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Assessment of water-use efficiency for enhancing urban wastewater reuse – a case of Bhopal, India

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ABSTRACT

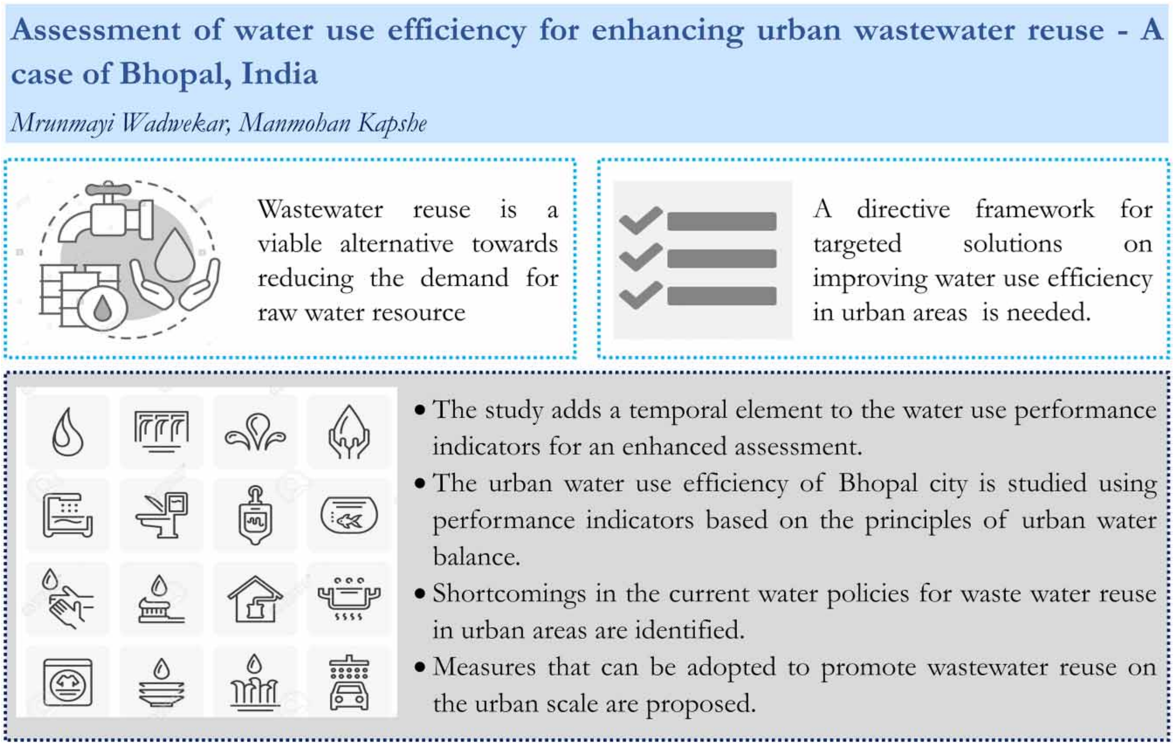
Wastewater reuse, a known alternative, lacks strong policy and institutional framework in India. There are various non-potable uses in urban areas that can be supplemented with treated wastewater for reducing the pressure on freshwater resources. The current policies in India promote use of treated wastewater for agricultural irrigation and industrial use, but they suggest no measures for reuse of the same in urban areas. The research aims to identify whether the water available in an urban area is used sufficiently and fulfils the needs of the city residents in a sustainable manner and advocates wastewater reuse as a possible option for improving its use efficiency. The study reviews the water-use efficiency of Bhopal city using performance indicators. The results suggest that Bhopal city receives enough supply for its needs; however, it is majorly dependent on its external resources. It is thus imperative that the city reuses its water efficiently and looks for wastewater as an alternative source. The research suggests a measurability framework for the local administration to set and identify targeted water use and reuse options within its periphery. The study also identifies certain shortcomings in existing policies and suggests measures to promote judicious reuse of wastewater in urban areas.

Key words: circular economy, hydrological performance, urban metabolism approach, water-use efficiency, wastewater reuse

HIGHLIGHTS

- The study adds a temporal element to the water-use performance indicators for an enhanced assessment.
- The urban water-use efficiency of Bhopal city is studied using performance indicators based on the principles of urban water balance.
- Shortcomings in the current water policies for wastewater reuse in urban areas are identified.
- Measures that can be adopted to promote wastewater reuse on the urban scale are proposed.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Urban areas are growing at an unprecedented rate and consume large quantities of resources to sustain themselves. Water is one such resource that is consumed in large quantities. Contrary to its natural cycle, in the urban water supply system, water as a resource is used in a manner similar to a manufacturing process; involving abstraction of raw resource from nature, its treatment and deployment, use for an activity, and disposal as wastewater in nearby streams. Due to the magnitude of the water used by the people in urban areas, this artificially created water cycle, with its linear approach, generates copious amounts of wastewater. Very often this process does not account for treating wastewater and bringing it back into the cycle for reuse.

