging in residential and commercial areas.
4. To promote rainwater harvesting and groundwater recharge.
5. To increase the capacity of drainage systems during heavy rainfall.
6. To protect public health and safety during and after flood events.

### 3. Understanding Urban Flooding: Types and Causes

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#### 1. Types of Urban Flooding

Urban areas can flood in several different ways, and effective infrastructure planning depends on correctly identifying which type or combination of types a city faces.

#### 2. Pluvial (Surface Water) Flooding

Pluvial flooding occurs when heavy rainfall exceeds the capacity of drainage systems or the ground's ability to absorb water, creating flooding that is independent of any river overflowing. It is also known as flash flooding or urban drainage flooding. It can happen very quickly, often with little warning, and is common in cities with large impervious areas. Because it is highly localized, it is difficult to forecast precisely. Underpasses, basements, low-lying roads and metro stations are particularly vulnerable.

#### Fluvial (River) Flooding

Fluvial flooding occurs when a river exceeds its channel capacity and spills onto adjacent land. It is caused by prolonged or intense rainfall in the upstream catchment, by snowmelt, or by dam or reservoir releases. Fluvial floods can last for days or weeks and may cover very large areas. Cities such as Dhaka, Bangkok, Cologne and Pittsburgh have all experienced significant fluvial flooding.

#### Coastal and Tidal Flooding

Coastal flooding results from storm surges, high tides, waves and sea level rise. Tropical cyclones, hurricanes and typhoons drive storm surges that push seawater inland. In low-lying coastal cities like Miami, Mumbai, Jakarta, Shanghai and New Orleans, coastal flooding can combine with heavy rainfall and high river levels, producing compound flood events. Even without storms, "sunny-day" or "nuisance" flooding is increasingly common at high tides in some cities.

#### Groundwater Flooding

Groundwater flooding occurs when the water table rises above ground level or into basements and underground structures. It is more common in areas built on permeable geology such as chalk or sand, and can persist for weeks or months after heavy rainfall. In coastal cities, rising sea levels push the water table upward, creating a slower but chronic form of flood risk.

#### Sewer and Drainage System Flooding

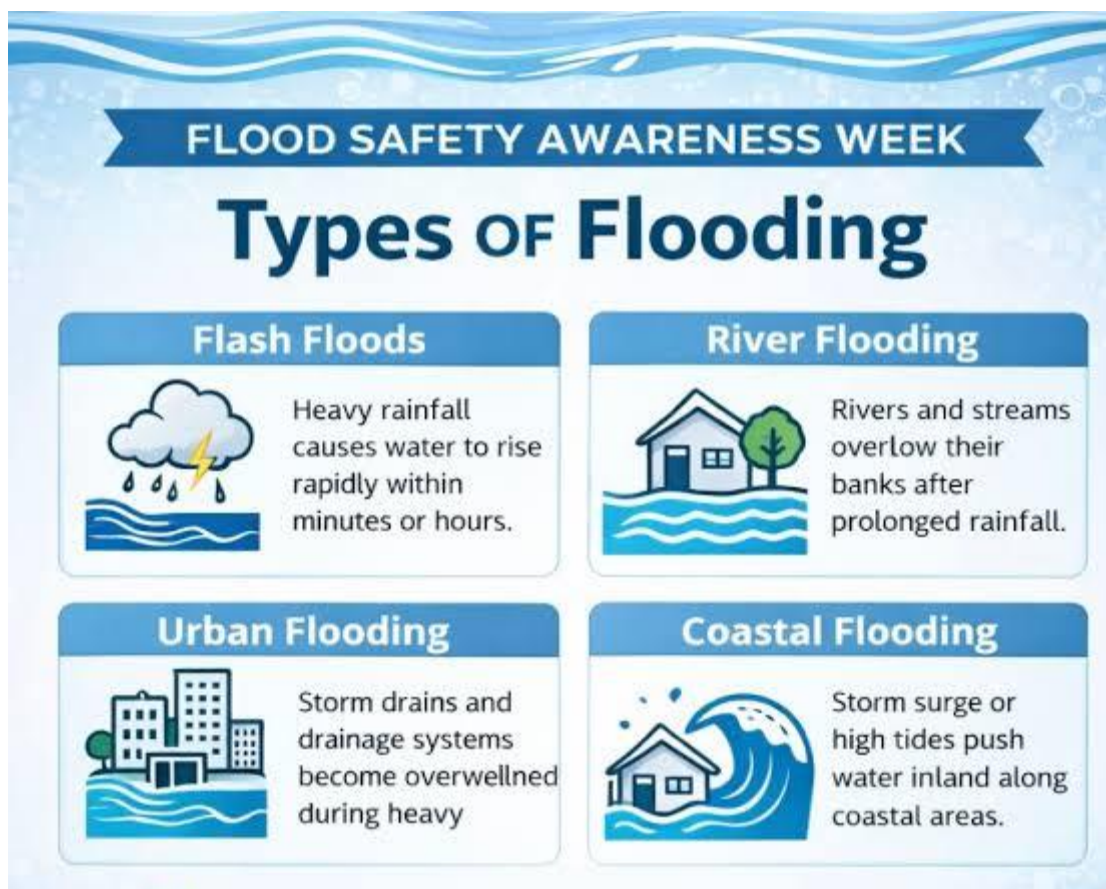
When combined or storm sewers surcharge, water can emerge from manholes, gullies and basements. In combined sewer systems, which carry both stormwater and sanitary wastewater, this may expose people to contaminated floodwater, creating public health risks. Blockages from solid waste, poor maintenance and sediment build-up often make this worse.

#### Infrastructure Failure Flooding

Floods can also result from failure of man-made structures such as dams, levees, embankments, water mains or pumping stations. The failure of the levees in New Orleans during Hurricane Katrina in 2005 demonstrated how a flood protection system that appears secure can become the source of catastrophic flooding when it fails.

## Compound and Cascading Flooding

Increasingly, floods are recognized as compound events in which two or more drivers combine, for example a storm surge coinciding with heavy rainfall and a swollen river. Cascading effects follow when flooding disables one system (such as electricity) which then impairs others (such as water supply, telecommunications and hospitals).



### 3. Natural Causes of Flooding

- **Intense or prolonged rainfall**, including monsoon rains, cyclones, thunderstorms and atmospheric rivers.
- **Snowmelt and glacial lake outbursts**, relevant to cities in mountain regions.
- **Storm surge and high tides**, driven by low atmospheric pressure and wind.
- **Saturated soils**, where earlier rain has filled the ground's storage so that additional rainfall runs off.
- **Topography**, since cities in valleys, basins or low-lying deltas are naturally prone to water accumulation.
- **Tsunamis and seiches**, less frequent but potentially devastating in coastal and lakeside cities.

### 4. Human-Induced Causes

Human activity often turns a natural hydrological event into a disaster.

**1 Increased impervious surfaces.** Replacing vegetated land with roads, roofs and parking lots dramatically increases the volume and speed of runoff. In heavily urbanised catchments, 70 to 100 per cent of rainfall can run off, compared to 10 to 20 per cent in natural woodland.

**2 Loss of floodplains and wetlands.** Building on floodplains removes natural storage and places assets directly in harm's way. Wetlands that previously absorbed floodwater have been drained or filled in many cities.

**3 Encroachment on natural drainage channels.** Informal settlements, roads and buildings frequently narrow or block streams, canals and nullahs.

**4 Inadequate or aging drainage systems.** Many drains are undersized for current rainfall and population, poorly maintained, or have been designed using outdated rainfall statistics.

**5 Solid waste and sediment.** Plastic, silt and debris block drains and culverts, reducing capacity precisely when it is needed most.

**6 Land subsidence.** Extraction of groundwater, oil and gas causes land to sink in cities such as Jakarta, Bangkok, Mexico City and parts of Houston, increasing relative flood exposure. Parts of Jakarta have been sinking by many centimeters per year.

**7 Poor land-use planning and enforcement.** Weak regulation allows development in high-risk zones.

**8 Climate change.** Increases in rainfall intensity, sea level and storm strength.

**9 Mismanaged reservoirs and river infrastructure.** Sudden dam releases or poorly coordinated operations can cause downstream urban flooding.

## 5. Urban Hydrology Basics

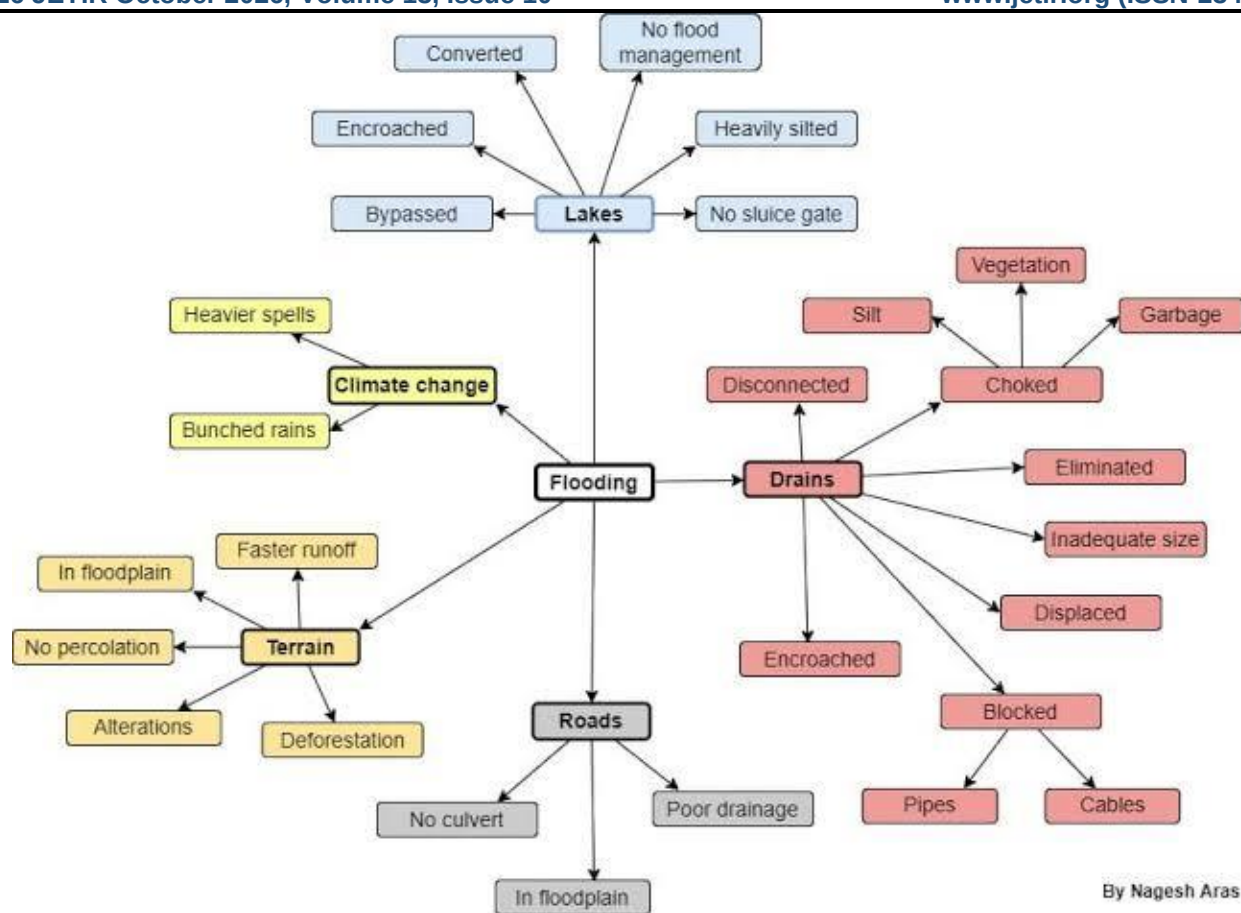
Understanding how urbanization changes hydrology helps explain why flood infrastructure is needed.

