

Innovative Flood Defense Systems

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Abstract: Flooding has become a critical challenge globally due to climate change, rising sea levels, and rapid urbanization. Innovative flood defense systems integrate advanced engineering, technology, and nature-based solutions to mitigate flood risks effectively. Smart flood barriers use real-time data and automation to respond dynamically to rising water levels, while sponge cities leverage permeable infrastructure to enhance rainwater absorption and storage. Nature-based solutions such as wetlands and mangroves act as natural buffers against flooding. Adaptive infrastructure, including floating and amphibious buildings, provides sustainable options for flood-prone areas. Digital monitoring systems and AI-driven flood prediction further enhance preparedness and response. Large-scale engineering projects like underground reservoirs and mobile seawalls complement these advancements, offering scalable solutions to protect urban and coastal regions. Together, these systems present a multifaceted approach to reducing the impact of flooding and building resilience.

Keywords: *Flood defense, smart flood barriers, sponge cities, adaptive infrastructure, nature-based solutions, digital monitoring, AI flood prediction, underground reservoirs, seawalls.*

I. Introduction

Flooding is one of the most devastating natural disasters, causing widespread damage to infrastructure, loss of life, and significant economic impact. Climate change, urbanization, and rising sea levels have amplified the frequency and intensity of floods worldwide, necessitating innovative solutions to address these challenges. Traditional flood defense systems, such as levees and embankments, often prove inadequate against extreme weather events. In response, modern flood defense strategies incorporate advanced engineering, cutting-edge technologies, and sustainable practices to build resilience. Smart flood barriers, sponge cities, nature-based solutions, adaptive infrastructure, and digital monitoring systems are at the forefront of this evolution. These approaches aim to not only prevent flooding but also enhance urban livability, promote ecological balance, and improve disaster preparedness.

Importance of Innovative Flood Defense Systems

1. Mitigating Economic Losses:

Flooding leads to extensive damage to infrastructure, businesses, and homes, resulting in significant economic losses. By implementing advanced flood defense systems, governments and communities can minimize these costs and ensure faster recovery. For instance, smart barriers and underground reservoirs protect critical urban centers, reducing the financial burden of post-flood reconstruction.

2. Enhancing Public Safety:

Floods are a leading cause of displacement and loss of life in many regions. Real-time monitoring systems, such as IoT-based sensors and AI-driven flood prediction, provide early warnings that save lives. Additionally, adaptive infrastructure like floating houses offers safe living conditions in flood-prone areas.

3. Supporting Urban Resilience

Urban areas are particularly vulnerable to flooding due to impermeable surfaces and dense populations. Sponge city concepts, which incorporate green infrastructure and water retention systems, enhance urban resilience by managing excess water efficiently while improving environmental quality.

4. Promoting Sustainability

Nature-based solutions such as wetland restoration and mangrove plantations not only mitigate flood risks but also enhance biodiversity, sequester carbon, and improve ecosystem health. These solutions align with global sustainability goals and provide long-term environmental benefits.

5. Combating Climate Change Effects

As extreme weather events become more frequent due to climate change, traditional flood defenses are proving inadequate. Innovative systems are designed to adapt to these dynamic conditions, offering scalable and future-proof solutions to protect vulnerable communities.

6. Advancing Technology and Innovation

The development and implementation of these systems drive technological innovation, fostering research and development in areas such as IoT, AI, and advanced materials. These advancements have broader applications in disaster management and urban planning.

7. Ensuring Global Food and Water Security

Flooding disrupts agricultural activities and contaminates water supplies, threatening food and water security. Effective flood defense systems prevent such disruptions, safeguarding resources critical to human survival.

8. Reducing Social and Environmental Inequalities

Floods disproportionately affect vulnerable communities. Implementing equitable and sustainable flood defenses ensures protection for all socioeconomic groups, reducing inequalities and fostering social cohesion.

II. SMART FLOOD BARRIERS

Smart flood barriers are advanced flood defense systems that use automation, real-time monitoring, and adaptive technology to protect against rising water levels.

1. Automated Operation:

- Barriers are equipped with sensors and hydraulic systems to detect water levels and deploy automatically.
- Example: The **Thames Barrier** in London, which rises to block storm surges and protect the city.

2. Real-Time Monitoring:

- IoT sensors track water levels, flow rates, and weather conditions, providing data for precise activation.
- Systems integrate with predictive models for proactive deployment.