Human actions adversely impact the natural water cycle due to continuous overuse of the resource, where the abstraction rate is more than the replenishment rate. Furthermore, unequal distribution and losses lead to wastage of resources, and the resources are also being polluted because of the improper disposal of the wastewater. The linear approach of human-managed water use, which is prevalent in a majority of urban areas today, is short-sighted and inherently unsustainable. This Take–Use–Discharge approach goes against the Circular Economy Principles (Tahir *et al.*, 2018). A modern city's 'metabolism' – its use, transformation, and discarding of resources – is shaped by the nature of its society and its involvement in the world economy (Baccini, 1997). Urban areas should thus relook into developing a more circular and sustainable approach towards a much-needed scarce resource. Circular economy is a concept to reduce the wastage of resources and extend the life cycle of a product. This approach aims to reuse an end product in another process to continue its usability.

The application of circular economy principles has a high potential to change the value proposition of the urban water supply system while ensuring its purpose and function. The circular economy approach will help in creating a shift that seeks value from the wider system rather than just from the fixed point at which consumption applies (Tahir *et al.*, 2018; Kakwani & Kalbar, 2022). Taking a holistic view towards the resource on a broader scale and fine-tuning it to a household or neighbourhood level should thus be given immediate attention. A circular approach is relevant, timely, and achievable and offers opportunities for commercial advantage (Tahir *et al.*, 2018).

The circular economy approach has been gaining rapid attention recently in the water sector because of the imbalance in water resources and the prevailing wide-scale linear approach in this sector (Kakwani & Kalbar, 2020). Within the circular economy paradigm, waste is considered a resource and with the above-discussed challenges in the water sector, there exist certain opportunities to manage wastewater sustainably using this perspective. However, to do so, the local administration needs decision-making support on how the water is used across the city and the amount of wastewater generated, the different uses and users in the city, a measurability indicator to assess the use efficiency of the available resource, and policy measures on how to achieve it. The research aims to address these questions on how and how much of the wastewater can be used across a city through a directive framework by assessing the water-use efficiency of the city and suggests measures to adopt a more cyclic approach towards reusing some of its treated wastewater. The focus of the research is not only to assess the sufficiency of the resource but also to analyse whether the use is judicious and what measures can be adopted to improve efficiency of the resource utilisation.

The purist definition of the term circular economy does not include the involvement of society or the physical elements of the urban area that uses and processes these resources. It is mainly limited to the economistic approach rather than the social dimension to build a broader, more ambitious collaboration between environment and society (Lazell *et al.*, 2018). Urban land use and urban morphology govern how and where water is consumed and where wastewater is generated. It can also help in identifying the potential consumers of treated wastewater. Our study tries to include these spatial elements in broadening the scope of the circular economy principles by incorporating specifics such as society, land use, and urban morphology, and giving it a more encompassing definition through the urban metabolism approach. The study proposes modifications to the existing water policies towards reusing treated wastewater for non-potable use in urban areas. For the purpose of this study, we have looked for wastewater reuse alternatives for the city of Bhopal in India using these principles.

2. MATERIALS AND METHODS

Urban water balance is a concept of assessing the water-use efficiency of an urban area and an effective tool to assess the performance of a city towards its water-use efficiency. A review of methods used to evaluate urban water performance by Renouf and Kenway found that, with the exception of the Water Sensitive Cities Index, evaluation criteria are often misaligned from the visions and objectives of urban water management (Atkins *et al.*, 2021). Kenway proposed a method known as the Urban Water Metabolism Framework in which he included both anthropogenic and natural water flows (Atkins *et al.*, 2021; Kenway, 2011). Atkins improved on previous work on urban water balance by including more components and developing spatially contextual performance indicators (Atkins *et al.*, 2021). This research uses the methods laid down by Atkins to analyse the water-use efficiency of the study area and identifying the integrant for an improved policy directive as shown in Figure 1. A spatial boundary for the study area is first identified in order to differentiate between internal and external resources. To assess and evaluate the water-use efficiency, information regarding the capacity, frequency, and location of the supply reservoirs connected to the municipal supply is also procured and mapped. Since this study also introduces a temporal element, information for year of construction is also collected. To

