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WATER SYSTEMS IN THE GLOBAL SOUTH: TRANSITIONS TO SUSTAINABLE FUTURES

IIHS-GCEW WORKING PAPER SERIES

DOI: https://doi.org/10.24943/WSITGSTTSF11.2024

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TRANSITIONING URBAN WATER AND SANITATION SYSTEMS: KEY ELEMENTS FOR SUSTAINABLE CHANGE

IIHS WORKING PAPER

AUGUST 2024

Citations
Ragavan, K. V. S., Revi, A., Sudhakar, S., Vijendra, M., Vimala, P. P., & Wankhade, K., 2024,
Transitioning Urban Water and Sanitation Systems: Key Elements for Sustainable Change, Bangalore, India,
The Indian Institute for Human Settlements and the Global Commission for the Economics of Water.

Design & Layout: Nawaz Khan | Reviewed by Prachi Prabhu & Padma Venkataraman IIHS Communications & Design

ISBN: 9788198256829
DOI: https://doi.org/10.24943/9788198256829

First published in Bangalore, August 2024

This paper is part of a series of working papers commissioned by the Global Commission for the Economics of Water (GCEW).

TRANSITIONING URBAN WATER AND SANITATION SYSTEMS: KEY ELEMENTS FOR SUSTAINABLE CHANGE

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Abstract

Significant gaps and inequities in urban water and sanitation services persist, with a growing risk of exacerbation due to changes in the climate, global water cycle, and patterns of urbanisation. Urban water and sanitation systems need to transition to accelerate access to safe, equitable, and sustainable water and sanitation services, while enhancing resilience to respond to increasing risks. This paper reviews the persistent challenges in water and sanitation services, emerging risks from climate change, and imbalances in the global water cycle that threaten to impact urban water cycles, and potentially disrupt existing urban Water, Sanitation and Hygiene (WASH) systems. It identifies critical concerns in three areas: institutional arrangements (including informal service provisioning), technology and infrastructure, and financing (including operations and maintenance). The paper concludes by identifying critical elements required in these areas for successful transition of water and sanitation services and systems.

1. Introduction

Safe drinking water and sanitation is fundamental to human health and well-being. Although the global burden of disease due to enteric infections, often caused by contaminated food and water, reduced by 66 per cent between 1990 and 2021 (IHME, Global Burden of Disease 2024), unsafe water and sanitation continue to cause an estimated 1.4 million deaths annually (WHO, 2022a). Diarrheal diseases, including cholera, account for most of this burden and are spreading alarmingly due to climate change and conflict.

As urban areas expand, now encompassing 57 per cent of the global population (World Bank, 2018), 0.6 billion urban residents lack access to safe water, and 1.7 billion lack access to safe sanitation (UNICEF & WHO, 2023). Severe gaps persist in securing the full cycle of urban water and sanitation[1]. Although no region is on track to meet Sustainable Development Goal (SDG) 6 for universal access to drinking water and sanitation services, some areas, such as Latin America and the Caribbean, have regressed in terms of drinking water coverage (UNICEF & WHO, 2023).

WASH systems are “all the social, technical, institutional, environmental and financial factors, actors, motivations and interactions that influence WASH service delivery in a given context” (Huston & Moriarty, 2018). The economic implications of this are significant, with inadequate WASH systems leading to economic losses of approximately USD 260 billion annually in 136 low- and middle- income countries (UN-Water, 2021).

While cities continue to struggle with the classical challenges of inadequate access, unsafe, and unreliable services, their WASH systems must also adapt to the challenges posed by climate change, such as water scarcity (too little), floods (too much), disruptions due to extreme events and significant water quality risks (too dirty) risks, where blue water is contaminated by black and grey water (Grafton et al., 2023). Although water for domestic use (urban and rural) accounts for only a small percentage of total water use (approximately 10 per cent), securing this water in the context of changing climate is critical for human health.

Water and sanitation systems need to transition to address these emerging challenges while simultaneously expanding to meet the needs of those without access. In addition, urban WASH systems have the potential to reduce environmental impact by incorporating water-use efficiency, energy efficiency, and minimising environmental contamination (water, soil, and air) at each stage of the full cycle of water and sanitation.

The paper outlines the gaps in global progress towards SDG 6, highlighting key regional differences and data gaps in considering each component of the full cycle of urban water and sanitation. It synthesises the latest evidence from research and practice on the challenges underlying these persistent gaps in urban WASH and frames the analysis of these challenges by focusing on four key areas — institutions, technology and infrastructure, costs and funding, and behaviour change. The paper also explicates critical elements around each of these areas to offer key recommendations to achieve desired water and sanitation outcomes.

The paper is structured as follows: the interaction between the Global Water Cycle, the Urban Water Cycles and the Urban WASH systems (section 2), review of the current status of water and sanitation systems (section 3), impact of urban growth on urban WASH systems (section 4), analysis of the status and challenges in water and sanitation services (section 5), followed by a concluding section with recommendations to accelerate urban water and sanitation transition (section 6) .

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[1] The full cycle of urban water and sanitation includes extraction, storage, and treatment of water, which is then supplied to various users. After consumption, the resulting wastewater is collected, conveyed, treated and either disposed of or reused.

2. Interaction between the Global Water Cycle, Urban Water Cycle and Urban WASH Systems

The Global Water Cycle (GWC) is an intricate system encompassing oceans, atmospheric water, soil, and terrestrial water bodies. This cycle is sustained by the continuous exchange of water between these reservoirs through processes like evapotranspiration, precipitation, and runoff, collectively referred to as components of the water cycle. These fluxes are significant and play a crucial role in supporting life and human activities (Oki et al., 2004).

However, the GWC is being rapidly altered by the growing global population, increasing demand driven by economic prosperity and urbanisation, and mounting ecological stress exacerbated by climate change (Ligtvoet et al., 2018). Human-induced changes have altered the GWC across local to global scales, including 'changing the source of all freshwater, precipitation, and triggering extreme water events' (Douville et al., 2021; McGrane, 2016; Grafton et al., 2023). These changes have led to a global water crisis, often manifested as water scarcity (too little), floods (too much), and water pollution (too dirty), impacting millions of people and posing significant challenges to sustainable development from local to global scales (Güneralp et al., 2015; He et al., 2021; Pörtner et al., 2022; Grafton et al., 2023).

The GWC and climate change are intricately interlinked. IPCC assessments show that human-caused climate change has altered the global water cycle since the mid-20th century and will continue to reshape it on both global and regional scales (Pörtner et al., 2022). The impact of climate change on the water cycle is being observed through rising sea levels, precipitation variability, evapotranspiration, very dry and wet events including occurrences of floods, droughts, and extreme events (Pörtner et al., 2022). These climate-induced impacts will worsen with increase in global temperatures. Changes to the GWC, such as shift in precipitation patterns or changes in runoff, can directly affect the availability of water resources. This might lead to periods of water scarcity or abundance, influencing water management strategies and infrastructure planning.

In urban settings, though the principal structure of the water cycle remains the same, it becomes more complex due to the impacts of urbanisation on the environment, and the necessity of providing essential WASH services such as water supply, drainage, and wastewater management for urban residents, especially in dense settlements. This modified water cycle with added components such as WASH services is referred to as Urban Water Cycle (UWC) (Marsalek, 2006). One of the key features of the UWC is import of water from outside urban boundaries or catchments. UWC is part of the GWC and is impacted if there are changes in GWC. For example, changes in GWC will change the availability of water within the urban boundaries which leads to increased reliance on water import.

The UWC while inherently linked to the broader GWC, becomes increasingly vulnerable as climate-induced changes to the GWC intensify. As urban areas rely on external water sources and experience growing pressures from urbanisation, disruptions to the GWC, such as extreme weather events and shifting oceanic patterns, exacerbate water scarcity and infrastructure challenges. Consequently, urban WASH systems face heightened risks from extreme events such as floods and droughts. Increased frequency and intensity of rainfall, storm surges, can cause urban inundations, pose risks to human life and well-being, damage infrastructure, contaminate water sources, and disrupt essential services. However, due to the interplay between thermodynamic processes and atmospheric dynamics, predicting whether such events will increase in a specific location remains uncertain. Additionally, non-greenhouse gas factors—such as aerosols—may also play a significant role in affecting rainfall patterns, potentially masking or intensifying the impact of greenhouse gas emissions (Philip et al., 2019). Further, droughts can reduce water availability and place additional strain on aging infrastructure (Wang et al., 2022), droughts and depleted groundwater levels can increase water stress, impact food security, and cause natural contamination, including higher levels of fluoride, arsenic, solids, iron, nitrate in groundwater (Famiglietti, 2014; Gorelick & Zheng, 2015).

Sudden shifts in ocean circulation patterns, rapid glacial collapse in polar regions leading to rising sea levels, and the accelerated melting of snow and ice significantly impact the GCW. These disruptions can result in reduced snowmelt runoff and trigger rain-on-snow events, which further exacerbate flooding and water availability issues (Seibert et al., 2021; Lagerloef et al., 2010). As urban infrastructure is not always built to withstand extreme weather events, retrofitting and upgrading become essential to enhance resilience. This includes reinforcing drainage systems to cope with storm surges and adapting water storage infrastructure to maintain supply during droughts (Wang et al., 2022).

It is estimated that by 2050, environmentally critical streamflow will be affected in 42–79 per cent of the world's watersheds (Lee et al., 2021), resulting in decreased flows to urban reservoirs and threatening the sustenance of urban water services. In regions like South and Southeast Asia, nearly three-quarters of the urban land is at risk of high-frequency floods (Güneralp et al., 2015). Additionally, South Asia, South America, and mid-latitudinal Africa are projected have the largest urban areas exposed to floods and droughts (Güneralp et al., 2015), which disrupt water and power supplies and cause damage to WASH infrastructure.

In addition to GWC impacts, urban WASH systems are increasingly affected by other changes in the ecosystem. WASH is closely connected to five of the nine planetary boundaries (Rockström & Noone, 2009; Steffen et al., 2015), including the three that have already been transgressed: climate change, rate of biodiversity loss, and changes to the global nitrogen cycle (Carrard & Willetts, 2017).

Conversely, the UWC has a limited impact on GWC. Although urban WASH water demand has increased substantially in recent years, water for WASH accounts for only around 10 per cent of global water demand (Grafton et al., 2023), indicating that agricultural and industrial water use have a greater influence on the GWC. However, due to a lack of clarity on the exact end use of water, especially in industrial and urban areas, consumption by other sectors is often incorrectly attributed to the agricultural sector.

There are other ways in which UWC is impacting GWC. Globally, WASH water use intensity was around 400-450 km^3/ year in 2010 and is projected to reach 700-1,500 km^3/year by 2050 (Lee et al., 2021; McDonald et al., 2014; Wada & Bierkens, 2014). This suggests growing water stress, especially in urban areas, necessitating increased reliance from distant sources, major infrastructure investments and more efficient water management due to rising costs and energy consumption.

WASH water demand is met by extracting water from a mix of surface and groundwater systems. In addition to water scarcity, poor water quality drives extraction from distant sources. With 42 per cent of total global domestic wastewater being discharged into the environment untreated (UN-Water, 2023), the quality of blue water[2] is reduced (by converting blue to black and grey), thereby diminishing its availability for key end uses. Large cities (population >750,000, representing 33 per cent of global urban population) obtain 78 ± 3 per cent of their water from surface sources, some of which are located far away (McDonald et al., 2014). These cities transport 184 km^3 of water annually over a distance of 27,000 ± 3,800 km (McDonald et al., 2014) resulting in approximately 29.4 million tonnes of CO_2 emissions each year[3].

The scale of this extraction can increase surface evaporation due to the greater amount of water in direct contact with the atmosphere, affecting the GWC (Douville et al., 2021).

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[2] The water in the lakes, rivers and aquifers are referred to as blue water. Blue water occurs in two different forms: surface runoff in surface waterbodies and renewable groundwater runoff in the aquifers.

[3] Energy consumption for delivery of imported water is 4.7 kWh/ m^3 over 575 km and CO_2 emission 3.4 kg/m^3 (Yaron, 2022)

The implications of the interaction between GWC, UWC and WASH systems are:

1. Challenges such as water scarcity, flooding, and emerging contaminants are impacting the safety, sustainability, and resilience of urban WASH systems.
2. Urban WASH equipment, which typically have a life span of 15 to 20 years (Laakso et al., 2019) (with Sewage Treatment Plants lasting more than 50 years (NetSolWater, n.d.), is designed based on historical water availability and demand patterns. Since these are influenced by the GWC, the infrastructure may need to be retrofitted or expanded in response to changing conditions, requiring a reassessment of planning and design assumptions. This includes reservoir management, distribution systems, stormwater management, and wastewater treatment facilities.
3. There is a need to diversify water sources beyond traditional ones like rivers and groundwater. Such diversification needs different types of distribution and treatment systems, such as combination of decentral and central, or transitioning from one type of system to the other. To manage these transitions, institutions and governance structures have to evolve alongside other enablers such as technology.
4. Urban areas are where the challenges of changes in the GWC are complex and acutely felt, and the solutions developed in these settings have significant potential to be scaled up and applied in other contexts, across the urban-rural continuum including different settlement types and sizes, such as metropolitan cities to small and medium towns.

3. Current Status across Water and Sanitation Systems

The full cycle of urban water and sanitation includes the extraction, storage, and treatment of water, which is then supplied to various users; after consumption, the resulting wastewater is collected, conveyed, treated, and either disposed of or reused. Various components of this full cycle are tracked and monitored as part of SDG 6. However, there are gaps, with components such as water storage and wastewater reuse not being covered by the indicators.

Table 1: Stages of full cycle of water and sanitation and SDG 6 indicators

Stages of the full cycle of water and sanitation	SDG indicators
Water extraction	6.4.1 Change in water-use efficiency over time 6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources
Water storage	None
Water treatment	6.3.2 Proportion of bodies of water with good ambient water quality
Water distribution / access	6.1.1 Proportion of population using safely managed drinking water services
Wastewater containment	6.2.1 Proportion of population using safely managed sanitation services, including a hand-washing facility with soap and water
Wastewater collection and conveyance	6.3.1 Proportion of wastewater safely treated
Wastewater treatment	6.3.1 Proportion of wastewater safely treated
Wastewater disposal / reuse	None

Source: (UN-Water, 2017a)

Tracking SDG 6.1 and 6.2 Progress

As we move closer to 2030, glaring gaps in universal and equitable access to safe drinking water (SDG 6.1) and sanitation (SDG 6.2) persist. In 2022, 73 per cent of the global population and 81 per cent of urban population had access to safely managed drinking water services, yet 2.2 billion people remain underserved. On the sanitation front, 57 per cent of the global population and 65 per cent of urban population had access to safely managed services in 2022, leaving 3.5 billion people without safe services. Additionally, 75 per cent of the global population had access to basic handwashing facilities, but nearly 2 billion people still lacked this essential service for preventing disease transmission (UN-Water, 2023).

While significant progress has been made, there is a considerable variation in progress, and deep inequalities persist across regions, within regions, and within countries. For instance, in Sub-Saharan Africa (SSA) urban drinking water services coverage in 2022 ranged from 11 per cent in Central Africa Republic to 80 per cent in South Africa. In Eastern and South-Eastern Asia, the coverage in urban areas ranged from 27 per cent in Lao PDR to 100 per cent in China and Singapore (UNICEF & WHO, 2023). In Northern Africa and Western Asia, access to safely managed drinking water services also varies widely. Gulf countries such as Kuwait (100 per cent), Qatar (97 per cent), Bahrain (99 per cent), Israel (99 per cent), Tunisia (76 per cent) have high access rates due to substantial investments in desalination and water infrastructure. In contrast, countries like Iraq (60 per cent), Georgia (69 per cent) and Lebanon (48 per cent) have lower access rates. Yemen, facing conflict and water scarcity issues, has no data on safely managed services, and even basic services are only at 62 per cent (UNICEF & WHO, 2023).

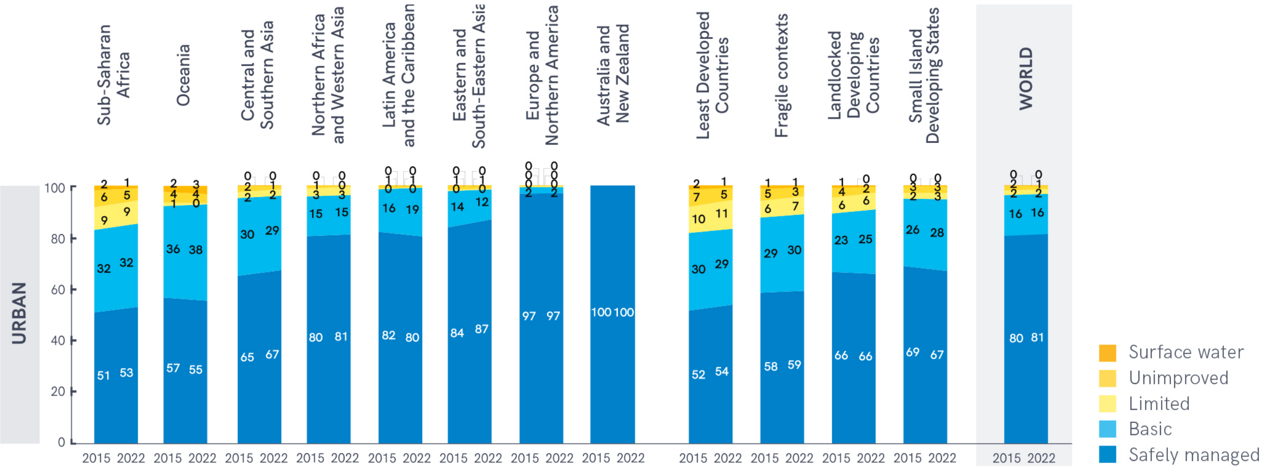
As with drinking water, intra-regional disparities in sanitation are stark across all regions. For instance, urban sanitation services coverage in Eastern and South-Eastern Asia ranges from 30 per cent in Thailand to 85 per cent in China and 100 per cent in Singapore in 2022. In Europe and North America, eastern European countries such as Serbia, urban coverage was only at 22 per cent in contrast to 100 per cent coverage in Switzerland, Austria, Andorra and Monaco (UNICEF & WHO, 2023).

Countries in Europe and Northern America generally have high levels of access to safely managed drinking water and sanitation services, given well-established infrastructure and regulatory frameworks. However, disparities still exist at more localised levels, affecting marginalised communities and areas with aging infrastructure. For example, while the Joint Monitoring Program (JMP) reported only a 0.01 per cent gap in 2019, Capone et al., (2020) identified that nearly 0.37 per cent of the urban population in the United States — about one million people — still lacked access to basic sanitation services based on regional survey data.

From 2015 to 2022, global access to safely managed drinking water services grew by four per cent (urban by one percent), while access to safely managed sanitation and hygiene grew by seven per cent (urban by five percent) (UNICEF & WHO, 2023).

Progress in urban coverage of safely managed drinking water services varied across the regions. While it marginally increased in Eastern and South-Eastern Asia, Central and Southern Asia and SSA, there was a slight decline in Oceania and Latin American and the Caribbean (UNICEF & WHO, 2023).

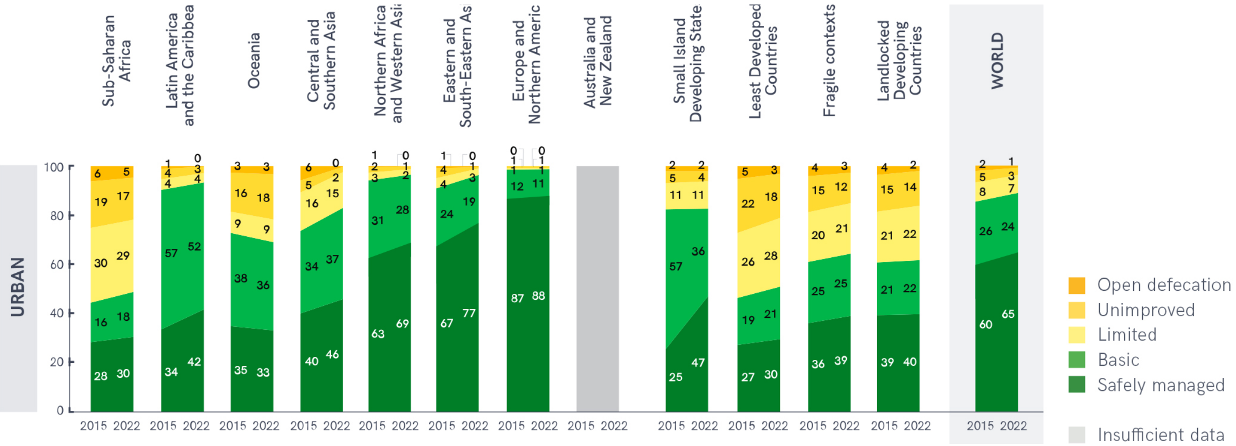
Figure 1: Urban Drinking Water Coverage, by service level and SDG region, in 2015 and 2022 (%)



Source: (UNICEF & WHO, 2023)

In terms of safely managed sanitation services, most regions saw an increase except for Oceania. The Eastern and South-Eastern Asia experienced the highest urban coverage increase from 67 to 77 per cent followed by Latin America and the Caribbean, where urban coverage grew from 34 to 42 per cent (UNICEF & WHO, 2023).

Figure 2: Urban Sanitation Coverage, by service level and SDG region, in 2015 and 2022 (%)



Source: (UNICEF & WHO, 2023)

Beyond these regional statistics, significant disparities in WASH access exist between urban and rural populations. In 2022, urban coverage of safely managed drinking water services was at 81 per cent compared to 63 per cent in rural areas. For safely managed sanitation services, urban coverage was at 65 per cent, while rural areas were at 46 per cent.

However, between 2015 and 2022, rural areas saw substantial improvements, largely attributable to their initial low coverage levels. Access to safely managed drinking water increased from 56 to 63 per cent compared to the 80 to 81 per cent in urban areas. Rural coverage for safely managed sanitation also grew from 36 to 46 per cent, with urban coverage increasing from 60 to 65 per cent (UNICEF & WHO, 2023).

Table 2: Population provided with safely managed drinking water and sanitation services in 2022

Country groups	No. of countries (As per WHO classification)	Safely managed drinking water services		Safely managed sanitation services	
		2015 (%)	2022 (%)	2015 (%)	2022 (%)
Low-income countries	26	24	29	28	35
Lower-middle income countries	51	56	62	61	74
Upper-middle income	54	83	86	86	94
High-income countries	86	95	94	99	>99

Source: UNICEF & WHO, 2023

There are notable differences between the rich and poor within countries as well (see Table 2). Existing data likely conceals larger and more significant inequalities with countries, especially when disaggregated by household income and gender (UNICEF & WHO, 2023). There is also limited focus on equity and inclusion, particularly concerning disparities within communities, marginalised groups, and on climate change and disaster risk resilience.

In five countries—Congo, Fiji, Georgia, Honduras, and Togo—the disparity between the richest and poorest quintiles exceeded 50 percentage points (UNICEF & WHO, 2023). Data also highlight that women and girls bear the primary responsibility for water collection in 80 per cent of households without access to water on premises (UNICEF & WHO, 2023; WHO, 2022b). The growing income gap and the uneven impact of environmental changes on regions and countries will likely perpetuate severe inequalities in access to water and sanitation (Sachs et al., 2023).

At the current pace of progress, achieving the 100 per cent target by 2030 seems unlikely. Projections indicate that billions will remain without access to these essential services by the end of the decade.

Table 3: Existing gap and required progress by SDG target

SDG 6	Coverage by 2030 (per cent)	People without services by 2030	Required increase in progress	Rate increase in LDCs and fragile contexts*
Safely managed drinking water	77	2 billion	Sixfold	14x and 19x
Safely managed sanitation	65	3 billion	Fivefold	16x and 15x
Basic hygiene services	84	1.4 billion	Tripling	27x and 18x
*LDC - Least developed Countries (UN classification) Fragile context - Countries with high levels of institutional and social fragility, violent conflict (World Bank Classification)				

Source: (UN-Water, 2023)

The estimated gap (see Table 3) highlights a stark reality. It is likely that the gaps are even higher, considering the challenges related to the definitions and monitoring of the SDGs (UN-Water, 2023). For example, a recent study of safely managed drinking water services in 135 low- and middle-income countries estimated a gap of 4.4 billion, more than double the JMP estimate in 2020 (Greenwood et al., 2024). This is largely attributed to methodology used by the study which involved geospatial mapping and household surveys (Hope, 2024).

Current data on SDG 6 targets often emphasise implementation efforts rather than the actual impact on people's lives, such as improvements to health and well-being, making it difficult to assess true progress (Stoler et al., 2023; van Puijenbroek et al., 2023). Indicators tend to focus only on microbial impacts and historical definitions of disease burden and public health challenges (Stoler et al., 2023). Discrepancies in definitions and interpretations of national and global indicators, as well as differences in methodologies for calculating and reporting data, undermine the accuracy of these estimated gaps.

Progress across the Full Cycle of WASH

The SDG WASH dataset has limited national and policy salience as it is global and has not been fully standardised. For instance, while global access to piped drinking water has increased, this does not necessarily equate to access to safely managed drinking water[4] as issues such as inadequate quantity, and intermittent supply persist (UNICEF & WHO, 2023).

From 2015 to 2022, access to safely managed drinking water has increased by four per cent, whereas access to piped water has grown by only two per cent. This highlights the significant reliance in some regions on alternative modes of supply / improved sources such as water ATMs/kiosks, borewells, packaged water etc (Garrick et al., 2019; Plappally & Lienhard V, 2013).

Data also indicate that on-site sanitation is more common than sewer connections across all regions except Europe and Northern America. Globally, in 2022, a larger share of the population used on-site sanitation facilities (46 per cent) compared to those with sewer connections (42 per cent) (UNICEF & WHO, 2023).

However, within the safely managed sanitation category, a larger share of households had sewer connections (33 per cent) as opposed to on-site systems (24 per cent), indicating significant gaps in the sanitation chain for most households with on-site systems, leading to only limited and basic access to sanitation (UNICEF & WHO, 2023). ince the 2000s, the percentage of the population with sewer connections has been rising at an average rate of 0.41 per cent per year. However, the growth of on-site sanitation systems has been even more rapid. Specifically, septic tanks have increased by 0.54 per cent per year, and improved latrines by 0.25 per cent per year. In urban areas, the share of the population with sewer connections has remained relatively stable, going from 62 per cent in 2000 to 63 per cent in 2022. In contrast, the proportion of urban residents using septic tanks rose from 15 to 22 per cent during the same period. The rise in OSS is driven by rapid urban growth outpacing sewer expansion, and its affordability and ease of implementation to meet the immediate needs of newly urbanised areas. The increase in numbers could also be due to improved data coverage and reporting in low- and middle-income countries (UNICEF & WHO, 2023)

The disparity between the coverage of containment and / or conveyance systems (OSS or sewer connections) and treatment infrastructure highlights a critical challenge in advancing towards safely managed sanitation. In 2022, 58 per cent of global household wastewater was safely treated, a modest increase from 56 per cent in 2020, with treatment rates ranging dramatically across regions, from 24 per cent in Central and Southern Asia to 86 per cent in Europe and North America (UN-Water, 2023).

While 97 per cent of wastewater is safely managed in high-income countries such as the Netherlands, only one-third of wastewater receives adequate treatment in Puerto Rico. This disparity is evident in upper-middle-income countries like Brazil (71 per cent coverage and 39 per cent treated) and Armenia (72 per cent coverage

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[4] To monitor progress by countries towards achieving this target, the Joint Monitoring Programme (JMP) has classified drinking water sources and sanitation facilities into unimproved or improved types and factored in service levels to further categorise them into 'safely managed', 'limited or 'basic. Beyond households, WASH infrastructure encompasses facilities serving schools and healthcare facilities (UNICEF & WHO, 2023).

and less than 1 per cent treated) (UNICEF & WHO, 2020, 2023). These discrepancies underscore the urgent need for improved wastewater management, enhanced monitoring, better sludge removal services, and increased investment in treatment infrastructure to meet SDG target 6.3, which aims to halve the proportion of untreated wastewater by 2030 (UN-Water, 2023; UNICEF & WHO, 2023).