- **Runoff coefficient.** The proportion of rainfall that becomes runoff. It rises with imperviousness.
- **Time of concentration.** The time taken for water to travel from the most remote point in a catchment to the outlet. Urbanization shortens it, so flood peaks arrive sooner.
- **Peak discharge.** The maximum flow rate. Urban catchments typically produce higher, sharper peaks.
- **Return period.** The average interval at which a flood of a given magnitude is expected. A "100-year flood" has a 1 per cent chance of being equaled or exceeded in any year. This does not mean it happens once per century, and under a changing climate historical return period may understate the true risk.
- **Hydrograph.** A graph of flow versus time, which becomes taller and narrower after urbanization.

A widely used simple method for peak flow estimation in small urban catchments is the **Rational Method**:

$$Q = C \cdot i \cdot A$$

where  $Q$  is the peak discharge,  $C$  is the runoff coefficient,  $i$  is the rainfall intensity for a duration equal to the time of concentration, and  $A$  is the catchment area. More complex catchments are modelled using hydrological and hydraulic software (for example SWMM, HEC-HMS, HEC-RAS, MIKE URBAN and TUFLOW).



## 6. Flood Risk: Hazard, Exposure and Vulnerability

Flood risk is commonly described as a function of three components:

**Risk = Hazard × Exposure × Vulnerability**

- **Hazard:** the probability and intensity of flooding (depth, velocity, duration).
- **Exposure:** the people, buildings, infrastructure and economic assets located in flood-prone areas.
- **Vulnerability:** the susceptibility of those elements to damage, including physical design, socio-economic conditions, awareness and ability to recover.

Infrastructure strategies may target any of these: structural defences reduce hazard, land-use planning reduces exposure, and flood-proofing, insurance and preparedness reduce vulnerability.

## 4. Impacts of Urban Flooding

### 1. Human and Social Impacts

Floods affect more people globally than any other natural hazard. Direct impacts include drowning, injuries, displacement and loss of homes. Indirect impacts are often larger and last longer: outbreaks of waterborne disease such as cholera, typhoid, leptospirosis and dengue; mental health consequences including anxiety, depression and post-traumatic stress; interruption of schooling; and disrupted healthcare. The 2005 Mumbai floods, in which nearly a metre of rain fell in a single day, caused more than a thousand deaths in Maharashtra state. The 2021 floods in Germany's Ahr valley and neighbouring regions killed well over 180 people, demonstrating that even wealthy countries with advanced warning systems remain vulnerable. In 2022, devastating floods in Pakistan affected tens of millions of people.



## 2. Economic Impacts

Economic losses from flooding include:

- **Direct damage:** to buildings, contents, vehicles, roads, bridges, utilities and industrial plant.
- **Indirect losses:** business interruption, supply chain disruption, lost working days and reduced productivity.
- **Intangible losses:** loss of life, heritage, community cohesion and wellbeing, which are difficult to monetize.
- **Long-term effects:** declining property values, higher insurance premiums, investment avoidance and fiscal burdens on governments.

Global annual flood losses are estimated in the tens of billions of US dollars, with some analyses projecting that by mid-century, coastal flood losses alone for large cities could reach hundreds of billions per year without adaptation. Hurricane Sandy (2012) caused tens of billions of dollars of damage in the New York region, and the floods in Thailand in 2011 disrupted global supply chains, particularly for electronics and automobiles.

## 3. Infrastructure and Service Disruption

Urban flooding disrupts the networks that cities depend on:

- **Transport:** flooded roads, underpasses, rail lines and metro tunnels halt movement of people, goods and emergency vehicles.
- **Energy:** substations and underground cables fail; power outages follow.
- **Water and sanitation:** treatment plants flood, pipes are contaminated and sewage overflows.
- **Telecommunications:** exchanges, cell towers and data centers can lose power or be damaged.
- **Healthcare and emergency services:** hospitals may be inundated or isolated just when demand is highest.

Because infrastructure systems are interdependent, failures cascade. A power failure can disable pumping stations, which worsens flooding, which damages more power equipment.

#### 4. Environmental Impacts

Floodwater picks up and spreads pollutants from roads, industrial sites, sewers and waste dumps. Combined sewer overflows discharge untreated sewage into rivers. Erosion and sedimentation can damage aquatic habitats. Conversely, healthy floodplains and wetlands provide ecological benefits, which is one reason nature-based solutions are valued.

#### 5. Unequal Distribution of Impacts

Flood impacts are not distributed equally. Low-income communities often live in the most flood-prone locations because land there is cheaper or informal settlement is tolerated. They typically have less access to insurance, savings, quality housing and information, so recovery is slower. Women, children, older people, people with disabilities and migrants may face additional barriers. A flood-resistant infrastructure strategy that ignores these disparities risks leaving the most vulnerable behind.

## 5. Principles of Flood-Resilient Urban Design

### 1. From "Fight the Water" to "Live with Water"

Historically, flood management relied on a "predict and control" approach: build higher walls and bigger pipes to keep water out. This approach has real value but also limits. Defences can be overtopped by events larger than their design standard, and they can induce a false sense of security that encourages further development in protected areas (the "levee effect"). When a defended area floods, damage can be far greater than if development had been restricted.

Contemporary practice has therefore moved towards **integrated flood risk management** and the idea of **living with water**. The approach recognizes that flooding cannot be eliminated, that water should be given room, and that cities should be designed so that when floods occur, they cause minimum harm and recovery is quick.

### 1 Core Design Principles

**2 Manage risk, not just hazard.** Evaluate not only how often floods happen but also what is exposed and how vulnerable it is.

**3 Use a multi-layered approach.** Often described as a "multi-layer safety" or "defense-in-depth" strategy: (a) prevention through defenses and drainage, (b) spatial planning and flood-proof design to limit consequences, and (c) emergency management and preparedness.

**4 Slow, store, move, protect.** Slow down the water where it falls, store it where it can be held safely, convey it along designed routes, and protect critical assets.

**5 Design for exceedance.** Plan what happens when the design capacity is exceeded. Where will water go? Which routes serve as overland flow paths? Which assets will remain protected? A system that fails gracefully is better than one that fails catastrophically.

**6 Embrace multi-functionality.** Use spaces that serve more than one purpose, for example sports fields or plazas that are normally dry but can store floodwater temporarily.

**7 Adaptive and flexible design.** Because climate and urban conditions change, infrastructure should be designed to be upgraded over time, using approaches such as adaptive pathways rather than one fixed design.

**8 Work at catchment scale.** Water ignores administrative boundaries. Upstream land-use decisions affect downstream flooding, so planning must be coordinated across the whole catchment.

**9 Integrate with other urban systems.** Combine flood goals with transport, housing, green space, heat mitigation, water supply and biodiversity objectives for greater value.

**10 Prioritise critical infrastructure.** Hospitals, power stations, water treatment works, emergency services and communications should have higher protection standards.

**11 Include people.** Community engagement, awareness and equitable access to protection are essential.

## 2. Key Concepts and Frameworks

### Sponge City

The Sponge City concept, promoted notably in China since 2013 to 2015, aims to make cities behave like sponges: absorbing, storing, purifying and reusing rainwater, and releasing it slowly. It combines green infrastructure, permeable surfaces, wetlands and storage with conventional drainage.

### Sustainable Drainage Systems (SuDS) and Low Impact Development (LID)

SuDS (common in the UK and Europe) and LID (common in North America) aim to manage rainfall as close to its source as possible, mimicking natural hydrology. Water Sensitive Urban Design (WSUD) in Australia is a similar concept that integrates urban water cycle management into planning and design.

### Room for the River

Pioneered in the Netherlands, this approach lowers flood levels by giving rivers more space (for example by relocating levees, deepening floodplains and creating side channels) instead of simply raising embankments.

### Blue-Green Cities

An approach that integrates water (blue) and vegetation (green) throughout urban design, delivering flood management together with amenity, biodiversity and climate benefits.

### Resilience Thinking

Resilience is commonly assessed through attributes such as robustness, redundancy, resourcefulness, rapidity, flexibility and inclusiveness. These guide the design of systems that can absorb disturbance and recover quickly.

### Adaptation Pathways

Instead of committing to a single plan, adaptation pathways identify a sequence of actions and decision points triggered by monitoring signals such as sea level thresholds. This was applied in the Thames Estuary 2100 Plan and Dutch Delta Programme.

## 3. Design Standards and Levels of Protection

Flood protection standards vary widely. Typical approaches include designing drainage for a 5 to 10-year storm, major urban systems for a 100-year event, and critical defences for 200 to 1,000-year events or higher. The Netherlands applies some of the highest standards in the world, with some flood protection ranging from 1-in-1,000 to 1-in-100,000 years in the most densely populated areas, now defined in terms of acceptable individual risk of death. Many other cities rely on far lower standards. Selecting standards should

consider the consequences of failure, economics, climate projections and public acceptance, not just historical statistics.

## 6. Grey (Engineered) Flood Infrastructure

Grey infrastructure refers to conventional engineered structures built from concrete, steel, earth and pipes. It remains the backbone of urban flood protection, particularly in dense areas where space is limited and where high levels of certainty are needed.

### 1. Storm Drainage Networks

Storm drainage systems collect runoff from roofs, streets and paved areas and convey it to receiving waters.

#### Components:

- **Inlets and gullies (catch basins)** that collect surface water from roads.
- **Pipes and culverts** conveying water underground or beneath roads.
- **Open channels and canals** for larger flows.
- **Manholes and junction chambers** for access, maintenance and connection.
- **Outfalls** discharging into rivers, lakes or the sea, often fitted with flap valves to stop backflow during high tides.

