doi: 10.2166/9781789063714_0265

Chapter 24

Urban water infrastructure: distribution and collection

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ABSTRACT

Significant urbanization has occurred in the last few decades, especially in the Global South. The provision of sustainable water infrastructure is crucial for making these urban areas liveable, inclusive, and environmentally sustainable. Planning, designing, and operating water infrastructure is highly challenging because of the unpredictability of the growth of urban agglomerations, dwindling water resources, competing needs, transforming governance structures, limited finances, and the impact of climate change. This chapter focuses on issues involved in the planning and operation of water distribution and wastewater and stormwater collection systems in rapidly growing cities, especially in the Global South.

Keywords: water supply systems, sewerage systems, storm drainage systems, integrated planning, flexible planning

24.1 INTRODUCTION

It is projected that by 2025, more than 50% of the population in the Global South will be living in urban areas, accounting for a population of 3.75 billion. The provision of sustainable water infrastructure (water supply, sewerage, and stormwater drainage systems) is crucial for making these urban areas liveable, inclusive, and environmentally sustainable. Piped water distribution networks (WDNs) supply treated water, sourced from dams, lakes, ponds, aquifers, and so on, to the consumers through a network of pipes, valves, pumps, and storage tanks. The main purpose of the water distribution system is to deliver water to consumers in the required quantity, quality, and adequate pressure. Any inefficiency in operating WDNs, such as wastage of water and degradation of water quality, is akin to poor utilization of the already dwindling freshwater resources.

The chapter is from the book *Technological Solutions for Water Sustainability: Challenges and Prospects – Towards a Water-secure India*, Ligy Philip, Thalappil Pradeep and S. Murty Bhallamudi (Editors).

In many urban areas, except where onsite and decentralized sanitation systems are adopted, the wastewater generated in residential and commercial areas needs to be collected through a system of interconnected sewers for treatment before disposal. Discharge of untreated wastewater leads to an unhygienic environment, public health problems, and contamination of sources. The third major component of the water infrastructure is the stormwater drainage system. As discussed in Chapter 23 on 'Sustainable Urban Drainage Systems', the provision of an appropriate stormwater drainage system is essential for avoiding urban pluvial flooding. In the past, many cities in India (e.g. Chennai), other Asian countries (e.g. Antananarivo), and in Africa (Douglas *et al.*, 2008) incurred significant damages due to both fluvial and pluvial flooding. Efficient drainage systems, based on urban design concepts that consider the need for flood protection, can help to mitigate the damage. Proper management of stormwater also protects water resources from pollution by urban surface runoff.

In this chapter, we discuss the issues involved in planning, designing, and operating water infrastructures in rapidly growing cities, especially those in the Global South. In this chapter we do not discuss the related important questions of water and wastewater treatment, and water quality issues since they are covered in other chapters of this book.

24.2 CHALLENGES TO WATER INFRASTRUCTURE PLANNING

Planning, designing, and operating water infrastructure is highly challenging because of the unpredictability of the growth of urban agglomerations, dwindling water resources, competing needs, transforming governance structures, limited finances, and the impact of climate change.

24.2.1 Unpredictable urbanization

Water distribution and drainage infrastructures are usually planned and designed to last 50–75 years into the future because of the cost and effort involved. The design of the infrastructure is based on the needs of the future population, which is estimated using conventional (e.g., statistical extrapolation) forecast methods. In the case of cities in the Global South, there is a significant uncertainty in the estimation of future total population as well as spatial variation in the population density. It is difficult to predict in which direction the city will be expanding. This, in turn, has a cascading effect on the sizing of distribution and collection systems. Errors in the estimation of future land use and land cover lead to errors in the estimation of design storm runoff, making it difficult to appropriately size the stormwater drainage system.