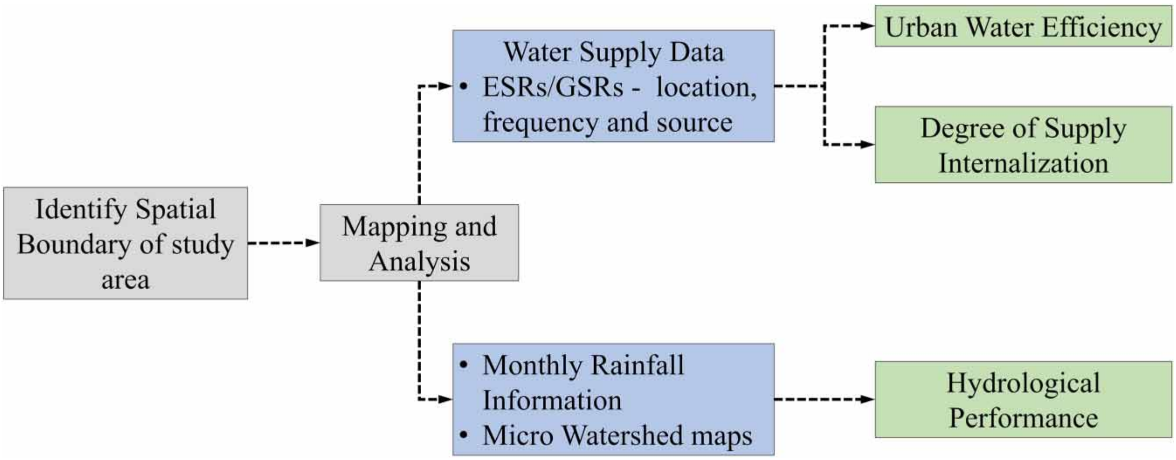


Fig. 1 | Research methodology.

analyse the change in the hydrological performance, surface runoff is then calculated for different assessment years using precipitation data and micro watershed and land cover mapping.

Renouf *et al.*, Farooqui *et al.*, and Atkins *et al.* have identified indicators that use commonly reported information, based on the same concept of mass balance, with an improvement to spatially differentiate water sourced internally and externally from the system boundary (Farooqui *et al.*, 2016; Renouf *et al.*, 2017; Atkins *et al.*, 2021). These indicators have been used in similar studies for Cape town, Bangalore, Johannesburg, among others (Paul *et al.*, 2018; Atkins *et al.*, 2021; Kakwani & Kalbar, 2022). The applicability of these indicators is preferred due to its simplified and formulaic approach and standardisation of the input data. For this research, three performance indicators were identified based on the primary assessment of the availability of the data for the study area while also introducing a temporal element to it as detailed in Table 1. The three indicators analyse the information to assess the resource efficiency of an urban area within and outside its spatial limits.

'Water Supply Internalization' is the proportion of total water demand met from internal resources or through harvested/recycled water in comparison to the water sourced from external resources.

'Urban Water Efficiency' is the per capita water supplied from resources external to the system boundary. These include resources that are from designated, centralised supply systems such as water supplied from treatment plants and Elevated/Ground Service Reservoirs (GSRs).

Table 1 | Performance indicators to assess water-use efficiency

Indicator	Description	Equation
Water supply internalisation	Proportion of total urban water demand met by internally harvested/ recycled water	$(C_{int} + D)/(C_{int} + C_{ext} + D)$
Urban water efficiency	Total external water use per capita (kL/capita/year)	C_{ext}/Population
Hydrological performance	Ratio of post-urbanised (i) to pre-urbanised (o) annual stormwater runoff (Rs) and groundwater recharge (Re)	Rs(i)/Rs(o), Re(i)/ Re(o)

Note: C_{ext} indicates resources outside the system boundary, C_{int} indicates resources within the system boundary, and D indicates the decentralised resources. *Source:* Compiled from (Renouf *et al.*, 2017; Atkins *et al.*, 2021).

'Hydrological Performance' informs the degree of departure from predevelopment hydrological flows, in terms of the magnitude of annual flows. It can be calculated as the difference in surface runoff or the change in storage for groundwater resources from base year to the assessment year. A ratio >1 means that the magnitude of annual flow/flux is greater than the landscape developed before, and a ratio <1 means it is smaller.