#### Types of system:

| System             | Description                                   | Advantages                                 | Disadvantages                                   |
|--------------------|-----------------------------------------------|--------------------------------------------|-------------------------------------------------|
| Separate           | Stormwater and sewage in different pipes      | Avoids sewage in floods; simpler treatment | Two networks needed; cross-connections possible |
| Combined           | One pipe carries both                         | Lower initial cost in old cities           | Overflows contaminate floodwater and rivers     |
| Partially separate | Roof/yard water to sewer, road water to drain | Compromise                                 | Complex to manage                               |

**Design considerations** include rainfall intensity-duration-frequency (IDF) curves, pipe slopes and velocities (to keep pipes self-cleansing while avoiding erosion), backwater effects from downstream water levels, and climate change allowances, commonly an uplift of 20 to 40 per cent on design rainfall depending on region and guidance. Maintenance, such as regular desilting and cleaning of inlets, is as important as capacity.

### 2. Embankments, Levees and Flood Walls

Levees (also called dikes or dykes) are raised earth embankments along rivers or coasts. Flood walls are vertical or near-vertical concrete or sheet-pile barriers used where space is constrained, such as along urban waterfronts.

#### Design issues:

- **Crest height** based on design flood level plus freeboard (safety margin).

- **Foundation and seepage control**, since water can flow beneath or through levees causing "piping" failure.
- **Slope stability and erosion protection** using riprap, grass or concrete revetments.
- **Overtopping resistance**, because overtopped earthen levees can erode and breach rapidly.
- **Inspection and maintenance regimes**, because settlement, burrowing animals, vegetation and utility penetrations can compromise integrity.

**Limitations:** levees confine rivers, raising flood levels elsewhere, may worsen drainage of the protected side if water cannot exit, and create residual risk. The Katrina experience and the 2021 central European floods highlighted that protection is never absolute.

**Modern practice** includes designing for safe failure, such as lowered sections that overflow in a controlled way into designated areas, and combining walls with amenity such as promenades and parks so that protection is also an urban asset.



### 3. Flood Gates, Barriers and Surge Barriers

Movable barriers protect rivers, estuaries and harbors from storm surge while allowing navigation and normal flow at other times.

- **Thames Barrier (London):** a series of rotating steel gates across the Thames, operational since the early 1980s, protecting central London from tidal surges.
- **Maeslantkering (Netherlands):** one of the largest moving structures on Earth, a pair of huge floating arms closing the Nieuwe Waterweg near Rotterdam during severe storm surges.
- **MOSE (Venice):** a system of mobile gates at the lagoon inlets, activated during exceptional high tides (acqua alta), first operating in earnest in 2020.

- **Eastern Scheldt Barrier (Netherlands):** part of the Delta Works, with large sliding gates that normally remain open to preserve tidal ecology.
- **Inner Harbour Navigation Canal barrier (New Orleans):** part of the post-Katrina Hurricane and Storm Damage Risk Reduction System.

Smaller-scale gates and sluices on urban canals and drainage outfalls are also vital, preventing backflow of tidal water into drains.

#### 4. Pumping Stations

Where gravity drainage is not possible, for example in low-lying polders, areas below sea level or when river levels exceed drain levels, pumping stations lift water out of the urban area. Key design issues:

- **Capacity and redundancy:** multiple pumps with standby units.
- **Power reliability:** backup generators, dual power supplies and elevated electrical equipment, because pumps fail at the time they are most needed if power is lost.
- **Fish-friendly and debris-resistant design,** including screens and trash racks.
- **Location and flood-proofing** of the station itself.
- **Operation and control** using automation, level sensors and remote monitoring.

New Orleans and Dutch polder cities depend heavily on pumps, and many Asian megacities, including Bangkok and Jakarta, have extensive pumping networks.

#### 5. Detention and Retention Storage

Storage reduces peak flows by temporarily holding water.

- **Detention basins** hold stormwater for a short period, then release it slowly at a controlled rate. They are usually dry between storms.
- **Retention ponds** hold a permanent pool of water and provide additional storage during storms, with water-quality benefits.
- **Underground storage tanks** are used where land is scarce, for example beneath car parks, playgrounds or buildings.
- **Large-scale storage reservoirs and flood diversion areas** protect whole cities by holding river floods upstream.
- **Multi-purpose storage** such as sports fields, plazas or car parks designed to flood occasionally, as in Rotterdam's water squares.

#### 6. Deep Tunnel and Underground Flood Diversion Systems

Megacities with extremely limited surface space have built vast underground facilities.

- **Tokyo's Metropolitan Area Outer Underground Discharge Channel (G-Cans):** completed in the mid-2000s, this system includes a tunnel of around 6.3 kilometers, huge vertical shafts roughly 70 meters deep, and a giant pressure-adjusting tank with massive pumps. It diverts floodwater from small rivers during typhoon rains into the Edogawa River. It is among the largest of its kind.
- **Kuala Lumpur's SMART Tunnel (Stormwater Management and Road Tunnel):** a dual-purpose tunnel that diverts floodwater in extreme storms and carries road traffic at other times. When

flood storage is needed, the road section is closed to vehicles.

- **Chicago's Tunnel and Reservoir Plan (TARP):** a network of deep tunnels and reservoirs capturing combined sewer overflows and flood flows.
- **Singapore's Deep Tunnel Sewerage System** is primarily for wastewater but demonstrates deep infrastructure planning; Singapore also builds large stormwater detention facilities.

**Considerations:** very high capital cost, long construction times, energy demand for pumping, and the need for careful geotechnical investigations. These systems are best suited to dense, high-value areas where other options are limited.

## 7. Channel Improvement and River Training

Widening, deepening, straightening or lining channels can increase conveyance capacity. Concrete lining reduces roughness and increases flow speed, but speeds can worsen downstream flooding and eliminate habitat. Contemporary practice favours naturalising channels where space allows, such as restoring meanders and floodplains, while retaining engineered sections where necessary. Regular dredging and sediment management are required.

## 8. Coastal Defences

- **Seawalls and revetments** protect against waves and surge.
- **Breakwaters and groynes** reduce wave energy and manage sediment.
- **Beach nourishment** replenishes sand to maintain natural defence.
- **Raised promenades or multifunctional barriers** combine protection with public space, as in the planned barriers for Lower Manhattan.
- **Land reclamation and raising ground levels** for new districts, used in places like Singapore and some Dutch projects.

## 9. Strengths and Weaknesses of Grey Infrastructure

**Strengths:** predictable performance, high capacity, effective in dense areas, long track record, standards and codes available.

**Weaknesses:** high capital and maintenance cost, limited adaptability, potential for catastrophic failure, can transfer flooding downstream, often single-purpose, carbon-intensive construction, and ecological disruption.

The most robust approach is typically **hybrid**, combining grey infrastructure with green and blue measures.

# 7. Green and Blue Infrastructure

Green infrastructure uses vegetation, soils and natural processes to manage water; blue infrastructure refers to water bodies and features such as ponds, wetlands, canals and rivers. Together, they provide **nature-based solutions (NbS)** that reduce flood risk while delivering additional benefits.

## 1. Principles of Nature-Based Flood Management

Green-blue approaches work by:

- **Infiltration:** enabling water to soak into the ground. **Interception and evapotranspiration:** vegetation captures rain and returns some to the atmosphere
- **Slowing flow:** roughness from plants and microtopography reduces velocity.
- **Storage:** ponds, wetlands, soil and depressions hold water.

- **Filtration and treatment:** improving runoff quality.

They are especially effective against frequent, moderate storms and can significantly reduce runoff volumes. During extreme events, their capacity can be exceeded, so they complement rather than replace conventional drainage.

## **1. Source Control Measures**

### **Green Roofs**

Vegetated roof systems retain rainfall in growing media and plants. Depending on depth and design, they can retain roughly 30 to 70 per cent of annual rainfall and delay runoff peaks. They also reduce building energy use, mitigate urban heat and provide habitat. Limitations include structural load, cost and maintenance. Cities such as Stuttgart, Copenhagen, Singapore and Toronto have policies promoting them.

### **Rainwater Harvesting**

Collecting roof runoff in tanks or cisterns reduces peak runoff and provides a water supply for irrigation, toilet flushing or cleaning. Systems can be designed with a dedicated storage volume that empties before a forecast storm, increasing flood benefit.

### **Permeable (Porous) Pavements**

Permeable asphalt, porous concrete and permeable interlocking pavers allow water to pass through to a stone sub-base where it is stored and infiltrates or is slowly released. They suit car parks, low-traffic streets and footpaths. Clogging by sediment is a key risk, so maintenance, such as vacuum sweeping, is essential.

### **Rain Gardens and Bioretention Cells**

Shallow, planted depressions with engineered soil that collect runoff from roofs and roads. Water infiltrates or is filtered and discharged slowly via an underdrain. They are scalable from single-house gardens to street-wide networks.

### **Bioswales and Vegetated Channels**

Linear, gently sloped channels with vegetation that convey and treat runoff while allowing infiltration. They can replace conventional kerbs and pipes along roads.

### **Tree Pits and Street Trees**

Structural soil or soil cells under pavements allow trees to receive and store runoff. Trees intercept rain, take up water and provide shade.

### **Soakaways and Infiltration Trenches**

Gravel-filled trenches or pits that allow stormwater to percolate into the ground, appropriate where soils are permeable and groundwater is deep enough.



## 2. Site and Neighbourhood-Scale Measures

- **Detention ponds and constructed wetlands:** provide storage and water quality treatment, and can become landscape features.
- **Multi-functional parks and open spaces:** lowered playing fields, amphitheatres or plazas designed to flood in extreme storms.
- **Water squares** (such as Benthemplein in Rotterdam): public spaces that act as playgrounds or sports courts in dry weather and as temporary storage during heavy rainfall.
- **Floodable car parks** with designated depths and warning signage.
- **Urban canals and open streams** (daylighting): restoring buried streams to open channels to increase capacity and add amenity.
- **Green corridors:** linked networks of green space that create overland flow paths.

## 3. Catchment and City-Scale Measures

- **Floodplain restoration and reconnection:** removing or setting back levees so rivers can spread onto designated land.
- **Wetland protection and restoration:** wetlands store floodwater and trap sediment; urban wetlands such as the East Kolkata Wetlands play major roles in drainage and wastewater treatment.
- **Upstream forest protection and reforestation:** improves infiltration and slows runoff, although effects diminish with very large floods.
- **Mangrove and coastal marsh restoration:** reduce wave energy and stabilise shorelines. Studies indicate mangroves can significantly attenuate waves, particularly in moderate events.
- **Oyster reefs, dunes and living shorelines:** nature-based coastal defences, increasingly used in the United States and elsewhere.
- **Managed realignment:** deliberately allowing coastal land to flood to create saltmarsh that absorbs wave

energy.