24.2.2 Multiple stakeholders

There are multiple uses of water in an urban area. While the demand for domestic water is high in the core city area, the need for agricultural water is generally high in the peri-urban areas. The proportion of the demand in different sectors continuously changes as peri-urban areas transition into urban areas. There is also a demand for water from industrial establishments. Water bodies provide crucial eco-services and should not be exploited beyond a tipping point. Therefore, the planning of water infrastructure should be based on the sustainable allocation of water among different competing sectors. Social and macroeconomic problems could arise if water is not distributed equitably among all the stakeholders with varying income levels. The way different sections of society respond to a drought or a flood and the coping mechanisms they adopt are complex, making it challenging to plan a resilient system.

24.2.3 Increasing gap between demand and supply

The gap between demand and supply in urban areas is ever increasing for the following reasons: (1) increase in the population, (2) aggregation due to urbanization at locations away from sources, (3) changing lifestyles, (4) industrialization, (5) climate change, and (6) dwindling usable water sources due to overuse by other sectors and increasing pollution. For example, as the city of Chennai has expanded its peripheries over the last few decades, many water bodies have disappeared due to encroachment, which otherwise could have been used for water storage. There is a significant gap between the amount of sewage generated and the existing capacity for sewage treatment in many cities in India. The discharge of untreated wastewater into the environment is deteriorating the water quality in many sources, making them unfit for use. Over-exploitation of aquifers in coastal areas is inducing seawater intrusion, making many aquifers saline.

24.2.4 Climate change

Climate change will affect all parts of the hydrologic cycle. Warming climate will: (a) increase the evaporation losses, (b) alter the spatial and temporal distribution of precipitation, (c) alter the frequency of occurrence and intensity of extreme events, (d) change the surface run-off and stream flow, (e) increase the seawater intrusion, (f) change water quality characteristics, and (g) change the water demand. There is a likelihood of more variability in climate in the future as compared to the present. This will have to be factored into planning robust, flexible, and resilient water infrastructure systems. Climate change will have a significant effect on intensity–duration–frequency curves (Chandra *et al*., 2015), which are basic inputs for planning stormwater drainage systems. It is important to note that the uncertainty in the quantification of climate change effect increases with decreasing scale in time and space, posing challenges to planners. For example, the uncertainty of local design storms (a few hours) is much higher than long-term water balances.

24.2.5 Other challenges

Most urban agglomerations in the Global South are characterized by fragmented, top-down decision-making processes, and governance in silos. Many a time, there is little coordination between different governmental organizations, which are independently responsible for the planning of water supply, sewerage, and storm drainage systems. Typically, the planning and implementation of different components are carried out at different times. In contrast, the interdependent systems perspective is needed to establish circular material flows. Governance practices should enable the participation of all stakeholders and enhance the capacity to respond in an adaptive manner to changes.

24.3 WATER INFRASTRUCTURE PLANNING: GLOBAL SOUTH VS GLOBAL NORTH

Planning of water infrastructure differs from country to country because of: (a) economic conditions, (b) social–cultural–political structures, (c) data availability, (d) the current state of infrastructures, and (e) development dynamics. These differences are especially perceptible between countries belonging to Global North and Global South. Herein, this important issue is brought forth through a brief discussion on how the planning of water infrastructure in India differs from that in Germany (Dilly *et al*., 2020).

Data scarcity poses the biggest challenge for planners in India. For example, sub-hourly rainfall data and high-resolution digital elevation models, essential for urban drainage system planning, are not available for most Indian cities. The planning process, involving stakeholders in decision making and governance is more structured in Germany, as compared to that in India. A basic input required for planning either a water supply or a sewerage system is the spatial distribution of the water supply demand or wastewater generation in the future. In Germany, the population in several areas is expected to decrease in the future, as opposed to a rapid increase in the urban population in India. The difference in planning objectives is also obvious from the way ‘Smart Cities’ goals are articulated differently in the two countries.