3. Modular and Portable Designs:

- Lightweight, easy-to-install barriers like **AquaFence** are suitable for temporary flood defense in urban areas.

4. Durable Materials:

- Constructed using corrosion-resistant and high-strength materials to withstand extreme conditions.

Advantages:

- Rapid deployment and minimal manual intervention.
- Cost-effective for urban and industrial areas.
- Scalable for small- or large-scale flood management.

Applications:

- Protecting cities, ports, and industrial sites from storm surges.
- Temporary defenses for regions prone to flash flooding.

III. SUPPORTING URBAN RESILIENCE THROUGH FLOOD DEFENSE SYSTEMS.

Urban resilience refers to the ability of cities to anticipate, absorb, recover, and adapt to adverse events such as flooding. Innovative flood defense systems play a vital role in enhancing urban resilience by mitigating flood risks, protecting critical infrastructure, and improving overall livability. Here's a detailed exploration:

1. Reducing Urban Flood Risks

Urban areas are characterized by dense populations, impermeable surfaces (roads, pavements), and complex infrastructure, making them vulnerable to flooding. Modern flood defense systems address these vulnerabilities through:

- **Smart Drainage Systems:** Integrated networks of underground pipes and reservoirs manage stormwater effectively.
- **Permeable Surfaces:** Materials like permeable pavements allow rainwater to seep into the ground, reducing runoff.
- **Rainwater Harvesting:** Systems capture and store rainwater for reuse, preventing excess water accumulation.

2. Enhancing Critical Infrastructure Resilience

Flooding disrupts essential services like transportation, energy, water supply, and healthcare. Flood defense systems protect this infrastructure:

- **Flood-Proof Transit Systems:** Elevated railways, waterproof tunnels, and protective barriers ensure uninterrupted mobility.
 - Example: **Tokyo Metro Flood Control**, incorporating gates and pumps to protect subway lines.
- **Energy Infrastructure Protection:** Barriers around power plants and substations prevent outages during floods.

3. Improving Urban Design

Resilient cities integrate flood defense into urban planning.

- **Sponge Cities:** Designed to absorb, store, and reuse water, sponge cities reduce urban flooding and improve groundwater recharge.
 - Example: Wuhan, China, incorporates permeable pavements, green roofs, and wetlands.
- **Retention Ponds and Urban Wetlands:** These act as temporary reservoirs for floodwater, while enhancing biodiversity and providing recreational spaces.

4. Leveraging Technology for Resilience

- **Real-Time Monitoring:** IoT sensors and AI systems track weather patterns, water levels, and drainage capacity to provide early warnings.
- **Predictive Analytics:** Advanced models forecast flood scenarios, helping authorities plan and deploy resources efficiently.
 - Example: **FloodAlert Systems** in the USA.

5. Community Safety and Well-Being

Flood defense systems ensure public safety by minimizing the physical and psychological impacts of flooding.

- **Safe Zones:** Elevated shelters and flood-resistant housing provide refuge during extreme events.
- **Public Awareness and Preparedness:** Smart systems communicate alerts to residents, ensuring timely evacuations and safety measures.

6. Economic Resilience

Flood defense reduces financial losses by protecting businesses, homes, and public infrastructure.

- **Continuity of Services:** Ensures uninterrupted business operations and prevents costly repairs.
- **Insurance Benefits:** Advanced flood defenses lower insurance premiums for urban property owners.

7. Environmental Benefits

Nature-based solutions integrated into urban flood defenses improve environmental quality.

- **Urban Green Spaces:** Parks, gardens, and tree-lined streets act as water absorbers and reduce the urban heat island effect.
- **Restored Ecosystems:** Floodplains, wetlands, and mangroves enhance ecological resilience and biodiversity.

- Wetlands act as natural sponges, absorbing excess water during floods and releasing it slowly.
- Example: **Kissimmee River Restoration Project, Florida, USA**, restored natural floodplain functions, reducing downstream flooding.

- **Mangrove Forests:**

- Dense mangrove roots dissipate wave energy and reduce storm surges.
- Example: In Vietnam, restored mangroves protect coastal areas and support local livelihoods through sustainable aquaculture.

- **Restored Floodplains:**

- Floodplains provide overflow areas during river floods, reducing pressure on embankments.
- Example: The **Room for the River** program in the Netherlands.

