



Urban Drainage Management: Evaluating Drainage Infrastructure and Flood Resilience in Delhi city

Anika Passi¹, Tanuj Goswami¹, Tushar Agrawal¹, Dr. Geeta Singh²
Delhi Technological University, New Delhi

Date of Submission: 13-05-2024

Date of Acceptance: 25-05-2024

Abstract: Urban flooding year after year has become a commonplace event in India's capital city, Delhi. Since 1900, Delhi has experienced nine major floods due to River Yamuna's rising water levels, in the years 1924, 1947, 1976, 1978, 1988, 1995, 1998, 2010 and 2013. Recently, in July 2023, the city was flooded yet again when water level in River Yamuna reached an alarming high of 208.48 metres. This can be attributed to unprecedented rainfall, rapid urbanisation causing encroachment of floodplains and lack of proper urban planning. A research claims that Delhi's drainage system, designed in 1976, is only capable of holding 50 mm of rain. Therefore, it is imperative to upgrade the city's current drainage system since, in the near future, a combination of population growth, economic expansion, and climate change is expected to put more strain on the municipal water system. The paper discusses causative factors responsible for flood risks in Delhi, the immediate need for proper flood risk reduction and management strategies. The purpose of this study was to explore the current deficiencies in the drainage system of the national capital and suggest improvements to reduce and manage flood risks, while also comparing the drainage system with other modern drainage systems across the world.

Keywords: Flood, Drainage system, Flood management, Delhi Flood

I. INTRODUCTION

India's capital, New Delhi, is spread out across an area of approximately 1,484 square kilometres in northern region of the country, along the Yamuna River's western side. The city is bounded by Haryana on three sides, while to the east across the Yamuna River lies the state of Uttar Pradesh.

It is one of the fastest growing cities in the country. Rapid urbanisation has changed the landscape from majorly rural to majorly urban. As per latest census, 97.50% of the population of the city lives in urban areas. The total population of the city (according to 2011 census) stands at 16.78 million.

The National Capital Territory (NCT) of Delhi, which is located on the globe at 28°N and 77.23°E and has a total area of 1483 km², is the subject of this study. Delhi is bordered by the almost level Thar Desert in the west, the Aravalli hill ranges in the south, and the Indo- Gangetic alluvium plain in the east and north. Yamuna enters close to Palla village from the northeastern side.

1.1 TOPOGRAPHY

Geographical location of this city is latitude 28.68 N and longitude 77.21 E in the north-west of the country. The Delhi Union Territory's eastern section simultaneously borders the State of Uttar Pradesh, while its northern, southern, and western portions border the State of Haryana. The Yamuna River, a tributary of the Ganges River, flows to the south in the east of the Delhi Union Territory, while the Aravalli Mountains to the west serve as the administrative border with the Uttar Pradesh Region.

1.2 SOIL AND VEGETATION

In terms of soil, Delhi can be divided into three parts.

Yamuna Floodplains: The eastern part of Delhi is dominated by the expansive floodplains of the Yamuna River. These fertile plains are prone to seasonal flooding during the monsoon, contributing to the lush greenery in the region. Despite the challenges posed by periodic floods, the Yamuna floodplains play a crucial role in the city's ecosystem.

Ridge Area: The northern and central parts of Delhi are marked by a prominent feature known as the Delhi Ridge. This hilly terrain, an extension of the ancient Aravalli Range, provides a natural elevation to the city. The Ridge not only acts as a watershed for various water bodies but also offers elevated vantage points, such as the historic Tughlaqabad Fort and the modern Rashtrapati



Bhavan.

Alluvial Plains: The western and southern parts of Delhi are characterized by gently sloping alluvial plains. These plains are home to the majority of the city's population and infrastructure. The terrain here is relatively flat, facilitating urban expansion and the development of residential and commercial area.

1.3 WEATHER PATTERNS

Delhi is situated around 160 kilometers south of the Himalayas. Thus, from December to February, the city feels the chilly effect of the snowcovered mountains, with temperatures ranging from 3°C to 21°C. There will likely be mild rain, chilly winds, and a thick fog at this time. Springtime is heralded in March by the singing of birds and the blossoming of trees, which can last until mid-April at most. In May, as spring ends and summers take over, the city becomes searing hot. Delhi exhibits an intense continental climate due to its considerable distance from sea. Summer temperatures rise to highs up to 47°C, necessitating precautions against heat strokes and dehydration. Violent dust storms, locally known as "loo," are common during the hot and dry summer months. The arrival of the monsoon in early July brings much-needed moisture to the parched earth, vegetation, and animals, bringing relief. However, the monsoon is erratic, sometimes coming early or late. The next two months see a drop in temperature to the more tolerable 30s°C. Even though it's September, there's humidity, and by October, the days are cooler. Delhi is enveloped by winter once more by November.

1.4 PRECIPITATION PATTERNS

Generally, considerable rainfall occurs during the rainy season, specifically in the months of July, August, and September. New Delhi experiences dry periods in March, April, May, October, November, and December. On an average scale, July stands out as the wettest month, receiving around 202 mm (7.9 inches) of precipitation. Conversely, November is characterized as the driest month, with an average of 6 mm (0.2 inches) of precipitation. The total annual precipitation typically amounts to 709 mm (27.9 inches).

1.5 DRAINAGE

National Capital Region in general, is a part of well integrated drainage system of the Ganga basin. The extremely gentle gradient that spreads almost all over the region restricts the

degradational activities of the streams/drains. The region forming the metropolitan area of Delhi, almost entirely comprises plain land which is characterised by the presence of two main features - a long rocky ridge extending roughly in the southwest - north-east direction and a river, entering from the north-eastern edge of the territory and flowing across its south-eastern edge. The general slope of the land in Delhi is from north to south and the Ridge acts as the local watershed dividing the drainage system of the region into two sectors. While the eastern region drains directly into the Yamuna, the western region does the same through the Najafgarh drain. On the basis of topographical characteristics, the National Capital Territory of Delhi has been divided into five major drainage basins viz. Najafgarh basin, Alipur basin, Shahadra basin, Kushak- Barrapullah basin and Mehrauli basin. This drainage system is such that all waters collected through the main drains, link drains and small rivulets are directly or indirectly discharged finally into the Yamuna.

II. CAUSES OF RECENT FLOODS

2.1 DIRECT CAUSES

2.1.1 Yamuna River's Flooding

The majority of the significant floods were caused by the Yamuna River. The Yamuna River, a prominent Ganges tributary, originates from the Yamunotri Glacier at an elevation of around 6387 meters above mean sea level. It empties into Delhi in the vicinity of Palla village, sharing a border with Uttar Pradesh and Haryana.

The river flows through Delhi for almost fifty kilometers, from Palla to Jaitpur. Before entering Uttar Pradesh, the water is halted by the Wazirabad water supply facility, the ITO, and the Okhla barrages, which regulate the river's flow.

The Yamuna's flow through Delhi is significantly impacted by the 240 km upstream release of the Tajewala Headwork. When it rains heavily in a tropical area, Tajewala loses a lot of water. Depending on the river flow rate below the river, the Yamuna level in Delhi rises over the course of 48 hours. The city's dams re- fill with water due to rising water levels.