The current state of water infrastructure development also affects the planning process. At present, many cities in India neither have proper sewerage nor a stormwater drainage system. The Government of India plans to invest significantly in this sector, and it has mandated that the municipalities should go for separate systems. Germany, by contrast, has already achieved 97% coverage, and the majority of the systems are combined systems. Thus, measures like sewer network control to reduce the frequency of combined water overflows are not an issue in India. Recycling of treated wastewater for domestic use is encouraged in India to bridge the gap between supply and demand, unlike Germany. The main drivers for the adoption of sustainable drainage systems in India include the reduction of peak storm flows and enhancing the water supply. However, low impact development measures (LIDs) in Germany are designed to minimize the effect on the urban hydrologic cycle. Also, differing socio-economic conditions introduce differences in planning processes in both countries.

24.4 WATER INFRASTRUCTURE PLANNING AND DESIGN: IMPORTANT ISSUES

Sustainable water allocation, consideration of multifunctional infrastructure, integrated planning of water infrastructure systems, the introduction of decentralized systems, and adaptive planning are important issues to address water infrastructure planning challenges.

24.4.1 Sustainable water allocation

Sustainable water allocation among different stakeholders is a critical prerequisite to the planning and design of water infrastructure. This task can become complex given: (a) the interdependency of the systems, (b) differences in the required water quality depending on the type of use, (c) availability of water from different types of sources having varying quality, (d) geographical distribution of sources, (e) seasonal variation in water availability, and (f) uncertainty in the estimation of future demand. Also, there could be a water scarcity situation, making equity in water allocation a prime issue.

The difficult task of sustainable water allocation may be facilitated by mathematical models. For example, the software WEAP is a popular tool used for integrated water resources planning. It facilitates the allocation of limited water resources from different sources to different users, based on the scenarios (set of rules) specified by the planner (https://www.weap21.org/; downloaded on 05-04-2023), using an embedded mass balance model with link-node architecture. It has in-built simulators to calculate water demand in different sectors, supply, components of the hydrologic cycle, storage, pollution generation, treatment, discharge, and in-stream water quality under varying hydrologic and policy scenarios. However, WEAP cannot be used for optimal allocation based on specified objectives and constraints. Recently, Dilly *et al.* (2022a) developed a linear programming-based tool for holistic decision making for planning water supply, urban drainage, wastewater treatment, and water reuse based on the urban water mass balance

24.4.2 Multi-functional infrastructure

The paradigm of multi-functional infrastructure is becoming popular in urban planning, especially in the context of the evolution of eco-cities due to factors, such as climate change, the necessity for maintaining ecological balance, resource crunch, and a greater appreciation of the water–food–energy nexus. For example, improper implementation of transportation infrastructure interferes with local urban hydrology and has a bearing on urban flooding (Narasimhan *et al.*, 2016). Multi-functional planning of the transportation infrastructure can be based on the function of roads as transportation corridors as well as drainage routes during heavy rainfall events. Similarly, objectives of urban drainage networks can include: (i) minimization of flooding, (ii) provision of water during scarcity, and (iii) creation of water bodies for recreation and reduction of the heat island effect (Dilly *et al.*, 2022b). Sewerage systems with the tertiary treatment of wastewater can be planned for providing treated wastewater for domestic and industrial water supply. In the context of water-sensitive urban design, the entire water infrastructure may be treated as one single system with multiple functions.

24.4.3 Integrated planning of water infrastructure systems

The implementation of water circularity will have a significant impact on how the water infrastructure is planned, designed, and operated. On-site and decentralized treatment of grey water and wastewater for reuse purposes would reduce the amount of flow into the existing sewerage system, resulting in increased maintenance problems. Thus, for retrofitting existing water supply and sewerage systems to incorporate treated wastewater reuse, the total cost of the system should be minimized to obtain an optimal solution. The total cost consists of the capital cost of different components, the operational cost of the wastewater treatment plants, the maintenance cost of the sewerage system, and the cost of supplying fresh water through the existing system (Dev *et al.*, 2021). Recently, Zhang *et al.* (2023a) developed an optimization tool that provides pareto-optimal solutions for sewerage system design based on minimizing capital cost, minimizing energy consumption, and maximizing the water reuse capacity. In the case of new water infrastructure, significant cost saving can be achieved if the reuse of wastewater for potable purposes is factored upfront and the planning and design of both systems are carried out simultaneously. The cost reduction occurs due to a reduction in the required sizes and capacities.