2. INTEGRATING GREEN INFRASTRUCTURE IN URBAN AREAS

- Green infrastructure reduces runoff, improves water quality, and enhances urban sustainability.
- **Permeable Pavements:**
 - Allow water to infiltrate the ground, replenishing aquifers and reducing surface runoff.
 - Example: Used extensively in **Singapore's ABC Waters Program** to manage urban stormwater.
- **Green Roofs and Walls:**
 - Absorb rainfall, reduce urban heat, and improve air quality.
 - Example: Green roofs in Copenhagen, Denmark, significantly reduce stormwater runoff.
- **Rain Gardens:**
 - Shallow, vegetated basins that collect and filter rainwater.
 - Example: Portland, Oregon's rain garden program reduces sewer overflows and improves water quality.

3. REDUCING CARBON FOOTPRINT OF FLOOD DEFENSE SYSTEMS

- Sustainable flood defense minimizes environmental impact through eco-friendly materials and renewable energy sources.
- **Eco-Friendly Materials:**
 - Use of recycled or biodegradable materials in barriers and levees.
 - Example: Bamboo flood defenses in rural Asia provide a sustainable alternative to concrete.
- **Energy-Efficient Systems:**
 - Renewable energy powers flood pumps and monitoring systems.

IV. PROMOTING SUSTAINABILITY THROUGH INNOVATIVE FLOOD DEFENSE SYSTEMS

Sustainability in flood defense focuses on balancing environmental, social, and economic needs while ensuring long-term resilience against flooding. Innovative systems integrate natural processes, eco-friendly materials, and sustainable urban planning to protect communities while maintaining environmental integrity. Here's a detailed exploration:

1. NATURE-BASED SOLUTIONS FOR SUSTAINABLE FLOOD MANAGEMENT

- Nature-based solutions mimic or enhance natural ecosystems to mitigate flood risks and provide co-benefits like carbon sequestration and biodiversity enhancement.
- **Wetland Restoration:**

- Example: Solar-powered water pumps in India manage floodwaters in off-grid areas.

4. PROMOTING WATER REUSE AND CONSERVATION

- Flood defense systems can integrate water storage and reuse mechanisms to reduce waste and enhance sustainability.
 - **RECHARGE WELLS:**
 - *Direct excess stormwater into aquifers, improving groundwater availability.*

5. ENHANCING COMMUNITY RESILIENCE

Sustainable flood defenses support local communities by improving livelihoods and reducing inequalities.

- **Community-Based Solutions:**
 - Involve local populations in the design, maintenance, and monitoring of flood defenses.
 - Example: Community-managed mangrove restoration in Bangladesh protects villages while providing resources like fish and firewood.
- **Equitable Infrastructure:**
 - Flood defenses designed to protect marginalized communities, ensuring no group bears disproportionate risks.

6. MITIGATING URBAN HEAT AND AIR POLLUTION

Green infrastructure contributes to flood management while addressing urban environmental challenges.

- **Cooling Effect of Vegetation:**
 - Urban greenery mitigates the heat island effect and reduces energy consumption.
 - Example: Tokyo integrates green roofs into flood management to improve air quality and lower urban temperatures.
- **Air Filtration:**
 - Vegetation traps pollutants, improving public health.

7. LONG-TERM ECONOMIC BENEFITS

Sustainable flood defenses offer cost savings over time compared to traditional methods.

- **Reduced Maintenance Costs:**
 - Nature-based systems require less frequent repairs than hard infrastructure.
- **Improved Ecosystem Services:**
 - Enhanced biodiversity supports tourism, fisheries, and agriculture.

CASE STUDY: THE NETHERLANDS' ROOM FOR THE RIVER PROGRAM

The Netherlands is a global leader in sustainable flood management:

- **Approach:** Restoring natural river dynamics by creating overflow zones, lowering dikes, and relocating vulnerable structures.
- **Benefits:** Increased flood capacity, biodiversity preservation, and enhanced recreational spaces.

5. CHALLENGES AND CONSIDERATIONS

- **Land Use Conflicts:** Nature-based solutions require space, which may conflict with urban or agricultural development.
- **High Initial Costs:** Implementing green infrastructure can be costly upfront but offers long-term savings.
- **Policy and Community Engagement:** Successful projects require policy alignment and active community involvement.