Box 1: Data Limitations

Ensuring that data on WASH progress accurately reflect ground realities is challenging, particularly when global systems do not collect data at a disaggregated level (UN-Water, 2023; UNICEF & WHO, 2023). Issues like data availability, contextual relevance, and transparency further hinder accurate monitoring and informed decision-making.

For example, although SDG 6.1.1 covers water quality and data is collected accordingly, the comprehensiveness and consistency of data reported can vary depending on the country and monitoring systems in place. Since 2017, low and lower-middle-income countries (LMICs) have made significant progress in expanding the availability of data for safely managed sanitation and drinking water, largely due to the integration of water quality testing and on-site sanitation management indicators into household surveys. This has resulted in a notable increase in both rural and urban estimates. Conversely, despite over 50 high-income countries having comprehensive estimates on water quality, fewer than 25 of these provide detailed data for safely managed drinking water across both rural and urban areas (UN-Water, 2023).

Additionally, data on WASH services is often incomplete or lacking in certain regions and for specific populations. The GLAAS 2021/2022 country survey, which covers 121 countries and territories, represents only 66 per cent of the world’s population. This includes 94 per cent of the population in SSA and 86 per cent in least developed countries. Data coverage for global WASH indicators varies widely between SDG regions, with significant gaps remaining, particularly regarding components of the full cycle of safely managed water and sanitation services.

4. Impact of Urban Growth on WASH Systems and Services

Increasing urbanisation is aggravating challenges for water and sanitation services in both developed and developing countries. The nature of urbanisation and its scale makes the progress on achieving SDG 6 even more challenging.

Currently, 57 per cent of the global population lives in urban areas, which is expected to increase to 68 per cent by 2050 (World Bank, 2018). From 1950 to 2018, the urban population surged from 0.8 billion to an estimated 4.2 billion, representing 55 per cent of the total global population (UN Department of Economic and Social Affairs, 2019) . This growth is attributed to four main factors: natural population increase, rural to urban migration, reclassification of rural towns into urban areas, and the expansion of urban cities by merging of neighbouring urban and rural areas (UN Department of Economic and Social Affairs, 2019).

According to the United Nations’, World Urbanization Prospects (2018), Northern America (82 per cent), Latin America and the Caribbean (81 per cent), Europe (74 per cent), and Oceania (68 per cent) are the most urbanised regions. Asia follows with 50 per cent urbanisation, and Africa at 43 per cent, with the latter expected to urbanise more rapidly in the future (UN Department of Economic and Social Affairs, 2019).

It is important to note that the UN defines urban areas based on various country-specific criteria such as population thresholds, density, infrastructure, employment patterns, and city size, leading to complexities in measurement of urban areas. The highly heterogeneous nature of urban forms globally, influenced by varying geographic and socio-economic factors, adds to this complexity (Dempsey et al., 2008; Pickett et al., 2017). These complexities, along with the presence of 'rural' areas exhibiting urban characteristics can result in underestimations of urbanisation (Ritchie et al., 2024). Hence, the above numbers are likely to be an underestimation.

The challenges to WASH services due to urbanisation span across water quality and quantity, wastewater management, and overall service delivery (Kookana et al., 2020). Even without the assumed underestimation, it is evident that urban growth is outpacing cities' ability to provide adequate services and adding to the existing deficits. For example, between 2015 and 2020, SSA and Southern Asia experienced the highest urban population growth rates (4 per cent and 2.4 per cent, respectively). At current rates of urbanisation, 90 per cent of urban growth will occur in the Global South by 2050, particularly increasing the prevalence of slums in Africa and Asia (Knudsen et al., 2020). These regions are among those with the largest gaps in access to safely managed drinking water and sanitation services. For instance, the WASH access gap in India's urban slums is likely to expand, as slum populations continue to grow at 6 to 8 per cent annually, outpacing overall urban growth rate of 2 to 3 per cent per year (Swami, 2017).

While the global population living in slums decreased by four per cent between 2000 and 2018, one in four urban residents live in informal settlements as of 2020 (Knudsen et al., 2020), where the number of people lacking basic services, especially water and sanitation, continues to rise (Birch et al., 2012; Cohen, 2006). Urban poor communities lack resilient WASH systems and are highly susceptible to environmental shocks, as they are often located in vulnerable areas easily exposed to hazards like floods, fires, and landslides (UN-Water, n.d.). The irregular layouts, remote locations, limited space, and high population density of these informal settlements make expanding WASH systems challenging and expensive. These areas often lack secure land tenure, restricting governments from servicing them (Senn & Spuhler, 2014). Studies of LMICs highlighted that the uncertain land tenure, unclear legal claims, slum rehabilitation, and upgradation initiatives often impact slum dwellers' security and willingness to invest in WASH facilities and adopt toilets (Abdulhadi et al, 2024).

Additionally, high poverty rates mean residents often cannot afford improved services (Senn & Spuhler, 2014). For example, in India, about 70 per cent of those benefiting from subsidies channelled to private water connections are not poor, while 40 per cent of poor people do not receive subsidies because they do not use any public water services (WSP, 2011).

Inadequacies and inefficiencies in infrastructure and service delivery are exacerbated by rising demand and dependence on a mix of options including private informal sector and self-supply. This often leads to coping mechanisms like informal water tankers, bottled water / sachets, water carts, ATMs, open dumping of wastewater, and pit emptying services.

Apart from the growing urban population, the specific nature of urban growth also has implications on urban WASH systems. Specific factors that can impact UWC and WASH services are increases in land areas, densities, migration, and rural-urban shifts. For example, in the Goonja draining basin (Seoul) between 1975 and 2005, the shift from natural to urban landscapes (impervious ratio increased from 43 to 84 per cent) led to decreased evapotranspiration (29 per cent), increased surface runoff (41 per cent), and significantly reduced groundwater recharge (74 per cent) (Lee et al., 2010).

Even though urban land area accounts for less than one per cent of total land area, it is rapidly expanding, with low- and middle-income countries expected to drive most of this growth (UN Department of Economic and Social Affairs, 2019). From 1975 to 2020, urban land area expanded from 0.2 per cent to 0.5 per cent of the total land area and is projected to reach 0.7 per cent by 2070. Cities are expanding in land area at twice the rate of their population growth, potentially tripling global urban land area between 2000 and 2030 (Khor et al., 2022). Most of this expansion is likely to take the form of urban sprawl, significantly affecting the urban poor. This growth is expected in low-income countries, where urban land area could increase by 141 per cent compared to 44 per cent in lower-middle-income countries and 34 per cent in high-income countries, based on 2020 (Khor et al., 2022).

Without proper design, urban expansions increase impermeable areas and reduce vegetation cover. This in turn impacts water cycles through increased surface runoff, and reduced groundwater recharge. Such land use and land cover changes also lead to higher risk of flooding, altered evaporation, and degradation in water quality and ecosystems. Most urban low-income settlements are at greater risk of exposure to these hazards, as they are often located in low-lying areas or close to canals, waterways, and drains, and typically lack adequate infrastructure.

Urban settlements are also becoming denser, with varying expansion and densities across regions. Specifically, densities in low-income countries on an average have increased from 7,000 to 11,000 inhabitants per sq. km between 1975 and 2015. However, in regions like North America and Europe, where densities are lower, land area has grown much faster than the population, leading to increased energy consumption, greenhouse gas emissions, climate change, environmental degradation, and higher cost of providing infrastructure (Khor et al., 2022; Knudsen et al., 2020). Urban water and sanitation infrastructure is typically designed based on specific population densities and projected growth over its lifespan. Higher densities can lead to efficiencies, such as lower per capita energy consumption for pumping. However, if densities exceed design limits rapidly, it can result in disruptions and overflows, with substantial costs for infrastructure replacement. Conversely, when densities fall below design capacity, the required flows may be insufficient, potentially affecting system performance.

Migrant settlements in urban areas differ from older, more incremental informal settlements. The nature of work for rural-urban migrants, such as gig-economy jobs, influences their settlement location, hazard exposure, and access to services. These settlements are often temporary, crowded, and located near workplaces due to the short and seasonal nature of work. As a result, access to safe water and sanitation is inadequate, with overcrowded facilities and poor-quality infrastructure.

In addition, when rural areas are reclassified as urban, changes in land use, such as agriculture to residential and commercial, happen over a short period, which can significantly affect water quality and availability. Different institutional arrangements for rural and urban WASH services and the lack of capacity within public service providers further hinder their ability to respond to the changing nature of demand for WASH services.

In the coming decades, as urbanisation accelerates and climate change-induced shifts in precipitation patterns and damages to aquatic ecosystems intensify, the demand for resilient WASH services will become imperative, necessitating greater investment merely to sustain existing service standards (Juuti et al., 2012; Sedlak, 2019). Although economic growth is expected to improve access to basic services, overcrowding, poor urban planning, and weak institutions are likely to worsen disparities in access to basic WASH services within urban areas, especially in informal settlements (UNICEF, 2019).

5. Analysis of Status and Challenges in Water and Sanitation

The status of urban water and sanitation services worldwide point to several underlying complex challenges that must be addressed to achieve universal access. Despite the recognition that WASH has received, the current situation and trends in urban water and sanitation services suggest by 2030, billions of urban residents will still lack access to safe water and sanitation services (UN-Water, 2023). Evidence indicates that 25 per cent of water points fail within four years, and there are frequent reports of people reverting to open defecation practices, underlining that one-time investments are not sufficient, but require sustained O&M (Banks & Furey, 2016). This underscores the critical need for sustainability to prevent regression and achieve environmental goals. Additionally, since the urban poor make up a significant portion of those without access, ensuring equity and inclusion in water and sanitation services is essential.

While there is much discussion around the need for increased capital investments, the challenges in urban sanitation and water go beyond mere infrastructure investment. They include institutional barriers, financial constraints, maintenance and capacity issues, behavioural factors, inclusion gaps, and poor data and measurement. Even while most of these well-recognised challenges persist, there are new, or emerging issues that have gained attention recently. These include the inadequate focus on green infrastructure and its links to services, as well as new threats such as novel contaminants, antimicrobial resistance, and climate change.

The different areas of action are synergistic, with improvement in one often leading to improvement in other areas. For instance, strengthening of institutions through capacity and competency improvements has led to better service delivery and cost recovery (Biswas et al., 2021; Goksu et al., 2019).

This review identifies five critical action areas—institutions, technology, infrastructure, funding and behaviour change. While there are other areas, improvements in these five areas can have cascading impacts of other areas such as on data and measurement, and monitoring and evaluation.

Prioritising these specific areas helps build a broad yet systematic approach to transitioning urban water and sanitation, addressing immediate needs, and achieving long-term environmental and public health outcomes. Below, we discuss these five key areas for our analysis in greater detail.

5.1 Evolving Understanding of Institutional Arrangements and Drivers

The urban WASH system consists of a wide range of institutions and actors who play various roles—such as policy formulation, regulation, infrastructure design and implementation, service delivery, and monitoring—across different scales (city, regional/ provincial, national, and global). The UNICEF global framework classifies these institutions into government and parastatal agencies, private sector organisations, global actors, and national/ international technical specialists (UNICEF, 2019).

At the global level, financial institutions, bilateral development agencies, foundations, and the UN play crucial roles in influencing national development programmes where public investments are weak. There are also international research institutions and NGOs involved in developing solutions and knowledge dissemination (Mumssen et al., 2018; UNICEF, 2019).

National government and parastatal agencies include ministries responsible for water and sanitation policy and legal frameworks, regulatory bodies overseeing standards, monitoring, and enforcement, and government departments at various levels involved in planning and service delivery. Urban local bodies, public utilities or parastatal agencies, which may be publicly owned or structured as public-private partnerships (PPPs), often deliver services at the sub-national and local level (UNICEF, 2019). Various types of private institutions are also involved in service provisioning, with different cities adopting different formal and informal arrangements (Beard & Mitlin, 2021). The private sector's role extends to infrastructure development, technological innovation, and providing financial investment and expertise to scale up interventions across the full cycle of water and sanitation.

Private sector participation in water and sanitation services has been brought in through corporatisation of public entities and / or through direct involvement (with market competition), with the aim of enabling competition to improve efficiency and increase financial investments (Mumssen et al., 2018; OECD, 2009). Types of private organisations involved range from formal large corporations and multinational companies that operate across the full cycle of water and sanitation to informal small-scale enterprises such as water tankers, packaged water vendors, and de-sludging operators that make up for deficiencies in public services (Howard, 2005; OECD, 2009).

The formal companies engaged in both infrastructure creation and service delivery across both water and sanitation have taken the form of public-private partnerships or privatisation of parts of the service chain which involves the creation and transfer of assets or operations. The participation of private sector is characterised by some level of risk sharing between the public sector and private entities that is defined through a wide range of contractual arrangements. Examples of which include service contracts, leases, several variations of build-own-operate-transfer (BOOT) agreements, joint ventures, water co-operatives or public limited companies (OECD, 2009).

The objectives of these arrangements are to deliver better outputs in terms of increased coverage and service levels along with better financial management such as billing and cost recovery. They have also sought to catalyse more private funding and investment in the sector. While the role of private sector involvement has diversified significantly over the years (OECD, 2009), the results of their efforts have been inconclusive, with some studies showing no or limited efficiency improvements and low private investment levels relative to public expenditure (Marin, 2009; Mumssen et al., 2018).

However, the existing configuration of public and private institutions has struggled to deliver safe, equitable and sustainable urban water and sanitation services. The persistent lack of progress in this area, compounded by external drivers such as water scarcity and environmental changes, has highlighted shortcomings in formal institutional setups, often more so than in other areas of technology and financing (Barbier, 2022; Herrera, 2019).

Weak institutional arrangements (such as where there are gaps and overlaps in responsibilities, non-alignment of financial and administrative authority, poor planning, coordination and decision-making, and lack of accountability) and their suboptimal functioning are leading to inefficiencies and inadequacies in service delivery, eroding public trust in urban water and sanitation systems (Mumssen et al., 2018).

Water and sanitation systems are inherently complex, extending beyond municipal, regional, and national boundaries (Edelenbos & Teisman, 2011). This complexity is further compounded by the involvement of numerous institutions with differing, and sometimes conflicting interests—such as prioritising water quality over water provisioning. The division of responsibilities among various institutions overseeing policy, regulation, financing, and service delivery often results in a misalignment between policies framed at the national level and programmes, which are typically implemented by local and sub-national authorities (Herrera, 2019). Additionally, there is also lack of horizontal alignment of cross-organisational agendas due to entrenched departmental cultures (Edelenbos & Teisman, 2011). Siloed decision-making that neglects interdependencies, has led to inefficient and ineffective resource use (World Bank, 2020).

Institutional reliance on expert-led and top-down decision-making approaches often results in superficial engagement with local communities and stakeholders. This approach fails to leverage tacit knowledge and overlooks important socioeconomic, cultural and environmental values, leading to weak community ownership and poor sustainability of outcomes. While decentralisation of institutions is often promoted for its emphasis on bottom-up decision-making and greater community participation, it does not necessarily make a case for decentralisation in all contexts. Even when decentralisation is pursued, partial efforts that devolve administrative responsibilities without granting adequate fiscal authority limit the resources available to local institutions (Bernal et al., 2021; Herrera, 2019; Tsinda et al., 2021). Such incomplete decentralisation has hindered community buy-in and engagement in decision-making, which are essential to achieving equity and sustainability outcomes.

Inadequate resources, specifically in terms of human capacity and competency (such as the ability to challenge power bases, detect irregularities, and enforce regulations) have also often created environments conducive to corruption and other abuses of power, such as cronyism, and low tariffs in exchange for votes (Camancho, 2021; Soppe et al., 2018). Institutional capture by vested interests and perverse incentives, along with weak accountability systems, have led to the neglect of certain communities' needs (Herrera & Post, 2014; Soppe et al., 2018).

Additionally, the current institutional structures have been slow to adapt to rapidly changing conditions such as water availability and urban growth (Barbier, 2022). This sluggishness is partly due to the 'path dependency' of these institutions, established during periods of relative water abundance when innovative approaches to meet increasing demands were not necessary (Barbier, 2022).

The inability of formal institutions to deliver adequate water and sanitation infrastructure and services to all has given rise to thriving informal service providers (Evaristo et al., 2023; Garrick et al., 2019; Herrera, 2019; Zozmann et al., 2022). This review did not find a comprehensive study that quantifies the global size of informal water and sanitation services. However, evidence from several regions suggest an estimated 25 to 70 per cent of urban population worldwide could be relying on informal service providers for water and sanitation (Arias-Granada et al., 2018; Asian Development Bank, 2023; Garrick et al., 2019). Estimating the size of informal markets is challenging without a mandate for national and international monitoring systems to standardise definitions of informal services and collect data.

5.2 The Formal to Informal Continuum of Service Providers

In many LMICs, service provisioning often exists on a spectrum between formal or informal arrangements, rather than being distinctly one or the other. These arrangements can sometimes complement formal services or, in other cases, conflict with them (Garrick et al., 2019; USAID URBAN WASH, 2023). Informal providers may fill gaps across the full cycle of water and sanitation services, offering alternatives to non-existent or unreliable formal services, or act as competitors by reducing the customer base for formal systems.

Increasingly, informal service providers are recognised as critical to achieving universal access, especially in informal settlements. For example, in the Philippines, Manila Water partnered with water cooperatives to expand coverage to low-income settlements. While the utility provided infrastructure to the edge of these settlements, private service providers extended the network within the settlements and oversaw service provision. Manila Water managers trained local providers to read bulk meters and restricted them from charging more than 20 per cent of the bill amount (Asian Development Bank, 2023; Agarwal et al., 2023). In Burkina Faso, the National Office of Water and Sanitation (ONEA) extended pipelines to the edge of informal settlements and delegated construction within these areas to private informal providers, who were already operating there. This approach resulted in rapid coverage expansion and revenue growth for ONEA (Goksu et al., 2019).

Along with the total lack of formal services, inadequacy in the form of poor quality or unreliability of formal services also drives demand towards informal providers. In some cases, public utilities cannot keep pace with the rapid growth of urban areas and the high capital investment requirements, leading to co-opting of informal service providers to meet requirements in informal areas (Garrick et al, 2020; USAID URBAN WASH 2023). For example, in India, about 75 per cent of municipal tap water users receive less than the national benchmark of 135 litres per capita per day (lpcd) (Safe Water Network, 2016). The urban poor are the most severely affected, with residents in affluent neighbourhoods of large cities consuming up to 10 times more water than those in poorer areas (Babu, 2021; Times News Network, 2017). In slums, daily water supply is often insufficient, with many households using less than the World Health Organisation's recommended minimum of 50 lpcd (Safe Water Network, 2016). Additionally, water contamination levels are high, both in the water provided and in stored supplies (Safe Water Network, 2016).

Informal markets are characterised by a proliferation of small and medium-sized private providers, primarily serving informal settlements but not limited to them (Garrick et al., 2019). These markets often develop locally, with enterprises set up by residents from the areas they serve (Arias Granada et al., 2018). These enterprises offering water and sanitation products and services are highly diverse, with flexible and dynamic business models that allow them to adapt to changing contexts (Gero et al., 2014).

However, there is a persistent notion that informal service providers tend to exploit the poor, exacerbating inequality and vulnerability. While serving the poor is not necessarily a priority for these providers—due to limited economies of scale to offset the low fees poorer households can afford—there is evidence that some informal providers offer flexible pricing to enable poor households to enter the market. Yet, this remains a challenge in most contexts (Gero et al., 2014). The relatively higher prices charged by informal providers are often due to higher upfront, unsubsidised supply chain costs and the inability of households to store large quantities of water, rather than the market power of the service providers (Garrick et al., 2019; Zozmann et al., 2022).

Despite the growing importance of informal markets in expanding coverage, there is a lack of conclusive evidence on the actual quality and affordability of the services provided (Garrick et al., 2019; Zozmann et al., 2022). While consumers may perceive informal water sources to be better and are willing to pay a premium, evidence does not support this perception (Post & Ray, 2020). Certain modes of informal services may inherently lack the capacity to advance affordability and equity goals (Mitlin & Walnycki, 2020; Zozmann et al., 2022). In addition, the viability of informal markets is because of their illegality stemming from an absence of institutional capacity, which also makes it difficult to regulate these services (Garrick et al., 2019).

Yet, given the chronic delays in expanding formal services, and the urgent need to address service gaps particularly for the urban poor, it is essential to harness the burgeoning role of service providers through effective regulation and financial support as well as social protection and safety measures. Diverse modes of service delivery along with diverse technologies and infrastructure, offers cities several options to ramp up safe and resilient universal coverage.

5.3 Diversity of Technologies and Infrastructure and their Application

Infrastructure and technology[5] have played a key role in enabling and improving service provision and enhancing WASH outcomes. In LMICs like India, challenges in WASH are often attributed primarily to poor governance and socio-cultural issues rather than technologies (Government of India, 2012; Kumar, 2014).

SDG 6 explicitly highlights the role of technology and infrastructure in accelerating coverage, increasing the efficiency of WASH systems, and securing water sources. The role of technology spans across different stages[6]

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[5] Technology in this note refers to technologies for WASH infrastructure (membrane technology in treatment infrastructure), measurement (sensing), monitoring and control (IT-IOT)

[6] In this paper, stages or basic process of WASH systems refer to water extraction, water treatment, water distribution, wastewater collection and conveyance, and wastewater treatment and reuse/disposal; these are common for various types of technologies and infrastructure; in certain types of technologies and infrastructure all stages are integrated in a single system such as septic tank-soak away or renewable energy-driven water extraction-treatment units

of WASH systems, characterised by a complex landscape shaped by operational efficiencies, environmental impacts, and economic and social considerations (Soares et al., 2017; Obaideen et al., 2022).

While broadly technology and infrastructure can be classified as centralised and decentralised, there are continued debates (see Box 2) about which form is better. The choice between these models depends on factors such as land availability, population density, local governance capabilities, skills levels, and financial resources (Andersson et al., 2016; Bernal et al., 2021; Chirisa et al., 2017; Lawrencia et al., 2023).

Box 2: Centralised or decentralised systems

The debate over which system is most appropriate continues to garner attention, and that largely depends on specific circumstances (Mitra et al., 2022). For example, centralised systems are often best suited for densely populated urban areas where large volumes of wastewater can be managed effectively at lower costs. Conversely, decentralised systems are more suited for regions where such scalability is unnecessary or unfeasible (Bernal et al., 2021). Each system plays a pivotal role in the broader strategy of water and sanitation services, complementing the other by catering to different geographical and socio-economic contexts (Andersson et al., 2016; Chirisa et al., 2017; Gikas & Tchobanoglous, 2009; Lawrencia et al., 2023; Silva, 2023). Given the pace and nature of urban growth, transitioning from one system to the another must consider various factors, including the strengths and weakness of the existing systems (TNUSSP, 2018).

Despite differences, certain conditions, features and challenges are common across various technologies and stages of WASH systems.

Failures in WASH systems are often attributed to inadequate management or neglect of O&M by responsible agencies, particularly in decentralised systems (DFID, 1998; Müllegger et al., 2011). For example, in SSA, approximately one third of a million handpumps are non-functional at any given time due to poor maintenance (Andres et al., 2018). In addition, aging infrastructure is a widespread issue across all stages and different types of WASH systems (UN Water, 2017).

Measurement and monitoring are also often given low priority. The pace of technological innovation is much faster than the time needed to understand its impacts fully (Andres et al., 2018). Without adequate feedback on the impact of the technologies, decisions are made on uncertain grounds, potentially leading to adoption and scaling of inappropriate technologies and path dependence of these technologies. The effects of climate on water cycles and the emergence of new contaminants are not yet fully understood, resulting in multiple approaches to improve WASH systems (Sedlak, 2014). Addressing these challenges requires ongoing research and adaptive strategies to ensure that technologies remain effective in changing conditions.

The next sub-sections offer an analysis of existing technologies and infrastructures across the different stages of WASH systems—water extraction, water treatment, water distribution, wastewater collection and conveyance, and wastewater treatment—to highlight the adequacy and challenges.

Water Extraction

Water extraction is a crucial component of both centralised and decentralised WASH systems. Traditional water systems have long utilised diverse sources like open wells, surface water, and rainwater, tailored to local contexts with small-scale storage solutions. Innovations in drilling, plumbing, and pumping techniques brought efficiencies and access to larger sources, fundamentally changing how growing settlements sourced water. However, traditional methods continue to exist, especially in rural areas of India, Bangladesh, and China, and are even making a comeback in urban areas (Martínez-Santos et al., 2020).

Today, most large[7] cities globally rely primarily on surface water from single, large sources (McDonald et al., 2014) due to depleting groundwater and reduced availability of other local sources. Cities are increasingly focusing on rainwater harvesting for direct use and to replenish their groundwater sources. The costs of water supply through rainwater harvesting can vary significantly from USD 0.63 to USD 1.75 per cubic metre depending on the project's size (Cooley et al., 2019). Though rainwater has the potential to serve as a regular or supplementary water supply source for about 6 per cent of the global population, its potential has not been realised, mainly because storage is considered expensive (UN Department of Economic and Social Affairs, n.d.). Storage can take many forms—such as tanks (made of concrete and polymers), reservoirs, or managed aquifer recharge—and plays a critical role in ensuring that collected water is available when needed (García-Avila et al., 2023). Harvested rainwater is typically stored in tanks for non-potable uses, such as gardening or cleaning. However, at larger scales, adequate treatment infrastructure is essential to ensure that stored water can be safely used for potable purposes (García-Avila et al., 2023; Gao et al 2024). Water retention and recharge methods through infiltration pits, ponds, or aquifers provides a sustainable way to enhance water availability (Huang et al 2021). Developing cost-effective storage options and promoting their adoption will help make rainwater a more viable water supply source.

Water extraction is highly dependent on energy. Groundwater pumping is more energy- intensive than surface water pumping, except when water is imported from long distances. When designing or improving a water extraction and distribution system, it's essential to consider the overall WASH system rather than focusing only on extraction and distribution. For example, in Australia, a cost comparison of water transmission methods showed that obtaining water through local desalination was more economical than transporting it from a distant source (Plappally & Lienhard V, 2013).

To reduce energy consumption and dependency on fossil fuels, integrating energy-efficient and renewable energy sources with WASH systems is increasingly being adopted for small communities (Bamford & Zadi, 2016). While renewable energy integration has worked in small-scale WASH systems, significant challenges remain for large-scale operations. High costs of energy storage devices and space requirements are limiting the widespread adoption of renewable energy for water extraction (Hamawand, 2023; Liu et al., 2022; Murgatroyd & Hall, 2020).

Water Treatment

Water treatment systems operate at two scales: household level, commonly known as Point-of-Use (PoU) systems, and community or city scale. Despite the aspiration of many cities to have city-scale centralised system, PoU systems are gaining popularity. PoU water treatment technologies are particularly important for those without access to safely managed water, although their use is not limited to such contexts. Even in countries like the US, where more than 96 per cent of the population has access to centralised treatment systems, PoU technologies are widely used. Incidents of water contamination like those in Flint, Michigan, have heightened awareness of water quality issues, driving many to seek more control over their water safety, making PoU systems a popular choice (Lawrencia et al., 2023; Siwila & Brink, 2019; Wu et al., 2021).

Numerous PoU technologies are widely used, with many patented innovations such as filter caps (UNICEF). These systems are designed to remove both standard and emerging contaminants. PoU technologies can be as basic as boiling water, the most prevalent PoU method in Southeast Asian countries like Cambodia, Indonesia, Timor-Leste, and Vietnam, (Plappally & Lienhard V, 2013). For removing emerging contaminants like pharmaceuticals and plasticisers, technologies such as granular activated carbon, integrated membrane systems, radiation, and

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[7] McDonald et al., surveyed 50 large cities (population >750,000) and a representative sample of more than other 100 large cities

activated oxidation are available (Sharma & Bhattacharya, 2017; Wu et al., 2021). Some PoU technologies, such as ceramic filters, chlorination, and solar disinfection (SODIS), are effective against biological contaminants and can operate with low or no energy requirements.