For the management of stormwater runoff, there is an opportunity for employing LID measures for simultaneously tackling spatially and temporally varying water excess as well as the risks of water scarcity (Yang *et al.*, 2020). For example, Chennai city has implemented a policy of rainwater harvesting (RWH) to tackle the chronic problem of water scarcity. However, these spatially distributed RWH measures can be factored in while designing the stormwater drainage system. Similarly, Chennai Metropolitan and Sewerage Board is implementing projects wherein treated wastewater would be stored in rejuvenated ponds and abandoned stone quarries for indirect potable use. It is important to note that many of these water bodies can also be utilized as flood detention and recharge structures, underscoring the importance of integrated planning and design of all components of water infrastructure.

24.4.4 Decentralized systems

Conventional water infrastructure systems are centralized because they have been designed to perform single functions, and the constraints have been manageable. For example, domestic water supply was sourced from one or two large surface reservoirs and distributed in the entire city. However, the necessity to look for alternative and sustainable sources such as tertiary treated wastewater, spatially distributed groundwater pumping, and so on, makes it imperative to plan a water supply system as a decentralized system. Similarly, in recent years there has been a push to go for decentralized sewerage and stormwater drainage systems because of factors such as the topographical conditions, spatial variation in population density, rapidly transforming peri-urban areas, effect on the environment, the necessity for treated water recycling, and so on. Zahediasl *et al.* (2021) developed an optimization algorithm for designing a decentralized sewerage system that is cost-effective and sustainable. Hesarkazzazi *et al.* (2022) presented a novel framework to investigate the impact of adding redundant flow paths on resilience for optimal centralized versus decentralized urban stormwater networks.

24.4.5 Flexible planning

Planning of expensive water infrastructure in rapidly expanding urban agglomerations in the Global South is complex because of uncertainties associated with the prediction of urbanization, lack of land area, transforming governance structures, limited finances, and so on. It is essential to adopt a flexible design framework to consider system changes, growth, multi-period constructions, new technological developments, and other uncertainties (Cunha *et al.*, 2019). In a flexible design approach, although initial planning and design are based on predictions for the future, spanning the entire lifetime of the project, the project is implemented in multiple stages. At the beginning of each stage, predictions for the remaining lifetime are carried out again, and the design of the system is revised if needed. Zhang *et al.* (2023b) have developed an innovative multi-stage planning framework for hybrid low-impact development and grey infrastructure urban drainage systems in response to land-use changes. One can also explore the possibilities of applying model predictive control concepts (Herman *et al.*, 2020).

24.5 OPERATION OF WDNS

24.5.1 Leakage management

The magnitude of water loss in a WDN is typically quantified by 'unaccounted-for-water (UFW)', which is defined as the ratio of the difference in the quantity of water supplied and delivered to the total amount of water supplied. This UFW includes water lost through leaks in WDNs and unauthorized use of water. It is estimated that the average water loss in many countries in Global South could be as high as 40–50%. The UFW rates are higher in the Global South, where WDNs are poorly monitored for leakage due to limited instrumentation and improper operation. Besides the loss of precious resources, leakages also lead to longer pumping times, higher energy consumption, and water quality degradation.

Techniques based on transient analysis of pressure, acoustic, or magnetic flux signals caused by leaks in pipelines are possible (Colombo *et al.*, 2009). Another approach called the inverse analysis uses hydraulic models, simulators, and measurements to estimate the location of the leak. Machine-learning methods are also becoming popular. Network theory and water balances have also been used to identify and isolate leaks (Rajeswaran *et al.*, 2018).