Another factor contributing to the city's flooding is the network of eighteen large water pipelines that extend outside its borders. The Delhi region is frequently inundated by the Yamuna River, which collects water from Haryana and the Sahibi River via the Najafgarh drain. In addition, the lower Yamuna (Khadar) flood basins are susceptible to recurring floods.



Table 1: River Yamuna peak levels at ORB in major Delhi floods

Year	Discharges in lakh cusec	Peak at ORB Delhi
03 Sept 1978	7,09,000	207.49
25 Sept 1988	5,77,522	206.92
05 Sept 1995	5,36,188	206.93
20 Sept. 2008	4,09,576	206
20 Sept 2010	7,44,507	207.11
17 June 2013	8,06,464	207.32
28 July 2018	5,03,925	206.05
18 Aug 2019	8,28,000	206.6
11 July 2023	3,59,760	208.66

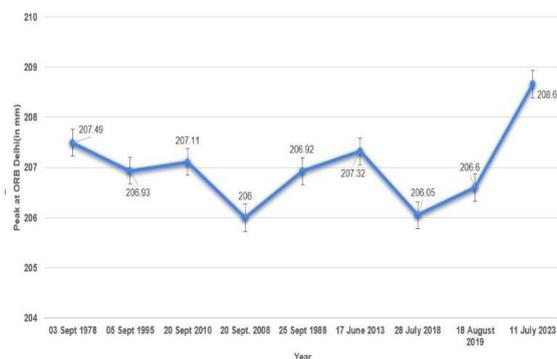


Fig 1: River Yamuna levels in major delhi floods

2.1.2 Sahibi River's Role

The Rajasthani region of Jaipur is the source of the Sahibi River. It enters the U.T. from Delhi at Dance, after traveling via the Alwar area of Rajasthan and the Gurgaon District of Haryana. Expulsions from Sahibi used to be rather mild till they started happening in Delhi years ago. Very little water used to enter the U.T. of Delhi because of the blockade of Jahajgarh and other lakes and underground reservoirs in Rajasthan and Haryana. It is clear that every year, the quantity of water entering Delhi rises quickly and the areas of Najafgarh Jheel start to submerge for a year due to land expansion and the growth of the pipeline system in Haryana. In 1964, connections and a controller at Dansa were constructed to monitor the input of water from Delhi. At the same time, a significant and unprecedented flood in Sahibi resulted in a breach of the Dansa Bund and the submersion of numerous Najafgarh Vimba areas in deep water. Sahibi saw similar floods in 1967 and 1977. Even if the 1967 flood did not harm the Delhi region, the 1977 flood made matters worse than they were in 1964 because it endangered remote parts of Delhi like Janakpuri and other areas.

2.2 INDIRECT CAUSES

2.2.1 Temperature Trends

An average surface warming of 3.5 to 5°C is predicted to occur this century in Delhi as a result of mean extreme temperatures, maxima, and minima rising by 2 to 4 °C. Second, by the later part of this century, average mean rainfall is expected to rise by 7 to 20 percent because of the rise in mean temperature and its effect on the Indian monsoon cycles. (Mehrotra, 2011)

2.2.2 Interaction between western disturbances and monsoon trough

The interplay between a Western Disturbance, a low-pressure system originating from the Mediterranean region, and the monsoon trough, a low-pressure zone along the monsoon wind belt, is chiefly responsible for the severe rainfall in North India. As a result of this interaction, areas like Himachal Pradesh, Uttarakhand, Punjab, and Haryana experienced heavy rainfall.

An extratropical storm system known as the Western Disturbance arises in the middle and high latitudes. It forms when the jet stream, a swift air current in the high sky, collides with the Himalayas and western regions of central Asia. The disturbance develops as a result of this interaction creating a low-pressure area.

2.2.3 Inadequate Drainage system

Research has shown that the drainage of storm water, which affects areas in the NCT-Delhi Sub-region, Rajasthan, U.P., and Haryana, is not well planned. This is a regional issue. Most of the region's drains still carry untreated sewage, which eventually empties into the Ganga and Yamuna rivers. Slum dwellers' encroachment along the drains reduces carrying capacity, clogging the drains and causing flooding in the upstream neighborhoods. Solid trash is still being poured down the sewers, which clogs them. District-specific master plans have not been created. Not even the hydraulic survey, which evaluates the state of the drains, has been conducted on a regular basis.

III. EFFECTS OF FLOODS IN DELHI

III.1 Diseases

Floods lead to rise in many kinds of diseases and ailments like-

- Vector-borne diseases: Still water post floods provide breeding grounds for mosquitoes,



causing malaria, dengue fever, chikungunya, and Zika virus

- **Leptospirosis:** This bacterial disease is often associated with floods and can be contracted through contact with water contaminated with the urine of infected animals
- **Respiratory infections:** Mold growth on damp walls and the release of airborne allergens and irritants, leads to respiratory issues such as asthma exacerbations and allergic reactions
- **Gastrointestinal infections:** Cholera, dysentery, gastroenteritis, and E.Coli infections are common. Symptoms are diarrhea, vomiting, abdominal pain, and dehydration
- **Skin infections:** Fungal and bacterial skin infections. Skin contact with polluted water can also lead to rashes and irritation
- **Wound infections:** Floods can cause injuries and wounds, and these wounds can become easily infected due to exposure to dirty water and lack of proper wound care
- **Mental health issues:** Psychological impacts of a trauma can lead to anxiety, depression, post-traumatic stress disorder (PTSD), and other mental health issues
- **Heat-related illnesses:** Hot and humid climate can increase the risk of heat exhaustion and heatstroke, especially if access to safe drinking water and cooling facilities is limited.

III.2 *Damage to Property*

Floods have the potential to damage or destroy residential houses, commercial buildings, and critical infrastructure such as roads, bridges, railways, power lines, and communication networks. The least-productive formal establishments are the most vulnerable to floods: a 10 percent increase in flood exposure leads to a 0.6 percentage point increased probability of exit among low-productivity firms (Hossain 2020). Floodwaters can damage or wash away crops and pose a threat to livestock, affecting agriculture and rural livelihoods. Capable of damaging or destroying vehicles and other valuable assets. Flooding in urban areas can have severe consequences on historical sites, public institutions, and the overall urban infrastructure. The floods have caused damage to several buildings, infrastructure, and properties in low-lying areas in Delhi such as ITO, Mukundpur, Kashmere Gate, Yamuna Bazar, GT Karnal Road and Vishwakarma Colony. Water intrusion has led to structural damage, electrical issues, and damage to foundations, walls, and flooring. This means

substantial repair and renovation costs for property owners. According to the NDMA, floods affect about 75 lakh hectares of land and inflict damage worth Rs 1,805 crore to crops, houses, and public utilities every year in India. In 2023, floods caused extensive damage to several landmarks in Delhi, such as the Red Fort and the Supreme Court.