V. ADAPTIVE INFRASTRUCTURE IN FLOOD DEFENSE SYSTEMS

1. DEFINITION AND PRINCIPLES

ADAPTIVE INFRASTRUCTURE INTEGRATES ENGINEERING, TECHNOLOGY, AND NATURE-BASED SOLUTIONS TO ENABLE URBAN AND RURAL SYSTEMS TO:

- Adjust to varying water levels.
- Minimize damage during extreme weather events.
- Adapt to long-term environmental changes.

KEY PRINCIPLES INCLUDE FLEXIBILITY, SCALABILITY, SUSTAINABILITY, AND RESILIENCE.

2. TYPES OF ADAPTIVE INFRASTRUCTURE

A. FLOATING AND AMPHIBIOUS STRUCTURES

THESE STRUCTURES ARE DESIGNED TO FUNCTION ON LAND DURING NORMAL CONDITIONS BUT CAN FLOAT OR RISE DURING FLOODING.

- **Floating Buildings:** Permanently rest on water and adjust with water level changes.
 - Example: Floating houses in Maasbommel, Netherlands, rise with floodwaters.
- **Amphibious Houses:** Built on buoyant foundations that float temporarily during floods and return to the ground afterward.
 - Example: Amphibious homes along the Maas River in the Netherlands.

B. FLOOD-RESILIENT URBAN DESIGN

URBAN INFRASTRUCTURE DESIGNED TO ADAPT TO FLOODING CONDITIONS WHILE SERVING MULTIPLE PURPOSES:

- **Multi-Use Spaces:** Parks and plazas that function as recreational spaces during normal conditions but act as retention ponds during floods.
 - Example: **Water Square Benthemplein** in Rotterdam collects rainwater during storms.
- **Elevated Infrastructure:** Roads, bridges, and railways built above flood levels to ensure uninterrupted transportation.

C. MODULAR AND FLEXIBLE FLOOD BARRIERS

BARRIERS DESIGNED TO BE DEPLOYED OR RECONFIGURED QUICKLY BASED ON FLOOD SEVERITY.

- **Portable Flood Walls:** Lightweight, movable barriers such as **AquaFence** are used temporarily during flood events.
- **Inflatable Barriers:** Structures like **FloodBreak** automatically rise when water levels increase.

D. DYNAMIC COASTAL PROTECTION

COASTAL DEFENSES THAT ADJUST TO RISING SEA LEVELS AND STORM SURGES:

- **Movable Barriers:** Large-scale structures that can open or close depending on water levels.
 - Example: The **MOSE Project** in Venice, Italy, protects the city from high tides.
- **Sand Engine:** Artificial sandbanks designed to shift naturally along coastlines, reinforcing beaches against erosion and flooding.
 - Example: The Netherlands' Sand Engine project.

GREEN AND BLUE INFRASTRUCTURE

INTEGRATING NATURAL FEATURES TO ENHANCE ADAPTABILITY:

- **Green Roofs:** Absorb rainwater, reduce runoff, and provide insulation.
- **Wetlands:** Serve as natural flood buffers, absorbing excess water.
- **Urban Forests:** Trees reduce surface runoff and provide cooling effects.

3. BENEFITS OF ADAPTIVE INFRASTRUCTURE

1. **Flexibility:** Adjusts dynamically to varying water levels and flood risks.
2. **Sustainability:** Often incorporates renewable energy sources and eco-friendly materials.
3. **Cost-Effectiveness:** Reduces long-term costs by minimizing flood damage and maintenance needs.

4. **Improved Resilience:** Protects critical infrastructure, reducing disruptions to urban life and the economy.
5. **Ecosystem Integration:** Promotes biodiversity by combining natural and built environments.

VI. CASE STUDIES

A. MAASBOMMEL, NETHERLANDS

- **Solution:** Floating and amphibious houses.
- **Impact:** Residents remain safe during floods, and the structures adapt seamlessly to changing water levels.

B. THAMES BARRIER, LONDON

- **Solution:** A movable barrier system that adjusts to tidal surges and protects central London.
- **Impact:** Prevented billions of pounds in flood damage since its installation.

C. WATER SQUARE BENTHEMPLEIN, ROTTERDAM

- **Solution:** A public space that collects and stores excess rainwater during storms.
- **Impact:** Combines flood mitigation with community amenities.