At the city scale, the intended use or required water quality determines the appropriate treatment technology. No single technology can address all water quality issues independently; instead, hybrid technologies are often necessary. Reverse Osmosis (RO) serves as an example, where coagulation, flocculation, and disinfection are part of the treatment system, and critical to prevent fouling and reduce damages to RO membranes. However, these necessary pretreatments introduce new challenges, such as the degradation of membrane integrity through chlorination, necessitating incremental innovations such as de-chlorination, Electrodialysis-Reverse Osmosis (ED-RO) (Plappally & Lienhard V, 2013; Sharma & Bhattacharya, 2017).

Membrane-based technologies such as Microfiltration (MF), Ultrafiltration (UF), Nanofiltration (NF), and RO are gaining attention not just for their efficacy but also for their versatility in addressing specific water quality goals. They are likely to see innovations that reduce fouling, improve efficiency, and lower costs, with new materials and designs that enhance performance and lifespan of membranes, making them more accessible and cost-effective (Obotey & Rathilal, 2020; Plappally & Lienhard V, 2013). Desalination, while effective, requires substantial energy, often requiring over 1 kwh per cubic metre of treated water (Bredariol et al., 2024). The use of renewable energy sources in centralised water treatment systems with RO and desalination are increasingly considered for enhancing environmental sustainability (Obotey & Rathilal, 2020; Plappally & Lienhard V, 2013).

Various options are available for water treatment at different scales, and the adoption of these technologies is influenced by socioeconomic, environmental, and cultural factors, including water literacy, affordability, and indigenous perspectives, as seen in studies from Malawi and Malaysia (Lawrencia et al., 2023).

Water Distribution

Water distribution systems encompass a wide range of methods, from pipelines and canals to water tankers, bottled water, and water ATMs (Garrick et al., 2019). In SSA, diverse water supply methods cater to the needs of the ‘unconnected’ urban population. Standpipes are a primary water source for many, while household resellers significantly supplement water supply, especially in areas where formal connections are sparse. Mobile vendors play a crucial role in high-conflict or poorly connected areas, and small-scale independent providers are significant in peri-urban zones not served by main networks (Keener et al., 2010).

Currently, the operational efficiency of the water distribution through networks is very low, as evidenced by high levels of Non-Revenue Water (NRW), resulting in a global loss of USD 39 billion (Liemberger & Wyatt, 2019). Long-distance water transmission and distribution further increase the likelihood of leaks and system failures. There is a widespread deployment of technologies to reduce NRW, which are in various stages of implementation across different regions.

Table 4: Average NRW by region and countries

Region	NRW Region (average l/capita/day)	Highest		Lowest	
		Country	NRW (l/capita/day)	Country	NRW (l/capita/day)
Sub-Saharan Africa	64	Mauritius	233	Togo	11
Australia and New Zealand	36	Australia	30	New Zealand	67
Caucasus and Central Asia	152	Armenia	541	Kazakhstan	60
East Asia	42	Mongolia	91	China, Macao SAR	26
Europe	50	Montenegro	595	Netherlands	9
Latin America and Caribbean	121	Guatemala	693	Haiti	26
Middle East and Northern Africa	96	Bahrain	223	Palestine	18
Pacific Islands	211	Guam	387	Niue	9
Russia, Ukraine, Belarus	65	Ukraine	80	Belarus	56
South Asia	93	Malaysia	155	Cambodia	8
Southeast Asia	81	Pakistan	196	Afghanistan	46
United States and Canada	119	United States	123	Canada	64

Source: Liemberger & Wyatt, 2019

A critical aspect of water distribution systems is the energy consumption per volume of water supplied, along with associated costs and carbon emissions. Energy consumption varies widely, primarily due to terrain differences. For example, Loudoun, Virginia, uses 2.28 kWh/m^3 of water distributed due to its mountainous terrain, while Alexandria, with flatter terrain, uses 0.55 kWh/m^3. In Auckland, energy consumption is 0.21 kWh/m^3, while Taipei, with older infrastructure, uses between 0.26 and 0.51 kWh/m^3 (Sharif et al., 2019). There is a need to improve network energy efficiency by improving water quality, optimising pumping methods, right sizing the network, and overall comprehensive planning that accounts for various critical aspects, including terrain conditions.

Wastewater Collection and Conveyance

Wastewater collection and conveyance technologies have seen little change over time as opposed to water technologies. Traditional methods, such as using sewers and the manual or mechanical emptying of pits and septic tanks, have largely persisted, leading to a certain degree of path dependence. Conventional sewers were originally built as combined systems to manage stormwater, greywater, and eventually blackwater. These systems continue to serve large populations, particularly in developed countries. Generally, older systems or those serving smaller populations tend to be combined, whereas newer systems are usually separate (Moreira et al., 2016). Consequently, historic city centres often have a higher proportion of combined sewers, while newly developed suburban areas typically feature separate systems (Abbas et al., 2019).

However, combined sewer systems can be problematic in modern urban settings, particularly during heavy rains when they often overwhelm treatment facilities (UN World Water Assessment Programme, 2017b). Countries such as Finland (95 per cent), Portugal (>95 per cent), Sweden (88 per cent), France (68 per cent), Germany

(57 per cent), Cyprus (100 per cent), and Estonia (new structures) have prioritised separate sewer systems to enhance stormwater management and reduce pollution risks associated with combining sewage and stormwater (Milieu, 2016).

Addressing and correcting existing combined sewer systems is expensive. For instance, in the US, the investment needed to address existing combined sewer overflows is estimated at approximately USD 48 billion over a period of five years (Daguillard, 2016).

Maintaining aging sewer infrastructure is another costly challenge, particularly in cities like London, where Victorian-era sewers are still in use. These systems suffer from issues like corrosion and clogging, which results in sewage spills and water contamination. Addressing these problems requires significant investment. For instance, in the US, USD 52 billion is required to address such problems (Daguillard, 2016).

Overcoming the path dependence of these systems remains a challenge. In response to the high costs associated with traditional sewerage, simplified sewer systems (SSSs) have emerged as a successful cost-effective alternative, suitable for both high- and low-income neighbourhoods. SSSs are also preferred because they enable separation and allow for the reuse of stormwater. They are typically laid in small gradients and require few or no pumping systems. For example, in Brazil, the cost per person for simplified sewerage is significantly lower than conventional systems (UN-Water, 2017). However, SSSs too present challenges such as large spatial footprints, especially in cities like those in the UK, where narrow streets already house complex utility networks (Abbas et al., 2019). Additionally, they can lead to the direct discharge of polluted runoff, which can contain heavy metals and other contaminants from streets into rivers.

Advancements in sewer system design, construction, and maintenance have prompted a re-evaluation of traditional urban drainage. Initiatives by organisations like the USEPA, including real-time control systems, vacuum sewerage, and sustainable drainage systems (SuDS), offer new ways to enhance urban wastewater management (De Toffol et al., 2007; Mannina & Viviani, 2009; Quaranta et al., 2022).

Wastewater Treatment and Reuse

Wastewater treatment technologies are shaped by the specific needs of different contexts—urban, suburban, and rural—each with distinct land availability, disposal methods, and reuse intentions. On-site systems, such as pits, privies, cesspools, cesspits, and septic tanks are the traditional methods for containing, treating, and disposing or reusing wastewater across the globe (Bond et al., 2013; Water and Sanitation Program, 2008). These traditional systems were designed for reuse and safe on-site disposal. In many parts of the world, including India, China and Japan, stabilised waste material from the pits is used as manure for agriculture purposes. While urban centres are now provided with sewer networks, the use of on-site systems remain prevalent, particularly in small cities and peri-urban areas, where Faecal Sludge Management (FSM) plays an important role in closing the loop.

The key challenges with on-site systems include increased population density, which limits the on-site disposal of liquids from septic tank systems and pits due to limited soil absorption; poor functioning of improperly built on-site systems (TNUSSP, 2018); and the limited scaling of FSM. Multiple options exist to address these challenges, such as retrofitting to improve functionality and institutionalising FSM, but these needs to be scaled (CWIS, 2023). Additionally, advancements in decentralised wastewater treatment systems, along with the production of biofertilisers from such systems, support urban farming and contribute to circular economy practices (Estévez, 2022). On-site purification techniques like permeable reactive barriers and managed aquifer recharge effectively address on-site disposal and groundwater depletion challenges (Kalmakhanova et al., 2023).

There are many traditional and innovative technologies for centralised wastewater treatment, with the Activated Sludge Process (ASP) being the most prevalent globally, largely due to its established reliability (Barbier & Burgess, 2017; Soares et al., 2017; Kalmakhanova et al., 2023). In situations where land availability is not a constraint, technologies like Waste Stabilisation Ponds (WSP) and Constructed Wetlands (CW) are preferred due to their low operational demands and high efficiency. Conversely, in land-scarce settings, systems like Membrane Bioreactors (MBRs), Sequential Batch Reactors (SBRs), and Moving Bed Biofilm Reactors (MBBRs) are favoured for their high treatment efficiencies and smaller footprint. Innovations in wastewater treatment have focused on improving equipment design, controlling fouling, and developing membranes that offer increased water flow and resistance to fouling (Kalmakhanova et al., 2023; Khurelbaatar et al., 2021; Tsagarakis et al., 2003). There is also increasing focus on the reuse and recovery of resources from wastewater, given its high energy potential (Soares et al., 2017). Innovations in treatment technologies that allow for safe and efficient recycling of wastewater for various uses will play a critical role in addressing water scarcity (Chirisa et al., 2017; Ricart et al., 2021; Yalin et al., 2023).

Nature-based Solutions (NBS) are approaches that use or mimic natural processes to offer sustainable, cost-effective, and resilient alternatives to traditional systems. NBS include the restoration of forests, wetlands, and coastal systems, urban greening, sustainable agriculture, and other ecosystem-based approaches. Cities like Singapore, Melbourne, and Copenhagen are pioneering the urban application of NBS, using green roofs, walls, and parks to combat heat islands, manage stormwater, and bolster urban biodiversity. Similarly, China's 'Sponge City' initiative employs NBS to mitigate urban flooding, showcasing large-scale environmental adaptation (UN-Water, 2018).

Summary

An overall assessment of technologies across the full cycle of WASH systems highlights the importance of enabling cities to work with multiple technology options, including the adaptation of decentralised systems for higher density areas. In scenarios of water scarcity (too little water), advanced membrane technologies, water from air, rainwater harvesting and storage, desalination, and on-site systems such as Urine Diversion Dry Toilet, composting toilet, advanced/ retrofit septic tanks with reuse capabilities could potentially address challenges. (Cooley et al., 2019) highlight the importance of reducing water use and prioritising local sources by examining California's shift toward sustainable practices and noting the economic benefits of stormwater capture and urban water conservation.

Conversely, in situations of excess water (too much water), nature-based solutions—constructed wetlands and green infrastructure—can effectively manage stormwater runoff, reduce peak flows to treatment plants, and provide additional treatment through natural processes. Furthermore, wastewater treatment plants and on-site systems must be designed or retrofitted to withstand flooding and extreme weather conditions, ensuring continuous operation during and after such events. This can include sealing OSS to prevent overflow and contamination, elevating access points, ensuring proper siting away from high-risk flood areas, and designing buildings and infrastructure with elevated structures, flood walls, and materials that are resistant to water damage.

Adopting appropriate technology options will also require leveraging advances in Internet of Things (IoT) and Artificial Intelligence (AI), which could facilitate smarter water management systems (Daniel et al., 2023; Lee et al., 2015; Shahanas & Sivakumar, P. B , 2016; Yasin et al., 2021).

While technologies contribute to more sustainable practices, they fall short of completely solving the problems of water scarcity, excess water or contaminated water. This underscores the need to ensure that the planning, financing, management, governance aspects of WASH systems are oriented towards urban water conservation through reduced consumption, efficient use and prioritisation of local water resources.

5.4 Cost Assessments for Service Provision, and Recognising Funding Challenges and Evaluating Gaps

It is well acknowledged that meeting the targets of SDG 6.1 and 6.2 by 2030 requires not only increased funding but also more effective funding strategies. A critical challenge in optimising the allocation and utilisation of financial resources for WASH systems has been the accurate and comprehensive assessment of costs of services across the full cycle and over the long term.

Costs Estimates of WASH Systems

Several studies have attempted to quantify WASH costs, including capital expenditures, capital maintenance, and recurrent expenses, at different scales and for different contexts. The most recent World Bank data, covering 113 countries, estimates WASH costs to be nearly USD 210 billion annually (in 2017 constant prices) (Joseph et al., 2024). Another study assessing infrastructure gaps estimates that meeting the SDG targets (6.1 and 6.2) by 2030 in LMICs will cost between USD 171 billion and USD 229 billion. When operation and maintenance expenses are included, this figure rises to USD 406 billion to USD 509 billion, equivalent to approximately 1.1 per cent to 1.4 per cent of LMICs' GDP (Rozenberg & Fay, 2019).

Other studies have identified and evaluated key parameters that influence system costs in different contexts. These parameters include population densities, size and degree of centralisation, economies of scale, institutional and managerial arrangements, technology, labour costs, and various geophysical factors (Daudey, 2018; Libey et al., 2020; Manga et al., 2020). For example, a study in South Africa found that for population densities below 112 persons per hectare, simplified sewerage was more expensive than on-site sanitation options. This higher cost was associated with the maintenance of pumping stations and monthly household surcharges. However, for population densities above 198 persons per hectare, sewerage became cheaper than on-site sanitation options due to economies of scale (Manga et al., 2020).

Table 5 illustrates the range in cost estimates based on two studies on urban sanitation, highlighting the impact of methodological and contextual differences. The study by (Sainati et al., 2020) draws on data from 25 cities in 10 countries to calculate the Total Annualised Cost per Household (TACH) for sewerage systems. In comparison, the Boston Consulting Group (BCG) study provided per capita costs based on extensive secondary analysis and interviews with WASH experts in developing countries (Carins-Smith et al., 2014).

Table 5 Costs of sanitation systems based on different estimation methodologies

	Total costs (capital and operating)	Capital costs	Annual operating costs
*Unit**	*Int$ 2018 / household / year*	*$ / person*	*$ / person / year*
Source	*(Sainati et al., 2020)*	*(Carins-Smith et al., 2014)*	*(Carins-Smith et al., 2014)*
On-site septic tanks-based system	81 – 267	105 – 155	4 – 10
Decentralised simplified sewer-based system		70 – 360	4 – 12
Container-based sanitation	189 – 309	N/A	N/A
Centralised conventional sewer-based system	513 – 1,192	220 – 940	12 – 28

*Costs are presented in different units and do not consider service life due to the varying methodologies used in the studies. They are provided solely to illustrate the complexities involved in estimating and comparing costs

(Sainati et al., 2020) evaluated on-site sanitation technologies, including container-based sanitation with mechanised emptying, transfer stations, and composting (aerobic treatment), as well as on-site ‘septic’ tanks with mechanised emptying and anaerobic treatment. The focus of (Carins-Smith et al., 2014) was primarily on septic tanks, considering factors such as septic tank sizing, permeability and charges for conveyance and disposal based on distances. (Sainati et al., 2020) considered factors such as land rental, salaries, administration, and public concession costs to account for annual operating expenses.

Although the costs outlined above aim to be comprehensive, these figures may not fully account for the expenses related to aging infrastructure, which will need replacement, or the additional costs related to climate change adaptation. The estimated costs for safely managed water and sanitation services may also overlook the higher costs of last-mile service delivery, particularly for reaching vulnerable populations. Achieving inclusivity outcomes, such as occupational health and safety and social protection for sanitation workers, also may not be reflected in these figures.

There are several challenges in capturing these nuances and arriving at a realistic estimate of costs for the service provided. These includes difficulties in clearly disaggregating costs over the lifecycle of water and sanitation systems, linking them to service levels, and factoring in adaptation expenses related to emerging climate change challenges (see Box 3).

Box 3: Challenges in Estimating Costs for Water and Sanitation Systems

The literature identifies several challenges in urban water and sanitation cost reporting. These include underreporting, more so in sanitation than water, and inconsistencies in the methodologies used for reporting (Daudey, 2018). Additionally, there is a lack of a comprehensive and reliable global database that provides cost data estimated using standardised approaches (Daudey, 2018). This gap hinders the development of benchmarks for unit costs, which are necessary for making cross-geographic and cross-technology comparisons, for planning and directing investments, and facilitating effective decision-making and initiative development (Daudey, 2018).

A key limitation of cost estimates is the absence and inadequacy of data on non-networked water and sanitation services—both formal and informal—such as water tankers, bottled water supply, Water ATMs/kiosks, and cesspool trucks. Other significant drawbacks include the lack of reporting on operation and maintenance costs as well as on the costs of climate adaptation (Joseph et al., 2024). While these estimates are critical for estimating funding gaps at the global, national, and sub-national levels, efficient resource allocation and informed decision-making require disaggregated cost data. Understanding specific cost components of water and sanitation services is crucial (World Bank, 2019).

The variation in costs by region and within countries, arising from factors such as differing policies and approaches to technology upgrade and / or global macroeconomic conditions, poses significant challenges for providing recommendations on financing and implementation at the global level. For example, while SSA would require about USD 78 billion per annum between 2017 and 2023 to achieve SDG 6.1 and 6.2, Europe and Central Asia would need USD 8.8 billion, Latin America and the Caribbean USD 24.4 billion and South Asia USD 41 billion (Joseph et al., 2024). Compounding these challenges is the variability of data quality across different contexts, differences in lifespans of technology / infrastructure systems, and differences in service levels delivered by the different systems. Few systematic attempts have been made to evaluate the relationship between these parameters and costs based on empirical data at the necessary scale. Consequently, results often remain context-specific or based on models that have not been empirically validated.

A recent World Bank assessment of global spending in 130 countries estimates that nearly USD 165 billion (2017 constant prices) is spent annually in the water sector, including water supply and sanitation (WSS), irrigation, water transport, and hydropower. Water supply and sanitation accounts for more than half of the total spending (USD 141 to 153 billion, excluding official development assistance), with estimates ranging from about USD 80 billion to 91 billion per annum (2017 constant prices). Data from 69 countries showed that annual spending on drinking water was higher, at USD 31 billion, compared to USD 24 billion for sanitation (WHO/GLASS, 2022). The majority of the water and sanitation spending is directed towards capital expenses, estimated between USD 61 billion and USD 70 billion (2017 constant prices) (Joseph et al., 2024).

Regionally, East Asia and Pacific (including China) is the highest spender in water and sanitation, accounting for nearly 50 per cent (USD 40-41 billion) of the total. Meanwhile, SSA has seen the highest increase in spending over recent years. Despite an increase in water and sanitation spending in SSA from USD 99 to 116 million between 2017 and 2021, access to safely managed water and sanitation services remains the lowest among all regions. Spending on water and sanitation as a proportion of GDP remains small, ranging from 0.53 per cent in Middle East and North Africa to 0.14 per cent in South Asia (Joseph et al., 2024). In comparison, health expenditure as percentage of GDP ranges from 5.7 per cent in Africa to 8.7 per cent in Europe (World Health Organization, 2022).

The public sector, including state-owned enterprises, is the largest contributor to water sector spending, accounting for 92 per cent of the total. However, water sector spending represents only 1.2 per cent of total public spending on all human development sectors. In contrast, sectors such as education, health, and social protection receive nearly 60 per cent of the total public spending (Joseph et al., 2024). Of the total public spending in the water sector, 76 per cent is allocated to water supply and sanitation (Joseph et al., 2024).

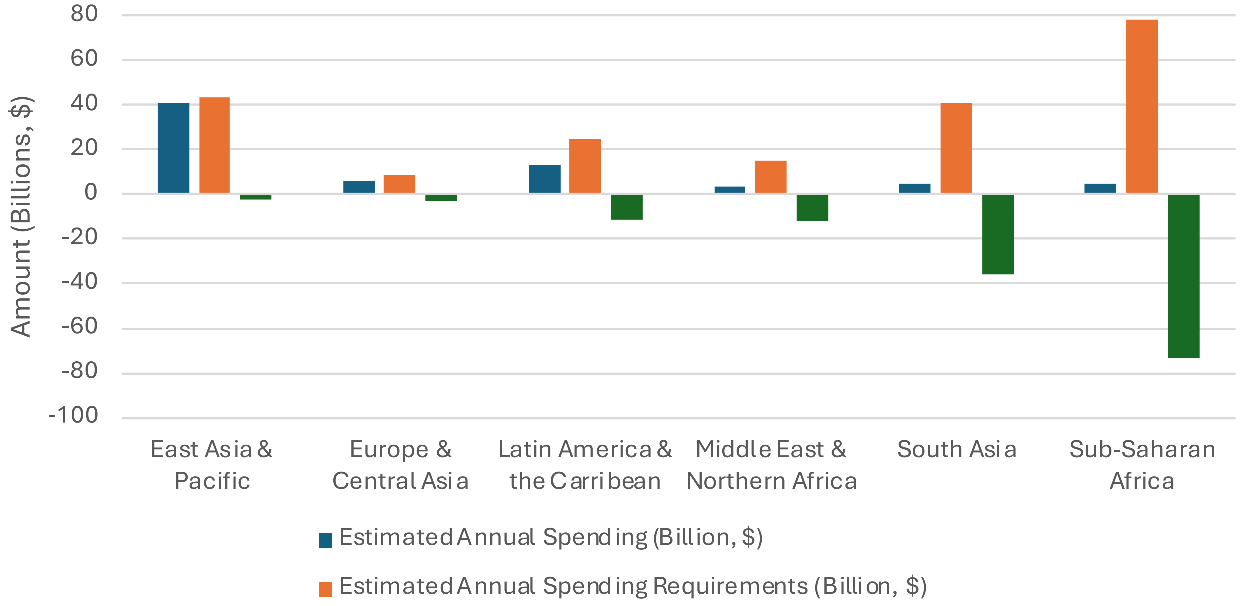
Within the water supply and sanitation sector, 80 per cent of the spending on infrastructure came from public entities (national and local governments), 11 per cent from state-owned enterprises, and about 9 per cent from the private sector (Joseph et al., 2024). These figures, however, likely exclude direct household spending, particularly on informal services. According to the Global Analysis and Assessment of Sanitation and Drinking Water (GLAAS) report (2022), 44 out of 121 countries, with a total annual WASH spending of USD 66.9 billion, reported that households were the largest source of funding at 61 per cent followed by government at 29 per cent, external sources 4 per cent and repayable finance at 6 per cent for the period from 2018-2022 (WHO, 2022).

Spending Requirement and Challenges

Globally, the levels of spending, specifically public spending, on water and sanitation services need to increase substantially to achieve SDG 6.1 and 6.2 by 2030. The required annual spending is estimated at nearly USD 210 billion (in 2017 constant prices), with operations and maintenance accounting for 54 to 58 per cent of the total (Joseph et al., 2024).

The highest spending requirements are in the SSA (USD 78 billion) and East Asia and Pacific (EAP) regions (USD 43 billion). However, the largest spending gaps are in SSA (USD 74 billion) and South Asia (SA) (USD 36 billion). Excluding India, the annual spending gap in South Asia significantly decreases to approximately USD 10.8 billion (Joseph et al., 2024).

Figure 3: Estimate Annual Spending, Spending Requirement and Spending Gap by Region



Source: (Joseph et al., 2024), 2017 constant prices

According to the GLAAS survey, key reasons for spending gaps include insufficient allocations to expand services and inadequate operations and maintenance, leading to higher capital renewal costs (WHO/GLAAS, 2022). Existing services are at a risk of deterioration and failure due to the significant challenges countries face in recovering costs (Garrick et al., 2019).

Low cost-recovery rates are a significant contributor to spending gaps. Only 35 per cent of the utilities in the International Benchmarking Network (IBNET) database can fully cover their operations and maintenance costs, and an even smaller share, 14 per cent of all utilities, can cover their total financial costs, including capital and O&M (Andres et al., 2019).

Another important factor contributing to spending gaps is poor budget utilisation (Joseph et al., 2024). The global average budget execution rate in the water sector is currently 73 per cent, driven primarily by low rates in the water supply and sanitation subsector, which are like those in the broader water sector. In contrast, the human development sector, which includes social protection, education, and health, has the highest average execution rate at 99 per cent (Joseph et al., 2024).

The low utilisation of funds is attributed to several factors, including low absorptive capacities, inadequate governance, and poor project planning and implementation. Underlying causes include inadequate human resource capacity and lengthy project implementation timelines, which average between six and 15 years (Joseph et al., 2024).

In addition to the size of spending gaps, the population segments affected by these gaps are a critical concern. A significant issue is the allocation of subsidies, which constitute a substantial portion of government spending, especially in developing countries. However, according to a study by Andrés et al. (2019), in 10 developing countries, an average of 56 per cent of subsidies is captured by the wealthiest 20 per cent of the population, while only six per cent reach the poorest 20 per cent. In developing countries where spending is already limited, poorly targeted subsidies exacerbate gaps for those most in need of funds (Andres et al., 2019; Joseph et al., 2024).

5.5 Recognising Factors Influencing Social and Behaviour Change

In Social and Behaviour Change Communication (SBCC) initiatives, identifying the specific behaviour to be modified, and the target population is key to starting interventions (Mosler & Contzen 2016). Water-related behaviours include sourcing water from safe locations, safe storage, and point-of-use disinfection of drinking water, while sanitation-related behaviours range from avoiding open defecation to proper emptying, maintenance and use of sanitation structures. While most behaviours, such as toilet use, are relevant to all stakeholders, responsibilities for tasks like safe storage of water, proper emptying of sanitation structures and point-of-use disinfection of drinking water may vary based on individual roles within the household or community. Thereby, identifying the appropriate target groups, such as women, men, children, vulnerable population, head of households, or community leaders, is crucial (Mosler & Contzen 2016).

There are different approaches to SBCC in water and sanitation that have been practised, such as water and sanitation messaging, psychosocial models, social marketing techniques and community-based approaches (De Buck et al., 2017). As a part of these approaches, there are several interpersonal, household level and external factors that influence behaviour change in the water and sanitation sector (Saurí, 2013).

The water and sanitation messaging approach uses a directive, one-way educational approach to enhance individuals' knowledge and skills to ensure better outcomes. The approach provides communities with evidence and data around water quality and safe treatment/handling practices that can help to overcome key knowledge barriers (UNICEF, 2023). In 1997, Bogotá, Colombia faced a water shortage and the government's initial emergency warning caused increased water consumption and hoarding. To counter this, the city educated residents on water conservation practices, shared daily consumption data, highlighted cooperative behaviour, and featured the mayor in a TV ad promoting water-saving techniques which led to lasting water use reductions (World Bank, 2015).

However, several studies have highlighted that while informativeness is an important factor in promoting behaviours, they may not always translate into behaviour change (Saurí, 2013). This is addressed in the psychosocial approaches which focus on factors other than knowledge such as emotional appeal, nudging, behavioural influencing and social pressure through various models (e.g. Integrated Behavioural Model (IBM-WASH), and Risks, Attitudes, Norms, Abilities, and Self-regulation (RANAS)) to promote behaviour change and close the knowledge action gap (Bakar et al., 2021) (UNICEF, 2023). For example, in Khulna, Bangladesh, it was identified that along with appropriate education, preference groups that the target community emulates, such as celebrities, local leaders and early adopters, were required to clarify expectations and incentivise the target population to adopt proper sanitation practices (Cookey et al., 2020).

While in the above example social pressure from community leaders with regular follow-ups and messaging led to rapid sanitation improvements, studies have shown that emotional and social pressure techniques can also be ineffective at times. A study in urban slums of Bangladesh used a mix of psychosocial and social marketing approach that involves promoting water and sanitation products and services using consumer-driven strategies. The mixed approach was used to understand the impact of emotional pressure messages and social marketing techniques on water chlorination use among residents. The study highlighted that disgust-and-shame messages did not significantly increase chlorination use for water treatment or willingness to pay for chlorine after a free trial ended. The qualitative household interviews from the study revealed that the feelings of disgust faded over time, and social concerns were low and one of the possible reasons for low uptake of disgust-and-shame messages was due to the poor reach of these messages to men (reached only 20 per cent of the male population) who were socially more influential in Bangladesh culture than women (Guiteras et al., 2015). In terms of social pressure and shaming, recent discussions in global health emphasise that it should not be used to promote better health outcomes, as it can cause psychological harm, particularly among low-income households that cannot afford necessary changes (Nelson et al., 2021). However, the social marketing component of the same project in urban slums of Bangladesh which was provisioning free supply of soapy water bottles showed a modest increase in handwashing, highlighting the greater influence of price over promotion or education (Guiteras et al., 2015).