III.3 *Displacement of People*

Floods are one of the most disastrous acts of nature and impact human life in multiple ways. Damages by floods in rural areas are more severe compared to urban counterparts due to poverty, limited infrastructures and access to resources and health care services (Kumar, Cheng, and Singh 2016). Floods compel people to evacuate their homes to escape rising waters and potential dangers, leading to forced migration. The displacement disrupts the normal lives and routines of those affected, causing emotional and economic stress. Floods can also create humanitarian crises by affecting the availability of food, water, sanitation, health care, and education. Displaced individuals may face increased vulnerability to diseases, malnutrition, and other health risks. According to the IDMC, floods displaced about 5.4 million people in India in 2020. In 2023, floods have displaced thousands of people in North India, especially in Himachal Pradesh and Punjab. Displaced individuals often require immediate shelter, and emergency response efforts are crucial to providing temporary accommodations. Relief efforts should address the basic needs of affected populations, including access to clean water, food, healthcare, and education.

III.4 *Economic Losses*

Floods can disrupt transportation networks and supply chains, impacting the movement of goods and services. Businesses may face challenges in accessing markets and customers, leading to economic losses. "An estimated Rs 200 crore worth of business has been affected due to rains and flooding in parts of the national capital". Between 1953 and 2011, 97,557 persons were killed, 1,913 million people were affected, and economic losses amounted to Rs 2,131 billion because of floods (Parida and Prasad Dash 2019). Floods can damage cultural heritage sites and natural attractions, impacting the tourism sector. The perception of flood-related risks may lead to a decline in tourism, affecting the revenue generated from this sector. According to a study by the World Bank, floods cost India about \$14 billion annually in direct losses.



IV. DEFICIENCIES IN CURRENT DRAINAGE SYSTEM

4.1. *Combined Sewer System Overloads:*

Delhi's drainage system faces significant challenges due to its combined sewer system, where stormwater and sewage are carried in the same pipes. During heavy rainfall, this system becomes overwhelmed, leading to widespread flooding and pollution. According to reports from the Centre for Science and Environment (CSE), approximately 60% of Delhi's sewage flows untreated into the Yamuna River during the monsoon season due to this overload. This untreated sewage not only poses health risks to residents but also contributes to the degradation of the Yamuna's water quality, impacting aquatic life and ecosystems. The inability of the drainage system to handle the volume of water during heavy rains exacerbates flooding in low-lying areas, causing damage to property and infrastructure. Despite efforts to upgrade the system, including the construction of new drains and pumping stations, the combined sewer system remains a significant flaw in Delhi's drainage infrastructure.

4.2. *Inadequate Infrastructure:*

Delhi's drainage infrastructure is outdated and insufficient to meet the needs of its rapidly growing population. According to a study by the Indian Institute of Technology (IIT) Delhi, the city's drainage capacity falls short by around 30% to 40%, exacerbating flood risks, particularly during the monsoon season. Aging pipes and pumping stations are prone to breakdowns and inefficiencies, further compromising the system's ability to manage stormwater and sewage. The inadequate infrastructure not only leads to frequent flooding but also poses health hazards due to waterborne diseases caused by sewage overflow. The Yamuna level in Delhi rises throughout the course of 48 hours, depending on the river flow rate below the river. Rising water levels also cause the city's dams to re-fill with water (Kumar, Sharif, and Ahmed 2017b). Despite ongoing efforts to upgrade and expand the drainage network, including the construction of new drains and treatment plants, the pace of infrastructure development has not kept up with the city's population growth, resulting in persistent flaws in the drainage system.

4.3. *Encroachment on Drains:*

Illegal encroachments along drainage channels and stormwater drains are a significant impediment to the proper functioning of Delhi's drainage system.

These encroachments, which include unauthorized constructions and settlements, obstruct the natural flow of water, leading to localized flooding and waterlogging, especially during the monsoon season. The Delhi Jal Board estimates that approximately 1,600 unauthorized colonies in the city encroach upon drainage channels, exacerbating flood risks in these areas. Despite efforts by government authorities to remove encroachments and clear obstructed drains, the problem persists due to limited enforcement capabilities and legal challenges. The unchecked growth of unauthorized settlements along drainage channels further compounds the issue, making it difficult to maintain clear pathways for stormwater runoff. The presence of encroachments not only hampers flood control efforts but also poses safety risks to residents living in flood-prone areas, highlighting a critical flaw in Delhi's drainage infrastructure management.

4.4. *Pollution of Water Bodies:*

The discharge of untreated sewage from Delhi's drainage system into the Yamuna River contributes significantly to water pollution in the region. The Yamuna River in Delhi is classified as one of the most polluted rivers in the country, with high levels of biochemical oxygen demand (BOD) and fecal coliform, according to data from the Central Pollution Control Board (CPCB). The untreated sewage contains harmful pathogens and contaminants that pose serious health risks to humans and aquatic life. Additionally, the pollution of the Yamuna River has far-reaching environmental consequences, including the degradation of aquatic ecosystems and the loss of biodiversity. Despite efforts to improve wastewater treatment and reduce pollution levels, the discharge of untreated sewage remains a persistent flaw in Delhi's drainage infrastructure, highlighting the need for urgent measures to address this issue and safeguard the health of both residents and the environment.

4.5. *Lack of Maintenance:*

Delhi's drainage system suffers from a lack of regular maintenance, leading to the accumulation of solid waste and silt in drains and pipelines. According to the Comptroller and Auditor General (CAG) of India, only about 40% of the city's drains were regularly cleaned as of a recent audit report. The buildup of debris and silt obstructs the flow of water, increasing the risk of flooding and waterlogging, particularly during the monsoon season. Additionally, the lack of



maintenance contributes to the deterioration of infrastructure components such as pipes, pumping stations, and culverts, leading to frequent breakdowns and inefficiencies in the drainage system. Despite occasional cleanup drives initiated by government authorities, the lack of sustained maintenance efforts represents a significant flaw in Delhi's drainage infrastructure management, requiring urgent attention to ensure the system's reliability and functionality.

4.6. Poor Planning and Design:

Many parts of Delhi lack proper urban planning and design, resulting in the absence of adequate stormwater drainage infrastructure. According to a study by the Delhi Development Authority (DDA), nearly 70% of the city's urbanized area lacks a proper stormwater drainage system, leaving residents vulnerable to flooding and waterlogging. The haphazard development of residential and commercial areas without sufficient consideration for drainage requirements exacerbates the problem, leading to localized inundation during heavy rainfall. Additionally, the lack of integration between land-use planning and drainage infrastructure development further complicates flood control efforts, making it challenging to address the root causes of drainage problems effectively. Despite initiatives to retrofit existing infrastructure and incorporate stormwater management features into new developments, the absence of comprehensive planning and design remains a critical flaw in Delhi's drainage infrastructure, necessitating holistic approaches to urban development and flood risk mitigation.

4.7. Inefficient Pumping Stations:

Delhi's drainage system relies on pumping stations to manage water levels and facilitate the flow of stormwater and sewage. However, many of these pumping stations suffer from inefficiencies and breakdowns, compromising the system's reliability and functionality.