#### 4. Benefits Beyond Flood Control (Co-benefits)

- Reduced urban heat island effect.
- Improved air and water quality.
- Habitat and biodiversity.
- Carbon storage.
- Recreation and health, including mental wellbeing.
- Increased property values and local economic activity.
- Social cohesion through shared public spaces.

These co-benefits are important for financing, since they strengthen the economic case and can attract multiple funding sources.

#### 5. Limitations and Challenges

- Performance varies with soil conditions, storm size and maintenance.
- Land requirements can be high in dense cities.
- Uncertainty about performance during extreme storms; most are designed for small to moderate events.
- Maintenance responsibility is often unclear, and neglected systems may fail.
- Mosquito breeding, safety concerns and perceived untidiness can reduce acceptance.
- Frozen ground and high groundwater may limit infiltration in some climates.
- Lack of design standards and trained staff in some regions.

#### 6. Combining Green and Grey: The Treatment Train

A **treatment train** (or management train) uses several measures in sequence: source control on rooftops and streets, site controls such as swales, regional controls such as ponds and wetlands, and finally conventional drainage and defences for extreme events. This provides redundancy and cost-effectiveness.

## 8. Flood-Resilient Buildings and Property

### 1. Why Building-Level Measures Matter

Even with the best public infrastructure, some flooding remains. Building-level measures determine how much damage floods cause and how quickly occupants can return. They are often cost-effective and can be implemented by property owners, developers and regulators.

### 2. Strategies for Building Flood Resilience

Approaches are commonly grouped into three categories:

- 1 **Avoidance**: do not build in high-risk areas, or elevate the building above flood level.
- 2 **Resistance (dry floodproofing)**: keep water out.
- 3 **Resilience (wet floodproofing)**: allow water in but limit damage and enable quick recovery.

### Elevation

Raising the lowest habitable floor above the design flood level plus freeboard is among the most reliable methods. Techniques include:

- Building on stilts, piles, columns or piers (typical in many Asian and coastal vernacular houses).
  - Raising on fill or compacted earth platforms (where permitted and not harmful to others).
  - Placing garages, storage and parking at ground level, with living space above (a common solution in the United States).
  - Raising existing buildings by lifting them and inserting new foundations.
- Elevation must account for wave action, velocity and debris impact in coastal and fast-flowing flood zones.

### **Dry Floodproofing**

Making the building watertight up to a certain height by:

- Applying waterproof sealants to walls.
- Installing flood shields or removable barriers over doors and windows.
- Fitting anti-flood air bricks and backflow valves on drains and sewers.
- Sealing service penetrations.

Dry floodproofing is generally limited to low flood depths (often under about 1 meter) because walls and floors may not withstand hydrostatic pressure at greater depths, and it relies on human action or reliable automatic systems. It is used mostly for non-residential buildings or as supplementary protection.

### **Wet Floodproofing**

Designed to let floodwater enter and exit with minimal harm:

- Using water-resistant materials such as concrete, ceramic tile, closed-cell insulation, treated or marine-grade timber, and stainless-steel fixings at lower levels.
- Installing flood vents or openings to equalize water pressure on both sides of walls and prevent structural collapse.
- Raising electrical sockets, wiring, boilers, meters and HVAC equipment above flood level.
- Using solid concrete floors, not suspended timber floors.
- Designing lower levels for simple, washable finishes and easily removable furniture

### **3. Amphibious and Floating Buildings**

In some regions, buildings are designed to rise with floodwaters, resting on buoyant foundations guided by vertical posts. Examples include amphibious houses in the UK (Buckinghamshire), the Netherlands (Maasbommel) and floating districts such as IJburg (Amsterdam). Floating structures are also used in Bangladesh and Southeast Asia, where communities have long used floating gardens and boats.



#### 4. Basement and Underground Space Measures

Basements are highly vulnerable to pluvial, sewer and groundwater flooding. Measures include:

- Backflow prevention valves on sewer connections.
- Sump pumps with backup power.
- Waterproof tanking and drainage membranes.
- Restricting basements for residential sleeping use in flood zones.
- Raising entrances, vents and light wells above surface flood levels.

#### 5. Site-Level Measures

- Grading ground to direct water away from buildings.
- Raised thresholds and door sills.
- Perimeter walls, bunds or earth berms.
- Permeable landscaping and rain gardens.
- Protected utility meters and substations.

#### 6. Retrofitting Existing Buildings

Most flood-prone buildings already exist, so retrofitting matters. Property-level flood resilience (PFR) programmes in the UK and similar approaches elsewhere offer guidance and grants to install door barriers, non-return valves and raised electrics. Retrofit challenges include cost, tenure (tenants vs owners), heritage constraints and fragmented decision making. Targeting buildings in repeated-flood areas and offering financial incentives helps.

#### 7. Building Codes, Standards and Certification

Building regulations can mandate minimum floor elevations, flood-resistant materials and engineered

foundations in flood zones. Examples include:

- The US National Flood Insurance Program (NFIP) requirements and ASCE 24 standard for flood-resistant design.
- UK guidance on flood resilient construction and the Environment Agency's planning requirements.
- Local floodplain management ordinances in many countries.

Insurance incentives, such as discounts for elevated or flood-proofed properties, reinforce these requirements.

## 8. Materials Selection

| Material                               | Flood performance                     |
|----------------------------------------|---------------------------------------|
| Reinforced concrete                    | Very good; resists water and impact   |
| Brick (engineering) with cement mortar | Good; dries slowly                    |
| Ceramic or stone tile                  | Good for floors and lower walls       |
| Closed-cell foam insulation            | Good; absorbs little water            |
| Treated hardwood                       | Moderate                              |
| Gypsum plasterboard                    | Poor; must be replaced after flooding |
| Chipboard and MDF                      | Very poor                             |
| Fibreglass or mineral wool insulation  | Poor; retains water                   |
| Carpets                                | Poor; difficult to clean              |

## 9. Resilience of Transport, Utilities and Critical Infrastructure

### 1. Interdependencies

Modern cities depend on networks that rely on each other. Electricity powers pumps, signals and telecoms; telecoms control power and water systems; transport carries fuel and repair crews. A **systems approach** identifies single points of failure and cascading risks, such as a flooded substation shutting down a metro line and several hospitals simultaneously.

### 2. Road and Highway Infrastructure

Roads serve as both transport routes and as major flood conveyance paths. Resilient design includes:

- **Adequate cross-drainage:** culverts and bridges sized for climate-adjusted flows.
- **Raised road profiles** on critical evacuation routes.
- **Flood-tolerant pavements:** stabilised bases and bound layers perform better when saturated; unbound granular layers are more vulnerable to damage.
- **Designated overland flow routes** along streets with raised kerbs or controlled depression to direct water safely when pipes are full.

- **Underpass protection:** automatic pumping systems, level sensors, warning signs, barriers or automated gates, and drainage separate from the general network. Underpass flooding has caused fatalities in several cities.
- **Evacuation routes** that remain above flood level and have capacity for contraflow.
- **Debris management:** trash screens upstream of culverts and bridges.

### 3. Bridges

Bridges must withstand hydrodynamic forces, debris impact and scour (erosion around foundations), which is the most common cause of bridge failure in floods. Design measures include deeper foundations, scour protection (riprap, mattresses), adequate clearance (soffit level above flood level) and, in some cases, designing bridges to be overtopped without catastrophic failure.

### 4. Railways and Metro Systems

Flooded tunnels and stations can halt a city. Examples include New York's subway during Hurricane Sandy, where seawater flooded tunnels and caused months of repairs, and Zhengzhou, China, in July 2021, where record rainfall flooded metro lines and trapped passengers. Mitigation includes:

- **Raising station entrances and ventilation shafts** above expected flood levels, often with a few steps or ramps.
- **Flood gates and deployable barriers** at entrances and tunnel portals.
- **Inflatable tunnel plugs** and flood doors between sections.
- **High-capacity pumping and drainage sumps.**
- **Sealing cable penetrations and elevating electrical equipment.**
- **Emergency shutdown and evacuation protocols** triggered by forecasts.
- **Elevated or on-grade alignments** in new lines where feasible.

### 5. Airports and Ports

Airports in coastal and delta cities (such as Kansai International in Osaka, flooded by Typhoon Jebi in 2018) are vulnerable. Resilience measures include raised runways and terminals, seawalls, protected power and fuel systems and flood response plans. Ports require elevated critical equipment, storm surge defences and contingency planning, because they are key to supply chains and post-disaster relief.

### 6. Electricity Infrastructure

- **Substations and transformers** should be located above flood level or protected by walls or flood barriers; vulnerable equipment can be raised on plinths or relocated.
- **Underground cables** need waterproof designs, since submerged cables can fail or become hazardous.
- **Distribution automation** helps isolate flooded sections and restore supply quickly.
- **Backup power** (generators, batteries, microgrids) for critical facilities, positioned above flood level.
- **Design standards** that incorporate flood risk into siting decisions for new generation and substations.

### 7. Water Supply and Wastewater

Water treatment plants and pumping stations are often located near rivers, making them vulnerable. During floods, contamination of water sources and failure of sewage treatment can create health crises. Measures include:

- Flood-proofing treatment plants (raised structures, perimeter walls, submersible pumps).
- Elevating electrical control systems.
- Backup water supplies and emergency treatment.
- Pressure maintenance in pipes to prevent contaminants entering.
- Backflow preventers and overflow storage in sewer networks.
- Sealed manhole covers on flood-prone sewers.

## 8. Telecommunications and Data Infrastructure

Exchanges, cell sites and data centres need elevated placement, waterproofing and backup power. Communication is essential for warnings, rescue coordination and community resilience; redundancy using multiple technologies (mobile, radio, satellite) is advisable.

## 9. Hospitals, Schools and Emergency Services

These facilities should be sited outside flood zones where possible or designed to remain operational: elevated main floors, protected generators and medical gas, and access routes that remain passable. Schools often serve as emergency shelters, so they should be designed with elevated multi-use floors and safe access.

## 10. Waste Management

Landfills, hazardous waste storage and industrial sites in flood zones risk spreading contamination. Regulations should require secure storage above flood levels or relocation. Efficient solid waste collection also prevents drain blockage.

### 1 Applying a Critical Infrastructure Resilience Framework

- 2 **Identify** critical assets and their dependencies.
- 3 **Assess** flood hazards at each asset using multiple scenarios.
- 4 **Evaluate** consequences of failure for the wider system.
- 5 **Priorities** based on risk and criticality.
- 6 **Select** measures: protect, relocate, redundancy, rapid recovery plans.
- 7 **Monitor, test and update** through drills and post-event reviews.

# 10. Urban Planning, Land Use and Policy

## 1. The Role of Spatial Planning

Spatial planning is arguably the most cost-effective flood management tool because it can prevent new risks from being created. Infrastructure protects what exists; planning determines what will exist in the future.