This indicates that approaches requiring significant financial investments or efforts have been found to be less effective. A study of 248 urban households in India revealed that water conservation behaviours such as reusing wastewater from filtration systems or installing water-efficient dual-flush toilets, were less popular. In contrast, simpler actions with no financial cost, like turning off the faucet while brushing teeth or washing dishes, were easily adopted by nearly 94 per cent of households (Ramsey et al., 2017).

Hence financial factors have a significant impact on SBCC approaches. For example, an imposition of water prices and taxes worked as an effective complementary instrument for water conservation messaging and marketing approaches in Spain. In Zaragoza, Spain, there was a reduction of 5.6 per cent in water consumption after one year of a water awareness programme combined with higher prices (Saurí, 2013) .

Additionally, there have also been examples of success of certain water conservation programmes when linked to previously experienced instances of water stress. When assessing the impact of public information campaigns on water conservation in four large regions of the US (northeast, north central, southern, and western), it was found that water consumption declined only in the West and not in the other areas, which as a rule did not suffer water scarcity (Saurí, 2013). Similarly, in Tehran, Iran, urban households were more likely to adopt water conservation behaviours when i) they saw water scarcity as a serious health risk, ii) felt the benefits of saving water outweighed the barriers, iii) they receive constant reminders, and iv) were ensured of self-efficacy for sustaining actions (Shahangian et al., 2022).

In the sanitation sector, community-based approaches, such as Community Led Total Sanitation (CLTS) and Participatory Hygiene and Sanitation Transformation (PHAST) are popular participatory methods to engage communities to improve sanitation practices (De Buck et al., 2017). These are considered highly effective as when neighbours improve their sanitation practices, households also benefit from the improved environment, a concept known as ‘herd protection’ (USAID, 2021). The Indonesia Urban Water, Sanitation, and Hygiene (IUWASH) project employed the CLTS model to improve urban sanitation in 54 cities where communities were less cohesive, and sanitation systems more expensive. The project introduced initiatives like community exchange visits to inspire action and foster peer learning. Training programmes and exposure visits for sanitation entrepreneurs aimed to build local capacity, while microfinance schemes were developed to make sanitation more affordable for households. Promotional materials emphasised the social status and security benefits of improved sanitation to further motivate communities. These interventions, addressing technical, institutional, and financial challenges along with promotional techniques, helped 2.5 lakh people access improved sanitation, with 1 lakh receiving WASH-related training (Myers et al., 2018).

Successful CLTS campaigns, have highlighted the importance of addressing multiple enabling conditions to influence behaviour change. In another instance, a project in Gulariya Municipality, Nepal (2014-2016), aimed to achieve Open Defecation Free (ODF) status through community engagement, training and institutional strengthening. Key elements included orienting Ward WASH Coordination Committees and training influential community members, with a strong emphasis on women’s groups participation. Institutional alignment with government frameworks at the start of the project was crucial for sustainability. The project resulted in over 5,385 individual toilets, 319 institutional toilets, and five public toilets and achieving ODF status in 11 wards within six months. A significant lesson learned was that integrating CLTS with household-centred approaches which focused on institutional processes proved more effective in diverse urban settings. Similarly, a pilot initiative in eight Ethiopian towns where community built their own toilets reinforced that urban CLTS success relies on government commitment and leveraging existing governmental platforms for sustained interventions (Myers et al., 2018).

As part of the enabling conditions, monitoring is a key aspect of sustaining SBCC interventions and can be carried out in various ways, such as reporting, verifications, and follow-up visits. A project in Fort Dauphin, Madagascar, used household competitions to improve toilet cleanliness, with health volunteers and neighbours rating latrines based on agreed criteria. Monthly rankings were displayed publicly, and families maintaining high standards for three months received incentives, promoting positive behaviour change (Myers et al., 2018). Similarly, India's Swachh Bharat Mission (SBM) promotes sanitation through an annual survey, the Swachh Survekshan, which ranks urban areas based on cleanliness, sanitation, and waste management. The rankings, based on municipal data, inspections, and citizen feedback, are publicised to encourage competition and motivate cities to improve service delivery. The Survey, launched by the Ministry of Housing and Urban Affairs (MoHUA) in 2016, has grown into the world's largest urban cleanliness survey, covering over 4,416 Urban Local Bodies (ULBs) and gathering feedback from nearly 15.9 million citizens (Government of India, 2023).

However, monitoring interventions have several downsides, including high costs, time and resource demands, potential reactivity from subjects, and the possibility of inaccurate reporting. Monitoring can also disrupt household and community routines. Despite these challenges, prioritising monitoring remains crucial for the sustainability of WASH interventions (Nelson et al., 2021).

The examples above demonstrate that SBCC can be effective when factors like socio-economic status, self-efficacy, and attitudes are considered and neglecting factors such as cultural contexts and price can result in less favourable outcomes. Additionally, urban areas are heterogeneous and characterised by presence of more migratory population, leased properties, dense areas, rigid institutional frameworks and varying occupational roles which can also influence SBCC interventions.

6. Accelerating the Urban Water and Sanitation Transition

Cities need to shift their focus from merely increasing water supply to emphasising efficient use and, where appropriate, recycling and reuse of used water, even in regions of relative year-round water abundance.

Achieving this requires a re-evaluation of traditional urban and infrastructure planning assumptions (Sedlak, 2019). Planning decisions must prioritise the sustainable use of water by integrating natural resource management into development plans. Given the connections between peri-urban and urban agriculture, ecosystems services, biodiversity conservation, and water availability, it is essential to link land use and land cover change decisions to water availability, use, and quality. Urban land use and land change decisions often drive master planning and real estate investment processes. The integration of water-related service delivery objectives into these processes, is becoming increasingly crucial to ensure equitable outcomes, especially for the urban poor.

Urban areas are learning laboratories to thoroughly test options against the range of urban challenges and develop innovative approaches that strengthen the enabling environment. This can help scale solutions, ensuring their sustainability and resilience. To address both deep-seated, structural issues and emerging challenges in urban water and sanitation service delivery, a spectrum of approaches ranging from incremental changes to disruptive innovations across technology, institutions, and finance are required.

This review concludes by discussing a few of the key elements essential for transitioning urban water and sanitation systems.

6.1 Building, Sustaining and Adapting Infrastructure

Given the pace and nature of urban growth, selecting an appropriate mix of centralised and decentralised systems is crucial in enabling innovation to scale in respond to local conditions (TNUSSP, 2018) and addressing emerging challenges.

In areas challenged by water scarcity (too little water) a range of technical options have been proven across the world, including advanced membrane technologies, rainwater harvesting and storage, desalination, and on-site systems water recovery systems such as Urine Diverting Dry Toilet, composting toilets, retrofitted septic tanks that enable reuse. However, there is a particular challenge in inadequate water storage infrastructure—whether physical (such as tanks, reservoirs, or cisterns) or natural (such as managed aquifer recharge systems)— that limits many communities' ability to adapt to climate variability and prolonged droughts. Addressing this challenge requires integrating technological innovations like stormwater capture, urban conservation, and decentralised recovery systems to enhance local water resilience and reduce dependency on external sources, as demonstrated by California's shift toward sustainable water practices (Cooley et al., 2019)

In areas challenged by excess water and flooding (too much water) nature-based solutions such as constructed wetlands and green infrastructure can manage stormwater runoff, reduce peak flows to treatment plants, and provide additional treatment through natural processes.

Wastewater treatment plants and on-site systems must be designed or retrofitted to withstand flooding and extreme weather conditions, ensuring continuous operation during and after such events. This can include sealing OSS to prevent overflow and contamination, elevating access points, and ensuring proper siting away from high-risk flood areas, designing buildings and infrastructure that can withstand flooding through elevated structures, flood walls, and materials that are resistant to water damage.

Enabling cities to work with multiple technology and infrastructure options, including making decentralised systems work effectively in high density urban areas, is important. Advances in IoT Internet of Things (IoT) and Artificial Intelligence (AI) can enable smarter water and wastewater management (Daniel et al., 2023;Lee et al., 2015; Shahanas, K. M., & Sivakumar, P. B , 2016; Yasin et al., 2021).

Recalibrating Demand and Reviving Local Supply

The primary mandate of service providers is often to supply more water, which has led to a prioritisation of large infrastructure projects and a political economy centred around water distribution, rather than universal, efficient and affordable service delivery (Shambaugh & Joshi, 2021). Given the current deep challenges around the UWC, cities should rethink traditional supply-centric approaches and explore options to reduce consumption and enhance efficiency rather than increasing their reliance on importing surface water and unsustainable extraction of groundwater.

Achieving this requires a thorough understanding of demand dynamics and the implementation of systematic and proactive demand-side measures, such as increasing use-efficiency and implementing disincentives for excessive per capita use (Shambaugh & Joshi, 2021). Long-term fixed benchmarks for municipal supply and wastewater treatment, which often overlook downstream requirements, should be reconsidered and optimised to ensure adequate supply to all.

This shift would also require decreasing dependency on external water sources. A combination of approaches could be employed, such as revisiting and reviving traditional methods of rainwater harvesting, along with reuse of treated wastewater, and improving stormwater management. Over time, practices like rainwater harvesting and operating septic tanks have taken a back seat due to the convenience of connecting to centralised networks, reinforced by entrenched institutional and technological path dependencies. However, with technological innovation and a deeper understanding of urban water and sanitation systems and the economics of network operations, traditional systems are increasingly being reconsidered in many contexts. If viable, this approach should be encouraged further (Hosagrahar et al., 2021; A. Sharma & Ji, 2024).

There are several innovations in treatment technologies that allow for safe and efficient recycling of wastewater for various uses (Ricart et al., 2021; Yalin et al., 2023; Chirisa et al., 2017). For instance, aerated wetlands, recommended for their high-efficiency and compact design, are ideal for urban settings, promoting the reuse of treated wastewater to close the urban water cycle loop (Nivala et al., 2020).

Stormwater management in a changing climate is a critical challenge, as it intersects with urban expansion and densification, hardscaping and transportation infrastructure planning. Effective stormwater management and urban flood management require coordinated efforts by multiple stakeholders to ensure service delivery is aligned with urban development strategies.

By effectively deploying green-blue-grey infrastructure, cities can separate stormwater from sewage, and address other waste streams, including new contaminants. This would increase the availability of clean water by replenishing local sources. This can be augmented by the reuse of treated wastewater at scale, as demonstrated effectively by Singapore (Quentin Grafton et al., 2023). With sufficient technology options available, a future focus should be on addressing behavioural and perception barriers.

Improving Use Efficiency

Improving efficiency in water supply is vital to address the inequitable use of water and reduce use of potable water for non-potable purposes. There is a need to explore ways to make decentralised systems viable in high-density urban areas. This can be achieved by retrofitting on-site and decentralised systems using advances in technology, automation, information technology and IoT (CWIS, 2023). By creating networks of these decentralised systems, local reuse and service provision can be scaled effectively. The potential for decentralised sources to contribute water to reuse networks where needed can be further explored, to enhance the resilience and efficiency of current water supply system.

As urban water distribution network expands, the need for scalable and efficient networks is important to conserve water and minimise economic losses. Therefore, improved network planning and management, assisted by advanced monitoring technologies are needed for reliable water supply. In addition, dual water distribution systems for potable and non-potable water can enhance water efficiency and reduce the volume of water treatment to potable standards.

There is also a need to improve network energy efficiency by limiting losses and exfiltration, improving water quality, pumping methods, network sizing, and improving the responsiveness of planning to terrain and ground conditions.

6.2 Strengthening Institutions

Strong institutions are pivotal to successful transitions (Goksu et al., 2019b; Herrera & Post, 2014; Mumssen et al., 2018), as they are central to creating an enabling environment, without which other interventions are less likely to take hold. Chronic system failures as well as crises such as water borne disease outbreaks and severe disruptions to drinking water supply have often been catalysts for institutional change (Goksu et al., 2019). During such events, heightened awareness and agency among citizens have driven demands for improved water and sanitation systems, compelling politicians and leaders to take cognisance of institutional failures. These crises have sometimes sparked sector-wide reforms encompassing policy, institutions, and regulation (Bertoméu-Sánchez & Serebrisky, 2018), which hinge on common principles of transparency, accountability, and participation (Camancho, 2021; Goksu et al., 2019; Mumssen et al., 2018). Understanding the pathways taken during crises and as preventive measures is crucial, as it may allow for certain conditions to be replicated to bring about the necessary shifts, even in the absence of emergencies.

While there is no one-size-fits-all institutional structure, below are a few key approaches to enhancing the effectiveness of institutions.

Addressing the Political Economy

Strong political commitment is essential for sustainable transitions of urban water and sanitation systems. High-level political leadership, government champions, and incentivised and competent managers play a vital role in safeguarding reforms from political interference (Biswas et al., 2021; Goksu et al., 2019).

To counter the political economy and the power of vested interests, institutional structures need to be agile and adaptable to changing circumstances. This includes shifting the type and scale of institutions when needed (Garrick et al., 2019) to improve governance, ensure regulatory compliance, and foster competent management. For instance, when incentives are not aligned with overall sector goals, employees of institutions sometimes prioritise personal or political goals instead, undermining institutional effectiveness (Goksu et al., 2019). Additionally, local communities and citizens must actively exercise their right to safe water and sanitation to drive political commitment and raise the bar on leadership.

Mandating Responsibility while Strengthening Advocacy, Incentives, and Competencies

Effective governance for sustainable water and sanitation outcomes are not determined by whether institutional structures are centralised or decentralised. Decentralisation is not always the most appropriate or necessary option for every context. While decentralisation in certain contexts can help insulate service providers from political interference and conflicts, its success depends on the devolution of financial authority and human resource capacity to local governments (Bernal et al., 2021; Herrera & Post, 2014; Tsinda et al., 2021).

For effective governance, decisions should be made by relevant authorities with adequate resources and a significant stake in positive outcomes (Herrera, 2019; Tsinda et al., 2021; World Bank, 2020a). It is essential to assign clear roles and responsibilities to institutions at local, regional, and national levels to achieve better water and sanitation outcomes (Herrera, 2019; Tsinda et al., 2021; World Bank, 2020a). This includes integrating local priorities at all levels of government, for which there is need to strengthen capacity of public and opinion leaders to influence politicians (Herrera, 2019; Tsinda et al., 2021; World Bank, 2020b). For instance, in Tamil Nadu, India, strengthening of the full chain of FSM as a viable standalone as well as complementary solution to networked sanitation was originally not on the government agenda. FSM was championed by government officers whose buy-in and commitment was fostered through orientations and exposure visits to successful FSM sites under the Tamil Nadu Urban Sanitation Support Programme (TNUSSP, 2021).

Strong leadership and champions have been crucial to successful institutional turnarounds in cities like Phnom Penh and Manila. However, the sustainability of these transitions can be short-lived without adequate capacity at all levels of the institution (Trimmer et al., 2022). Internal capacity building and incentivising performance has been the first crucial step in most reform programmes (Goksu et al., 2019). For example, the Phnom Penh Water and Sanitation Authority's (PPWSA) initiated reforms by streamlining workforce functions through education (training programmes) and motivation (promotions, higher salaries, and incentives) (Biswas et al., 2021; Goksu et al., 2019).

Capacity development should include the professionalisation of service delivery through investments in human resources and regulatory frameworks to enhance service levels to achieve better public health outcomes and tackle complex challenges (Howard, 2021). Improved capacity and competency have been shown to improve operational and financial efficiencies of institutions (Goksu et al., 2019).

Strengthening institutional capacity requires promoting education and training of professionals (public, private and communities), along with fostering co-operation and knowledge-sharing among all stakeholders.

Facilitating Community Ownership through Trust Building

The integrity of urban water and sanitation institutions, as well as the sustainability of the services they provide, depend on local communities holding these institutions accountable. Citizens must not only have access to grievance mechanisms related to poor service delivery but also be integral to the planning process. To achieve this, expert-driven methods should be replaced with collaborative approaches that actively involve and empower local communities (Barrington et al., 2021) and build trust. In addition, institutions should adopt decision-making processes based on the actual socioeconomic, cultural, and environmental costs and benefits of water and sanitation systems. Incorporating multidisciplinary perspectives and co-produced knowledge can make decisions more holistic, sustainable, and culturally sensitive (Barbier, 2022; Garrick et al., 2020; Ricart et al., 2021; Shields et al., 2022).

It is crucial to ensure that decision-making processes and forums are not dominated by elite interest groups. These processes should be structured to account for the constraints faced by the urban poor, such as lack of time, and enable participation from all communities and stakeholders. This shift will promote ownership, better integration of local knowledge, and more sustainable outcomes (Shields et al., 2022). With greater involvement of citizens, coupled with improved services, trust between service providers and citizens improves, allowing for better acceptance of key institutional reforms such as tariff increases or other cost recovery measures.

6.3 Reshaping Service Delivery by Strengthening Informal Services

A combination of formal and informal service arrangements is essential to ensure universal services and access to water and sanitation. Hence, it is essential to improve service levels and affordability of both formal and informal services (Trimmer et al, 2022). Informal services are widely recognised to play a crucial role in bridging service gaps, in public systems, which have the primary responsibility for service delivery (Garrick et al., 2019; Joseph et al., 2024).

This potential is demonstrated by models in Kisumu, Kenya; Manila, Philippines; South Mozambique; and Lusaka, Zambia. These models have transitioned completely from unregulated or informal services to ‘facilitated’ or ‘managed’ services demonstrating improvements in coverage and some impact on affordability and service levels (Agarwal et al., 2023).

A shift to a graduated model of provisioning can be facilitated through the creation and strengthening of regulation that does not disrupt functioning business models or push service providers to find ways to subvert regulation. Light-handed regulation that reduces financial disincentives, prevents rent-seeking while simultaneously addressing oligopoly and informational asymmetry and promoting safe services could be a viable alternative, especially in contexts with low institutional capacity and limited enforcement capacity (Gero et al., 2014). For example, in Tamil Nadu, India, the government opted to retain a regulated form of the existing on-demand de-sludging service delivery system along with introducing alternate approaches where the market had ‘failed’. The decision was driven by the state’s intention to leverage private sector delivery through private operators by not disrupting functioning business models through price-setting interventions. The state focused on reducing financial disincentives and introducing light-handed regulations such as a Standard License Agreement for Private Operators (TNUSSP, 2019).

Prospects for growth and assurance of business continuity and resilience, which are important to informal service providers can be enabled through access to credit along with business and technical skills development (Gero et al., 2014).

6.4 Increasing and Redirecting Financial Resources

Increasing Funding and Improving Financial Management

It is necessary to increase funding through higher budget allocations. Funding should be allocated to enhance service levels and increase resilience to changes in ecosystems. In addition, there is a need for financial sustainability which involves improving cost recovery rates, and better expenditure management, to address large current funding gaps in the sector. Better budget execution can be achieved by improving absorptive capacity and accelerating project implementation. Additionally, raising utilisation as well as cost recovery rates may require addressing governance effectiveness, political interference, and institutional capacity (Hutton & Varughese, 2016; Joseph et al., 2024).

Servicing Lifecycle Costs to Enable Service Sustainability

While there is a need to allocate funds to renovate aging infrastructure, investment in new infrastructure should be based on life cycle costing and stable O&M financing to ensure sustainable and sustained services. This can be achieved through increased transparency, better monitoring, and tracking of both formal and informal service delivery and their outcomes (Garrick et al., 2020; Howard, 2021; Hutton & Chase, 2016).

Improved long-term cost data can shift the focus from funding capital investments to paying more attention to the financial sustainability of system O&M. Benchmarking the direct and indirect costs and benefits of WASH, including public health, social, and environmental impact of different urban and water systems across geographies and technological systems, is essential and can inform planning, investment decisions, and effective resource allocation. Better costing of the full lifecycle costs of urban water and sanitation services can help prioritise funding decisions and focus on equity, safety and sustainability outcomes.

Expanding Funding Decision Criteria for Enhanced Impact

Funding decisions in developing and developed countries should target the sustained delivery of higher and equitable service levels, while accounting for climate resilience investments and factoring principles of the circular economy. Decisions should consider both the monetary and non-monetary values[8] of water and anitation systems that impact socioeconomic development and the environment, contributing to broader goals of sustainability (Howard, 2021; Hutton & Varughese, 2016; UN-Water, 2021; UN-Water, 2023). Climate finance is one such source of development investment that could be better scoped and structured to rehabilitate and safeguard water and sanitation systems, which play a critical role in urban climate resilience and adaptation (GWP, 2014.d.; Van Lieshout, 2023).

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[8] Water and water ecosystems have several economic, environmental and social values. Through its use in the production of food and goods for human consumption, water can deliver direct economic benefits that can be expressed in monetary terms. Water carries other non-economic values, which are difficult to monetise, through its role in spiritual, cultural, religious and emotional aspects (The Valuing Water Initiative, 2020; UN-Water, 2021)

Redirecting Subsidies to Improve Equity

Equitable outcomes can be achieved by more accurately targeting water and sanitation subsidies (Andres et al., 2019). They need to be redistributed between income groups, ensuring they reach the urban poor (Barbier, 2022). Subsidies need to be designed better, made transparent, and supported with complementary policy measures. They should be effectively redirected from centralised systems to other forms of decentralised, formal, and informal systems that are typically more responsive to the needs of the most vulnerable (Barbier, 2022). For example, in Nyeri, Kenya; Kampala, Uganda; and Dakar, Senegal, subsidised water connection charges enabled service coverage to more than double within a decade. In cities like Maputo, Mozambique, and Mzuzu, Malawi, informal supply modes such as standpipes and water kiosks are also subsidised. Some cities have introduced a reduced unit cost of water in the form of a free basic water allowance (South Africa) or Incremental Block Tariffs or Social Tariffs (Bengaluru, Nairobi, Colombo, and Santiago de Cali) (Beard & Mitlin, 2021).

Subsidies can help foster innovations that improve system efficiency. For instance, subsidies could be redirected to innovations that reduce leaks, limit service interruptions, maintain water pressure, or improve safe water reuse. (Barbier, 2022).

6.5 Effecting Sustained Social and Behaviour Change

SBCC interventions, particularly in urban environments, require a combination of strategies/approaches to effectively address multi-level challenges and ensure long-term sustainability (De Buck et al., 2017; Lüthi et al., 2010). For example, water and sanitation messaging to critical stakeholders combined with social marketing techniques can improve awareness on products followed by an increase in willingness to pay and uptake (De Buck et al., 2017). Similarly, while CLTS promotes community-level behavioural change, the lack of broader institutional support can be bridged by integrating the Household-Centred Environmental Sanitation (HCES) approach, which offers a structured, multi-stakeholder institutional framework covering the entire sanitation process from collection to disposal (Lüthi et al., 2010).

To further ensure sustained change, SBCC needs to be part of a broader set of enabling environment, interventions which need to include better institutional mechanisms, financing, capacity building, economic and technological improvements along with improved service provision (Saurí, 2013; UNICEF, 2023; USAID, 2020). Additionally, some key contextual factors identified as key enablers for success include social cohesion, leadership, and diverse involvement (particularly of women at various stages of design, planning, and implementation) (Nelson et al., 2021).

Finally, the recognition of different barriers that influence the implementation of different SBCC approaches can also have an impact on its effectiveness. For example, when considering a community-based approach, the lack of capacity in terms of trained community health promoters/volunteers and efficient institutional actors especially typical to developing countries can be potential barriers in sustenance. In social marketing approaches as well for purchase/construction of toilets, the bureaucratic loan process or high cost of water and sanitation products can be a barrier (De Buck et al., 2017). In a psychosocial approach, ignoring socio-economic categorisation of households can be a barrier to adopt water and sanitation costs for vulnerable households.

7. Conclusion

While deficits in urban water and sanitation systems are acute and complex, addressing them can play a crucial role in mitigating the global water crisis and enhancing sustainability in our cities. Climate change-induced disruptions to the global water cycle are increasingly impacting water availability and quality—resulting in too little, too much, and too dirty water. Change to the GWC have begun to impact the UWC, and hence the urban WASH systems. These changes exacerbate public and environmental health vulnerabilities, as access to clean and reliable water sources becomes more uncertain.

In the face of a growing number of extreme weather events, disasters, and emergencies, urban water and sanitation systems must be designed and adapted to be more resilient, ensuring the safeguarding of human health. There is a need to transition urban water and sanitation systems at scale by shifting from conventional approaches that were path-dependent and ignored non-monetary values of water.

Sustainable water use, considering availability, consumption, and quality, should drive urban planning, development and management decisions. Cities should focus on reviving local sources, reducing consumption, and enhancing efficiency and reuse. Achieving this requires creating enabling conditions through political will, effective leadership, incentives, advocacy, improved capacity and competency of service providers, greater trust between citizens and service providers, better funding decisions and management, and social and behavioural change.

Essentially, transitioning urban water and sanitation systems requires emphasis on all available technological and infrastructure options, along with innovative methods to address entrenched institutional, funding and behavioural barriers. Further research is necessary to clarify outcomes of these measures, identify potential disruptions from other sectors, and determine systematic pathways for transitioning urban water and sanitation systems.

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URBANISATION, URBAN SYSTEMS AND WATER

IIHS WORKING PAPER

JULY 2024

Citations
Beleyur, P., Revi, A. & Sami, N., 2024, Urbanisation, **Urban Systems, and Water**, Bangalore, India,
The Indian Institute for Human Settlements and the Global Commission for the Economics of Water.

Design & Layout: Nawaz Khan | Reviewed by Prachi Prabhu & Padma Venkataraman IIHS Communications & Design

ISBN: 9788198256843
DOI: https://doi.org/10.24943/9788198256843

First published in Bangalore, July 2024

This paper is part of a series of working papers commissioned by the Global Commission for the Economics of Water (GCEW).

URBANISATION, URBAN SYSTEMS AND WATER

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Introduction

More than 55 percent of the world's population now lives in urban regions, with urbanisation rapidly increasing in low- and middle-income countries in Asia and Africa (UN, 2018). As we move towards an increasingly urban planet, urban regions and their governments need to avoid getting locked into development pathways that put an increasing pressure on their natural and economic resources and may not be sustainable in the long run.

Most key urban Sustainable Development Goals (SDGs) assume the provision of some form of grid-based infrastructure to enable universal service provision in the areas of water and sanitation (SDG6), clean energy (SDG7) and sustainable mobility and ICT connections (SDG11). This is based on the 20th century experience of urbanisation in Europe, North America, Australia and parts of Latin America. This is neither true and may be unsustainable and unaffordable in parts of Asia, Africa and Latin America for the bulk of the incremental urbanisation of the 21st century, which will see an addition of 2.5 billion people to urban areas by 2050 (UN, 2018).

Cities and urban regions draw on natural resources, like water, from beyond their physical footprints. as well as create environmental and ecological impacts that extend beyond their administrative boundaries. The food-water-energy nexus is critical as resource and ecological constraints to urbanisation and urban expansion, in many regions. Urban regions are facing reduced availability and access to quality water. Urban water infrastructures are under threat from environmental degradation and land use change. They are simultaneously under severe pressure from changing climatic conditions such as irregular rainfall, a growing drought incidence, and rising temperatures, all of which are likely to be exacerbated by current development trajectories. As population densities and urban inequality increase, vulnerability and exposure to hazard risks also increase. All of these will have human well-being, public health, environmental health, and economic consequences.

Urban regions across the world therefore have populations that are increasingly vulnerable as the benefits of development are highly unequal across socio-economic classes. Access to water-related services and linked economic activity are deeply enmeshed with poverty, informality, sub-optimal technical arrangements and high relative costs. Nevertheless, there is widespread innovation that blends hyperlocal, local, and innovative services provision with a range of institutional and governance arrangements. Emerging planning and governing processes for urban regions need to begin to innovate urgently to respond to water and climate risks, while simultaneously building resilience.

The paper provides an overview of the current and emerging challenges that cities and urban regions face in the context of water stress, rapid environmental change, and social and political transitions. Drawing on case studies from key regions across the Global North and South, it points to some examples of ways forward.