According to data from the Delhi Jal Board, around 30% of the city's pumping stations are non-functional or operate below capacity at any given time, leading to delays in drainage and increased flood risks. The inefficiency of pumping stations is often attributed to inadequate maintenance, outdated equipment, and inadequate staffing, highlighting systemic flaws in the management of these critical infrastructure components. The frequent breakdowns and malfunctions of pumping stations not only disrupt drainage operations but also pose safety risks to

nearby residents and exacerbate flood-related damages, underscoring the urgent need for improved maintenance and modernization efforts to enhance the reliability and performance of Delhi's drainage system.

4.8. Lack of Public Awareness:

There is a general lack of awareness among the public regarding the proper disposal of waste and the importance of maintaining drainage infrastructure in Delhi. Surveys conducted by non-profit organizations like WaterAid India indicate that a significant portion of Delhi's population disposes of solid waste in storm drains, exacerbating clogging issues and impeding the flow of water. The indiscriminate dumping of garbage, construction debris, and other materials into drains not only contributes to drainage problems but also creates breeding grounds for disease vectors and contaminants, posing health risks to residents. Additionally, the lack of awareness about the consequences of improper waste disposal undermines efforts to promote civic responsibility and community engagement in drainage maintenance initiatives. Despite occasional awareness campaigns and outreach efforts by government agencies and civil society organizations, the persistent lack of public awareness represents a critical flaw in Delhi's drainage infrastructure management, necessitating comprehensive education and outreach programs to foster a culture of responsible waste management and environmental stewardship among residents.

4.9. Limited Financial Resources:

The Delhi government's budgetary allocations for drainage infrastructure are often insufficient to address the scale of the problem effectively. According to budget documents, only a fraction of the total funds allocated for urban development in Delhi is earmarked for drainage projects, resulting in competing priorities and resource constraints. The limited financial resources allocated to drainage infrastructure hamper efforts to invest in critical upgrades, maintenance activities

4.10. Inadequate Capacity for Rapid Urbanization:

Delhi's drainage system struggles to keep pace with the rapid urbanization and population growth occurring in the city. As urban areas expand and new developments emerge, existing drainage infrastructure becomes overwhelmed, leading to increased instances of flooding and



waterlogging. The lack of foresight in urban planning and infrastructure development exacerbates this issue, as drainage systems are often unable to accommodate the influx of stormwater and sewage generated by densely populated neighborhoods and commercial districts. Despite efforts to retrofit existing infrastructure and incorporate stormwater management features into new developments, the mismatch between infrastructure capacity and urban growth remains a significant flaw in Delhi's drainage system, necessitating comprehensive planning and investment strategies to address future challenges.

4.11. Climate Change Vulnerability:

Climate change has the potential to intensify the hydrological cycle, leading to more intense precipitation with associated changes in the intensity, frequency and severity of floods. Climate variability and change beyond a few years to a few decades ahead have significant social, economic, and environmental implications. It is believed that some aspects of this decadal variability could be predictable for a decade or longer in advance (Apurv et al. 2015). Delhi's drainage system is vulnerable to the impacts of climate change, including more frequent and intense rainfall events. As global temperatures rise, extreme weather events such as heavy rainfall and flash floods are becoming more common, placing additional stress on drainage infrastructure already struggling to cope with existing demands. The increased frequency and severity of flooding not only disrupt daily life and economic activities but also exacerbate public health risks by promoting the spread of waterborne diseases and contaminants. Despite growing recognition of the need to adapt to climate change, the integration of climate resilience measures into Delhi's drainage infrastructure has been limited, leaving the city ill-prepared to mitigate the impacts of future climate-related disasters. The lack of proactive planning and investment in climate-resilient infrastructure represents a critical flaw in Delhi's drainage system, highlighting the urgent need for adaptive strategies to enhance the city's resilience to climate change.

4.12. Informal Settlements and Slums:

Delhi's drainage system is challenged by the presence of informal settlements and slums, which often lack access to basic sanitation and drainage services. These densely populated areas are typically located in low-lying areas prone to flooding, exacerbating the vulnerability of

residents to water-related hazards. The absence of proper infrastructure, such as piped water supply and sewage networks, forces residents to rely on makeshift drainage solutions, including open drains and septic tanks, which pose health risks and contribute to environmental pollution. Despite efforts to improve living conditions in informal settlements through initiatives such as the Jawaharlal Nehru National Urban Renewal Mission (JNNURM), the scale of the problem remains vast, with millions of people living in substandard housing with inadequate drainage facilities. The persistence of informal settlements and slums underscores systemic flaws in Delhi's urban planning and housing policies, requiring holistic approaches to address the root causes of poverty and inequality.

4.13. Groundwater Depletion and Subsidence:

Delhi's drainage system contributes to groundwater depletion and land subsidence due to excessive extraction of groundwater and inadequate replenishment mechanisms. As stormwater is rapidly drained away from urban areas, it reduces the recharge of aquifers and depletes groundwater reserves, leading to land subsidence and instability. The overexploitation of groundwater exacerbates the problem, as residents and industries rely heavily on borewells and tubewells for water supply, further depleting aquifers and exacerbating subsidence risks. The loss of groundwater storage capacity not only affects water availability for drinking and irrigation but also increases the susceptibility of urban areas to flooding and infrastructure damage. Despite efforts to promote rainwater harvesting and groundwater recharge initiatives, the scale of groundwater depletion and subsidence in Delhi remains a significant concern, highlighting the need for sustainable water management practices and stricter regulations on groundwater extraction.

4.14. Poor Drainage in Peri-urban Areas:

Delhi's peri-urban areas, which lie on the outskirts of the city, often lack adequate drainage infrastructure, leading to waterlogging and soil erosion. These areas are characterized by fragmented land ownership, informal settlements, and agricultural activities, making it challenging to implement comprehensive drainage solutions. The absence of proper stormwater management infrastructure in peri-urban areas not only disrupts agricultural activities but also increases the risk of flooding and environmental degradation. The unchecked expansion of urban sprawl into peri-



urban areas further compounds the problem, as new developments encroach upon natural drainage pathways and exacerbate land use conflicts. Despite initiatives to improve peri-urban infrastructure through schemes such as the Pradhan Mantri Awas Yojana (PMAY) and the Smart Cities Mission, the lack of coordinated planning and investment in drainage infrastructure represents a critical flaw in Delhi's peri-urban development strategy, requiring integrated approaches to balance urbanization with environmental conservation and sustainable growth.

4.15. Inadequate Institutional Capacity and Governance:

Delhi's drainage system suffers from institutional inefficiencies and governance challenges, which hinder effective decision-making and implementation of drainage projects. The management of drainage infrastructure involves multiple agencies and departments, leading to coordination gaps and bureaucratic hurdles. The lack of clarity in roles and responsibilities often results in overlapping mandates and conflicting priorities, delaying critical maintenance and repair activities. Additionally, issues such as corruption, political interference, and lack of transparency further undermine the effectiveness of governance mechanisms, eroding public trust and accountability. Despite efforts to streamline institutional arrangements and enhance stakeholder engagement through initiatives such as the Delhi Master Plan, the systemic challenges in governance and institutional capacity remain a significant barrier to improving the resilience and functionality of Delhi's drainage system. Addressing these governance flaws requires comprehensive reforms to enhance accountability, transparency, and coordination among relevant stakeholders, ensuring that drainage infrastructure is managed efficiently and sustainably for the benefit of all residents.