CHALLENGES AND LIMITATIONS

1. **High Initial Costs:** Adaptive infrastructure projects often require significant upfront investment.
2. **Technical Complexity:** Requires advanced engineering and precise planning.
3. **Maintenance Requirements:** Dynamic systems need regular upkeep to remain functional.
4. **Integration with Existing Systems:** Retrofitting adaptive infrastructure into older cities can be challenging.

Future Directions

1. **Smart Adaptive Systems:** Integration of IoT and AI for real-time monitoring and automated adjustments.
 - Example: Smart pumps and gates in Venice's MOSE system.
2. **Climate-Responsive Designs:** Infrastructure designed to adapt to projected future climate scenarios, including higher rainfall and sea-level rise.
3. **Community Involvement:** Collaborative design processes to ensure adaptive infrastructure meets local needs.
4. **Sustainable Materials:** Use of renewable and recyclable materials to build eco-friendly systems.

Experimental Setup: Testing the Effectiveness of Flood Barriers

Objective:

To evaluate the effectiveness of different types of flood barriers in preventing water ingress under varying flood conditions (water levels, flow rates, and duration).

VII.

Materials Required:

1. Flood barriers (e.g., inflatable barriers, movable flood walls, permanent barriers).
2. Water tanks or reservoirs to simulate flooding.
3. Flow meters and water level sensors.
4. Data logger for real-time data collection.
5. Environmental control system (for simulating rain, tides, or waves).
6. Measuring instruments (to assess barrier performance such as seepage, pressure, etc.).

VIII.

Experimental Procedure:

1. Set up the experimental site with water tanks and flood barriers placed along the intended flood zones.
2. Configure sensors to monitor water levels, flow rates, and the duration of flooding events.
3. Activate the water flow (either simulate rainfall or induce floodwaters) at varying flow rates and water levels.
4. Record performance data under different test conditions (e.g., barrier integrity, water penetration, seepage).
5. Measure barrier effectiveness in terms of water control, seepage rates, and any potential damage.

IX.

Experimental Variables:

- Independent Variables:
 - Water levels (low, medium, high).
 - Flow rates (slow, moderate, rapid).
 - Type of flood barrier used (e.g., inflatable, fixed, movable).
- Dependent Variables:
 - Water seepage rate.
 - Pressure on the barrier.
 - Structural integrity of the barrier.
 - Time taken to breach or control water flow.

Test No.	Barrier Type	Water Level (m)	Flow Rate (m ³ /s)	Duration (hrs)	Seepage (L/hr)	Pressure (Pa)	Performance (Pass/Fail)	Observations
1	Inflatable	0.5	0.2	3	10	2000	pass	Minimal seepage, stable under pressure
2	Fixed Barrier	1	0.5	4	0	5000	Pass	No water ingress, stable performance
3	Movable	0.75	0.3	2	5	3500	Fail	Slight seepage, pressure increase
4	Inflatable	1	0.8	5	25	7000	Fail	Significant seepage, partial failure
5	Fixed Barrier	0.6	0.4	6	0	4000	Pass	No issues, stable water retention

X.

Explanation of Columns:

- Test No.: A unique identifier for each experiment.
- Barrier Type: Type of flood barrier used in the test (e.g., inflatable, fixed, movable).
- Water Level (m): The height of water in the test setup to simulate different flooding conditions.

- Flow Rate (m^3/s): The rate at which water is introduced into the system, simulating various flood intensities.
- Duration (hrs): How long the test is conducted, representing the flood duration.
- Seepage (L/hr): The amount of water that leaks through or around the barrier per hour.
- Pressure (Pa): The amount of pressure exerted on the barrier by the water.
- Performance (Pass/Fail): Whether the barrier successfully prevented water ingress (Pass) or failed.
- Observations: Additional notes on the barrier's performance, including any issues such as structural deformation, leakage, or excessive seepage.

XI. analysis of Results:

From the data table, you can analyze the following:

- Effectiveness of Different Barrier Types: Compare how inflatable, fixed, and movable barriers performed under similar conditions.
- Water Control Ability: Check if certain barriers can withstand higher water levels and flow rates without significant seepage or failure.
- Environmental Considerations: Understand the pressures exerted on barriers over time and how they hold up under prolonged flooding.

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2. References

The references should be formatted according to IEEE citation standards. Below is an example of how you might format your references:

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