Urban water

Urban settlements are marked by the diverse uses of water at differing scales as it includes: the household scale of domestic use, a larger quantum of use in economic and industrial uses of water and water-linked ecosystem services water often at the scale of the urban region. Across these types of uses, urban water is often sourced from beyond the region through piped water infrastructure and more locally through groundwater aquifers. While many urban neighbourhoods are connected to gridded piped water infrastructure, there are several others that continue to stay outside the formal water system (Colenbrander, 2016). Communities outside the gridded water infrastructure rely heavily on groundwater directly (sourcing water from within the urban boundary) or indirectly (through tankers and water vendors who could extract surface or groundwater from beyond the urban boundary). The latter often is an unregulated water supply market where vendors charge costly premiums to customers (Beard & Mitlin, 2021). Urban residents are willing to pay premium prices for consistent water supply in the absence of a reliant formal water connection (Magnusson & Van Der Merwe, 2005). Access to water has deeper implications beyond the financial cost of the resource. It has interconnected implications on access to food and energy, access to infrastructures of health, sanitation, and education among others (Bharathi et al., 2022) . These interdependencies make urban settlements a crucial site for the integrated local implementation of the SDGs.

At the moment there is a dissonance between institutions that are responsible for water supply along the lines of use (domestic, industrial and ecosystem services), source (surface water, groundwater) and scale (municipal/ local, regional and federal). This means that there is very little horizontal or vertical interaction between the institutions in charge on questions of urban water security (Gupta & Pahl-Wostl, 2013). This is a fundamental issue that is at the heart of water management and is a pivotal reason to use water as the organising principle. This is all the more important in the context of future urban transitions that will have a large water footprint not just in terms of domestic water consumption but in the process of creating the social and physical infrastructure that an urban settlement requires. Centering water and climate change at the heart of future developments is a necessity to ensure that we stay within the safe operating space of water use (Grafton et al., 2023).

Urban water use may not be comparable in terms of quantum as compared to other types of water use, especially irrigational use: 70% of freshwater goes into agricultural uses while only 12% of freshwater is utilised for domestic purposes (UN, 2024). However, the implications of urban water are far reaching. Urban water demand has impacts on water resources that are direct (e.g. through overuse of water, and pollution of sources) but also has embedded for food, energy and infrastructure. It is estimated that by 2030, there will be a global 40% freshwater shortage (Koop et al., 2017) which will have serious implications in the way urban transitions will occur. Additionally, latent challenges such as large gaps in data, poor capacity, lack of sufficient and consistent finance apart from the underlying fragmented institutional structure, make the urban water situation a complex one to unpack, in most regions. In the next section we aim to elucidate some of the major challenges around governing urban water and use case studies from the Global North and South to illustrate them.

Challenges with governing urban water

The challenges around governing water at the urban scale are unique due to the diverse types of water use vis-a-vis the quantum of water used and the fragmented governance of each use and type of water. In this section we address a few key challenges such as fragmented water demand, backward and forward linkages of urban water, financial and capacity constraints and finally the fragmented governance processes. We begin by describing the water crisis at the urban scale, particularly drawing attention to tangible and latent water consumption around urbanisation.

Scale of the problem

Urbanisation is a resource intensive process that is important not only at the subnational scale, but also globally. It is a complex process motivated by multiple factors, of which global politics and investments are important drivers. Decisions made around global trade and politics have deep implications at the local urban scale, particularly in the rapidly developing countries in the global south. Increasingly, investments towards industrial and economic growth are tied to urbanisation processes through mega projects like economic corridors (S. Anand & Sami, 2016). While economic prosperity that follows such developments in the form of increased GDP may improve access to utilities and services, it will be at the cost of depleting natural capital, in turn affecting marginalised and vulnerable populations (Grafton et al., 2023). Further, in the face of large-scale future urban transitions, trade-offs between natural resource management and conservation, dealing with urban environmental challenges, particularly climate change, as well as balancing the aims of balanced and just economic growth are critical to understanding and addressing the unique challenges and demands of urbanisation. An understanding of the deeply embedded nature of water in urbanisation processes is essential to enable sustainable urban futures.

Urbanisation is also not a uniform process and is influenced by particular histories that shape the realms of equity, access and demand with regard to urban resources in the contemporary period. The urban fabric therefore is heterogeneous, where urban neighbourhoods are diverse but also segregated along socio-economic markers. (Bharathi et al., 2022) illustrate an inverse relationship between urban segregation and availability of public services which is important to consider since the asymmetry in access to water is often not captured in administrative data collection processes. Balakrishnan & Anand (2015) refer to ‘shadow areas’ reflected in Master Plans, that are neighbourhoods with poor access to health and education. They use variables in the Indian context to show the correlation between access to water and sanitation to the socio-economic status and housing access of urban populations. Drawing from socio-economic data analysis in the context of Bengaluru, they argue that there are sub-cities marked by access to basic urban utilities. In this scenario, participatory bottom-up approaches towards gathering data and making policy decisions is necessary to understand the complexity of these issues and address them appropriately. Fragmented water demand makes it challenging to account for different water uses in urban settlements. In the next section we highlight a few important urban blue and green water uses while reflecting on the interconnected nature of the SDGs through them.

Fragmented water demand

Urban water use is particularly difficult to manage due to the diversity of water demand in a relatively dense region. It includes 12% that goes into domestic water use consumed at a household scale, 20% that is consumed for economic/commercial/industrial purposes at a much larger scale and the ecological and environmental flows in the urban region which are scattered across the urban region (UN, 2024). An added layer of complexity lies in the fact that each of these categories use water from different sources with a varying ratio that depends on access and tariff of water.

Water for these diverse uses is sourced from beyond the urban region through piped water infrastructure and more locally through groundwater aquifers and is supplied through diverse mechanisms raising questions of equity and access. There is also a dissonance between institutions that govern water according to use (domestic, industrial and ecosystem services), according to source (surface water, groundwater) and according to scale (municipal/local, regional and federal). While this paper only concerns itself with the use of blue and green water, an equally important point to note is the production of grey and black water[1] from these above-mentioned spaces that need to be included in the holistic governance of urban water. We look below at different components of urban water demand and their implications for sustainable water management in urban regions

Domestic consumption

At the domestic scale, universal access to piped water supplied via a network is lacking in most urbanising areas of the global south. Gridded water infrastructure in the form of piped water supply is uneven in urban areas due to embedded historical inequalities that have been reproduced across time (N. Anand, 2017). More often than not this has resulted in marginalised communities having to pay premiums to access water from private vendors since they are not connected to formal water infrastructure. Water connections in urban settlements are closely linked to property and tenure rights of residents, in the absence of formal documents to acknowledge these rights residents’ access to urban resources is further weakened. Balakrishnan & Anand (2015) show a correlation between socioeconomic status and access to housing, to access to water and sanitation infrastructure. Increasing urbanisation, especially in cities of the Global South, will exacerbate urban water equity and access concerns (Amankwaa et al., 2022)particularly in off-grid and low-income neighbourhoods in the Global South. Digital water infrastructure such as water ATMs (automated standpipes. Additionally, weaker access to safe infrastructures of water and sanitation is linked to health and wellbeing of urban residents. In the larger context

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[1] See ‘IIHS Working Paper: Transitioning Urban WASH’ for a more detailed analysis of urban grey and black water management.

of implementing the SDGs, concerns around access to water should be extended to access to social infrastructures. SDG 6 (clean water and sanitation) must be read and implemented in coordination with SDG 10 (reduced inequalities), SDG 11 (sustainable cities and communities) and SDG 3 (good health and well-being). These issues however, cannot be addressed only with a top-down approach and require participatory processes to understand the heterogeneity of these challenges across the urban fabric.

Economic demand

A second use of urban water is as an economic resource/input, has been growing with increasing urbanisation. Currently 20% of the global freshwater reserves are used for industrial purposes, estimated to rise to 24% by 2025 (UN, 2011, 2024). Currently, availability of water does not guide economic planning in urban areas, leading to unplanned extensions and extraction of water. While environmental regulations around water pollution and treatment are stringent in most countries, the supply side of the equation is not addressed with the same meticulous forethought. High commercial tariff is a common regulatory tool that plays a role in the consumption of blue and green water. However, users often bypass this method of federal monitoring by accessing off-grid water through borewells, tankers etc. (Tomer et al., 2021). This is crucial to consider particularly because the lack of affordable water could become a severe constraint to economic growth and incremental development in brownfield settlements.

A World Bank report states that economic growth rates are forecasted to decrease by up to 6% in certain regions by 2050 due to the effects of water shortages (World Bank, 2016). Alternate solutions to local water scarcity may prove to be too expensive, making drought prone and water scarce regions unsuitable for economic development. It is equally important to move away from a regulatory framework that is highly dependent on the tariff gradient since this disproportionately affects smaller economic/industrial enterprises in urban areas. Urbanisation, economic development and industrialisation are closely tied phenomena and have been driven by conceptions of mega infrastructure projects. In the last few decades, the resource-intensive infrastructure industry has boomed particularly around big urban centres.

Ecosystem services

Urban water systems provide critical ecosystem services such as facilitating drainage and stormwater management, hosting urban floral and faunal biodiversity, reducing evapotranspiration, replenishing groundwater tables, regulating micro climate, mitigating urban floods, and in the larger maintenance of the water cycle (Garcia et al., 2016; J. Li et al., 2020; Lundy & Wade, 2011; MEA, 2005). A unique feature of urban areas is the confluence of grey, blue and green infrastructures that have a significant impact on the microclimate. The issue of scarcity ("too less") is often highlighted as a failure to meet urban water demands, however, the complementary issue of urban flooding ("too much") is an equally pressing matter. Urban flooding due to the lack of appropriate and sufficient drainage systems is an overwhelming issue caused by multiple factors. Understanding drainage patterns and water systems in addition to monitoring rainfall, is crucial to create an urban environment that is resilient to risks like floods. Integrating these pools of data with urban planning methodology is crucial to allow a more compatible practice of city building. In many urban settlements, the increasing erasure of wetlands and water basins has contributed to the poor drainage that leads to floods (Ranganathan, 2015).

Conservation of water resources and wetlands such as lakes, tanks, groundwater aquifers contribute to the larger percolation and drainage of excess water (Alikhani et al., 2021). Creating innovative solutions at the urban region scale by implementing nature-based solutions through the integration of blue, green and grey infrastructures is the need of the hour (Kabisch et al., 2017). This is particularly important since urban water consumption does not occur in isolation and has many backward and forward implications as we highlight in the coming section.

Backward and forward linkages of urban water

The water consumed in urban settlements has consequences that extend well beyond the confines of the city. Cities are not self-sufficient entities and require resources from surrounding regions, this includes natural resources like water. In this section we focus on backward and forward linkages of urban water use to illustrate the impacts of considering the entire water supply chain. We refer to backward linkages as impacts of sourcing water before the supply to urban settlements. This includes ecological impacts on watersheds, biodiversity and non-urban communities. We refer to forward linkages as impacts post the usage of water in an urban area. This includes tracing the path of wastewater and its consequences on settlements downstream an urban area.

Gridded piped water infrastructures rely heavily on large water sources like rivers and reservoirs to fulfil urban water demands. Large scale and consistent extraction from these water bodies can have long lasting impacts on water levels which would in turn impact the biodiversity and hydrology of the waterbody. Additionally, groundwater extraction in aquifers outside the urban jurisdiction has dire effects on communities who rely on them for domestic household use. In rural jurisdictions where agriculture is a major economy, the water diversion to urban areas has severe impacts on the levels of groundwater. The unchecked use of groundwater within and beyond urban landscapes have long term impacts on the resilience of aquifers. Changes to aquifers and watersheds in turn impact the larger ecosystem they belong to, starting with soil biodiversity, a keystone in agricultural economies.

Subsequently, water post use, in the forms of grey and black water, is disposed outside the urban regions it is generated in. Globally, 80% of wastewater is disposed of into the environment (UN, 2018). A combination of treated and untreated wastewater joining a flowing water body like a river adversely impacts communities that are downstream. The contaminants also affect the biochemical properties of the flowing water that impacts life under water. The safe disposal of waste water is embedded not only in SDG 6 (clean water and sanitation) but also in SDG 3 (good health and wellbeing) and SDG 14 (life below water). However, in order to implement coordinated and integrated actions in the future, we must have a clear understanding of the current situation. Creating evidence-based decisions is possible only with accurate granular data that is periodically collected at granular levels as we highlight below.

Poor monitoring of the urban water crisis

A big gap in the way urban water is governed is the lack of accurate timely data around consumption of water. Considering that 80% of global gross domestic product (GDP) is generated in urban settlements, the monitoring of urban resource consumption is key to finding more sustainable ways to develop (Hodson et al., 2012). With regard to water use and consumption, it is critical to collect and record data regarding 1) natural water systems including groundwater consumption, aquifer percolation rates, water quality, drainage patterns, rainfall patterns etc; 2.) consumption data from gridded infrastructures - such as the piped water network; and 3.) consumption data from off-grid sources of water - that are often primary sources of water for marginalised urban residents. These are also key parameters in understanding the relationship of water to other social indicators such as access to health and sanitation as we will show further in this section.

Data collection and monitoring has advanced significantly with the development of new technology that allows for sensitive and real-time data collection and processing. State of the art Internet-of-Things (IoT) technologies allow capturing data such as contamination detection, pipe leakage detection, flood forecasting among several others(Fu et al., 2022). While data around water consumption and treatment is important for urban water management, it also plays a critical role in addressing urban inequality. Using water data in coherence with data around social security indicators such as access to healthcare, education, housing, sanitation etc would enable a more integrated approach to addressing inequality in urban settlements. As Balakrishnan & Anand (2015) and

Bharathi et al. (2022) illustrate in the case of Bengaluru, there is a correlation between access to public services like water and sanitation facilities, to the socio-economic status and housing access of urban residents. Data around urban inequality must be used to fulfil particular needs of marginalised communities outside the gridded infrastructure. In the larger goal to implement SDGs, data around water can be used intersectionally to create infrastructure, governance mechanisms and policies that are context specific and data driven.

In the absence of a holistic data availability, projections around urban water demand have been inflated in large cities such as Mumbai as illustrated by (Tiwale, 2021). Ironically, the increased water demand and supply has not necessarily meant equal access to the resource within the city. Marginalised groups and residents in urban slums still do not have access to safe water. Furthermore, the narrative of scarcity in Mumbai has led to redirecting water from other urban settlements and villages (ibid). At a larger scale, the demand for piped water has led to larger investments in dam projects, interfering with irrigational infrastructures and justifying the diversion of water from the hinterland.

An important point to consider while discussing problems around data and technologies that can capture and record real-time sensitive data is the monetary and human resource investment necessary for them. Countries in the global south often are not able to invest financially in these expensive technologies which not only require expertise to manage but also timely maintenance. Underinvestment in water infrastructure is an existing issue, which we illustrate in the coming section, that will extend to modern technologies without a serious amendment to the status quo.

Underinvestment in urban water systems

Many instances of infrastructure failure have been traced to insufficient re-investment in archaic hydraulic infrastructures and the poor capacity development of staff in the responsible institutions. Underinvestment in water infrastructure has led to high levels of Non-Revenue Water and leakages along the system, which impacts the financial sustainability of water utilities and supply institutions. This can also lead to a shortage of piped water infrastructure as urban boundaries expand (N. Anand, 2015). When the repair and maintenance of piped water infrastructure is not accounted for, it further exacerbates constraints in accessing safe water and its associated health benefits. Paradoxically, increased investment in large water infrastructure like dams has only increased the pressure on old piped urban water infrastructures due to the lack of periodical maintenance (Adams et al., 2020; Barkin, 2011; Hordijk et al., 2014).

Related to the low investment in maintenance and repair of water infrastructure is the trend of water privatisation. Private players entering the water delivery space has commodified water use leading to intensified inequalities across urban settlements. The pressure to increase return on the investment, often drives up the cost of water that many urban residents cannot afford. This system inevitably reproduces patterns of inequity that are manifested spatially across the urban fabric. Despite the focus on price, privatisation in the water sector has not been successful in many countries. After a brief rise in the 1990s, private participation in the sector has significantly decreased (MEA, 2005) resulting in the remunicipalisation of water without appropriate investment in the upskilling of state actors or upgradation of technology (McDonald, 2018).

Capacity challenges

An associated issue is the poor staff capacity around technological and governance upgradation. Investment in capacity training and strengthening is often not part of reform initiatives, creating a gap in the deployment of new technologies and management practices, by governmental system. Water unavailability is often addressed by modernising and upgrading engineering systems without enabling the appropriate knowledge transfer to local stakeholders. (Empinotti et al., 2018). Capacity building challenges however are not restricted to state actors. They can extend to non-state actors who play vital roles in participatory governance. Efforts to enable a larger support system to maintain urban water infrastructures that include non-state actors will allow a more diverse decision-making process. Investing in the training and upgradation of all actors involved in decision making and monitoring and evaluation to bridge knowledge gap, is important. However, the upskilling of state actors on new technologies must be integrated with tacit knowledge on the urban water systems. Magnusson and Van Der Merwe (2005) illustrate the importance of creating context specific policies around urban water use using the case study of Windhoek in Namibia (see Box 2). The Namibian case study highlights the importance of addressing unsustainable water use as well as issues of access to safe water through a participatory governance mechanism that includes non-state actors such as private water vendors in the larger discussions around urban water security. We also use the case of Mexico (see Box 2) where water reforms did not include elements of capacity building and timely flow of finance to local governments, leading to an overall poor governance mechanism. This brings us to the underlying challenge of fragmented governance across sectors and across multiple scales and jurisdictions. The subsequent section delves into issues around fragmented governance and its impact on the siloed practice of urban planning.

Box 1: Water Demand Management in Windhoek, Namibia

Magnusson and Van Der Merwe (2005) describe the water demand management in the city of Windhoek, Namibia through the lens of water justice resulting in a context specific policy architecture. Water managers of Windhoek have to tackle a dual challenge of increasing urbanisation along with unsustainable urban water use across a city that is segregated along serviced and unserviced neighbourhoods. Serviced neighbourhoods are connected to the formal piped water infrastructure while those unserviced by the gridded infrastructure buy water from private water vendors who charge them a costly premium. The result is an urban water management system that can be interpreted and adjusted to the specific characteristics of the neighbourhood’s context. In serviced neighbourhoods, water managers chose to increase awareness campaigns around decreasing water use and used a block tariff to incentivise efficient water consumption. Whereas in the unserviced neighbourhoods, water managers chose to include private water vendors into the regulatory framework while they regulated and supervise the water distribution system which increased access to safe and affordable water, without extra investment into infrastructure. This is an effective example of how the demand and need for water are both considered important issues to be addressed by water managers who are instrumental in facilitating and calibrating water management tools.

Box 2: Regulatory challenges in Mexico

Barkin (2011) illustrates the weakness of the Mexican regulatory system despite devolving important responsibilities such as water distribution to local governments, due to lack of timely support. Water distribution in Mexico is the responsibility of local governments following a mandate from the 1983 Constitutional amendment. This was a step to devolve responsibilities from the Federal government to regional and local government. However, many local governments do not have the institutional capacity or financial resources to procure, construct and maintain water infrastructure. Therefore, they are increasingly dependent on federal funds for operations and investment. Adding to this issue is the fact that much water consumption is not measured and many users are not registered in the system, causing heavy revenue losses and weak regulation. Local agencies are often not supervised and do not have a way to address grievances and demand accountability, creating an overall weak regulatory framework.

Fragmented governance structures

The most striking challenge in the governance of urban water is the existing fragmentation of governance and planning institutions across sectors reflected at many scales beginning with the global, sub-national and below. Several scholars have observed that the fragmented nature of governance within countries presents obstacles to effectively coordinating water management and planning with economic and urban development (Cook, 2014; Gupta et al., 2013; Hordijk et al., 2013; Pahl-Wostl & Knieper, 2014). The dissonance arises from the perception of water as an economic resource by institutions focusing on economic development, as a natural resource by those overseeing land use, agriculture, forests, and biodiversity, as a public good by consumers, and as a resource imbued with cultural significance by other stakeholders. Further, long legacies of institutions working with limited purviews and fixed responsibilities has cemented the respective values of water in the way it is governed. This makes it additionally challenging to change fundamental structural patterns even when new integrative policies are introduced. In the case of Botswana illustrated in Box. 3, the disjunct between urban planning and urban water planning has led to an overall poor governance of urban water.

Box 3: Urban water planning in Botswana

Botswana's urban planning and land-use planning has been codified through Development Plans since 1997, after years of haphazard and reactive urban expansion. The practice of urban planning in the country, is a highly centralised process, reflected in administrative structure where local agencies are highly dependent on the central government. The urban planning process involves surveys and data collection around land use patterns, health and education infrastructure, economic activities and employment patterns and housing. However, water demand assessment is addressed only by calibrating the water supply infrastructure. Urban water planning is fragmented across institutions that are in charge of urban planning and water planning and is not practised as an integrated process. This results in a myopic understanding of how urban water must be managed, reducing it to issues of supply and demand rather than a more holistic approach including conservation and management.
(E. Toteng, 2002).

Associated with fragmented urban institutions is the fragmented manner of urban planning praxis. The spatial and financial bias in the planning process, results in the inadequate consideration of natural resources in the urbanisation process. It does not consider perspectives of political ecology and ecosystem services, and minimises issues of water to that of insufficient engineering (Mehta et al., 2014). The benefit of implementing a participatory governance mechanism is the easy inculcation of a participatory planning mechanism. A just urban planning praxis is a crucial to tackle issues of inaccessibility and inequality. By ignoring elements of the urban environment and climate change, cities are facing multiple simultaneous extreme water events. With growing urbanisation and water scarcity, it is critical to unpack such disjuncts and work towards creating a more sustainable and integrated governance and planning framework.

An instance of poor coordination between urban planning and urban wetland conservation can be observed in Bengaluru, India. Bengaluru's urban hydrology depends heavily on the man-made water tanks (a.k.a lakes) built as a network infrastructure across the city over the last two centuries (Unnikrishnan et al., 2017). It was designed to ensure smooth drainage and percolation of surface water to rejuvenate underground aquifers. Periodical encroachment of the water bodies to create urban land has resulted in a rapid decrease in groundwater reserves. Furthermore, dense urbanisation in the city over the three decades has created a more intensive freshwater use in the city, adding pressure on the groundwater supply (Unnikrishnan et al., 2021) . At the moment, the scattered governance of the lakes, in addition to a spatially motivated urban planning practice has resulted in a governance framework that relies on short-term solutions that do not account for natural resource flows.

Another instance of poor urban water management having dire consequences on urban land is that of land subsidence in coastal cities such as New York, Jakarta and Mumbai (Abidin et al., 2011; Nalakurthi & Behera, 2022). A NASA-led study has reported that there have been variations in the land elevation of the New York metropolitan area. They suggest that land use practices are among the reasons for the land subsidence, making it more vulnerable to flood risks (Younger, 2023). Severe groundwater extraction has been attributed to being a major factor in occurrence of land subsidence, making the link between land and water management a critical one.

Opportunities/solutions

Thus far, we have discussed challenges in creating a holistic urban planning system, in the next two sections we explore a few ways in which it can be done. Water sensitive planning, for cities in particular, has been implemented in cities in Australia and China. We look at a few key elements essential in addressing challenges that we have identified above.

Developing water-sensitive plans for cities

A foundational principle while making water sensitive plans is the integration of water and urban planning. Currently urban land use, economic development, transport planning, and water planning are usually parallel processes with different line departments in charge of each process. The spatial and financially biased land-use planning practice should be integrated with the hydraulic practice of water planning. Further, water planning itself must plan for water of all kinds, moving away from the understanding that water security can only be measured through the quantum of water in the gridded piped water supply. Water planning must include blue, green, grey and black waters in the urban settlement since governance of these types of water is intrinsically linked to urban land management. The prior mentioned elements of data around water use could then be seamlessly integrated while making decisions around the urban area in question. Additionally, with a more democratic, egalitarian and participatory planning and governing mechanism, tacit and traditional knowledge around urban water systems can be used to create small scale solutions organically developed with local communities (Sen & Nagendra, 2022). We look at two different approaches to creating water sensitive planning in China and Australia (see Boxes 4 and 5 respectively). Water Sensitive planning includes planning for future infrastructure aligned with the local hydrology. Infrastructure in the urban settlements has focussed dominantly on availability of land and finance. As a result, dimensions of the urban environment are ignored which in turn produce environmental risks such as urban flooding, heat risks etc that are costly to address. When water is considered as the organising principle, the local hydrology becomes central to the way urban settlements are envisioned. Retaining and integrating natural drainage systems with modern sewerage infrastructure for instance would ensure lower backflow. Sustaining and maintaining urban wetlands would increase percolation and recharge of the groundwater, conserving urban biodiversity. (Sridharan et al., 2023).

Box 4: China's Sponge City initiative

China's Sponge City initiative is an active attempt at creating sustainable urban water management through the use of nature-based solutions and usage of tacit knowledge directed at preserving water security and ecological restoration. (X. Li et al., 2016; Yao & Bell, 2022). Innovative building practices such as Water Sensitive Urban Design (WSUD), Sustainable Urban Design System (SUDS), and Low Impact Urban Design and Development (LIUDD) have been implemented in select Chinese cities after 2015. The initiative includes vital actions such as urban natural ecological protection of green spaces and wetland as well as ecological restoration which includes repair and maintenance of ecological infrastructure that were damaged in the process of urban development. In some instances, it has involved planning at a larger regional scale, by connecting surrounding water bodies through human-made channels to increase surface water storage which also improves flood resilience. Small-scale solutions have involved replacing older plumbing systems with new ones to prevent the mixing of stormwater with polluted water which is collected in separate tanks for future natural infiltration into groundwater. (X. Li et al., 2016).

Box 5: Water sensitive planning in Australia

The Australian government's mandate to plan cities using Water Sensitive Urban Design (WSUD) began with its initial focus to manage stormwater appropriately which informed a larger more comprehensive framework to form a sustainable urban water management system (Wong, 2006). The framework considered institutional fragmentation, which used innovative governance arrangements that included local, regional and state department actors. It also considers community participation and engagement by involving them in understanding water problems as well as finding suitable strategies to overcome them. The inclusion of diverse non-state actors has resulted in small scale solutions. The separate collection of household grey water and rainwater and their delivery to tertiary treatment plans, has been successful. Further, the use of recycled wastewater and rooftop harvested water for non-potable purposes reduced the use of freshwater by 80 percent. (Brown et al., 2009; Fogarty et al., 2021; E. Toteng, 2002; E. N. Toteng, 2008; Wong & Brown, 2009).

Addressing fragmentation in governance structures

A closely related element in the pathway to attain better governance of urban water is addressing the fragmentation between governance institutions that are directly and indirectly responsible for water. While this seems simplistic, to have an effective governance mechanism in the long term, the governance process must be a result of an integrated planning and governance system. Agencies and institutions in charge of these processes must work in a coordinated manner even in the absence of a conflict. The disjunct between institutions is a glaring issue that is reflected at many scales beginning with the global, sub-national and below.

Intergovernmental water treaties and agreements have proved to be ineffective in most subnational jurisdictions because sub-national governments have limited mandates, resources and agency in dealing with transboundary issues. A serious recalibration of institutional processes and structures is necessary to address underlying fragmentation of urban and urban governance, to create more holistic governance and institutional arrangements for the future. (Gupta & Pahl-Wostl, 2013).

At the sub-national scale and below, a critical move towards having a robust governance system is by integrating institutional processes across line departments. Fragmentation across ministries and departments in countries is a well-studied concern across the globe (OECD, 2011). A New Culture of Water and Integrated Water Resources Management (IWRM), are suggested responses to the fundamental disconnect between different state and non-state stakeholders (Barkin, 2011; Biswas, 2013). A reconciliation of how water is valued and viewed by different institutional stakeholders is key to establishing an integrated process. This arises from the perception of water as an economic resource by institutions focusing on economic development, as a natural resource by those overseeing land use, agriculture, forests, and biodiversity, as a public good by consumers, and as a resource imbued with cultural significance by other stakeholders. Building a pragmatic regional consensus on the values of water could play an important role in adjusting the goals, mandates and responsibilities of institutions, which is a critical first step in coordination and integration of their functions. (Hubendick & Hebart-Coleman, 2023).