V. Modern Drainage Systems Adopted Around the World

Table 2: Population vs Drainage Capacity for capital cities around the world

Country	Capital City	Population (Million)	Drainage Capacity (Million m ³ /d)	Population/ Drainage capacity
China	Beijing	21.86	3.735	5.85
Germany	Berlin	3.5	0.59	5.93
India	Delhi	32.94	2.034	16.19
Netherlands	Amsterdam	0.822	0.115	7.14
Luxembourg	Luxembourg City	0.134	0.021	6.38
Japan	Tokyo	37.194	4.567	8.14
France	Paris	12.271	1.542	7.95
Singapore	Republic of Singapore	6.014	0.847	7.1
Egypt	Cairo	22.183	4.002	5.54
South Africa	Cape Town	4.89	1.2	4.07

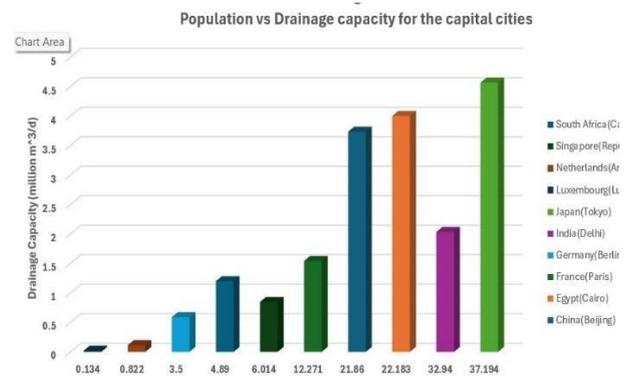


Fig 2: Population vs Drainage Capacity for capital cities around the world

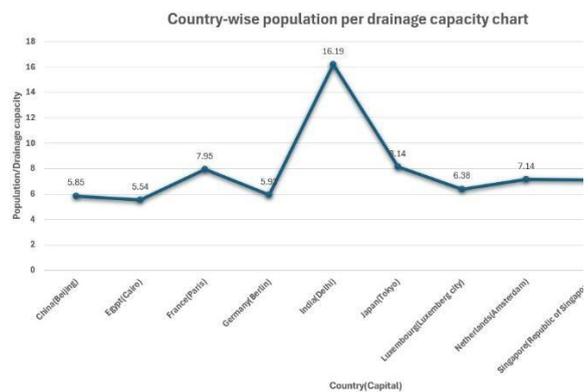


Fig 3: Country-wise population per drainage capacity chart

5.1. Singapore Case.

Delhi, the capital city of India, grapples with significant drainage issues and frequent flooding, particularly during the monsoon season. The rapid urbanization, coupled with inadequate drainage infrastructure, exacerbates these challenges, leading to property damage, traffic disruptions, and health hazards (Singh, Nielsen, and Greatrex 2023). However, Singapore,



renowned for its advanced drainage technologies and effective stormwater management strategies, offers valuable lessons and insights that Delhi could leverage to address its drainage and flood problems.

Singapore has implemented Bioretention basins, sometimes referred to as rain gardens, are a type of best management practice (BMP) that have been proven to effectively decrease the amount of runoff and eliminate pollutants (Wang, Chua, and Shanahan 2017). Tang et colleagues demonstrated that the implementation of bioretention basins, notwithstanding their limited coverage of urban areas, may effectively mitigate the negative hydrological impact caused by impermeable surfaces.

Deploying a Surveillance-based Sewage Wastewater Monitoring System (SSWMS) integrated with Internet of Things (IoT) technology (Kumar and Hong 2022) in Delhi will provide significant advantages for flood control. This system would offer continuous monitoring and predictive analysis of water levels, pressure, and quality in the city's drainage systems, enabling efficient flood management. This proactive strategy facilitates early detection of possible floods, enabling prompt evacuations and precautionary actions. Additionally, it enhances the allocation of resources, mitigates the likelihood of accidents associated with exposed manholes, and facilitates data-informed decision-making for urban planning. Nevertheless, in order to achieve effective implementation, it is necessary to tackle obstacles such as substantial upfront expenses, the requirement for specialised knowledge, and the assurance of data confidentiality.

5.1.1 Addressing Flood Problems: Singapore's holistic approach to flood management offers valuable insights for Delhi in tackling its flood problems. By adopting adaptation pathways that combine structural and non-structural measures (Buurman and Babovic 2016), Delhi has the potential to create durable and flexible strategies for urban drainage infrastructure, taking into account the unique difficulties presented by flooding. This may entail the discovery and implementation of a blend of conventional grey and cutting-edge green infrastructure solutions to efficiently handle rainwater and mitigate the danger of floods. (Manocha and Babovic 2017). Furthermore, Delhi could benefit from Singapore's experience in conducting comprehensive risk assessments and scenario planning to anticipate

future flood scenarios and prioritize mitigation efforts. By identifying high-risk areas, vulnerable populations, and critical infrastructure, Delhi can allocate resources effectively, implement targeted interventions, and enhance preparedness for extreme weather events.

5.2. *Japan (Tokyo) Scenario*

Delhi grapples with recurring drainage issues and heightened flood risks, especially exacerbated during the monsoon season (Kumar, Sharif, and Ahmed 2017). Japan has emerged as a global leader in stormwater management, leveraging innovative green infrastructure and smart technologies to address similar challenges. By embracing Japan's expertise, Delhi can revolutionize its drainage and flood management systems, mitigating risks and enhancing resilience to extreme weather events.

Key Insights:

Green Infrastructure Integration: Japan's successful integration of green infrastructure offers promising solutions for Delhi's drainage woes. Green roofs, rain gardens, and permeable pavements play crucial roles in reducing stormwater runoff and alleviating pressure on drainage systems (Kinoshita and Ozaki 2024). Green roofs absorb rainwater, mitigating flooding risks (Vijayaraghavan 2016), while rain gardens and permeable pavements facilitate infiltration, replenishing groundwater reserves (Charlesworth 2010). A rain garden in Japan serves several purposes, including reducing and delaying flood peaks, facilitating groundwater recharge, and promoting biodiversity. (Lin et al. 2023). Delhi can replicate Japan's approach to strategically implement green infrastructure across the city, transforming urban landscapes while improving drainage efficiency.

Smart Technologies for Real-Time Monitoring: Japan's utilization of smart technologies provides real-time insights into drainage system performance. Sensors, telemetry systems, and GIS platforms enable continuous monitoring of water levels, flow rates, and infrastructure conditions Campisano et al. (2013). Delhi can leverage similar technologies to enhance its drainage network's operational efficiency and responsiveness. Predictive analytics and data-driven decision support systems empower authorities to anticipate flood risks, optimize drainage operations, and deploy timely interventions, minimizing flood impacts and ensuring public safety.