## 2. Flood Risk Mapping and Zoning

**Flood hazard maps** show areas likely to flood for different probabilities and depths. **Flood risk maps** add information on population and assets. **Floodplain zoning** typically divides areas into categories:

- **Floodway:** where flow is deepest and fastest; development is prohibited or tightly restricted.
- **Flood fringe:** where some development may be allowed with conditions.
- **Low-risk zones:** where minimal restrictions apply but residual risk is communicated.

Maps should be updated regularly to reflect development, new data and climate change. In the European Union, the Floods Directive (2007) requires member states to produce hazard and risk maps and flood risk management plans. Public availability of maps helps buyers and insurers make informed decisions.

### 3. Land-Use Control Tools

- **Development restrictions** in high-risk areas, including prohibiting critical facilities.
- **The sequential and exception tests** (England): directing development to areas of lowest risk and permitting building in higher-risk zones only if clear benefits and safety measures exist.
- **Setbacks and buffer zones** along rivers and coasts.
- **Minimum floor level and design requirements.**
- **Density and impervious cover limits**, with credits for green infrastructure.
- **Stormwater management requirements for new developments**, such as "no increase in runoff" or "match greenfield runoff rates".
- **Transfer of development rights** and **buy-outs** to move people out of flood-prone areas voluntarily.

### 4. Managed Retreat and Relocation

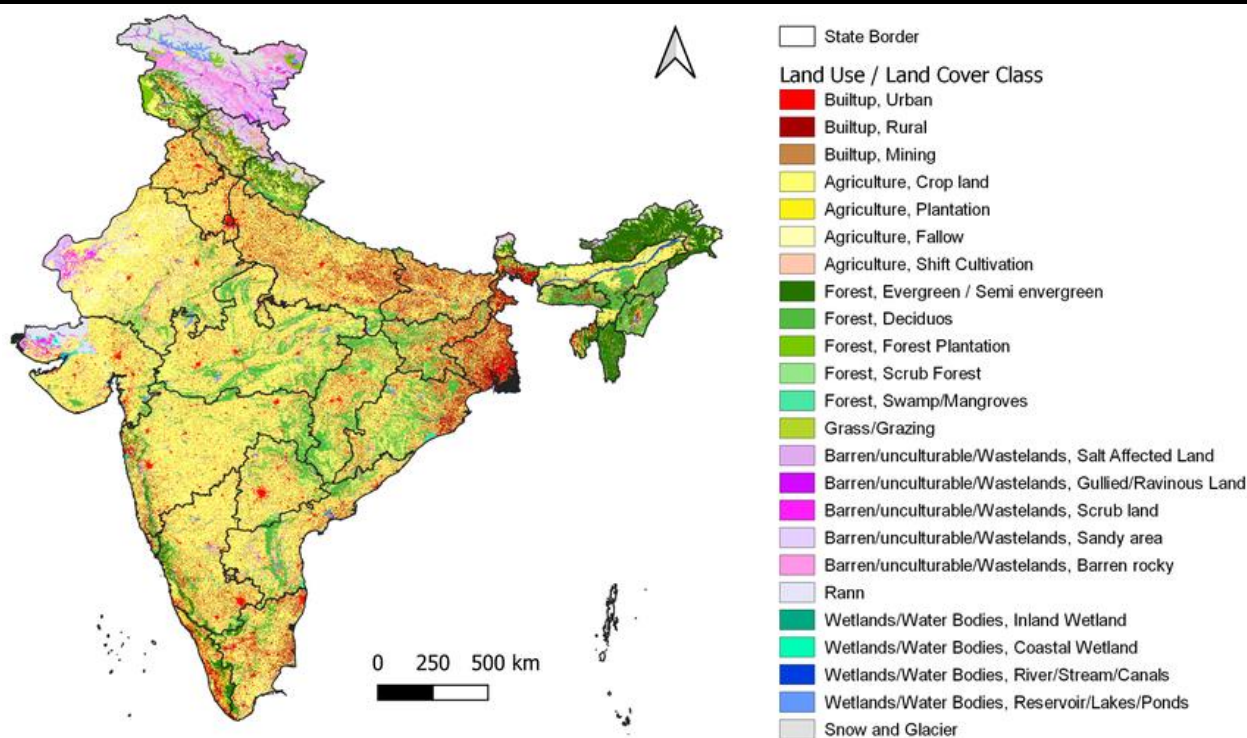
In places where flood risk is extremely high and protection is not feasible or economically justified, relocation can be the best long-term solution. Examples include government buy-out programmes in the United States, planned relocation in parts of Indonesia and several Pacific island states. Retreat raises complex social, cultural and legal issues: fair compensation, community consent, livelihoods and a sense of place. It works best when voluntary, well-planned and offered alongside alternatives.

### 5. Integrating Flood Risk into Urban Development

- **Master plans and zoning** should embed flood resilience goals.
- **Infill and redevelopment** offer chances to introduce water-sensitive design, such as converting parking lots to green space.
- **New towns and greenfield developments** can use blue-green networks and natural drainage patterns from the outset.
- **Brownfield regeneration along waterfronts** should combine protection with public space, for example elevated promenades.
- **Informal settlements** need upgrading with drainage, secure tenure and improved access, rather than eviction alone.

### 6. Regulation and Standards

Governments establish rules on design standards for drainage, flood protection levels, building codes, stormwater controls and environmental assessment. Enforcement is critical; many cities have strong regulations on paper but weak enforcement in practice, leading to encroachment on drains and floodplains.



## 7. Institutional Arrangements and Governance

Flood management in cities often involves many agencies: water authorities, municipal governments, transport departments, environment agencies, utilities, emergency services and private owners. Fragmented responsibilities cause gaps and conflicts. Good governance features:

- **Clear mandates and accountability for each aspect of flood risk management.**
- **Coordination across jurisdictions at catchment level (river basin organisations, regional authorities).**
- **Integration of flood risk with land-use, transport and housing planning.**
- **Long-term funding for operation and maintenance.**
- **Transparent data sharing and public participation.**
- **Legal frameworks that define liability, insurance and compensation.**

Examples include the Dutch Water Boards, among the oldest democratic institutions in the world, which are responsible for flood defences and water management at regional level, and Singapore's Public Utilities Board (PUB), which integrates water supply, drainage and wastewater.

## 8. Insurance and Risk Transfer

Insurance spreads financial risk and can incentivise risk reduction when premiums reflect risk. Challenges include affordability in high-risk areas, low insurance penetration in developing countries and moral hazard. Schemes include the US National Flood Insurance Program, the UK's Flood Re (a reinsurance scheme to keep home insurance affordable), France's CatNat system and parametric insurance, which pays out when predefined triggers such as rainfall level or river height are reached, allowing rapid payment.

## 9. Maintenance as a Policy Priority

Many floods are caused or worsened by lack of maintenance: choked drains, silted channels, defective pumps and unrepaired defences. Dedicated budgets, asset management systems, inspection schedules and clear responsibilities are vital. A good rule of thumb is that infrastructure must be planned along with the

ongoing funding to sustain it.

# 11. Early Warning Systems, Modelling and Smart Technology

## 1. Flood Forecasting and Early Warning

Early warning reduces loss of life and allows protective actions such as deploying barriers, shutting down transport and evacuating. An effective **end-to-end early warning system** has four elements:

- 1 **Risk knowledge:** understanding hazards, exposure and vulnerabilities.
  - 2 **Monitoring and forecasting:** rain gauges, radar, river gauges, satellites and numerical weather prediction.
  - 3 **Warning dissemination and communication:** reaching people through sirens, SMS, cell broadcast, apps, radio, television and community networks, in understandable local language and with clear instructions.
  - 4 **Response capability:** preparedness plans, evacuation routes, shelters and public awareness.
- Early warnings for pluvial flash floods are harder because lead times are short. Nowcasting using radar can provide minutes to a few hours of notice. International initiatives such as the UN's "Early Warnings for All" campaign aim to extend coverage globally.

## 2. Monitoring Technologies

- **Rain gauge networks** and **weather radar** for rainfall measurement.
- **River level sensors** and **water level gauges** in drains and canals.
- **Satellite remote sensing** for rainfall estimation, flood extent mapping, land subsidence monitoring (InSAR) and land-cover change.
- **Drones (UAVs)** for rapid post-flood assessment and mapping.
- **Internet of Things (IoT) sensors** that provide real-time data from low-cost devices placed in drains, underpasses and on roads.
- **Crowdsourced data** from social media, mobile apps and citizen science.

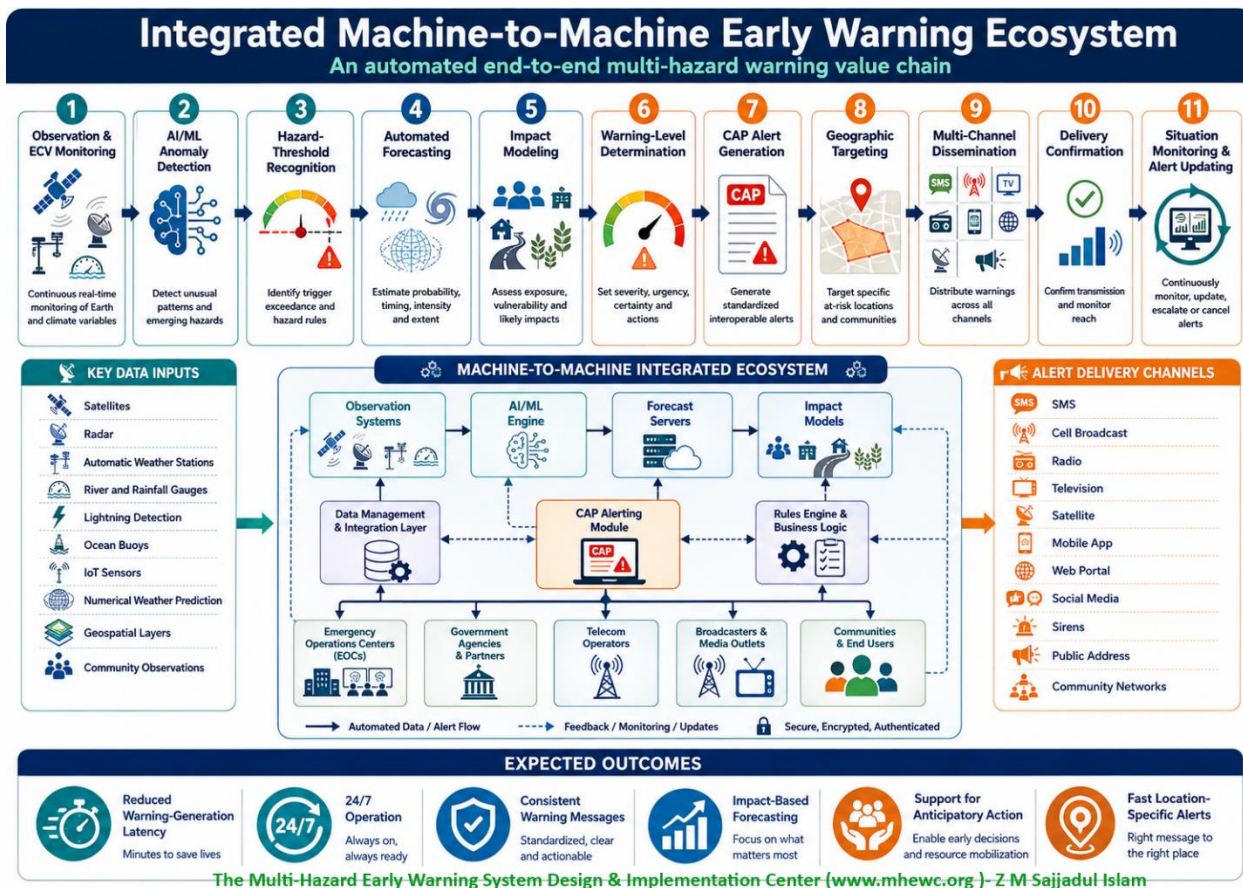
## 3. Flood Modelling

Models help understand flood behavior, test infrastructure options and priorities investment.