Moving further, the recalibration of institutional processes must include meaningful implementation of participatory processes, without which elements of water justice and equity will not be complete. Participatory processes do exist in most countries in some form, however the main critique of this method of seeking public participation is that it works at hyperlocal or local scales and is challenging to scale up. Community engagement is also challenging across metropolitan and urban regions as most communities are not homogenous and do not have equal power and agency. Despite these valid criticisms, it is important to have participatory processes to include non-state stakeholders, with varying levels of mandate and agency. We use the example from Accra, Ghana (see Box 6) to illustrate the value of participatory processes in creating an adaptive governance system. Water governance is an intrinsically political endeavour and should include stakeholders from all strata to create an equitable system of governance. (Adams et al., 2020; Batchelor, 2007).

Box 6: Participatory processes in urban water governance in Accra, Ghana

Morinville and Harris (2014) illustrate successes and challenges with participatory processes around urban water in Accra, Ghana. They focus on public participation through Local Water Boards (LWB), established by elected representatives from local communities with the help of Ghana Water Company Limited (GWCL), the municipal water supply company. The establishment of LWBs was an attempt to create an adaptive governance system and increase local participation. According to the local context and requirement, LWBs have also taken up additional responsibilities such as being in charge of delivering water to the community by managing water tankers and kiosks among other administrative tasks. LWBs have proven to be beneficial in extending water access to underserved urban communities, the reduction of non-revenue water, in managing water prices and payment processes as well as contributing to infrastructure development at the local scale. However, LWBs depend on voluntary time and effort of individual members without compensation, highlighting the burden of devolution and participatory governance on local community members. They also report that LWBs are not effective in all the communities they have been established in, impacting the overall adaptive governance of the city. This example highlights the complexities of participatory urban governance strategies. Public participation poses numerous challenges, among which the social power and clout of individuals to influence processes stand out as significant (Pahl-Wostl, 2009).

Lastly, the inculcation of traditional/tacit knowledge of water systems into the larger political and technocratic process of water governance is important to create a sustainable and equitable urban governance system. Modern water infrastructures rely heavily on gridded piped water supply is the major water source. This has proved to be insufficient in many cities and towns of the global south, resulting in large fractions of urban consumers relying on supplementary sources of water. Rejuvenation of traditional decentralised water infrastructures could help conserve groundwater and revive urban wetlands. The integration of modern scientific methods with traditional technology is vital to ensure urban water security and conservation of the urban environment. Conservation of urban wetlands and green infrastructures with modern technology is still challenging. We use the case study of Jodhpur (see Box 7) to highlight how an incomplete integration of traditional water systems with the grid-based piped water system exacerbated environmental risks (Mehltretter et al., 2023; van de Meene et al., 2011).

Box 7: Use of traditional water knowledge in Rajasthan, India

The water scarce Indian state of Rajasthan has many traditional water conserving technologies that have enabled efficient collection of sparse rainfall. Over the last century, these water bodies and auxiliary drainage infrastructure have gone to disuse. In an attempt to conserve water, the city of Jodhpur rejuvenated a few stepwells, *Jhalras*, that have significantly increased the groundwater table. However, as the city's piped water infrastructure is the major source of water, the dependence on traditional water harvesting systems has reduced considerably. The rejuvenation of the *Jhalras* along with dependence on piped water supply has led to a situation where a rising groundwater table has become a peril. The rejuvenation of the water bodies in addition to excess wastewater has contributed to shallow groundwater that inundates buildings and causes property damage. The combined volume of water also causes backflow of sewers and water logging. The case study highlights the importance of integrating technologies appropriately, in a given context, where traditional tacit knowledge and modern scientific method must be implemented in synergy. (Sridharan et al., 2023).

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AUGUST 2024

Citations

Beleyur, P., Revi, A. & Sami, N., 2024, **Reimagining Sub-National Water Governance**, Bangalore, India,
The Indian Institute for Human Settlements and the Global Commission for the Economics of Water.

Design & Layout: Nawaz Khan | Reviewed by Prachi Prabhu & Padma Venkataraman IIHS Communications & Design

ISBN: 9788198256805
DOI: https://doi.org/10.24943/9788198256805

First published in Bangalore, July 2024

This paper is part of a series of working papers commissioned by the Global Commission for the Economics of Water (GCEW).

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IIHS WORKING PAPER

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Introduction

Governing water, although not a new challenge, has assumed a renewed significance globally, particularly in the context of multiple emerging crises across social, ecological, economic, and spatial systems. Water governance is a complex and ongoing process involving stakeholders across regions and time-scales, where the future of water is a critical point of discussion in the context of sustainable development in the coming decades. Humans are radically changing and modifying the water cycle: solving the challenge of water governance is critical to the success of the SDGs: water is deeply embedded across all the SDGs and addressing the challenge of water governance requires a 'systems-thinking' approach that brings together water, climate change, biodiversity loss, land use change, and urban growth (Quentin Grafton et al., 2023). Work across research and policy has focused on efforts across scale and sector and have emerged from a range of disciplinary approaches (Woodhouse & Muller, 2017). In Windhoek, Namibia for instance, local water managers were able to solve issues around water demand and water need using perspectives from water economics (by using tariff as a tool) for residents of high-income neighbourhoods and sociological perspectives to include private water vendors into the regulatory system to monitor the sale of safe water for low income neighbourhoods, resulting in the larger conservation of urban water (Magnusson & Van Der Merwe, 2005). Research has also examined a range of existing, emerging, as well as proposed institutional mechanisms to enable equitable water governance. However, the challenge around questions of water governance remains, and has in many ways been exacerbated by the pressures of a changing climate, biodiversity crisis, rapid urbanisation, growing inequality and economic development.

Governance of water has been shaped by many actors and institutions at varying scales across the last few decades, particularly at the global scale through a range of agreements and treaties and include global institutions such as the different UN agencies and the World Bank among other multilateral organisations (Gupta & Pahl-Wostl, 2013), as well as through multiple convenings/conferences at the global scale around the question of water (Quentin Grafton et al., 2023). Although member countries sign and commit to these agreements, there is limited implementation at the country level due to multiple constraints such as existing institutional arrangements and as well as the scale, number and types of stakeholders who should be involved in these processes (Gunderson, 2018). Variations in governing arrangements and systems at sub-national levels also makes implementation of global level agreements challenging. Moreover, there are a range of issues such as sharing, allocation, capacity, and administrative insufficiencies around water use, management, and conservation that emerge specifically around regional and local scales for which contextualised governance solutions are needed. Sub-national governance of water resources has not received as much attention, especially in the context of rapidly urbanising regions in the Global South.

This paper makes a case for focusing on the governance of water particularly at the sub-national scale and unpacks critical issues at this scale of governance set in the context of rapid urbanisation and growing concerns around climate change and biodiversity loss. Rising inequality and imbalance economic development across the world has led to increasingly unequal access to natural resources, water being a critical one. A re-examination of water governance is critical since water is embedded within and critical to the implementation of several of the Sustainable Development Goals (SDGs), directly (for example, SDG 6 - clean water and sanitation) or indirectly (for example, SDG 3: good health and wellbeing, SDG 9: infrastructure, SDG 11: sustainable cities and communities, and SDG 13: climate action) and will have a large impact on the way the future is shaped.

Countries in the Global South face a disproportionate burden as multiple crises converge around ecological, economic, social and spatial systems (Lobo et al., 2023). Over the past 50 years, water disasters including floods, droughts, storms, and extreme temperature changes have impacted more than two million people in the Global South (Q. Grafton et al., 2023). Water, is emerging as a critical constraint, since it is embedded within various systems and water insecurity has implications for equitable and sustainable growth. Many regions in the Global South are investing heavily in water and wastewater infrastructure systems as they grow and urbanise and inappropriate developmental, technological and institutional choices may mean that they could get locked into unsustainable development pathways.

Moreover, as we have seen in the case of multi-level climate governance, sub-national governance processes and mechanisms do not always align with national and international goals and policies (Jörgensen et al., 2015). Water governance mechanisms particularly need to be aligned with local and regional developmental aims and growth agendas, since global treaties and agreements often fail to be implemented at the sub-national scale due to incompatible internal governance and policy structures (Gupta et al., 2013). Developing multi-level governance processes for water at the sub-national scale is also an important point of investigation since it allows us to study how policies disseminate and devolve within an existing governance structure in a riparian state. The success of global initiatives such as the Sustainable Development Goals (SDGs), depends on how these are interpreted and implemented at local scales. This is particularly relevant to water since it is directly or indirectly embedded in the SDGs. SDG 3 (good health and wellbeing) is directly linked to the availability and access to safe water and at a larger scale to infrastructures of water and sanitation that would come under the purview of SDG 6. Access and availability of water, sanitation and health are in turn connected to SDG 10 (reduced inequalities) bringing into the picture the socio-economic indicators that determine access to water (Balakrishnan & Anand, 2015; Mehta et al., 2014).

In this paper, we attempt to make a case for focusing on sub-national governance arrangements across three key aspects: types or colours of water; different types of uses of water; and across a range of settlement patterns ranging from the rural to the urban. We focus on blue and green water that constitute the major freshwater sources used for human and non-human activities at the household level for domestic consumption, economic development and ecosystem services at the larger regional scale. We investigate current governance practices in the larger context of increasing urbanisation, particularly in countries of the Global South where most urban growth will take place (UN, 2018). Understanding water governance is key to addressing the current fragmentation of water governance as we describe further in the paper.

Setting the context

The issue of water governance has been examined across multiple sectors and from different disciplinary perspectives and geographies. At the global scale, collective agreements and actions such as the Millennium Development Goals (MDGs), multilateral transboundary river sharing agreements and more recently the Sustainable Development Goals (SDGs) have seen some success in implementation at respective national levels. Most multilateral agreements and resolutions on the issues of water have been at the global scale, mobilised by the UN and global institutions such as the World Bank and the OECD, where representatives of riparian states have agreed towards collective action and goals. Initiatives like the Global Water Partnership (GWP) have been instrumental in advocating for strategies such as the Integrated Water Resources Management (IWRM) to improve coherence at the global but also at the national scales. Challenges around water values, pricing, privatisation, justice and equity have been discussed extensively across multiple geographies citing gaps in the way global water governance is imagined and therefore designed (Quentin Grafton et al., 2023).

While global conventions are important as they bring together a collective agreement towards an issue particularly around shared resources like water, there is little downstream implementation at the sub-national scale. The subnational scale is a heterogeneous territory since historical trajectories of policy, legislation and governance of individual riparian states are not uniform, and can vary significantly. Thus, when global agreements are to be implemented at the subnational scale through legacy institutions and policies, they fail due to incompatibilities between the objectives and visions of water governance, the political economy of local institutions, policy instruments and incentives. For instance, the vision around IWRM requires an inter-connected governmental structure that allows for a collective vision to be implemented across ministries and sectors.

However, this is not possible in many countries, with their current fragmented governmental setup that has strict silos in the way they govern different types of water use (Biswas, 2013). The intrinsic relationship between land and property rights and water management also has a large bearing on the way countries govern green water (Bosch & Gupta, 2023)

The lack of implementation of global agreements at the sub-national scale is due to multiple factors including unfavourable institutional lock-in, infrastructural lock-in, technology barriers, mismatch between the stakeholders involved and their interests along with issues of a scale-mismatch in the larger governance framework (Q. Grafton et al., 2023). Institutional hierarchies and structures at the national level are a result of their policy histories that are difficult to adapt to new policy objectives, particularly those made at a global scale. Further water governance systems and frameworks tend to be fragmented across ministries, sectors, and jurisdictions as well as along use, type and source leading to siloed planning and governance of water within a geographical jurisdiction(OECD, 2011). This makes it particularly challenging to implement strategies such as the IWRM (Biswas, 2013). The OECD report on the 'Water governance challenges in African cities' (OECD, 2021) states that weak institutional structure particularly around IWRM, in addition to poor integration between sectoral policies contribute to overall poor water governance.

Further, the fragmentation of water governance along the types of water is a pertinent issue since most governance frameworks focus on blue water without its integration with the other colours (grey, black and green) of water. A stark issue in the future would be the integration of green and blue water governance, since it has a strong relationship with the way land is owned, planned and governed. In addition to this is the difference in governing water used for different purposes such as industrial, domestic, irrigational and ecosystem services, as well as across space across the rural-urban continuum. Scattered governance across multiple institutions and scales reiterates the different values of water which guides the eventual governance of the water in their respective jurisdictions. Differing institutional values creates a dissonance in the way water is imagined and therefore governed. Many countries have established river-basin governance arrangements that bring together multiple stakeholders to address a water sharing and governance.

Stakeholders on the urban-rural gradient will need be mobilised to create more coherence in the way blue and green water is governed across that continuum. Participatory governance and planning as well as devolution of decision making around water are can create conducive spaces to implement larger SDGs and IWRM-linked strategies. Long term solutions guided by a holistic vision around an integrated water governance framework is the need of the hour. Towards this end, we offer a few perspectives through the course of this paper.

Approaches to subnational water governance

Water governance at the national and subnational scales are typically driven by hydro-hierarchies, with unequal power wielded by key actors who have the authority to make decisions around water (Q. Grafton et al., 2023). To move away from legacy based institutional decision making and policies, new perspectives to value water will need to be imbibed. A part of this transition would be to account for the different colours of water and their unique governance requirements. For instance, the governance of green water (soil moisture) is inexplicably linked to the governance of land-related institutions related to green water.

Centring water in the governance of other sectors is fundamental towards building a resilient and sustainable future. In order to achieve this, there is an urgent need to build coherence in policies and objectives within the water sector as well as across sectors (Gupta et al., 2024a). Presently, the different colours of water are governed within narrow context due to narrow objectives of institutions in charge of them.

Blue water governance includes addressing challenges around freshwater across different sources such as rivers, aquifers and other surface water bodies between subnational institutions. Besides governing for their use, the framework must also include the downstream impacts of using the freshwater. Post-use, blue water from urban regions are often transformed into grey and black waters which are dense in organic matter and inorganic pollutants. Leaving these pollutants in the water affects human and non-human health and well-being, not to mention compromises the quality of water. Aligning sanitation infrastructures with water supply infrastructures is critical in developing more efficient and equitable water consumption systems, particularly in rapidly urbanising countries of the Global South. Coordinated actions like this will automatically allow countries to successfully implement interconnected SDGs. These actions, would for instance, address objectives of SDG 6 (Clean Water and Sanitation), SDG 3 (Health and Wellbeing) as well as SDG 14 (Life Below Water).

Similarly, green water (soil moisture) is tied closely to property rights and soil health. The use of land for different purposes therefore has deep implications for the conservation of green water. In rural settings, this has implications in the way agriculture is practised, often resulting in nitrate-polluted green water that is unsuitable for the microbial soil biome which further impacts agricultural productivity in the long term (Gupta et al., 2024c; Singh et al., 2024). The fundamentally unsustainable agricultural practice that is dependent on chemical fertilisers and pesticides to grow water intensive crops, impacts the quality of green water (Gupta et al., 2024a). At the national scale, the governance of green water is tied to the vision and practice of agriculture and global trade, strengthening the water-energy-food and environment nexus. Further, in countries of the Global South, where tenure and ownership status of land is often a contested, implementation of blanket policies and regulations around the conservation of green water is neither useful or equitable. Modernising land records and updating local revenue records, on the other hand, would significantly aid the process of creating evidence-based policies around green water governance. Here, for example, we see the potential of achieving goals of SDG 10 (reduced inequalities) and SDG13 (climate action) through integrating water governance mechanisms, which may allow us to address the overuse of the fossil fuel and chemical fertilisers in modern agriculture. Moving away from agricultural practices like monoculture of water-intensive crops, that consume fossil fuel-based fertilisers and pesticides, towards diversified local crops would significantly reduce water and carbon footprint of countries (Singh et al., 2024).

At the global level, there have been a few approaches to water governance that have been advocated such as the Integrated Water Resources Management (IWRM) through the Global Water Partnership (GWP). Many countries have adopted the principles of IWRM into their existing governance systems to allow for a more collaborative and participatory system of water management. It includes user groups at the community scale to increase accountability and build a network to promote inclusion of tacit knowledge along with modern technology (Rahaman & Varis, 2005). Another approach that has origins in the Spanish social movement is the New Culture of Water (NCW) that hinges on the key principle of power distribution, not allowing administrators complete control of the resource (Barkin, 2011). Another important element of this approach is the culture of water use, taking into account the social dimensions around water management. Besides a holistic governance and a political system, participation from members of society is critical to its success.

In order to fruitfully implement these visions, it is important to address institutional challenges at subnational scales, like states, provinces, cities and regions. Institutional challenges stemming from fragmented governance structures are passed down the governmental system and get reproduced across times. Besides having a fragmented structure, institutions are also burdened due to financial limitations and insufficient capacity among others (Q. Grafton et al., 2023). Addressing these challenges at their respective scales is important to address governance dysfunctions at a larger scale.

This is closely linked to the way different types of water use including economic/industrial, domestic and ecosystem services are governed. Institutions across scales typically have narrow mandates over a fixed jurisdiction. While this is helpful in creating accountability, it often hinders the implementation of larger system-wide goals such as the SDGs. Relevant state and non-state stakeholders participating in the water governance process is important to create more equitable and inclusive governing arrangements. This would also be useful in allowing a bottom-up approaches to respond more adaptively to diverse local policy environment. Creating adaptive governance is crucial to designing evidence-based and context-driven water management systems, strengthened by traditional and tacit knowledge of water, embedded in local context. We elucidate a few of these approaches and challenges in the next section and present case studies to illustrate them.

In this paper we focus on blue water or freshwater and its interlinkages with green water, given its inherent relationship to land and property rights. We begin by illustrating how the sub-national space plays an important role in the governance of water particularly in the context of future urbanisation. A critical requirement to create resilient and robust governance frameworks, is a reliable, granular and consistent data architecture across sectors. Capturing timely data is important not only to understand current circumstances but also to project future trajectories. Data around different types of water uses integrated with data from different ministries has the potential to create a robust planning mechanism.

Creating a robust data architecture around water

A recurring issue across multiple sectors is the lack of reliable and consistent data, a vital requirement to create robust policy and regulatory frameworks. Data when available, represents large populations and does not have the granularity required to illustrate an accurate picture of reality. In the specific context of water, data around water extraction, consumption, replenishment and treatment is rather poor making it challenging to project future consumption patterns. This issue leaks into other administrative challenges around underinvestment in water infrastructure, under delivery of services, inaccurate projection of future resource use (Tiwale, 2021). Balakrishnan & Anand (2015) elucidate issues around data through a case study of Bengaluru, analysing data across 9 parameters. They argue that administrative boundaries are too large resulting in data being homogenised, therefore not giving an accurate picture of urban inequality. The lack of granularity of data therefore allows ‘shadow areas’ to exist in master plans, where there is very low access to basic social infrastructures like health, education, water and sanitation. As an extension, data around different types of water use across different sources, and institutional and sectoral jurisdictions would allow stakeholders to design a more inclusive society. Understanding water consumption from a socio-ecological perspective will allow stakeholders to address issues around equity, sustainability and conservation (Mehta et al., 2014). Analysing material flows will contribute to creating more efficient systems and contribute to the larger goal of sustainable resource management while prioritising just allocation and access to water (Gupta et al., 2022; Hodson et al., 2012). Using modern technologies to capture more accurate real-time data is a seemingly easy solution on paper, however, the reality of implementing these solutions is slightly different. Often, the lack of consistent finance to install the technology and maintain skilled staff to operate and analyse the data to inform policy processes can be a serious constraint. Bridging the financing gap across the governmental hierarchy is necessary but may not be the only solution to addressing key issues around water. In the next section, we offer possible approaches that align interests around water governance with those with national and global traction, such as climate and heat action.

Financing

Constraints in finance is a considerable roadblock for many institutional activities, particularly at the sub-national scales. At the same time, many nations are now investing actively in climate funds and green funds to address climate change at the national level, devolving responsibilities to the lower levels of government. Climate action funds at the national scale is an opportunity to bring together different stakeholders, towards creating an inclusive regulatory framework. Inculcating water goals through initiatives such as these allows stakeholders from across the board to work together. The Green Fund of South Africa for instance is an initiative that promotes the transition to a greener economy. The fund is a collaborative effort between the Development Bank of Southern Africa and the Department of Forest, Fisheries and Environment, and funds private enterprises as well as subnational governments like municipalities allowing state and non-state actors to participate. Another collaborative initiative is the National Adaptation Fund for Climate Change (NAFCC) in India funded through the National Bank for Agricultural and Rural Development (NABARD). The bank aids the implementation of projects identified by State Action Plans on Climate Change prepared by individual subnational states and includes capacity building as an identified area requiring upgradation. Innovative financing mechanisms are critical in tackling complex interconnected issues particularly around climate change and natural resource management. It facilitates small scale solutions and cohesion across existing funding frameworks, allowing water to be integrated into the larger goals (Koop et al., 2017). Financial security is a crucial element the absence of which triggers a sequence of related barriers particularly around capacity as we discuss further.

Capacity

The complexity of water governance challenges requires specific types of capacity building within governing institutions: existing governing institutions are not only deeply understaffed; they also lack the technical knowledge as well as access to cutting edge science. Capacity building needs to focus not only on building the ability of state institutions to manage complex issues around water, but also to develop structures that draw on technical experts, community knowledge and multi-scalar and multi-sectoral approaches. Issues around capacity do not pertain only to the skill set of state actors but also to the way capacity systems are imagined. This is particularly important since there is no organisation at the global and national level dedicated to governing the water cycle (Q. Grafton et al., 2023). Horizontal and vertical linkages across different scales of government and concerned agencies is crucial in building adaptive capacity particularly in the face of accelerating climate change (R. Q. Grafton et al., 2011; Gupta et al., 2024b).

In addition to training and building skill sets of state cadres, it is equally important to design a system that is able to adjust policies and practices in changing circumstances. A system that anticipates change and responds proactively through an interactive network of information, capacity and finance (Koop et al., 2017). Keeping water justice and equity at the centre of multi scalar urban governance systems, deliberate attempts must be made to ensure that spatial inequalities are not reproduced (Bharathi et al., 2022)or neighbourhood residential sorting within a ward (the elementary administrative and political unit in urban India. Parallel mechanisms in the realm of climate action, can be appropriately borrowed to enable a better cohesion across the organisational, network and government levels (Willems, 2004). Subnational government institutions such as cities, states and provinces in America, have been able to work together by implementing climate action strategies in their administrative jurisdictions (Osofsky, 2010).

Reimagining the role of state and non-state stakeholders in water governance

An important observation across different federal water governance systems is the shift away from state-led hierarchical governance models to more participatory frameworks of governance that include non-state stakeholders. While this is an important step towards creating a more democratic model of water governance, there is a need to integrate these processes across scale and across sectors. The inclusion of non-state stakeholders like individual water users, private sector players and civil society groups have played important roles in water advocacy and infrastructure creation that have enabled hybrid models of governance (Gupta et al., 2013).These non-state actors have played crucial roles in supplying alternative water supply systems and off-grid solutions at the neighbourhood scale in many Global South cities, supplementing the larger state supplied water network. However, appropriate regulation is a necessary to protect against monopolies over land and water resources, that will contribute to increasing urban inequality. The inclusion of non-state actors in governance arrangements and negotiations, have been inconsistent, contextual and dependent on power hierarchies. It has often restricted the creation of a level playing ground, as differential power, grounded in economic, political and social identities and the limited clout of these non-state stakeholders has a bigger impact on the decision-making process (Adams et al., 2020).

Often efforts to decentralise have not been successful as they lead to local territorial competition and conflict rather than conservation, making the exercise counterproductive (Pinel et al., 2018).For instance, the failed devolution of water management to local governments in Mexico led to the re-centralisation of federal power (see Box 1). Multi Stakeholder Platforms (MSPs) are often offered as a solution to issues around participatory planning to encourage and inculcate public participation. However, they may not always be a solution to this complex challenge. MSPs have a tendency to “homogenise the problem” where perspectives are antagonistic leaving little room for a collaborative decision-making process. In such a situation, technocratic models of water governance, that have been the norm, take over as a default method of water regulation and governance (Batchelor, 2007).

Box 1: Recentralisation of power in Mexico

Water reforms in Mexico brought about the creation of a 1983 Constitutional amendment that made it the legal responsibility of local governments to manage and treat water in their jurisdictions, under the supervision of the National Water Commission (CONAGUA). These local agencies face many constraints including financial and capacity deficits to respond to an overwhelming demand to meet international water management.

At the same time, federal authorities created incentives to involve private participation in the water sector to help modernise infrastructure. Public-private participatory models such as the BOT (build, operate and transfer), often placed the burden of cost-recovery on local agencies, many of whom are not equipped for the task. The quality of the privately constructed infrastructure, caused an overall loss of revenue. In a lax regulatory environment where local agencies are unable to enforce environmental regulations and standards, unchecked extraction of groundwater, and pollution, could well ensue.

Financially insecure local agencies became heavily dependent on federal funds even for operations. As a result, the CONAGUA which was originally imagined to be an advisory and supervisory body, took on the core responsibilities of modernising water sector technology, “intensifying its efforts to promote the international private sector for the modernization and management of the infrastructure” (Barkin, 2011). A growing market of industrial and commercial users supported by local power groups caused an increase in local water extraction. Local governments are typically not equipped to monitor or regulate a diverse set of water arrangements leading to a situation where CONAGUA has eventually (re) centralised powers over the country’s water resources (Barkin, 2011).

Box 2: River Chief System in China: a collaborative governance model

The River Chief System in China is an example of collaborative governance established within a hierarchical institutional framework. Instituted in 2016, this system operates through hierarchical representation at the provincial, urban, county, and township levels. At each scale, the River Chief is responsible for coordinating concerned departments to solve intersectional water issues. The cadre of River Chiefs, at different scales, are in-turn tasked with coordinating and managing water resources both horizontally and vertically within the institutional framework. This system has enabled greater inter-departmental collaboration and cross-scale collaboration, creating a more holistic approach to water governance. (Wang & Chen, 2020)

Governing for water security and equitable access to water

Current water governance systems do not prioritise just and equitable access to water. The lack of a uniform understanding of water security and justice has led to a situation where objectives of institutions vary significantly based on the metrics and values of water, they consider more important. There is often a deep dissonance in the way access to water is understood across ministries and agencies in a typical urban, regional and national system. Adding to this is the disjuncture between water security and water access where water security of a country does not translate to equitable access to water within it (Hordijk et al., 2013). Rapid urbanisation exercises have resulted in urban jurisdictions being expanded beyond gridded infrastructure of institutions in charge of water supply. Peripheral urban neighbourhoods relying on off-grid solutions often tap into water sources from neighbouring agricultural and rural jurisdictions, negatively impacting the aquifer in question. Water running in gridded infrastructures is also sourced from outside the urban hydrological boundary, severely impacting the source environment. Additionally, is the increasing virtual water footprints across urban areas, agriculture and economic activity. Irrigational water is also a supplied gridded infrastructure that depends on water sources distant from the point of use. The invisible use of water through commodities and services imported into a settlement has adverse impacts on the larger hydrological system and the Global Water Cycle.

A critical re-examination of stakeholders, water values and jurisdictional boundaries is crucial to build an integrated cross-scale water governance system. The convergence and regulation of state and non-state stakeholders from state- provided municipal water utilities, private utilities, informal markets among others is necessary to create an equitable water governance system. A reassessment of governance of water from different and types for different uses is urgent to recalibrate the fundamental fragmentation between blue and green waters for the coming decades. (Hordijk et al., 2014).

Box 3: Governing water sharing between regions: the Cauvery River basin in India

Flowing through India's southern peninsula, the Cauvery River marks the basin boundaries across four south Indian states: Tamil Nadu, Karnataka, Kerala, and the Union Territory of Pondicherry. The water sharing dispute in the Cauvery River basin in southern India illustrates the challenges around sub-national water governance. The Indian states of Tamil Nadu (downstream) and Karnataka (upstream) have shared water from the Cauvery for over a century, in spite of many altercations around water sharing, since the late 1800s.

The dispute primarily focuses on the sharing of water between the two states, especially in times of water scarcity. Both states have been trying to get a larger share of the river water to cater to the needs and demands of growing populations and economic activity. This conflict is exacerbated by growing water demands by increasing urbanisation in Karnataka (where Cauvery water caters to the megacity of Bengaluru's water supply), growing population as well as irrigation and other economic developments.