Implementing Low Impact Development Practices for Stormwater Management. The objective of the LID practices is to mitigate runoff pollution, decrease runoff volume, and regulate peak flows by implementing decentralised and small-scale retention and infiltration facilities near the source of runoff. These practices are outlined in studies (Lin et al. 2023; Rong et al. 2024).

An AI-powered surveillance system utilising machine learning algorithms can significantly enhance flood management by monitoring drainage pumps (Wille 2023). Pump sensors collect data on flow rate, pressure, and vibration, which is then analysed in real-time by machine learning algorithms to identify problems and forecast potential breakdowns. This facilitates preemptive maintenance, guaranteeing optimal performance of pumps during crucial periods of floods.

SCADA systems, also known as Supervisory Control and Data Acquisition systems, are extensive solutions utilised for the remote administration and control of water infrastructure (Fujita 2002). These systems comprise hardware components such as Remote Terminal Units (RTUs) and Programmable Logic Controllers (PLCs). These components collect real-time data from field sensors and operate equipment like pumps and valves. The data is transmitted to a central SCADA programme over a communication network. The software then processes the data, offers a user interface for monitoring and control, and allows for the automation of repetitive activities (Fujita 2002). The system would mechanise reactions to floods, such as controlling pumps and floodgates, and furnish data for study.

Japan's innovative deployment of green infrastructure and smart technologies offers a transformative solution for Delhi's drainage and flood management challenges. By adopting Japan's proven strategies, Delhi can enhance its drainage capacity, mitigate flood risks, and build resilience to climate change impacts

Collaboration between policymakers, urban planners, and technology experts is essential to effectively implement these solutions and create a safer, more sustainable urban environment for Delhi's residents.

5.3 Netherlands Case

Stormwater management in urban areas is crucial for mitigating flooding and improving water quality. Three key technologies— Structural flood control measures and Nature based solutions,

—offer sustainable solutions to these challenges, drawing insights from experiences in both the Netherlands and Delhi.

Structural flood control strategies encompass many techniques such as dikes, flood walls, storm surge barriers like the Maeslantkering, reservoirs, detention basins, and channel alterations. The purpose of these physical infrastructures is to mitigate the impact of increasing water levels, avoid floods, and minimise the danger of downstream flooding, hence protecting lives, property, and infrastructure (Silva, Dijkman, and Loucks 2004). Implementing flood embankments along the Yamuna River, enhancing the capacity of stormwater drains, and establishing detention basins to temporarily retain surplus runoff can effectively mitigate floods in low-lying regions of the city.

Introducing a variety of nature-based solutions (NBS) in Delhi can greatly enhance the city's ability to withstand and recover from floods. Green infrastructure, sustainable urban drainage systems (SuDS), natural flood management (NFM), ecosystem-based adaptation (EbA), blue-green infrastructure, and agroecological approaches provide a range of methods to effectively handle stormwater, decrease surface runoff, improve water absorption, and mitigate flood hazards (Costa et al. 2021).

The implementation of various solutions such as green roofs, permeable pavements, wetland restoration, coastal protection, urban ponds, and agroforestry not only helps to reduce flood risks but also has positive effects on biodiversity, ecosystem services, and sustainable development goals (Costa et al., 2021).

Bio-retention systems, such as rain gardens and vegetated swales, have been successfully implemented in the Netherlands to capture and treat stormwater runoff (Dutta, Torres, and Vojinovic 2021). Similarly, in Delhi, these systems can intercept runoff before it enters drainage networks, effectively improving water quality downstream. By promoting infiltration and groundwater recharge while enhancing biodiversity and aesthetics, bio-retention systems offer multifaceted benefits for urban environments in both regions (Dutta, Torres, and Vojinovic 2021).

VI. RECOMMENDATIONS

VI.1 Combined Sewer System Overloads:

Delhi's drainage system faces complex issues that can be addressed through a holistic strategy. Green infrastructure, such as bioswales,



permeable pavements, green roofs, and rain gardens, can alleviate strain and improve the area's visual appeal. Advanced technologies like membrane bioreactors and constructed wetlands can reduce untreated sewage discharge into the Yamuna River during heavy rainfall. Retrofitting the sewer system to segregate runoff and effluent can alleviate strain during intense precipitation. IoT-enabled sensors and monitoring systems can provide real-time information on water levels, flow rates, and quality parameters. Public awareness campaigns can encourage community engagement in river clean-up drives and rainwater harvesting. Policy reforms, institutional frameworks, and climate resilience considerations can enhance the municipality's capacity to withstand climate change-induced challenges. Collaboration among academic institutions, private enterprises, government agencies, and civil society is crucial for the long-term success of these solutions.

VI.2 Inadequate Infrastructure:

Delhi's outdated drainage system requires a comprehensive strategy to address its issues. This includes modernizing and expanding the system using advanced materials and technologies to improve durability, reliability, and efficiency. The capacity deficit should be narrowed to 30% to 40%, focusing on decentralised wastewater treatment facilities, green infrastructure, and sustainable urban drainage practices.

Technological advancements, such as sensor networks and real-time monitoring systems, can enhance operational resilience. Awareness campaigns, community engagement initiatives, and flood preparedness are also crucial for public participation. Promoting favorable policy frameworks and sufficient funding are essential for long-term progress and investment in infrastructure. By implementing these strategies, Delhi can rectify infrastructure shortcomings, reduce flooding risks, improve public health, and strengthen its capacity to withstand climate-related challenges.

VI.3 Encroachment on Drains:

To address the issue of unauthorised intrusions into Delhi's drainage channels, a comprehensive strategy is needed. Geospatial technologies can be used for precise detection of encroachments, while collaboration with law enforcement agencies and community involvement can enhance enforcement. Surveillance

technologies and a specialized task force can ensure prompt identification and remediation of encroachments. Policy reforms and legal amendments are needed to improve administrative procedures and enforce penalties. Incorporating drainage infrastructure into urban planning can proactively prevent future encroachments. Capacity-building initiatives can enhance the capabilities of municipal officials and frontline personnel to confront encroachments, promoting collaboration and coordination among agencies. This approach can help alleviate the negative effects of unauthorised intrusions on Delhi's drainage system, reduce flood risks, and enhance sustainable development and urban governance.

VI.4 Pollution of Water Bodies:

The issue of untreated effluent discharge from Delhi's drainage system into the Yamuna River requires a comprehensive strategy involving technological, regulatory, and community-driven interventions. Advanced technologies in wastewater treatment facilities, such as membrane bioreactors and activated sludge processes, can improve effluent quality. Community-level decentralized treatment systems can reduce strain on centralised facilities. Real-time monitoring systems and remote sensing technologies can enforce water quality standards. Community involvement and public awareness campaigns can educate residents on waste disposal methods and encourage river cleanup efforts. Green infrastructure components, like vegetated swales and riparian buffer zones, can organically filter contaminants from stormwater runoff and sewage effluent. Promoting policy reforms and institutional strengthening can enhance wastewater management strategy implementation. Collaborative governance structures can support multi-stakeholder dialogue and decision-making processes.