24.5.2 Pressure management

The pressure at any point in a WDN should be above a minimum value so that water can be withdrawn from the system by the customers at an appropriate rate. At the same time, pressures should not be excessively high as to minimize the background leakage through joints. Originally, the concept of district metered areas (DMAs) was introduced as a convenient way to carry out continuous water auditing and easy detection of water-leaking areas by measuring flow rate using strategically located bulk flow meters (Khoa Bui *et al.*, 2020). A DMA may be defined as a discrete area of a WDN created either by temporarily closing boundary valves or permanently disconnecting pipes from neighbouring areas. Recently, Zhang *et al.* (2021) combined a graph theory algorithm, community detection algorithm, and two-objective optimization framework for creating DMAs, which minimizes the number of flow meters and cumulative pressure differences compared with critical points in each DMA.

24.5.3 Equitable water supply

WDNs are typically designed for continuous operation. However, the WDNs that are originally designed for continuous operation cannot be operated continuously in cases when either water is not available, or it is not possible to ensure appropriate pressures. Hence, the operators are forced to supply water intermittently to manage the resulting stress based on some heuristics and consumption patterns. In most intermittent WDNs, the supply policies are often inadequate and inequitable (Bhave & Gupta, 2006). Although intermittent operation is common in the Global South, it is not as well studied. Minimization of pressure variations across the network for achieving equitable distribution is discussed in Vairavamoorthy *et al.* (2008). Equitable distribution and prevention of excess withdrawal are the focus of operational planning in intermittent networks, whereas, in 24/7 systems, it is mostly operation cost and quality of water supplied.

24.5.4 Energy management

Pumping costs are a significant portion of the operating expenses of a water utility operator and hence optimal pumping strategies can reduce energy consumption. The efficient operation of WDNs has gained a lot of interest in recent decades, and this topic has been recently reviewed by Mala-Jetmarova *et al.* (2017). These studies propose operational methods for minimizing pumping cost as a primary goal for the efficient network by pump scheduling. A common assumption in most of these studies, originating in the Global North, is the availability of a sufficient amount of water. Recently, an approach based on a non-linear model predictive control for optimal operation in water-deficient conditions was developed by Sankar *et al.* (2015). Kurian *et al.* (2018) have addressed the problem of optimal operation of WDNs with intermediate storage facilities.

24.5.5 Internet of Things and smart systems

Smart WDN monitoring using the Internet of Things (IoT) has received wide attention due to the geographical spread of water networks, buried pipelines, and difficulties in accessing vital components of the network. While cellular communication for voice and data has become ubiquitous, it is still expensive and energy-intensive for monitoring water networks. Low-power, short-range radios such as IEEE 80215.4 with multi-hop routing have been used. However, it increases the complexity of the network. PipeNet (Stoianov *et al.*, 2007), among others, is an early example of the use of wireless sensor networks (WSNs). Recently developed low-power wide area networks (LPWANs) based on SigfoxTM and SemtechTM are attractive alternatives to conventional cellular technology. LoRa-based communication can achieve 20 km or higher in range with line of sight (LOS) and about 2 km without LOS. It uses an unlicensed spectrum and can be deployed in each area without any additional subscription, whereas Sigfox is entirely operator managed. Although several works use LoRa for monitoring applications, relatively fewer works have reported the use of LoRa for the remote operation of valves (Chinnusamy *et al.*, 2018).

24.6 OPERATION AND MAINTENANCE OF WATER AND WASTEWATER INFRASTRUCTURE

The water distribution and sewerage collection systems are typically designed to operate for several decades. Unless these are well maintained, they will not provide the level of service expected of them. The reality is that continuous monitoring and maintenance of the infrastructure is not practised in most developing countries. The Central Public Health and Environmental Engineering Organisation (CPHEEO) of the Government of India has published manuals on the operation and maintenance (O&M) of water supply and sewerage systems. Broadly, the O&M activities can be grouped under the following areas:

(i) **Public health and safety:** To ensure that the supplied water meets the standards of water quality, it is necessary to monitor the water sources as well as the treated water. Water sources can be monitored by taking samples at appropriate intervals. Appropriate online instruments can be employed for continuous monitoring of the various water quality parameters. Although usually disinfection using chlorine is carried out in the treatment plant, water may get contaminated during transportation. Therefore, the residual chlorine at the delivery end should also be monitored. Models for the optimal dosing strategy to ensure minimum residual chlorine have been developed (Karaderek *et al.*, 2016).