While several attempts have been made over the years to negotiate use terms of the river water across the century, there has been no permanent long-term solution. India has implemented Integrated River Basin Management for decades. Yet, Cauvery River water sharing remains an ongoing conflict that is currently being mediated through the courts. In the late 1990s, the Cauvery Water Disputes Tribunal (CWDT) was established to resolve the issue. After two decades, the CWDT issued its ruling on water sharing between all four riparian states. This ruling remains contested and the conflict tends to resurface, during times of water scarcity.

The dispute between the states represents a classic upstream-downstream water sharing conflict. With increasing pressure on the Cauvery, the river is increasingly viewed as a mechanistic resource rather than a dynamic ecosystem, impacted by local and global processes, including climate change. There is an urgent need to rewrite the narrative around water sharing that not only prioritises the sustainable use of water, but also minimises ecological harm and is responsive to challenges posed by climate change. (Bhave et al., 2018; Garg & Azad, 2019)

Potential ways forward

As we have discussed through the course of this paper, the path forward must involve a critical rethinking in the approaches towards a holistic water governance system. One that involves diverse sets of stakeholders, knowledge areas and methods. This is possible only with a review of current processes and mechanisms to one cantered around water security, water justice and sustainability. A cross-sectoral effort including non-state stakeholders could streamline these processes and governance arrangements considerably. This requires governance mechanisms to transcend ministerial and departmental mandates to create a larger vision of water security that includes blue, green, grey and black waters. Integrating different forms of knowledge, technology and financing arrangements will also enable a more context specific water governance framework, as we describe using the case of Ahmedabad in Box 4.

Integrating multiple forms of knowledge into the water governance framework

Water governance is a complex ongoing process involving many stakeholders of varying power and influence. In order to achieve an equitable water governance system, in a particular context, all values of water must be considered including cultural and traditional values. Part of this endeavour would be bridging the current tacit and traditional knowledge with modern scientific knowledge. By default, this means the inclusion of citizens, residents and local community members in any governance arrangement. A collaborative process must include “diversity and debate” (Batchelor, 2007) without which integration is not possible.

Box 4: Integrating tacit knowledge with public participation in the mitigation of urban floods in Ahmedabad, India

A successful instance of integrating tacit knowledge with modern systems is that of Ahmedabad’s disaster resilience plan for urban floodings. Based on cycles of rain fed urban floods, the local corporator (representative of the urban local body) and the local community members have developed a communication system. When there is a risk of urban flooding, the corporator sounds the alarm and relays the information to the community residents who then turn off valves to avoid backflow of the rainwater into the sewage system. This system was built organically based on vernacular knowledge of the urban flood phenomenon in their neighbourhood, allowing the women in the community to organise themselves to seek help. The alarm was a prototype designed by the Mahila Housing Trust, Ahmedabad and has been crucial in keeping the community safe from flood risks. (Brahmbhatt & Jhabvala, 2020).

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WATER IN A CHANGING CLIMATE: NAVIGATING RISKS AND PATHWAYS TO A MORE RESILIENT FUTURE

IIHS WORKING PAPER

SEPTEMBER 2024

Citations

Bazaz, A., Ghoge, K., Krishnaswamy, J., Revi, A., 2024, **Water in a Changing Climate: Navigating Risks and Pathways to a More Resilient Future**, Bangalore, India, The Indian Institute for Human Settlements and the Global Commission for the Economics of Water.

Design & Layout: Nawaz Khan | Reviewed by Prachi Prabhu & Padma Venkataraman IIHS Communications & Design

ISBN: 9788195847358
DOI: https://doi.org/10.24943/9788195847358

First published in Bangalore, September 2024

This paper is part of a series of working papers commissioned by the Global Commission for the Economics of Water (GCEW).

WATER IN A CHANGING CLIMATE: NAVIGATING RISKS AND PATHWAYS TO A MORE RESILIENT FUTURE

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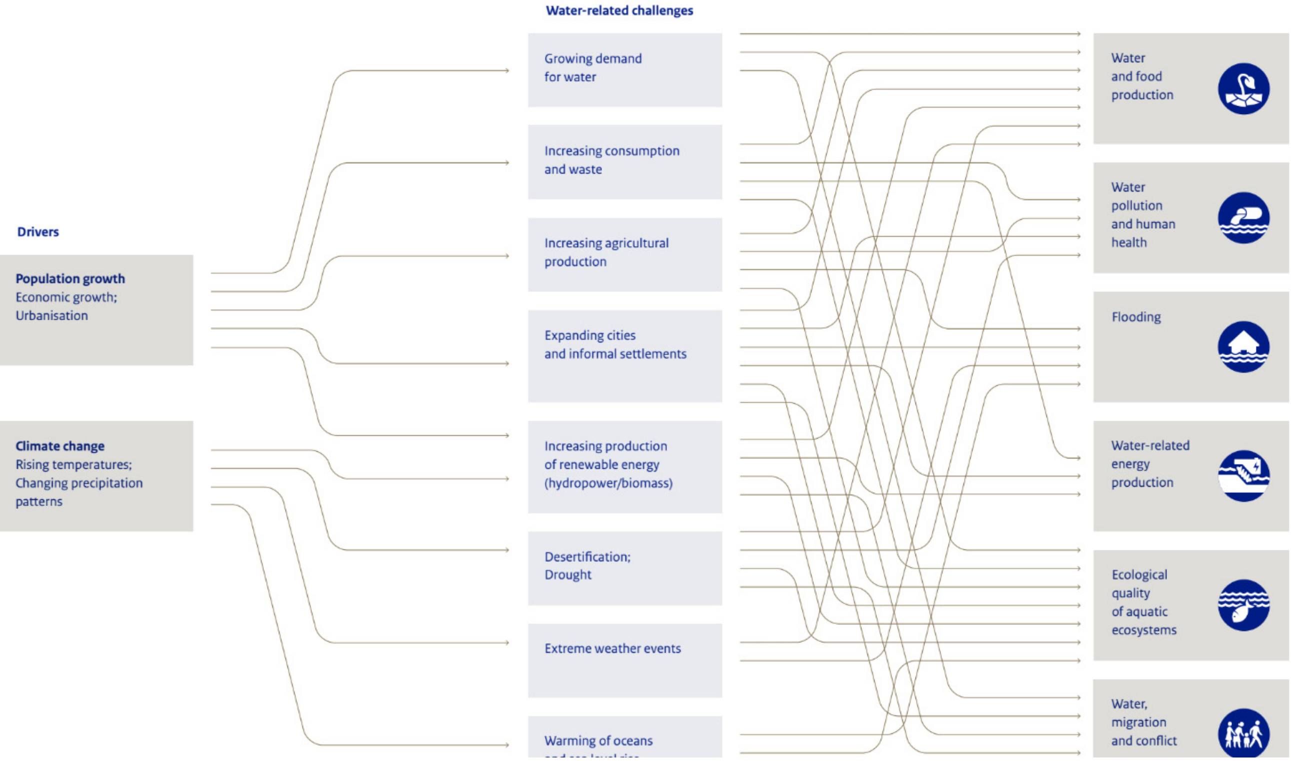
1. Introduction

The world stands at a critical juncture regarding the sustainability of the global water cycle. Rapid urbanisation, global population growth, rising demand fueled by economic prosperity, and escalating ecological stress intensified by climate change are swiftly altering the water cycle worldwide (PBL, 2018). Manifested as too little (water scarcity), too much (excessive floods), and too dirty (water pollution), the systemic water crisis affects millions of people today, and is the reason behind several local to global complex sustainable development challenges (Grafton et al., 2023). In the coming decades, the global water crisis can worsen climate risks as we overshoot 1.5° C, accelerate the biodiversity crisis, and lead to severe economic and social impacts ranging from increased food insecurity to conflict (Grafton et al., 2023). A sustainable future necessitates a deep understanding of the evolving risks linked to water and climate change between now and 2050 (PBL, 2018). The global water cycle and climate change are intricately interlinked as indicated in the figure below and climate impacts are often felt through water.

Figure 1: Linkages between climate and water-related challenges



Source: PBL, 2018

This working paper reviews current assessment and scholarship on the links between climate change and water, the impacts of climate-induced water risks, and water adaptation challenges and constraints. It makes a case for Climate Resilient Development (CRD) as negotiated by the IPCC in its Sixth Assessment to integrate water, climate, biodiversity and sustainable development agendas to bring about transformational change and briefly states key enabling conditions that can accelerate this change.

The next section of the paper (2) assesses how climate change is reshaping the global water cycle paper, followed section 3 that examines climate-induced water challenges, and section 4 that looks at vulnerability and adaptation to climate-induced water impacts. Section 5 discusses climate resilient development as an overarching framework to address climate and water crisis along with key enabling conditions to accelerate CRD.

2. Climate change is reshaping the Global Water cycle

The latest assessment from the IPCC on the physical science basis of climate change brings together robust scientific evidence on the climate impacts on hydrology and the water cycle. The impact of climate change on the global water cycle is evident in reduced snow cover, variations in precipitation, an increase in the frequency and intensity of extreme events such as floods and droughts and rising sea levels. IPCC assessments show that climate change has been altering the global water cycle since the mid-20th century and will continue to significantly change it at both global and regional levels (IPCC, 2021a). Many of the impacts of continued warming are expected to worsen in high emission scenarios in a world with temperatures above 2°C by 2060s.

Global warming is projected to increase variability in precipitation, surface water flows, and the severity of both wet and dry events. Projections suggest that average annual global land precipitation may rise by 0–5 per cent under very low greenhouse gas (GHG) emissions (Shared Socioeconomic Pathways (SSPs)[1] 1-1.9), 1.5–8 per cent under intermediate GHG emissions (SSP2-4.5), and 1–13 per cent under very high GHG emissions (SSP5-8.5) scenarios by 2081–2100 compared to 1995–2014 (IPCC, 2021a). While precipitation is expected to increase over high latitudes and parts of the equatorial Pacific and monsoon regions, decreases are projected over subtropical and select tropical areas under intermediate, high, and very high emission trajectories of SSP2-4.5, SSP3-7.0, and SSP5-8.5 (IPCC, 2021a). Continued warming is also likely to lead to an earlier onset of spring snow melt, leading to heightened peak flows and reduced summer flows in snow and glacier melt-dominated regions worldwide (IPCC, 2021a).

Warmer climate is also likely to impact flood and drought occurrence but the specifics of these extreme events in terms of their location, frequency and intensity hinge on other projected changes in regional atmospheric circulation, including monsoons. For instance, rainfall variability associated with El Nino-Southern Oscillation is likely to be magnified in the latter half of the 21st century under intermediate and high emission scenarios (IPCC, 2021a).

In the foreseeable future, climate models predict that monsoon precipitation is expected to rise world-wide, particularly impacting South and Southeast Asia, East Asia, and West Africa (IPCC, 2021a), although the uncertainty in some regions such as South Asia is higher. However, the monsoon season is likely to have a deferred onset in North and South America, West Africa, and a delayed withdrawal over West Africa. Non-monsoonal systems such as Western Disturbances that contribute significantly to regional water security are also likely to show shifts in timing and intensity leading to damaging impacts as already observed in recent years

Over the 21st century, droughts are also likely to become more frequent and severe and impact larger land areas. Agricultural and ecological droughts are likely to heighten in some regions due to increased evapotranspiration fueled by human-induced climate change (IPCC, 2021b). There is evidence to show that land-use changes and water extraction for irrigation also significantly impact local and regional water cycles by creating water imbalances including across transboundary aquifers with 'groundwater stress hot spots' showing up in the Indo Gangetic basin, Iran, Arabian Peninsula, and some parts of South Africa (Rodella et al., 2023).

Rising temperatures can also exacerbate demand for water due to increase in crop water demand, and dropping yields, leading to further groundwater depletion. Bhattarai et al. (2023) point out that in India, the net withdrawals are projected to increase by three times from 2041 to 2080. India is the world's largest user of groundwater for irrigation, covering more than half of the country's total irrigated agricultural area, responsible

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[1] SSPs are climate change scenarios of projected global socioeconomic changes up to 2100 as defined in the IPCC's AR6 assessment reports. They are used to derive greenhouse gas emission scenarios with different climate policies. Representative Concentration Pathways (RCP) are climate change scenarios to project future GHG emissions.

for 70 per cent of food production (IPCC, 2022b). However, excessive extraction of groundwater is depleting aquifers across the country, leading to shrunken water tables in large areas, especially in the northwestern states, where the Green Revolution started.

Estimates indicate that over abstracted groundwater in India could be in the range of 122 to 199 km^3 between 1996 and 2016 alone (Rodella, Zaveri, and Bertone, 2023). The World Bank working paper by these authors points to significant groundwater depletion world's arid and semi-arid regions, with most evident impacts in the Middle East and South Asia (Rodella, Zaveri, and Bertone, 2023). They state that while ground water has cushioned the worse impacts of climatic variability in the past, given the depletion levels, it may be unable to do so in the face of future adverse climatic impacts. Overall, the variability of the water cycle and associated extremes are expected to outpace mean changes across most regions globally, regardless of emissions scenarios (IPCC, 2021b).

A warming climate has also led to a rise in the global mean sea level, primarily due to loss of ice on land and the expansion of sea water caused by ocean warming (IPCC, 2021a). Between 1971 and 2018, thermal expansion accounted for half of the sea level rise, while glacier melt contributed 22 per cent, ice sheets 20 per cent, and changes in land-water storage 8 per cent (IPCC, 2021a). It is also estimated that extreme sea levels that occurred once per century in the recent past will occur about 20 to 30 times more frequently by 2050 and 160 to 530 times more frequently by 2100 across all major emissions scenarios (IPCC, 2021a).

3. Climate-induced water-related challenges

The number of people facing water stress is likely to increase in the face of rising higher average temperatures, variability in precipitation due to climate change, along with growing competition for water resources (PBL, 2018). Projections indicated in this report point to 25 per cent increase in global water consumption by 2050 largely driven by increased demand from agriculture, industries and settlements and The maximum water use stems from agriculture, more than 80 per cent, more so in South and East Asia, followed by industry, households and then electricity (PBL, 2018). Water stress and climate-induced changes to the water cycle have implications for agriculture and food security, freshwater ecosystems and biodiversity, energy production, and on our cities and infrastructure as discussed below.

3.1 Impacts on Agriculture

Droughts have been identified as a major driver for adversely impacting climate change and food insecurity, while the evidence of impact of floods on food production is limited (IPCC, 2022a). Climate variability and extremes account for 20–49 per cent of crop yield anomaly variance, with 18–45 per cent attributed to droughts and heatwaves (Vogel et al., 2019). Drought emerges as a leading cause of global yield reductions, supported by various studies (Anderson et al., 2019; Leng & Hall, 2019; Lesk et al., 2016; Zipper et al., 2016).

For instance, in Europe, droughts have had a detrimental impact on yields, with losses increasing threefold between 1964 and 2015 (Beillouin et al., 2020; Brás et al., 2021) . In West Africa, altered climate conditions, including drought, led to millet and sorghum yield losses between 10 per cent and 20 per cent, and 5 per cent and 15 per cent, respectively, from 2000 to 2009 (Sultan et al., 2019). Furthermore, between 2006 and 2016, droughts led to food insecurity and malnutrition in northern, eastern, and southern Africa, Asia, and the Pacific (IPCC, 2022a).

Modelled impacts of blue water and heat stress on global food production and hunger up to 2050 also show that global food supply could reduce by 6 per cent, 11 per cent, and 14 per cent on an average under the Representative Concentration Pathways (RCPs) and SSPs : RCP 4.5, RCP 8.5 SSP-2, and RCP 8.5 SSP-3 (Grafton et al., 2022). The extent of food supply losses however differ widely across regions and different climate scenarios. For instance, food supply in USA is projected to decrease by 4.8 per cent under RCP 4.5 and by 13 per cent under RCP 8.5 SSP-3 scenario, while in China, food supply is projected to fall by 9 per cent under RCP 4.5 and by 22 per cent under RCP 8.5 SSP-3 scenario.

The impact of climate-induced water-related hazards on agriculture also varies among populations and genders. Subsistence farmers, particularly in low-latitude regions with hotter and drier climates, face significant food insecurity risks due to hydroclimatic factors (Shrestha & Nepal, 2016; Sujakhu et al., 2016). These farmers, heavily dependent on agriculture for their livelihoods, historically bear the brunt of observed climate-induced hydrological changes (Savo et al., 2016). At the same time indigenous and local communities, deeply rooted in agriculture, possess valuable knowledge of observed changes, crucial for shaping farmers' perceptions and adaptation strategies (Caretta & Börjeson, 2015; Savo et al., 2016; Sujakhu et al., 2016).

3.2 Impacts on Freshwater Ecosystems and Biodiversity

There has been significant evidence of loss and degradation of freshwater ecosystems due to climate change although human abstraction is still the dominant driver of wetland loss. IPCC's special report (2019) on climate change and land has also reported on loss of wetlands since the 1970s.

Changes in precipitation in timing and intensity and enhanced snow melt can significantly impact river flow dynamics leading to unpredictable low and high discharges, increasing frequency of both droughts and floods and bringing more complex challenges to river basin management. Climate change also emerges as a critical driver impacting freshwater ecosystems through various avenues such as increased temperatures and declining rainfall (Díaz et al., 2019; Dziba et al., 2019). These changes induce physiological stress or mortality among species, disruption and limiting food supplies, prompting migration to new habitats, where possible, and potentially escalating competition with existing fauna in these new areas. Other drivers such as land use changes, water pollution, and invasive species often act synergistically with climate change or worsen due to climate change (Convention on Wetlands, 2021; Ramsar Convention on Wetlands, 2018).

It has been recorded that temperature fluctuations contribute to shifts in freshwater species distribution patterns, with warming temperatures driving poleward and up-elevation range shifts, ultimately leading to reduced range sizes, particularly affecting species in tropical regions (IPCC, 2022a). Tropical regions include the most biodiverse river basins and there has been a steady decline in their quality, which is projected to decline further up to the 2050s (PBL, 2018). The strongest decline in quality of freshwater systems with biodiversity is estimated from Sub-Saharan Africa and parts of Latin America and Asia, with the most decline having occurred in Europe and North America (PBL, 2018).

The Ramsar Convention on Wetlands (2018) highlighted a 35 per cent decline in freshwater wetland areas between 1970 and 2015. Notably, Madagascar and Indian Ocean islands (43 per cent), Europe (36 per cent), the tropical Andes (35 per cent), and New Zealand (41 per cent) recorded high levels of overall proportion of threatened species. Globally, about 75 per cent of projected freshwater biodiversity loss will be caused by a decline in wetland area and increasing eutrophication from increased nutrient emissions from cities and agriculture (PBL, 2018). A quarter of biodiversity loss is likely to result from hydrological disturbances caused by buildings thousands of new dams (PBL, 2018).

Evidence also suggests a warming trend in lakes, with summer surface water temperatures increasing by 0.34°C per decade between 1985 and 2009 (O' Reilly et al., 2015). However, individual lake responses vary based on local characteristics, with warming sometimes exacerbating eutrophication impacts . The main drivers for freshwater ecosystems decline and loss of biodiversity are population growth and unsustainable economic development including pressures from urbanisation, industries, agriculture that results in change of land use and pollution

(PBL, 2018). This is further compounded by climate change-induced impacts like increase in temperatures, declining rainfall, snow cover, and increased consumptive use of freshwater. These factors collectively lead to the decline and threaten the extinction of numerous freshwater-dependent populations.

3.3 Climate Change Mitigation and Energy Production

The profound climate change impact on future hydro-climatic patterns extends to the energy sector with significant consequences across the system (Fricko et al., 2016; Vliet, Beek, et al., 2016; Vliet, Sheffield, et al., 2016). The reliance on fossil fuels for power production means that climate-induced reduction in water availability and increased stream temperatures have significant impact on thermoelectric power generation, primarily reliant on water for cooling purposes (Larsen & Drews, 2019). Water also serves other functions in power generation, including pollution control, dust management, and cleaning processes (Larsen & Drews, 2019). Presently, 98 per cent of electricity generation hinges on thermoelectric (81 per cent) and hydropower (17 per cent) sources (IPCC, 2022b).

As the efforts to decarbonise the energy sector progress, renewable energy including hydropower, wind and solar photovoltaics will play a pivotal role in the energy mix. Hydropower accounted for 2.5 per cent and wind, and solar energy constituted1.8 per cent of the global primary energy supply in 2017 (IEA, 2019). By 2028, it is estimated that renewable energy sources will contribute over 42 per cent of the global electricity production, with wind and solar accounting for 25 per cent (IEA, 2023). While wind and solar energy operate independently of water, their efficiency is influenced by atmospheric conditions intertwined with hydrological processes.

In contrast, hydropower's operation directly hinges on water availability, serving as a crucial mitigating factor against seasonality, climate variations, and diurnal production fluctuation compared to wind and solar energy (IPCC, 2022b). But hydropower plants, particularly those lacking storage capacity, are susceptible to climate-induced variability such as drought, when there is not enough water to generate electricity (IPCC, 2022b). Increased warming, and more surface evaporation will also lead to less water storage and loss of generation efficiency, leading to potential conflicts over the water use for irrigation and power production Warmer water also accelerates biological growth, heightening the risk of water intake blockage. Increased precipitation can also impact power production by increasing debris accumulation and vegetation growth (IPCC, 2022b).

Overall, analyses indicate that the global impact of climate change on hydropower is relatively small but regional impacts are large and can be both good and bad. The projected gross global hydropower potential for the 2050s shows a slight decrease (Hamududu & Killingtveit, 2012), ranging between 0.4 per cent under low emission scenario and 6.1 per cent under high emission scenarios for the 2080s compared to the baseline scenario period of 1971-2000 (Vliet, Beek, et al., 2016).

Regional variations are larger with increases ranging from 5 to 20 per cent in high latitude areas and decreases in the same range for drought-prone areas (IPCC, 2022b). Since many thermoelectric plants rely on water for cooling, their proximity to rivers and coastal areas makes them vulnerable to flooding. Rising water temperature or limitations in cooling water availability pose risks to both hydroelectric and thermoelectric facilities. For instance, a mere 1°C increase in coolant water temperature can result in a power output decline of 0.12–0.7 per cent (IPCC, 2022b). While certain regions might witness capacity increases under climate change, globally, mid-century projections suggest thermal power plant capacity reductions ranging from 7 per cent to 12 per cent, depending on global emissions (IPCC, 2022b).

3.4 Impacts on Cities and Infrastructure

Climate change presents existential challenges to cities and urban areas across the world. By 2070, 7 billion people, nearly 70 to 75 per cent of the global population will be living in cities or urban areas, within a coastal area, river basin, delta or a dryland region (PBL, 2023). Cities and urban populations especially in the developing world will face greater water and climate-induced risks largely because of the concentration of people, buildings, infrastructure, economic activity, along with vulnerability and poverty and inequality.

Climatic impact drivers including heat, precipitation variability, cyclones, storm surge and sea level rise are projected to increase incidence of heatwaves, drought, water scarcity, floods, coastal erosion and flooding, tropical cyclones, and wind hazards in urban areas (Gallardo et al., 2022). In the future, as warming increases, cities will also face increasing cascading risks from compound and simultaneous climate events – drought with heat waves, heavy rains with floods and storm surges, tropical cyclones, floods and wind hazards - that can paralyse urban lives. Many of these risks will multiply as temperatures rise. Water is an essential requirement for performance of urban blue and green infrastructure for heat stress mitigation under climate warming. For instance, an additional 350 million living in urban areas are estimated to experience severe drought and water scarcity at 1.5°C, this number grows to around 410 million at 2 °C warming (Adelekan et al., 2022). By 2100, coastal flooding in cities is likely to impact up to 510 million people and expose infrastructure worth nearly USD 7.9 to 12.7 billion to flood damage and risks (Adelekan et al., 2022). For instance, by 2050, 60 per cent of Mumbai will be located in flood-prone areas; this area can increase even further with a one-meter rise in the sea-level (PBL, 2018). In many coastal cities, especially in the Asian delta, groundwater abstraction is adding to climatic risks, leading to subsidence and could impact an area larger than Spain, spanning 0.5 million Km2by 2070 (PBL, 2023).

People living in informal settlements in cities are most vulnerable to water and climate-related disasters, whether it is coastal flooding or water borne diseases. Ensuring a healthy living environment in urban areas through climate resilient infrastructure and services, including safe and adequate access to water and sanitation, especially to the urban poor is one of the most critical challenges of the future (PBL, 2023).

4. Vulnerability and Adaptation to Climate-induced Water impacts

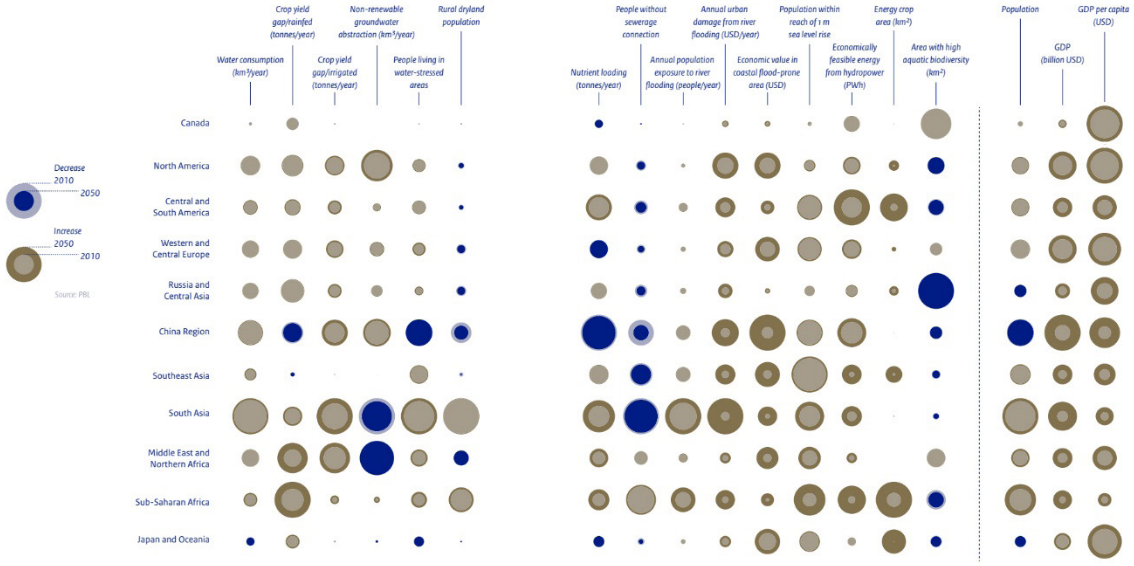
There is increased vulnerability to water-induced disasters such as flood, drought, and other hydrological changes across most sectors and regions (IPCC, 2022a). For instance, at 2°C of warming, several climate-induced changes linked to the water cycle and storms are likely to impact large areas and lead to region-specific changes compared to the recent past.

In Southern Africa, the Mediterranean, North Central America, Western North America, the Amazon regions, South-Western South America, and Australia, there are likely to be increases in droughts, aridity, and fire weather that can affect the agriculture, forestry and health sectors, and ecosystem health (IPCC, 2021b). In regions like North-Western, Central, and Eastern North America, the Arctic, North-Western South America, Northern, Western and Central and Eastern Europe, Siberia, Central, South and East Asia, Southern Australia and New Zealand, decreases in snow and ice or increases in river flooding is anticipated, which can impact winter tourism, energy production, river transportation, and infrastructure IPCC, 2021b).

Having said that, climate and water-related stress and risks are not borne by all people and regions equally. Evidence shows that regions and people with higher development constraints and deficits have higher vulnerability to climate hazards. Climate extreme events have exposed millions to increasing food security and water scarcity with the highest adverse impacts being observed in Africa, Asia, Central and South America, Least Developed Countries (LDCs), small islands and the Artic (IPCC, 2023). Globally the impact is borne disproportionately by indigenous peoples, small-scale food producers, low-income households, minorities, and women.