VI.5 Lack of Maintenance:

The Delhi drainage system needs a comprehensive strategy that incorporates technological advancements, community engagement, and institutional restructuring. Advanced technologies like CCTV cameras, drones, and GIS mapping will enable routine surveillance and inspections of the infrastructure. Predictive maintenance algorithms will proactively detect and resolve potential issues. Awareness campaigns and community participation will motivate residents to maintain clean pipelines and sewers, fostering a sense of ownership and timely



reporting of maintenance concerns. Performance-based contracts for maintenance contractors will motivate superior service delivery. Enhancing the capabilities of municipal personnel and contractors will ensure effective maintenance tasks. Asset management systems will optimize resource allocation and schedules. Policy reforms and institutional strengthening will instill a culture of routine maintenance. Public-private partnerships will leverage private sector investment and expertise. This research paper contributes to understanding resource allocation and policy decisions for urban resilience and sustainability.

VI.6 Single Ownership:

Eleven departments and agencies are the owners of Delhi's drainage system. The state government is responsible for around two thirds of the drains, municipal corporations are responsible for about 25%, and central government organizations like Delhi Development Authority are responsible for the remaining drains. Therefore, accountability and responsibility for the drains should be placed under one organization.

VI.7 Public awareness and involvement: The public should have access to prepared flood risk maps for various return period floods in order to raise awareness of the potential flood risk associated with various scenarios. The identification of vulnerable flood plains and flash flood-prone locations will aid in the planning of mitigation and emergency preparedness measures. At every level of the decision-making process, the stakeholders must be involved.

VI.8 Rejuvenation of water bodies:

Over time, many of the water bodies have become obsolete and aren't even correctly linked to their catchments. Rejuvenated water bodies serve as detention and recharge basins, which can be crucial in mitigating flooding. To lessen runoff into storm drains, they should be regularly inspected and maintained.

No encroachment or illegal development in wetlands should be allowed.

Regular desilting should be carried out to prevent deterioration in the storage capacity of the water bodies.

Waste dumping into water bodies should be prevented to protect ambient water quality.

VI.9 Flood plan zoning:

It is critically necessary to implement flood plain zoning for various return level flood plains, such as 1 in 25, 1 in 50, and 1 in 100, in

order to alter vulnerability to flood damage. A model bill for flood plain zoning has been developed by the Ministry of Water Resources, Government of India, and distributed to the states for the purpose of enacting appropriate legislation. Regretfully, most States—including Delhi—have not yet approved the legislation. Without legislation, floodplains are being indiscriminately occupied, leading to densely inhabited towns within them. Legislation is urgently required to minimize the loss of life and property in floodplains.

In addition to providing flood protection, the flood plain's vast, deep aquifers act as a massive natural water storage facility. Following the devastating flood of 1978, the Yamuna Standing Committee (YSC) declared at its 37th Meeting on April 26, 1979, that there should be a minimum of 5 kilometers between embankments. However, nowhere in Delhi is there a 5-kilometer gap between embankments. The Yamuna's active river edge was established by the YSC during its 72nd meeting in January 2007 at 1650 meters. However, there are few places where the flood plain's width is less than one kilometer. Experience from the floods in 2010 and 2013 indicates that the river's current width needs to be preserved in order to accommodate the peak flow of 12,750 cumec without overflowing.

VII. CONCLUSION

To summarise, this research article has explored the crucial subject of urban drainage management, specifically examining the assessment of drainage infrastructure and flood resistance in Delhi, India. This research has emphasised the urgent requirement for comprehensive and proactive actions to tackle flood hazards in Delhi. It has done so by analysing the historical backdrop of floods, the distinctive topographical difficulties encountered by the city, and the inherent flaws in its drainage system.

Delhi is prone to flooding due to several causes. These include its position along the flood-prone Yamuna River, the fast growth of urban areas that have taken over natural drainage routes, and the obsolete drainage system that is not designed to handle the rising levels of rainfall. Flooding in Delhi has several adverse consequences, including public health risks caused by waterborne illnesses, considerable destruction of property and infrastructure, and substantial economic losses.

A comparative examination with cities known for their sophisticated drainage systems,



such as the Netherlands, Tokyo, and Singapore, highlights the need of investing in strong drainage infrastructure and flood control measures. These cities have effectively reduced the impact of floods by using a combination of creative technical solutions, strict land use rules, and integrated water management measures. Delhi may learn from these cities and adopt similar strategies to address its own flood concerns.

In the future, it is crucial for policymakers, urban planners, and stakeholders in Delhi to give priority to improving drainage infrastructure and implementing efficient flood resistance measures. To tackle the current shortcomings in the drainage system, it is necessary to make a focused and collaborative endeavour. This involves incorporating sustainable urban design methods and improving community resilience by promoting awareness and readiness programmes.

Delhi can effectively address the negative effects of floods, improve its ability to withstand climate change, and promote sustainable urban growth by implementing a proactive and comprehensive urban drainage management strategy. This study adds to the existing information on urban flood resilience and offers significant insights for informing policy choices and initiatives that aim to create safer and more resilient cities in response to increasing environmental challenges.

REFERENCES

- [1]. Rafiq, Farhat & Ahmed, Sirajuddin & Ahmad, Shamshad & Amir, Ali & Khan, & Arabia, Saudi. (2016). Urban Floods in India.
- [2]. Sharma, D. & Kansal, A. (2013). Sustainable City: A Case Study of Stormwater Management in Economically Developed Urban Catchments. Mechanism Design for Sustainability: Techniques and Cases. 243-263. 10.1007/978-94-007-5995-4_12.
- [3]. Mehrotra, S., C. Rosenzweig, W. D. Solecki, C. E. Natenzon, A. Omojola, R. Folorunsho, J. Gilbride, 2011: Cities, disasters and climate risk. Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network, C. Rosenzweig, W. D. Solecki, S. A. Hammer, S. Mehrotra, Eds., Cambridge University Press, Cambridge, UK, 15– 42.
- [4]. Gupta, K. (2020) Challenges in developing urban flood resilience in India, Phil. Trans. R. Soc. A 378: 20190211.
- [5]. Gupta, S., (2017) Report on Impact of Floods in Delhi
- [6]. Parida, Yashobanta & Dash, Devi. (2019). Rethinking the effect of floods and financial development on economic growth: Evidence from the Indian states. Indian Growth and Development Review. ahead-of-print. 10.1108/IGDR-05-2019-0044.
- [7]. Gupta, Anil & Singh, Swati & Nair, Sreeja. (2013). Ecosystem Services for Disaster Risk Reduction: A Case Study of Wetland in East Delhi Region, India. 13. 36-47.
- [8]. Kumar, B. A., & Bhaduri, S. (2018). Disaster risk in the urban villages of Delhi. International Journal of Disaster Risk Reduction, 31, 1309–1325. <https://doi.org/10.1016/j.ijdrr.2018.04.022>
- [9]. Kumar, M., Sharif, M., & Ahmed, S. (2017, December 28). Flood risk management strategies for national capital territory of Delhi, India. ISH Journal of Hydraulic Engineering, 25(3), 248–259. <https://doi.org/10.1080/09715010.2017.1408434> [
- [10]. Roy, A.H., Wenger, S.J., Fletcher, T.D. (2008). et al. Impediments and Solutions to Sustainable, Watershed-Scale Urban Stormwater Management: Lessons from Australia and the United States. Environmental Management 42, 344–359 <https://doi.org/10.1007/s00267-008-9119-1>
- [11]. Zhou, Q. A Review of Sustainable Urban Drainage Systems Considering the Climate Change and Urbanization Impacts. Water 2014, 6, 976-992. <https://doi.org/10.3390/w6040976>
- [12]. Chan, F. K. S., Yang, L. E., Mitchell, G., Wright, N., Guan, M., Lü, X., Wang, Z., Montz, B. E., & Adekola, O. (2022, August 12). Comparison of sustainable flood risk management by four countries – the United Kingdom, the Netherlands, the United States, and Japan – and the implications for Asian coastal megacities. Natural Hazards and Earth System Sciences. <https://doi.org/10.5194/nhess-22-2567-2022>
- [13]. Webber, J. L., Fletcher, T. D., Farmani, R., Butler, D., & Melville-Shreeve, P. (2022, June 1). Moving to a future of smart stormwater management: A review and framework for terminology, research, and future perspectives. Water Research. <https://doi.org/10.1016/j.watres.2022.118409>
- [14]. Kumari, Kumari, & Malik. (n.d.).