Thus, water supply internalisation measures self-sufficiency of the urban area, while urban water efficiency assesses the total resource use, and hydrological performance assesses the impact of urbanisation over the years. Using these indicators can help in identifying the criticality of resource use and measures that can be taken to promote recycling and reuse of the resource.

3. INDIAN SCENARIO

Water and water resources in India is a state (provincial) subject according to the Seventh Schedule of the Constitution of India (Government of India, 1950). The management of water as a resource is governed by various policies in different states, while, on the contrary, water as a resource is shared by multiple states and is a cross-border resource. In India, a key concern is that none of the river basins have an operational river basin management plan and there is an absence of an institution that would oversee the implementation and enforcement of such plans. This leads to exploitation of the resource by the upper riparian administration without much forethought towards those in the lower basin (Bassi *et al.*, 2020). Indiscriminate use of freshwater and its improper disposal as wastewater leads to deterioration of the freshwater resource. Studies suggest that for developing countries such as India, regulatory standards and policies should be formulated that can lead to effective implementation of treated wastewater even in a small administrative unit (Shastri & Raval, 2012; Voulvoulis, 2018; Goyal & Kumar, 2022). In India, as of 2022, wastewater reuse forms a part of the State Water Policy in selective states of India, although its implementation is limited to irrigation and industrial reuse, with little or no option for non-potable use in urban areas (Mishra *et al.*, 2023). Fragmentation of responsibilities in the absence of a nationwide wastewater reuse policy and regulatory structure leads to delay in implementations, division of resources, and complexity of decision-making towards wastewater reuse projects in India (Kumar & Goyal, 2020). Lately, the water sector has seen several reforms in the water sector policies, such as cost recovery, public–private partnership, and water tariffs, making way for integrated sustainable development including privatisation of the sector with success stories in Vishakhapatnam, Surat, Nagpur, and Chennai (Kumar & Goyal, 2020).

Urban areas do not often have resources within their administrative limits and as the city grows, it usually procures resources from outside its immediate environment leading to involvement of the peri-urban areas (Renouf *et al.*, 2017; Atkins *et al.*, 2021). In India, the water supply and wastewater treatment systems are highly insufficient and fragmented. Most of the cities in India do not have different stormwater and sewage drainage systems. Indian cities rely on primary treatment of wastewater and dispose of the effluent in nearby waterbodies. This leads to the deterioration of an already scarce resource. Wastewater reuse, although a much-approved option theoretically, does not find wide-scale practical applications because there is a certain apprehension towards using it for drinking and lack of coordination among authorities. However, implementation of any of these well-documented actions at the local and community levels is a challenge in the absence of target-based guidelines and strong regulatory frameworks.

Over the years, various policies have been promoted in India for wastewater reuse, as shown in Figure 2. The National Urban Sanitation policy of 2008 proposes a minimum 20% reuse of treated water in every city. The Jawaharlal Nehru National Urban Renewal Mission (JNNURM), 2012, made it obligatory to undertake mandatory and optional reforms to formulate bylaws for wastewater reuse in cities and provided assistance for 100% sewage treatment facilities to ensure better quality and increased availability of water for generating lower grade