It is also projected that under a business-as-usual scenario, Sub-Saharan Africa and South Asia are likely to face the largest increase in water and climate-linked stress and challenges from 2010 to 2050, followed by Middle East and North Africa, and Central and South Africa (PLB, 2018). The figure below sourced from PBL (2018) shows the projected changes across regions for about 15 water and climate indicators including urban damage from river flooding, rainfed crop yield gaps, and people living in water-stressed areas, among others.

Figure 2: Water and climate-induced challenges across the globe



Source: PBL, 2018

The figure shows that economic damages from river flooding and coastal flooding across all regions is slated to increase from 2010 to 2050. Additionally, rainfed-crop yield gaps are likely to increase significantly in the Middle East, North Africa and Sub-Saharan Africa region. In China and South Asia, water-and climate-linked challenges, which are already severe are likely to get even more grim by 2050, specifically with regards to flood-related damages and fall in crop-yields. Major climate adaptation challenges linked to water include issues of water scarcity, heightened risks of floods and droughts, and adverse impacts of rising water temperatures on both water quality and biodiversity (PBL, 2018).

Evidence shows that business-as-usual development trajectories amplify exposure and/or vulnerability to water and climate change hazards, disproportionately affecting poorer regions. At the same time, developed countries also have to adapt to the changing climate and sea level rise by retrofitting much of their urban infrastructure and operations of many sectors that continue to be based on expectations of an older climate. While there has been progress on adaptation responses, much of the existing adaptation globally is 'fragmented, incremental, sector-specific, and unequally distributed across regions' (IPCC, 2023, p.8). Significant adaptation gaps exist across all geographies and climate-induced water impacts like flooding, droughts, and food security, with adaptation gaps being the largest for poorer populations across regions (IPCC, 2023).

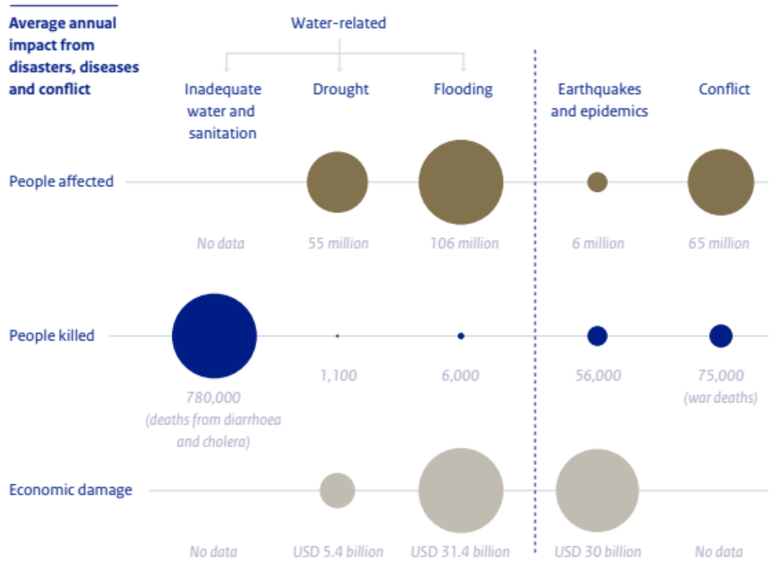
Structural failures in adaptation, as highlighted by the World Economic Forum among its top 10 global risks, underscore the urgent need for crafting collective adaptation frameworks to navigate the uncertainties ahead (PBL, 2018). Unlike climate mitigation pathways for reducing emissions, global adaptation frameworks that can align national efforts, and monitor and evaluate progress towards shared goals are yet to materialise (PBL, 2018).

Such frameworks are essential to guide strategies and interventions across multiple scales, addressing interconnected challenges and trade-offs, and coordinating the actions of diverse stakeholders (PBL, 2018). These can serve as the foundational step to fostering climate resilient development (CRD). CRD, a development framework introduced in the IPCC's Sixth Assessment Report, brings together sustainable development, climate action (both adaptation and mitigation), and biodiversity goals based on complementary development interventions rather than trade -offs between climate action and sustainable development (IPCC, 2022 ; IPCC, 2023; Stern and Stiglitz, 2023).

Figure 3 below shows the severity of potential impact in terms of damages and fatalities due to too little, too much and too dirty water. The projected annual fatalities from poor water quality due to water-borne diseases like cholera and diarrhoea stands at 0.8 million. The average annual economic damages from floods and droughts are estimated to be worth USD 31 billion and 5 billion (PBL, 2018). Further, without adequate adaptation, future water-related impacts of climate change on various sectors of the economy are estimated to lower the global GDP from 6 to 12 per cent by the 2050s, with higher losses projected in low- and middle-income countries (GCA, 2019; World Bank, 2016).

The World Bank report (2016) estimates up to 6 per cent GDP losses, pushing some regions into sustained negative growth post 2050s. And the GCA report (2019) projects losses from 7 to 12 per cent in the absence of effective water adaptation in countries like India, China, besides Central Asia and GDP loss of 6 per cent for much of Africa. Nearly 70 per cent of all risk to infrastructure stems from climatic hazards like storm surges, floods, landslides from deluge, with only 30 per cent associated with geological hazards like earthquakes and tsunamis (CDRI, 2023). CDRI (2023) report estimates the total average annual loss to infrastructure including buildings, health, and education sectors to be in the range of USD 732 to 845 billion, or 0.8 percent of current global economic output.The cost of these impacts underlines the need to accelerate adaptation to respond to an overshoot of 1.5°C in the near future and prepare for potential global warming that can exceed 2.5°C for a sustained period in this century.

Figure 3: Impact of water-related risks



Source: PBL, 2018

While global adaptation frameworks are yet to take shape, at least 170 countries and many cities have taken the first few steps to include adaptation in their climate policies and action plans (IPCC, 2023). There are several tried and tested adaptation interventions implemented across the globe, depending on local contexts with documented benefits.

Many of these effective adaptation options including those that ecosystem-based like the restoration of wetlands and natural water bodies, urban greening, sustainable water management practices including wastewater and stormwater recycling, and nature-based solutions like sponge cities are aimed at adapting to changes in freshwater ecosystems and addressing water challenges like urban floods, water scarcity and drought, and coastal flooding (IPCC, 2022a; IPCC, 2023; PBL, 2023). PBL report (2023) argues for adopting a river-basin and ecosystem approach towards spatial development and planning so that nature based solutions in design and planning, restoring natural habitats, regulating water and sediment dynamics, water proofing infrastructure gets mainstreamed in development plans.

Other effective adaptation options include sustainable land management practices, crop diversification techniques, irrigation, agroforestry, besides social infrastructure measures like early warning systems, disaster risk management, and social safety nets (IPCC, 2022a). For example, water and soil conservation practices, such as reduced tillage, mulching, are widely acknowledged as effective adaptation strategies for mitigating water-related climate impacts (IPCC, 2022a). These measures rank among the top four adaptation responses across all continents except Australasia. Water and soil conservation techniques also have economic advantages, positively impact vulnerable communities, offer significant water saving potential, and yield positive ecological and socio-cultural benefits (IPCC, 2022a).

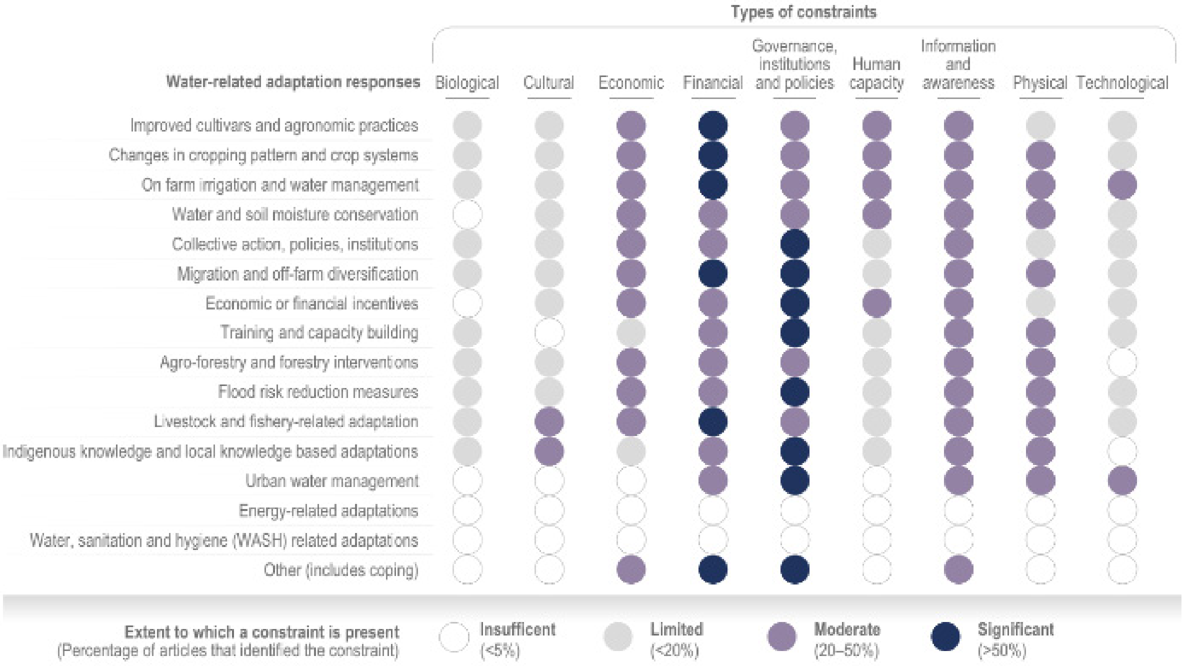
The effects of ecosystem-based adaptation and most water-linked interventions, decrease with increasing temperatures (IPCC, 2023). Hence, it's important to note that adaptation comes with limits – soft and hard – especially as warming increases. Soft limits currently being faced by small scale farmers and low-lying coastal households can be overcome with better policies, institutional responses, and finances. Hard limits are largely a point of no return when adaptation is no longer possible in the face of intolerable risks like sea level rise, that can force cities and settlements to retreat from the coastline. Some polar, coastal, and mountain ecosystems have reached hard adaptation limits (IPCC, 2023).

4.1 Water-linked Adaptation Constraints

Major barriers to adaptation include inadequate finances, lack of institutional, governance capacity, lack of private sector participation, low climate awareness, lack of political will, and slow uptake of technology (IPCC, 2023). Adaptation constraints for water-related adaptation can be biological, technological, financial, cultural, economic, physical, institutional, etc. as shown in the figure below. The IPCC assessment (2022a) shows that institutional constraints including governance, policy, and institutional arrangements, along with operational factors like path dependency, inadequate financial resources, and limited access to information pose significant challenges to implementing adaptation interventions in the water sector (see figure below).

Despite the implementation of various adaptation measures, water-related losses and damages are likely to persist in various regions of the world, particularly impacting vulnerable populations. Adverse climate impacts will also lead to increased losses and damages, and thereby reduce the scope for adaptation finance (IPCC, 2022a). In small islands with limited water resources and regions dependent on glaciers and snow melt, there are significant constraints to adaptation, with evidence pointing to hard limits (IPCC, 2022a).

Figure 4: Water-linked adaptation constraints across different dimensions



Types of constraints

Water-related adaptation responses	Biological	Cultural	Economic	Financial	Governance, institutions and policies	Human capacity	Information and awareness	Physical	Technological
Improved cultivars and agronomic practices	◔	◔	◕	●	◕	◕	◕	◔	◔
Changes in cropping pattern and crop systems	◔	◔	◕	●	◕	◕	◕	◕	◔
On farm irrigation and water management	◔	◔	◕	●	◕	◕	◕	◕	◕
Water and soil moisture conservation	○	◔	◕	◕	◕	◕	◕	◕	◔
Collective action, policies, institutions	◔	◔	◕	◕	●	◔	◕	◔	◔
Migration and off-farm diversification	◔	◔	◕	●	●	◔	◕	◕	◔
Economic or financial incentives	○	◔	◕	◕	●	◕	◕	◔	◔
Training and capacity building	◔	○	◔	◕	●	◔	◕	◕	◔
Agro-forestry and forestry interventions	◔	◔	◕	◕	◕	◔	◕	◕	○
Flood risk reduction measures	◔	◔	◕	◕	●	◔	◕	◕	◔
Livestock and fishery-related adaptation	◔	◕	◕	●	◕	◔	◕	◕	◔
Indigenous knowledge and local knowledge based adaptations	◔	◕	◔	◕	●	◔	◕	◕	○
Urban water management	○	○	○	◕	●	○	◕	◕	◕
Energy-related adaptations	○	○	○	○	○	○	○	○	○
Water, sanitation and hygiene (WASH) related adaptations	○	○	○	○	○	○	○	○	○
Other (includes coping)	○	○	◕	●	●	○	◕	○	○

Extent to which a constraint is present
(Percentage of articles that identified the constraint)

○ **Insufficent** (<5%)
◔ **Limited** (<20%)
◕ **Moderate** (20–50%)
● **Significant** (>50%)

Source: IPCC, 2022

5. Implementing Climate Resilient Development

Effective climate action to address climate- and water-linked challenges requires CRD. CRD anchored in principles of equity, justice, and inclusion integrates adaptation, mitigation, and sustainable development, into everyday activity. However, CRD cannot be implemented through siloed or sector-specific actions, it requires systems transitions across 5 key areas including urban and infrastructure, land, freshwater and ocean ecosystems, energy, industry, and societal behaviour tied to consumption and lifestyle choices.

Water is not only pivotal for each of the systems transitions, but it also cuts across and links all 17 SDGs. The majority of the SDGs cannot be met without access to adequate water (Ait-Kadi, 2016; Mugagga & Nabaasa, 2016). Over the years, water has also shown its potential to be a catalyst for cooperation rather than contention. It can serve as a unifying force, facilitating the convergence of interests, breaking through barriers, and fostering a collective vision for the future (PBL, 2018).

It is hence vital to mainstream water-led adaptation interventions in developmental frameworks and ensure synergies between mitigation and adaptative actions instead of trade-offs. This is important since there is evidence that both adaptation and mitigation actions can be maladaptive by leading to higher GHG emissions or causing water scarcity (IPCC, 2022a). For example, several mitigation pathways, including use of solar pumps, treatment and use of wastewater and desalination projects, depending on their contexts, can have adverse results such as depletion of groundwater, higher emissions due to energy-intensive processes, etc. (IPCC, 2022a). Similarly, increased demand for renewables in the face of energy transition is slated to increase in hydropower dam projects but these have considerable adverse impacts in terms of loss of freshwater biodiversity and fisheries, sediment flows to deltas and coastal zones that is required to counter sea level rise and subsidence (PBL, 2023).

Presently, adaptation strategies in developing countries often lean towards autonomous and incremental approaches, primarily focusing on mitigating water-related risks in agriculture (IPCC, 2022a). Conversely, developed countries tend to adopt more policy-driven measures, with a particular emphasis on urban areas (IPCC, 2022a).

While human activities are expected to be the major driver for future water scarcity at a global level, regional analysis shows that the uncertainty surrounding climate change means that reduced water availability is likely in several major river basins (IPCC, 2022a). This uncertainty persists even in basins where projections suggest an increase in precipitation and gross water availability due to a shifting climate. Uncertainties regarding projected water scarcity will be an important consideration contributing to future integrated water management policies and planning. Consequently, areas forecast to experience significant rises in water scarcity with substantial uncertainty, present the most formidable hurdles for both surface and groundwater management (IPCC, 2022a).

5.1 Accelerating Climate Resilient Development

IPCC (2022) outlines seven enabling factors that can help implement and accelerating CRD while achieving water security, facilitating systems transitions, and attaining the sustainable development goals. These include polycentric water governance, political support, gender, equity and social justice, adequate financing, the use of appropriate technologies, inclusion of indigenous and local knowledge, and participative and bottom-up engagement (IPCC, 2022a). We discuss five of these enabling principles below:

Polycentric water governance and political support:

Polycentric governance refers to an absence of central or unique authority and existence of multiple centres of decision-making. It has been shown to lead to better environmental outcomes and improvements in water governance (IPCC, 2022a). Enhanced governance and environmental outcomes are often attributed to more fairer decision-making processes that involve local communities, women, and indigenous people. Empirical evidence shows that polycentric water governance and management can support participatory, decentralised, and deliberative adaptation by bringing together diverse stakeholders across sectors such as irrigation, industrial, domestic use, and watershed institutions, operating across different levels from local to national governments (Baldwin et al., 2018; McCord et al., 2017; Pahl-Wostl & Knieper, 2014). For instance, a study by Baldwin et al. (2018) in Kenya’s Upper Ewaso Ng’iro basin found that collective action among water users was enhanced by overlapping authority and effective coordination between local, regional, and national units.

However, polycentric governance can also deepen existing inequalities if existing social hierarchies are reinforced, excluding marginalised actors such as indigenous people, minorities, and women from decision-making processes. For example, during a water crisis in Sao Paulo, existing power dynamics undermined polycentric governance due to a bias of the governance structures and elites towards certain political and social interests at the cost of environmental ones (Frey et al., 2021).

Using overarching principles of polycentric governance, a shared water agenda can be achieved through a multi stakeholder and multiscale process. This can help set clear goals and targets across national and local levels that is currently missing in water security and climate adaptation pathways (PBL, 2023).

A the same time, achieving a shared water agenda requires political awareness and support at national and global level. For example, putting water on the UN agenda can highlight its centrality in achieving global climate, sustainable development and global biodiversity goals and provide an enabling environment for international cooperation (PBL, 2023).

Gender, Equity and Social Justice:

Climate- and water-linked risks and impacts exacerbate existing inequalities associated with gender, class, social status, race, and education, compounding both existing and future vulnerabilities. Evidence shows that poor, socially marginalised individuals, and women often have limited adaptive capacities and are more vulnerable to water hazards such as droughts and water scarcity. Women, in particular, are excluded are excluded from decision-making processes regarding water access and management due to patriarchal norms, despite being primarily responsible for fetching water over long distances during scarcity (IPCC, 2022a). For instance, in India, caste and gender intersections continue to shape access to water due to deeply entrenched societal norms, even within government programs, and nongovernmental initiatives (Behl & Kashwan, 2024). Therefore, it is important to mainstream gender, equity, and social justice concerns in water adaptation strategies and actions to achieve CRD. This requires a justice framework to conceptualise and articulate water issues in a way that addresses structural inequalities and promotes sustainable water governance (Gupta et al., 2023; GCEW, 2024).

The GCEW report (2024) argues that this framework needs to bring together various strands of justice — interspecies, intergenerational, and intragenerational justice — so that the costs of inaction are not disproportionately borne by the most vulnerable, who have contributed the least towards the water crisis. This approach calls for governing water and the hydrological cycle as a public common good rather than a commodity, ensuring access to water as a legally binding human right, reallocating water budgets based on priority of use after water, sanitation and hygiene (WASH) needs are met, and recognising the rights of indigenous people (Gupta et al., 2023; GCEW, 2024).

Adequate Financing:

While 80 per cent of developing countries have developed adaptation plans, with a majority focusing on water, the financing available for climate adaptation is woefully inadequate (IPCC, 2022a; PBL, 2023). As of 2020, tracked green finance was about USD 83 billion, of which only USD 29 billion or about 34 per cent was for adaptation (PBL, 2023). The central costs of adaptation are estimated to be about USD 240 billion annually up to 2030, in the range of USD 130-415 billion every year, about 0.6 per cent of GDP (2021) for all developing countries (UNEP, 2023).

The highest adaptation costs are for water-linked projects like river and coastal flood protection and infrastructure in East Asia, Pacific, Latin America and the Caribbean (UNEP, 2023). UNEP (2023) estimates coastal protection adaptation costs at about USD 56 billion (until 2030) and flood protection and other water-linked events to be about USD 54 billion (until 2050) annually for developing countries. International finance flows for adaptation to developing countries is about ten to 18 times less than what is required (UNEP, 2023).

This shortfall in adaptation finance is due to various reasons, including bias in favour of mitigation, difficulty in monitoring and tracking adaptation finance due to its close links with development, local and context-specific nature of adaptation responses, and multi-dimensional risk profiles (Srinivasan et al., 2023). Traditionally, adaptation has been financed through public expenditure and domestic budgets, but its quantum is inadequate.

Given the climate vulnerabilities of the majority of developing country residents, prioritizing adaptation finance becomes crucial. This calls for mainstreaming adaptation in national programmatic frameworks and budgets to build adaptive capacity across vulnerable sectors, including water, reduce climate vulnerabilities and climate-linked physical asset risks (Srinivasan et al., 2023). To mainstream adaptation, climate risks will have to be integrated into decision-making processes at the national, regional and local governments, through legal mandates, appropriate financial resources and enhanced staffing and institutional capacity. At the same time, private adaptation finance needs to be incentivized through financial and policy interventions by development banks, governments, and financial institutions. International finance needs to be leveraged for adaptation especially in low-income countries. Adaptation investments need to focus on building resilient infrastructure and making up for the deficit in ecosystem services.

Use of Appropriate Technologies:

Technologies enhance water efficiency and reduce carbon emissions contribute towards successful climate adaptation. However, their benefits are contingent on avoiding negative distributional impacts. Historically, agricultural water management has leveraged technology, such as the widespread use of groundwater pumps in South Asia during the 1970s, which improved livelihoods but also increased agriculture's carbon footprint (IPCC, 2022a). More recent innovations, like drip and sprinkler irrigation, and the integration of Internet of Things, aim to improve water use efficiency. However, while use of drip and sprinkler irrigation can improve water efficiency, it can also be counterproductive when used for overextraction or to cultivate water guzzling crops, as has been seen in various regional contexts (Grafton et al., 2018).

Technological advancements in wastewater recovery and recycling for agriculture, creating potable water through desalination and solar-powered water management to reduce reliance on fossil fuels are also being used as effective adaptation options (Caldera & Breyer, 2020; Salgot & Folch, 2018).

Additionally, advancements in wastewater recovery, desalination, and solar-powered water management are becoming more prevalent. Machine learning and AI are being introduced in various water-use sectors, although mostly in high-income countries and often on an experimental basis. Remote sensing technologies coupled with geographic information systems (GIS) have been developed towards achieving sustainable coastal management (Kankara et al., 2014; Roy & Datta, 2018) such as to monitor coastal habitats, landforms, shoreline, water quality; classify coastal habitats; and conduct impact assessment of hazards such as cyclones, tsunami and sea level changes (Nayak, 2017).

The adoption and effectiveness of these technologies depend heavily on financial resources, suitability to local contexts, and strong institutional and governance frameworks. Furthermore, the unequal distribution of technological benefits, often favouring the wealthy, poses challenges to equitable adaptation. Ultimately, while technology plays a crucial role in water adaptation strategies, its success is influenced by broader societal factors, including governance, equity, and justice considerations (IPCC, 2022a).

Inclusion of Indigenous Knowledge and Local Knowledge (IKLK):

There is a strong consensus that genuine partnerships with indigenous peoples and local communities can improve adaptive capacities, reduce vulnerability and help decolonise water management and biodiversity conservation (IPCC, 2022a). For instance, there is robust evidence supporting the notion that indigenous peoples-led freshwater management can foster culturally inclusive decision-making and collaborative planning processes at both local and national levels (Harmsworth et al., 2016; Parsons & Fisher, 2020).

Community-led initiatives and restoration measures are proving instrumental in mitigating climate change and offering refuge to threatened freshwater species like adaptation strategies implemented by the Skolt Sami community in Finland to support the survival of Atlantic salmon populations in the Naatamo watershed (IPCC, 2022a). Atlantic salmon populations had declined with the increase in northern pike (that preys on salmon) in response to warming temperatures. Indigenous knowledge and management techniques including identifying and protecting spawning beds of salmon, increasing catch of pike helped in ecological restoration in this case. In Bangladesh's hill tracts, indigenous people working with local governments are help restore springs and natural wells (Sultana et al., 2019). 'Braiding' of indigenous knowledge with western approaches offers diverse benefits including improving understanding of socio-ecological systems and connections, implementing evidence-based action for biodiversity conservation, developing context-specific water and eco system protection (Mehltretter et al., 2023, p. 5).

Conclusion

The hydrological water cycle is increasingly out of balance from local to global scales due to many decades of unsustainable anthropogenic water use, massive land use and landcover change across most regions and climate change, accompanied by widespread mismanagement and pollution of ground and surface water (GCEW, 2024). The result is a global water crisis, which is set to worsen under business-as-usual development trajectories, leading to severe social, economic and ecological challenges ranging from increased food and water insecurity, vulnerability and losses borne by the most vulnerable, and expanding biodiversity loss that can exacerbate current and trigger new conflicts.

Climate change is a significant driver of the global water crisis. It is intricately linked with the global water cycle, with dislocations in each intensifying the other, through powerful feedback processes that are driven by contemporary development processes and the dynamics of national and the global economy. Many climate change impacts are manifested through water, including precipitation variability, reduced snow cover, an increase in extreme events such as excessive floods and droughts, and sea level rise (IPCC, 2022).

These climate-and water-risks can severely impact and endanger human life and well-being, ecosystem integrity, food security and hence, the global economy. Every degree increase in global mean temperature will further reshape the water cycle, affecting water availability and amplifying climate-induced water risks. For example, an additional 3 billion and 4 billion people will face water scarcity at 2°C and 4°C warming (GCEW, 2024).

Climate-induced water risks, including water scarcity, food insecurity, water-borne diseases, and economic losses, are not faced equally by all people and regions. They disproportionately impact regions and countries with higher development deficits, particularly affecting economically and socially marginalized groups, including minorities, women children and the aged.

While climate vulnerability, experienced through extreme weather events such as excessive floods, droughts, storm surge, wildfires, has forced countries to react and initiate adaptation plans, these actions are largely fragmented and sector specific. They fall short of addressing existing climate adaptation gaps across regions and systems. Unlike climate mitigation pathways that aim to reduce emissions in line with the shared vision of the Paris Climate agreement, there are no clear global climate adaptation pathways that can effectively mobilise collective action, secure financing, or align national efforts.

Most known and effective adaptation pathways, including those related to water are implemented from local to national-levels. Structural challenges to climate and water cycle adaptation pathways are constrained by poor and fragmented governance, inadequate and mistargeted finance, institutional constraints and lack of capacity, inappropriate technological choice and often climate maladaptation, lack of participation and access to technology and innovation, and gaps in information and knowledge.

Despite these challenges, a range of effective adaptation strategies have been implemented across regions and systems within local contexts, with documented benefits. Actions such as nature-based solutions in design and planning, water proofing of infrastructure, and restoring natural habitats like mangroves can be scaled based on a long-term adaptive strategy that balances human land use with river basins and ecosystems functioning (PBL, 2023). Other actions like improving adaptive capacities and reducing climate vulnerabilities have several co-benefits with the sustainable development goals like increasing social security nets for the poor, creating climate resilient affordable housing, and providing universal access to environmental services like sanitation, solid waste disposal, wastewater management.

Given this context, a resilient and sustainable future demands that we value water as a critical resource and the basis of all life, recognise the interlinkages between climate change, the global water cycle, regenerative agriculture, sustainable cities and communities and biodiversity. This implies a radical shift from existing 'value systems, policies and economic practices' and business-as-usual development frameworks (PBL, 2023, p.182). Climate Resilient Development (CRD), as outlined by the IPCC in its Sixth Assessment report, offers a new development paradigm for the Anthropocene. It integrates climate change (adaptation and mitigation) agenda with biodiversity and the SDGs. CRD, anchored in principles of equity and justice can be operationalised through five key systems transitions ¬: land, water and ecosystems, urban and infrastructure, energy, industries and societal systems (IPCC, 2023, IPCC, 2022)

Water can play a key role in achieving CRD as it is central to all systems transitions and all 17 SDGs (Ait-Kadi, 2016; Mugagga & Nabaasa, 2016). For years, it has served as a unifying force, converging interests and proving to a catalyst for cooperation (PBL, 2018). Under CRD, the water adaptation agenda and climate risks assessment can be mainstreamed into development trajectories, policy planning, financing and decision-making across systems and all levels from local to global, ensuring there are synergies between adaptation, mitigation and development goals.

Achieving a water-secure future and CRD is not going to be easy. However, water security, along with CRD, can be accelerated through key enabling conditions, which are discussed in this paper. These include polycentric and multilevel governance, adequate finance, use and access to appropriate technologies and innovation, gender, equity and social justice, and inclusion of indigenous and local knowledge (IPCC, 2022a).

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