- **1D hydraulic models** simulate flow in pipes and channels.
- **2D models** simulate overland flow across urban terrain, vital for pluvial flooding and exceedance flows.
- **Coupled 1D-2D models** combine drainage network and surface flow.
- **Coastal and surge models** simulate tides, waves and storm surges.
- **Hydrological models** estimate runoff from catchments.
- **Digital twins:** dynamic virtual replicas of cities that integrate real-time data with models to support operations and scenario testing, now being developed in Singapore, Rotterdam and other cities.
- **Machine learning and AI** are increasingly used for faster flood prediction, emulating complex models and detecting patterns in sensor data. These tools need high-quality data and careful validation.

Typical inputs include high-resolution topography (LiDAR), drainage network data, land use, rainfall and tide records and climate projections. Modelling outputs include flood depth, extent, velocity, hazard ratings

and damage estimates.



#### 4. Smart and Real-Time Control

- **Real-time control (RTC)** of drainage networks uses sensors and automated gates, valves and pumps to make the best use of storage in the system, reducing overflow and flooding without building new infrastructure.
- **Forecast-informed operation:** for example, pre-emptively lowering levels in reservoirs, ponds or storage tanks before a predicted storm.
- **Smart traffic management:** dynamic signs and automated closure of flooded roads or underpasses.
- **Integrated command and control centres** that bring together data from different agencies to enable coordinated response.

#### 5. Data, Decision Support and Risk Communication

Decision support tools combine hazard, exposure and cost data to evaluate options using cost-benefit analysis, multi-criteria analysis or robust decision-making. Visualisation tools, such as flood maps in smartphones, 3D models and augmented reality, help communicate risk. Clear language and trusted messengers' matter: people are more likely to act if warnings are specific (what, where, when, what to do) and come from credible sources.

#### 6. Limits and Risks of Technology

- Technology cannot substitute for sound planning and physical infrastructure.
- Sensors and systems require maintenance, power and communications; a failure during a flood defeats their purpose.
- Digital divides can exclude vulnerable populations from alerts and apps.

- Cybersecurity risks affect networked control systems.
- Over-reliance on models can be misleading if their assumptions are wrong or data is poor.

## 12. Global Case Studies

### 1. The Netherlands: Delta Works, Room for the River and Water Boards

About a quarter of the Netherlands lies below sea level, and about two-thirds of the country is flood-prone. The catastrophic North Sea flood of 1953 killed over 1,800 people and led to the Delta Works, a vast system of dams, storm surge barriers, sluices and dikes in the south-west Delta, including the Eastern Scheldt Barrier and the Maeslantkering. Later floods on the Rhine and Meuse in the 1990s, when about 250,000 people were evacuated, shifted thinking toward Room for the River (implemented roughly 2006 to 2015), which carried out dozens of projects to lower flood levels by relocating dikes, deepening floodplains, creating bypasses and removing obstacles. The Dutch also invest in urban water management such as water squares in Rotterdam, green roofs and floating homes, and use a legally mandated Delta Programme with adaptive planning and a Delta Fund for long-term financing.

**Key lessons:** strong institutions, long-term funding, legal safety standards, adaptive planning and a culture of living with water.

### 2. Singapore: ABC Waters and Integrated Water Management

Singapore, a dense island city-state, historically suffered frequent floods. It responded with a comprehensive strategy of drainage upgrades, flood-proofing requirements (such as minimum platform and crest levels for new developments) and the **Active, Beautiful, Clean (ABC) Waters Programme**, launched in 2006, which transforms concrete canals and reservoirs into attractive, naturalised waterways and parks. The **Marina Barrage** (completed 2008) forms a freshwater reservoir in the city, provides tidal flood control and supports water supply. Real-time water level sensors, rainfall radar and public alerts through apps enhance preparedness. The national water agency, PUB, manages water supply, drainage and wastewater in an integrated way.

**Key lessons:** integrated agency, high-quality design that engages people, combination of regulation, infrastructure and monitoring, and dual-purpose projects.

### 3. Tokyo, Japan: Underground Infrastructure and Disaster Culture

Tokyo faces typhoons, heavy rainfall and river flooding in a densely populated lowland area. Alongside river improvements and retarding basins, the city built the **Metropolitan Area Outer Underground Discharge Channel** (also known as G-Cans), a deep underground network that diverts floodwaters from smaller rivers into the Edogawa River. Japan also invests heavily in rain gauges, radar, warning systems, school and community drills, and building regulations. Japan's "comprehensive flood damage control" policies include requiring runoff control in new developments and designating parks and open spaces for storage.

**Key lessons:** where land is scarce, underground infrastructure can be effective; sustained public education and preparedness are crucial.

### 4. Copenhagen, Denmark: The Cloudburst Management Plan

On 2 July 2011, an extreme cloudburst dropped around 150 millimetres of rain in a few hours on Copenhagen, causing billions of Danish kroner in damage. The city responded with the **Cloudburst**

**Management Plan (2012)**, which relies on above-ground solutions. It uses **blue-green streets**, parks designed as retention areas, roads that act as water channels ("cloudburst roads"), and larger storm-water tunnels, while using conventional pipes only for frequent events. Hundreds of projects were planned, with financing partly through utility water fees. Analysis suggested that surface solutions were significantly cheaper than enlarging the sewer network alone, while adding urban amenity.

**Key lessons:** design for extreme events, use the city's surface as part of the drainage system, and integrate climate adaptation with urban improvement.

## 5. China: The Sponge City Programme

Following severe urban floods, China launched the Sponge City programme in 2013 to 2015, selecting initial pilot cities (including Wuhan, Shenzhen and Xiamen) and later expanding to dozens more. Targets included absorbing and reusing a large share of rainfall (around 70 per cent in qualifying built-up areas by 2030). Measures include permeable surfaces, green roofs, rain gardens, wetlands, storage ponds and restoration of urban waterways, in combination with drainage upgrades. Evaluations show progress in reducing frequent flooding and improving water quality in some places, but also challenges: cost and financing, uneven implementation, technical limits during extreme storms (such as the 2021 Zhengzhou flood) and the need for consistent maintenance and monitoring.

**Key lessons:** national policy and finance can mobilise action at scale; sponge measures help with frequent rainfall but must be integrated with major drainage, storage and warning systems for extremes.

## 6. New York City, USA: Post-Sandy Resilience

Hurricane Sandy in 2012 flooded large parts of New York and New Jersey, causing many deaths, subway and tunnel inundation, power outages and tens of billions of dollars in losses. Subsequent programmes include the **East Side Coastal Resiliency** project, an integrated flood protection system along Manhattan's East River shore with flood walls, floodgates and redesigned parks, the "Big U" concept from the Rebuild by Design competition, reinforced and raised utility infrastructure, subway flood barriers, stormwater green infrastructure (green roofs, bioswales) and building code updates. Residents also have access to updated flood maps that reflect climate change.

**Key lessons:** design competitions can generate innovative multi-benefit solutions; integrating protection with parks and community needs improves acceptance; climate projections should inform updated standards.

## 7. New Orleans, USA: Katrina and the Levee System

Hurricane Katrina in 2005 and the failure of floodwalls and levees flooded roughly 80 per cent of New Orleans and caused more than 1,800 deaths across the region. Investigations identified design flaws, construction issues and poor oversight. The subsequent investment of well over ten billion dollars produced the **Hurricane and Storm Damage Risk Reduction System**, with higher levees, stronger floodwalls, surge barriers and large pumping stations. The city has also promoted green infrastructure through the Greater New Orleans Urban Water Plan to "live with water" and tackle subsidence.

**Key lessons:** infrastructure must be designed, built and maintained to high standards with independent review; protection leaves residual risk; a mix of structural and non-structural measures is needed.

## 8. Mumbai and Chennai, India: Urban Floods in Fast-Growing Cities

Mumbai's flood of 26 July 2005, with nearly a metre of rain in one day, led to major losses. Contributing factors included heavily encroached natural drainage (such as the Mithi River), poor drainage capacity, tidal conditions and extensive paving. Responses have included river widening and cleaning, upgrades to the storm water drainage network under the BRIMSTOWAD project, new pumping stations, early-warning improvements and better coordination. Chennai's 2015 floods, which affected millions after exceptional rainfall and reservoir releases, similarly highlighted lost wetlands and encroached waterways. Subsequent actions include restoring water bodies, improved drainage plans and stronger coordination.

**Key lessons:** protecting natural drainage channels and wetlands is critical, and governance and enforcement matter as much as engineering.

## 9. Jakarta, Indonesia: Subsidence and Sea Level Rise

Parts of Jakarta are sinking quickly because of groundwater extraction, putting large areas below sea level. The city faces combined river, rainfall and coastal flooding. Responses include the National Capital Integrated Coastal Development (a large sea wall and associated development concept), river normalisation, polders and pumping, and efforts to control groundwater use and expand piped water. Indonesia has also decided to build a new capital, Nusantara, in East Kalimantan, partly reflecting these pressures, though Jakarta will remain a major city requiring protection.

**Key lessons:** controlling subsidence at its source is essential; physical defences alone may be overwhelmed if the ground continues to sink.