- Waterlogging in Mega City of India -Delhi: Challenges & Opportunities. *International Research Journal of Modernization in Engineering Technology and Science*, 04(08/August-2022).
- [15]. Zhang, Z. (2022, June 1). Can the Sponge City Project improve the stormwater drainage system in China? —Empirical evidence from a quasi-natural experiment. *International Journal of Disaster Risk Reduction*.
<https://doi.org/10.1016/j.ijdrr.2022.102980>
- [16]. Manocha, N., & Babovic, V. (2017). Development and valuation of adaptation pathways for storm water management infrastructure. *Environmental Science & Policy*, 77, 86–97.
<https://doi.org/10.1016/j.envsci.2017.08.001>
- [17]. Kumar, P. M., & Hong, C. S. (2022). Internet of things for secure surveillance for sewage wastewater treatment systems. *Environmental Research*, 203, 111899.
<https://doi.org/10.1016/j.envres.2021.111899>
- [18]. Buurman, J., & Babovic, V. (2016). Adaptation Pathways and Real Options Analysis: An approach to deep uncertainty in climate change adaptation policies. *Policy & Society*, 35(2), 137–150.
<https://doi.org/10.1016/j.polsoc.2016.05.002>
- [19]. Wang, J., Chua, L. H. C., & Shanahan, P. (2017). Evaluation of pollutant removal efficiency of a bioretention basin and implications for stormwater management in tropical cities. *Environmental Science. Water Research & Technology*, 3(1), 78–91.
<https://doi.org/10.1039/c6ew00285d>
- [20]. Tang, S., Luo, W., Jia, Z., Liu, W., Li, S., & Wu, Y. (2015). Evaluating retention capacity of infiltration rain gardens and their potential effect on urban stormwater management in the Sub-Humid Loess region of China. *Water Resources Management*, 30(3), 983–1000.
<https://doi.org/10.1007/s11269-015-1206-5>
- [21]. Singh, H., Nielsen, M., & Greatrex, H. (2023). Causes, impacts, and mitigation strategies of urban pluvial floods in India: A systematic review. *International Journal of Disaster Risk Reduction*, 93, 103751.
<https://doi.org/10.1016/j.ijdrr.2023.103751>
- [22]. Singh, H., Nielsen, M., & Greatrex, H. (2023b). Causes, impacts, and mitigation strategies of urban pluvial floods in India: A systematic review. *International Journal of Disaster Risk Reduction*, 93, 103751.
<https://doi.org/10.1016/j.ijdrr.2023.103751>
- [23]. Kumar, M., Sharif, M., & Ahmed, S. (2017). Flood risk management strategies for national capital territory of Delhi, India. *ISH Journal of Hydraulic Engineering/the Indian Journal of Hydraulic Engineering*, 25(3), 248–259.
<https://doi.org/10.1080/09715010.2017.1408434>
- [24]. Campisano, A., Ple, J. C., Muschalla, D., Pleau, M., & Vanrolleghem, P. (2013). Potential and limitations of modern equipment for real time control of urban wastewater systems. *Urban Water Journal*, 10(5), 300–311.
<https://doi.org/10.1080/1573062x.2013.763996>
- [25]. Kinoshita, T., & Ozaki, T. (2024). Estimation of possible locations for green roofs and bioswales and analysis of the effect of their implementation on stormwater runoff control. *Frontiers in Climate*, 6.
<https://doi.org/10.3389/fclim.2024.1287386>
- [26]. Vijayaraghavan, K. (2016). Green roofs: A critical review on the role of components, benefits, limitations and trends. *Renewable & Sustainable Energy Reviews*, 57, 740–752.
<https://doi.org/10.1016/j.rser.2015.12.119>
- [27]. Charlesworth, S. M. (2010). A review of the adaptation and mitigation of global climate change using sustainable drainage in cities. *Journal of Water and Climate Change*, 1(3), 165–180.
<https://doi.org/10.2166/wcc.2010.035>
- [28]. Osheen, N., & Singh, K. K. (2019). Rain Garden—A Solution to Urban Flooding: A review. *Lecture Notes in Civil Engineering*, 27–35. https://doi.org/10.1007/978-981-13-6717-5_4
- [29]. Viumdal, H., David, B. H., & Omholt, H. (2023). Surveillance system for drainage pumps with the use of machine learning. <https://openarchive.usn.no/usn-xmlui/handle/11250/3071621?show=full>
- [30]. Fujita, S. (2002). Full-Fledged Movement on Improvement of the Combined Sewer System and Flood Control Underway in Japan (Keynote Paper). *Global Solutions for Urban Drainage*.
[https://doi.org/10.1061/40644\(2002\)1](https://doi.org/10.1061/40644(2002)1)
- [31]. Silva, W., Dijkman, J. P., & Loucks, D. P. (2004). Flood management options for The



Netherlands. *International Journal of River Basin Management*, 2(2), 101–112.

<https://doi.org/10.1080/15715124.2004.9635225>

- [32]. Costa, S., Peters, R., Martins, R., Postmes, L., Keizer, J. J., & Roebeling, P. (2021). Effectiveness of Nature-Based solutions on pluvial flood hazard mitigation: the case study of the City of Eindhoven (The Netherlands). *Resources*, 10(3), 24. <https://doi.org/10.3390/resources10030024>
- [33]. Dutta, A., Torres, A. S., & Vojinovic, Z. (2021). Evaluation of pollutant removal efficiency by Small-Scale Nature-Based solutions focusing on Bio-Retention cells, vegetative swale and porous pavement. *Water*, 13(17), 2361. <https://doi.org/10.3390/w13172361>