(ii) **Environmental impact:** Direct and indirect emissions of greenhouse gases such as methane and nitrous oxide from sewerage systems, wastewater treatment facilities (WWTFs), and receiving waters must be monitored and minimized. Of recent concern is emerging contaminants such as pharmaceuticals and microplastics. The sludge from WWTFs can either be disposed of in landfills, in which case the impact of the sludge on surface and groundwater contamination must be monitored.

(iii) **Asset maintenance:** The equipment (pumps, pipelines, valves, sensors, controllers, filters, sedimentation tanks, and advanced reactors) used in the infrastructure for water supply and wastewater management need to be continuously monitored to assess their health and performance and take appropriate preventive maintenance strategies. With the advances made in sensing, communication, and control, it is possible to monitor these facilities and take prompt remedial action to prevent the breakdown of this equipment even centrally. The need for good record-keeping cannot be overemphasized. Also, it is imperative that the infrastructure be digitized and maintained up to date.

(iv) **Operational efficiency:** In water supply systems, 30–50% of the operating cost is on energy consumption. Similarly, in WWTFs, the cost of energy is 10–30% of the total annual operating costs. Advanced control strategies can be used to reduce energy consumption as well as the quantity of chemicals used. This requires several quality parameters to be monitored online using strategically placed sensors in the system.

24.7 NEED FOR NEW PLANNING TOOLS AND SOFTWARE

Several software packages are available for the design and simulation of WDNs, sewerage, and stormwater drainage systems. EPANET1 and WATERGEMS are public domain open-source and commercial software systems, respectively, for hydraulic simulation in WDNs. WATERGEMS can also be used for design. BRANCH is an optimization tool by the World Bank that attempts to minimize pipe costs for branched pipe networks with a single water source. Jaltantra is an open-source tool for designing branched rural water supply schemes developed by IIT Bombay. OpenFlows Sewer GEMS is commercial software for the design and operation of urban sanitary and combined sewer systems. The software can be used for optimal urban sewer planning. Software ++SYSTEMS of Tandler.com can also be used for this purpose. SWMM is public domain open-source software for the analysis of stormwater drainage management. It includes modules for analysing LID measures too.

SCADA systems (e.g., Aquis, Sedaru) used for monitoring and control typically do not include hydraulic models. Conventional and novel thermodynamic-based pump monitoring systems have been developed by Riventa. Sensus Analytics from Xylem can be used for meter management, billing, and leak detection. Several commercially available software offers real-time monitoring and operation packages for water network management.

There is a need to develop new tools for planning and operation utilizing state–of-art computational resources (hardware and open-source software). Presently available software tools do not model or account for network designs and operational practices in many countries in the Global South. For example, reservoirs in India are typically fill-and-draw type, which is not supported natively by standard tools. Further, in many countries in the Global South, water networks are operated intermittently even though this was not the design intent. Mathematical model-based optimal operation can be applied to obtain significant energy savings and improvements in supply (Kurian *et al.*, 2018). These are not available in standard software packages or management systems. Also, easy-to-use and computationally efficient software tools are not yet available for (i) integrated planning and design of all water infrastructure, (ii) adaptive planning, and (iii) planning of hybrid centralized–decentralized systems, as the research on these aspects is of recent origin.

24.8 SUMMARY

In this chapter, the focus of the discussion has been the planning of urban water infrastructure, a topic of paramount importance in contemporary urban planning. A comprehensive overview of the challenges that may arise during the planning process, as well as the necessity of context-based planning, have been carefully analysed. Critical factors and issues that must be considered during the planning stage have been thoroughly examined, highlighting the significance of integrated and flexible planning methodologies. The indispensable role of multi-functional infrastructure and decentralized systems in achieving efficient and sustainable water management has been discussed. The chapter concludes with an examination of the operational and maintenance issues that are fundamental to the successful implementation of any urban water infrastructure plan.

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