## 10. Lessons Across Cases

| Theme                 | Insight                                                                                            |
|-----------------------|----------------------------------------------------------------------------------------------------|
| Combine approaches    | Successful cities combine grey, green, planning and warning measures                               |
| Long-term commitment  | Dutch and Singaporean successes come from decades of consistent policy and funding                 |
| Governance            | Clear institutions and enforcement determine whether plans work                                    |
| Multi-benefit design  | Projects that deliver recreation, ecology or mobility win more support                             |
| Learn from disasters  | Copenhagen, New York and New Orleans acted strongly after major events; proactive action is better |
| Design for exceedance | All systems can be overwhelmed; plan for what happens next                                         |
| Address root causes   | Subsidence, wetland loss and encroachment must be tackled, not just symptoms                       |

# 13. Economics and Financing of Flood Resilience

## 1. The Economic Case

Investment in flood risk reduction typically yields strong returns. Studies by international organisations such

as the World Bank and the Global Commission on Adaptation have estimated benefit-cost ratios commonly ranging from about 2:1 to 10:1 for adaptation measures including early warning and resilient infrastructure, with some cases higher. Preventing damage is generally cheaper than repairing it, and the economic benefits include avoided losses, increased productivity, property value uplift and "triple dividends": avoided losses, economic gains from reduced risk, and social and environmental co-benefits.

## 2. Assessing Costs and Benefits

**Costs** include capital costs (design, land, construction), operating and maintenance costs, and replacement costs over the asset's life.

**Benefits** include:

- Avoided direct damage (**expected annual damage**, EAD, is commonly estimated by integrating damage across flood probabilities).
- Avoided indirect losses such as business interruption.
- Avoided health and fatality costs.
- Co-benefits such as recreation, amenity, biodiversity, carbon sequestration and reduced heat.

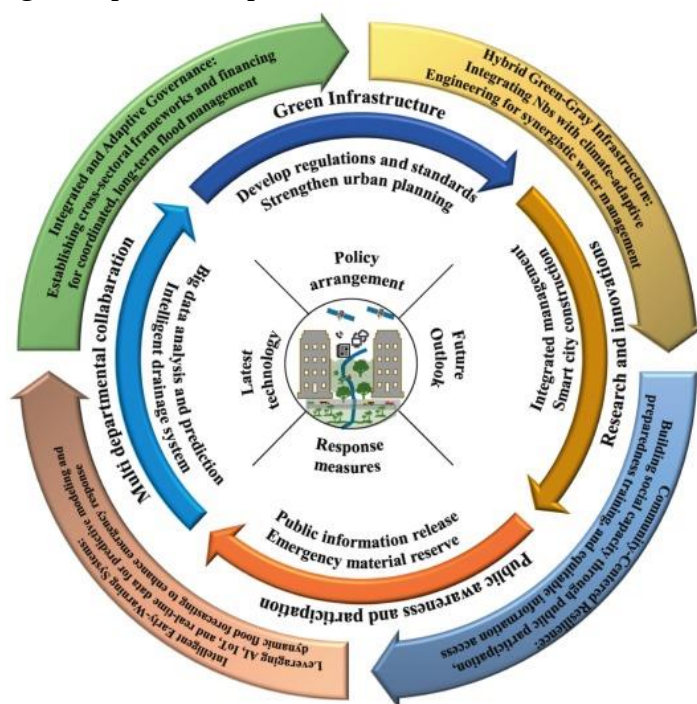
Methods used include **cost-benefit analysis (CBA)**, **cost-effectiveness analysis**, **multi-criteria analysis** and **real options** or robust decision analysis that account for uncertainty. Discount rates strongly influence outcomes; low rates favour long-term investments such as defences, while high rates favour near-term gains. Intangible and non-market benefits, such as lives saved and ecosystem services, are difficult to monetise but should not be ignored.

## 3. Sources of Funding

| Source                                           | Description                                                                                                                                    |
|--------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|
| National and local government budgets            | Core funding for public defences and drainage                                                                                                  |
| Stormwater utility fees                          | Charges based on impervious area, used in the US, Germany and Denmark; they link payments to runoff contribution and can reward green measures |
| Development charges and impact fees              | Developers contribute to drainage infrastructure                                                                                               |
| Betterment levies and value capture              | Capturing property value uplift from improved protection                                                                                       |
| Municipal and green or resilience bonds          | Raising capital for long-term projects; investors fund climate-resilient infrastructure                                                        |
| Multilateral development banks and climate funds | Loans and grants from World Bank, Asian Development Bank, Green Climate Fund, etc.                                                             |
| Public-private partnerships (PPPs)               | Private sector finances, builds or operates infrastructure under contracts                                                                     |
| Insurance and catastrophe bonds                  | Risk transfer and rapid post-disaster liquidity                                                                                                |
| Community and philanthropic funds                | Small-scale and local projects                                                                                                                 |
|                                                  |                                                                                                                                                |

#### 4. Innovative Financing Mechanisms

- **Resilience bonds and environmental impact bonds:** link returns to measurable risk reduction.
- **Parametric insurance:** automatic payments based on triggers allow quick recovery funding.
- **Catastrophe bonds:** transfer extreme event risk to capital markets.
- **Payment for ecosystem services:** downstream beneficiaries pay upstream landowners for protecting watersheds.
- **Stormwater credit trading:** developers who cannot achieve on-site retention buy credits from others who exceed requirements (Washington, DC runs such a scheme).
- **Pooling resources** among multiple municipalities or sectors.



#### 5. Barriers to Financing

- Benefits are public and diffuse, while costs fall on specific institutions.
- Short political cycles discourage long-term investment.
- Low creditworthiness of many municipalities, particularly in developing countries.
- Lack of reliable data to build a bankable case.
- Difficulty in funding maintenance, which often lacks a dedicated revenue stream.
- Siloed budgets between transport, housing, water and environment, even though projects deliver cross-sector benefits.

#### 6. Maintenance and Whole-Life Costing

Capital costs are often only a fraction of lifetime cost. Whole-life costing and asset management planning ensure that funds are available to keep infrastructure working. Green infrastructure typically has lower capital costs but requires regular maintenance such as vegetation management and sediment removal. Planning for maintenance responsibilities at the design stage avoids "orphan" assets.

#### 7. Equity in Funding

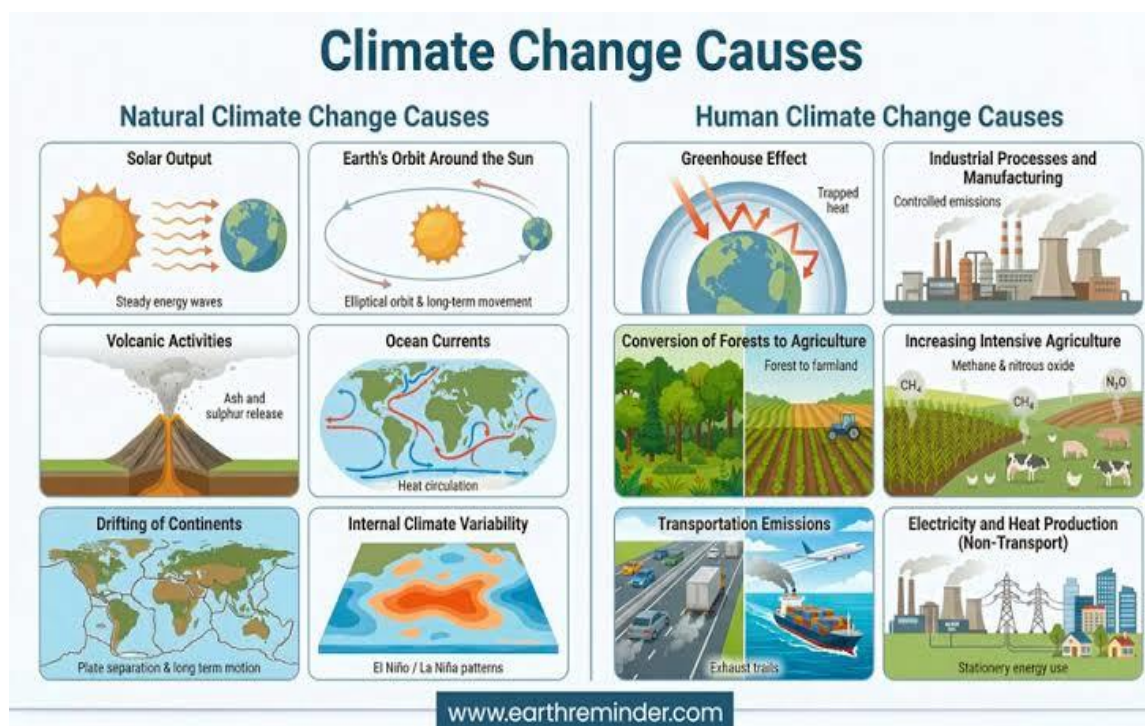
Funding frameworks should avoid concentrating protection in wealthy areas. Prioritisation criteria that consider social vulnerability, not just economic value, help ensure low-income communities are protected. A

pure benefit-cost approach tends to favour areas with high property values, so complementary criteria are necessary.

## 14. Climate Change and Future Challenges

### 1. How Climate Change Alters Flood Risk

- **Heavier rainfall:** A warmer atmosphere holds more moisture, increasing the intensity of extreme rainfall. Short-duration downpours, most relevant to urban drainage, may intensify even faster than daily totals in some regions.
- **Sea level rise:** Global mean sea level has been rising at an accelerating rate, raising baseline water levels for tides and storm surges. Even modest rises substantially increase the frequency of coastal flooding events, and reduce gravity drainage capacity of outfalls.
- **More intense tropical cyclones:** Evidence indicates a greater proportion of storms reaching high intensities and carrying more rainfall.
- **Changes in seasonality and snowmelt:** Altered timing and magnitude of river floods.
- **Compound events:** Higher likelihood of simultaneous surge and rainfall in some regions.
- **Heat and drought interplay:** Dry, hard soils after drought can increase initial runoff, and heat can stress green infrastructure.



### 2. Uncertainty and Deep Uncertainty

Projections of future rainfall, sea level (particularly ice-sheet contributions) and urban growth involve uncertainty. Designers should avoid relying on a single "best estimate" and instead consider ranges and plausible high-end scenarios, especially for long-lived or critical infrastructure.

### 3. Planning Approaches Under Uncertainty

- **Climate allowances:** adding uplift factors to design rainfall, river flows and sea levels, following national guidance.
- **Adaptive pathways:** planning sequences of measures, with signals and trigger points that indicate when

to implement the next stage.

- **No-regret and low-regret measures:** actions beneficial under all scenarios, such as maintenance, early warning, green space and avoiding new development in high-risk areas.
- **Flexible and modular designs:** structures that can be raised or extended later, such as levees with foundations designed for future heightening, or safeguarded land corridors for future defences.
- **Robust decision making:** stress-testing options across many futures.
- **Safeguarding space:** reserving land now for future flood storage or defences.

#### 4. Rapid Urbanisation and Informal Settlements

Much of the world's future urban growth is expected in regions with weak infrastructure and high hazard exposure. Informal settlements frequently occupy riverbanks, drains and marshes, with limited drainage and sanitation. Strategies include in-situ upgrading, community-led drainage improvements, provision of safe land and finance, and recognising residents as partners.

#### 5. Ageing Infrastructure

In many older cities, drainage and defences are deteriorating. Replacement needs compete with other budgets. Asset condition monitoring, risk-based prioritisation and gradual integration of green and smart elements during renewal can help.

#### 6. Interactions with Other Climate Risks

Flood adaptation should align with heat, drought, air quality and mitigation goals. For example, trees and green roofs help cool cities and manage stormwater; conversely, some measures, such as concrete-intensive defences, carry high embodied carbon. Lower-carbon materials and designs support both adaptation and mitigation.

#### 7. Emerging Innovations

- **Digital twins and AI-enhanced forecasting** for real-time operations.
- **Smart permeable materials** and advanced pavements.
- **Modular, deployable flood barriers** that can be installed quickly.
- **Nature-based coastal defences** such as engineered reefs and hybrid living shorelines.
- **Self-healing and resilient materials.**
- **Floating and amphibious architecture** for flood-prone regions.
- **Community-based early warning using mobile technology.**
- **Integrated urban water management** treating stormwater as a resource, for example for aquifer recharge and urban cooling.

#### 8. Key Gaps and Research Needs

- Better high-resolution rainfall projections for cities.
- Long-term performance data for nature-based solutions.
- Improved understanding of cascading failures in interdependent infrastructure.
- Affordable data collection and modelling for data-poor cities.
- Frameworks to integrate social vulnerability into infrastructure planning.
- Evaluation of retrofit costs and effectiveness.

# 15. Equity, Community Participation and Social Resilience

## 1. Why Equity Matters

Infrastructure alone does not guarantee resilience. Who benefits from flood protection, who bears the costs and who has a voice in decisions all influence outcomes. Disadvantaged groups often experience higher exposure, lower capacity to cope and fewer resources to recover. Poorly designed projects can also displace residents or create "green gentrification", where improvements drive up property prices and push out existing communities.

## 2. Principles for Equitable Flood Resilience

- 1. Recognition:** identify vulnerable groups and understand their needs, including informal residents, renters, people with disabilities, older adults, children, women and minority communities.
- 2. Procedure:** give affected people meaningful participation in planning and decision-making.
- 3. Distribution:** allocate protection, funding and benefits fairly, not only where property values are highest.
- 4. Capability:** strengthen the ability of communities to prepare, respond and recover.

## 5. Community Participation

Methods include public consultation, participatory mapping of flood hotspots, citizen science, community-based disaster risk management committees, school programmes and co-design workshops. Local knowledge, such as where water flows and which areas flood first, is valuable and often not captured in formal data. Participation builds trust, improves design, promotes maintenance and strengthens compliance.

## 6. Community-Based Flood Preparedness

- Local early warning networks and volunteer teams.
- Evacuation plans and drills; identification of safe shelters and routes.
- Household preparedness: emergency kits, raising valuables, documents stored safely, knowledge of utility shut-offs.
- Community storage and support for people with special needs.
- Cooperative savings and microinsurance.

## 7. Health and Wellbeing

Flood response must include public health considerations: safe drinking water, sanitation, vector control, protecting medical supplies, and mental health support. Long-term psychological impacts, including displacement stress and financial hardship, are significant and should be addressed in recovery planning.

## 8. Communication and Behaviour

Risk perception influences action. People who have not experienced a flood may underestimate the risk; those in protected areas may feel overly safe. Effective communication is clear, consistent, locally relevant and delivered through trusted channels. Visual cues, such as marking historic flood levels on buildings, help people remember past events.

## 9. Build Back Better

Recovery is an opportunity to improve resilience rather than replicate vulnerabilities. This includes updating building standards, relocating from high-risk areas where appropriate, upgrading infrastructure and

strengthening institutions. Delay and poor coordination in recovery can deepen inequality, so pre-event recovery planning and rapid financing are valuable.

## 16. Design Guidelines and Implementation Checklist

### 1. A Step-by-Step Framework

#### Step 1: Understand the risk.

- Compile historical flood records and local knowledge.
- Map hazards (pluvial, fluvial, coastal, groundwater) and overlay with exposure and vulnerability.
- Use models and climate scenarios to project future risk.

#### Step 2: Set objectives and standards.

- Define acceptable risk levels and design standards for different assets (typical examples: minor drainage 1-in-5 to 1-in-10 years; major system 1-in-100 years; critical infrastructure higher).
- Consider co-benefits and community priorities.

#### Step 3: Identify and assess options.

- Consider the full range: avoidance, source control, conveyance, storage, protection, building-level measures, warning and recovery.
- Evaluate with CBA, multi-criteria analysis and stakeholder input.

#### Step 4: Develop an integrated plan.

- Combine measures in a multi-layered strategy.
- Plan for exceedance, with overland flow paths and designated flood storage areas.
- Identify adaptive pathways with triggers.

#### Step 5: Secure governance and funding.

- Allocate roles, legal authority and budgets for construction and long-term maintenance.

#### Step 6: Implement.

- Phase delivery and include quick wins.
- Ensure quality control, independent review and community engagement.

#### Step 7: Operate, monitor and maintain.

- Inspect and maintain regularly.
- Monitor performance with data and post-event reviews.

#### Step 8: Learn and adapt.

- Update maps, standards and plans as conditions and knowledge evolve.

### 2. Design Checklist for a New Urban Development

- Site avoids high-risk floodplain, or justified with mitigation measures.
- Flood risk assessment includes climate change allowances.

- Post-development runoff does not exceed pre-development greenfield rates.
- Source control measures (permeable surfaces, green roofs, rain gardens) included.
- Surface layout designed with safe overland flow routes and exceedance storage.
- Finished floor levels set above design flood level plus freeboard.
- Critical services (electricity, communications) located above flood levels.
- Basements and underground spaces protected from flooding.
- Safe access and egress routes provided during flood events.
- Maintenance responsibilities and funding arrangements defined.
- Flood warning and emergency plan prepared.
- Impact on neighboring and downstream areas assessed.
- Community and stakeholder input included.

### 3. Design Checklist for Retrofitting an Existing Neighbourhood

- Hotspots identified through past floods and modelling.
- Blockages, siltation and maintenance backlog addressed.
- Opportunities for greening streets, parks and parking areas assessed.
- Drainage capacity upgraded where cost-effective.
- Property-level protection offered to vulnerable buildings.
- Underpasses and low points have warning and drainage systems.
- Key evacuation routes protected.
- Early warning and emergency plans in place and tested.
- Inclusion of lower-income and informal residents ensured.

### 4. Selecting Measures: A Quick Guide

| Situation                               | Suggested measures                                                              |
|-----------------------------------------|---------------------------------------------------------------------------------|
| Frequent minor flooding from heavy rain | Source control (permeable surfaces, rain gardens), improved drains, maintenance |
| Flash flooding in dense areas           | Underground storage, overland flow routes, real-time control, early warning     |
| River flooding                          | Floodplain storage, setback levees, upstream catchment measures, zoning         |
| Coastal and surge flooding              | Barriers, seawalls, dunes, wetlands, elevated development, pumping              |
| Groundwater flooding                    | Drainage controls, waterproofing, restricting basements                         |
| Low-lying or sinking land               | Pumping, controlling subsidence, polder systems, managed retreat                |
| Informal settlements                    | Community drainage, solid waste management, upgrading and secure tenure         |
| Critical facilities                     | Elevation, barriers, redundancy, backup power                                   |

## 5. Common Pitfalls to Avoid

1. Relying only on one type of measure.
2. Ignoring maintenance and long-term costs.
3. Using outdated rainfall or sea-level data.
4. Ignoring downstream or upstream effects.
5. Neglecting the exceedance event.
6. Treating flood management in isolation from planning and transport.
7. Excluding communities from decisions.
8. Assuming protection is absolute.

## 17. Conclusion

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Urban flooding is a growing global challenge, driven by expanding cities, loss of natural drainage and a changing climate. No single measure can eliminate the risk. Effective flood-resistant urban infrastructure combines structural defences and drainage systems with nature-based solutions, resilient building design, protected critical services, forecasting and warning, sound land-use planning and sustainable financing.

Four ideas stand out from this report. First, risk must be understood and managed in terms of hazard, exposure and vulnerability, so planning future development wisely is as important as building defences. Second, cities should adopt a multi-layered approach that plans for exceedance and designs systems to fail gracefully. Third, governance, maintenance and community engagement are decisive; the best-designed infrastructure fails without institutions and funding to sustain it and people who understand and support it. Fourth, adaptation must be flexible and equitable, responding to uncertain climate futures while ensuring the protection of the most vulnerable.

Cities that have succeeded, such as those in the Netherlands, Singapore, Tokyo and Copenhagen, show that sustained political commitment, integrated planning and innovation can reduce flood risk while improving urban quality of life. For rapidly growing cities in developing regions, the opportunity is to embed flood resilience into growth now, avoiding the costly retrofits that older cities face. Flood-resilient infrastructure is not only a defence against disaster but an investment in safe, live able, sustainable and prosperous cities.

## 18. Glossary

- **Adaptation pathways:** A planning method that sequences actions over time based on signals and thresholds.
- **Bioswale:** A vegetated channel that conveys, filters and infiltrates runoff.
- **Blue-green infrastructure:** Networks of water bodies and vegetated spaces that provide multiple urban benefits including flood management.
- **Combined sewer:** A pipe system carrying both sewage and stormwater.
- **Compound flooding:** Flooding caused by two or more interacting drivers, such as surge and rainfall.
- **Detention basin:** A dry storage area that temporarily holds stormwater and releases it slowly.

- **Exceedance flow:** Flow beyond the capacity of the drainage system.
- **Expected annual damage (EAD):** The average annual flood losses over the long term.
- **Floodplain:** Low-lying land adjacent to a river that is subject to flooding.
- **Freeboard:** A safety margin added above a design flood level.
- **Green roof:** A roof covered with vegetation and growing medium.
- **Hydrograph:** A graph showing flow rate over time.
- **Impervious surface:** A surface that does not allow water to infiltrate, such as pavement or roofs.
- **Levee:** An embankment built to prevent river or sea overflow.
- **Nature-based solutions (NbS):** Actions that use natural processes to address societal challenges.
- **Pluvial flood:** Flooding caused by rainfall overwhelming drainage, independent of rivers.
- **Return period:** The average time between events of a given size.
- **Retention pond:** A pond with a permanent pool that stores and treats stormwater.
- **Sponge city:** An urban planning approach that makes cities absorb, store and reuse rainwater.
- **Storm surge:** Abnormal rise in sea level generated by a storm.
- **SuDS:** Sustainable Drainage Systems.
- **Subsidence:** Sinking of land surface.
- **Time of concentration:** The time for runoff to travel from the farthest point of a catchment to its outlet.
- **Wet floodproofing:** Designing a building to allow water in while minimizing damage.

## 19. Suggested References

1. ChatGPT
2. Google
3. Claude