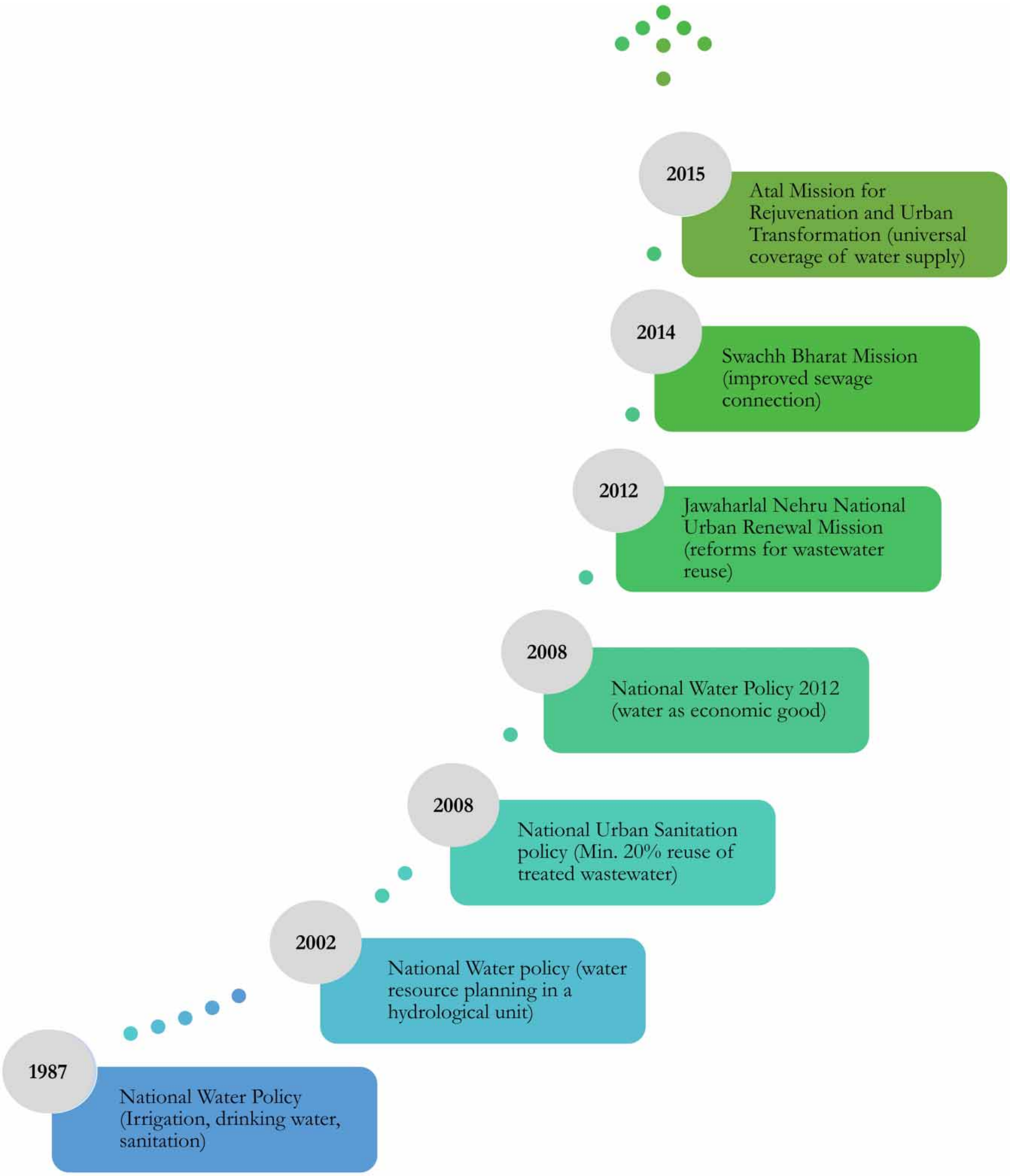


Fig. 2 | Water policies in India – a timeline and milestones (*source*: compiled by the authors).

water. The Swachh Bharat Mission 2014 and Atal Mission for Rejuvenation and Urban Transformation (AMRUT), 2015, encourage improved sewerage connection and reuse of treated water while the Namami Gange project of 2014 has identified several potential users for treated water (Kumar & Goyal, 2020). In spite of these efforts and policies, a comprehensive policy specifically directed towards wastewater reuse is missing in the Indian context (Goyal & Kumar, 2022). A compendium report by the Ministry of Housing and Urban Affairs, Government of India (MoHUA), for reuse and recycling of treated wastewater in the 54 million plus cities of India identified 32 cities practising reuse of wastewater, of which 11 cities also generate revenue from the sale of treated wastewater. Almost all cities reusing treated wastewater deploy it for agricultural irrigation and industrial plants while some use it for municipal horticulture and cleaning activities (CPHEEO, 2021). This suggests a positive approach to reuse and recycle wastewater; however, Indian cities lack wide-scale implementation due to various technical, social, economic, and legal barriers (Goyal & Kumar, 2022).

A well-drafted policy and its effective implementation rely on strong scientific data and information. Water as a resource does not follow physical boundaries owing to its very nature. Authorities therefore need a greater understanding of the flow and pattern of consumption on spatial and temporal scales in order to manage it efficiently. This understanding is the key to identifying, optimising, and utilising the resource sustainably in a more cyclic manner. Balanced utilisation of water in the agricultural systems, industries, and for domestic use within the ideology of the circular economy can be very well achieved and the need to formulate policies for safe reuse, recycling, and reclamation to achieve sustainable use of wastewater in the context of circular economy are needed (Kakwani & Kalbar, 2022). Urban areas are unique in terms of the intensity of use of resources in a limited spatial boundary. Therefore, certain elements of urban morphology such as land use, population density, and type of users play a vital role in the consumption of resources and generation of waste (Farmani & Butler, 2014; Diao *et al.*, 2019). The potential here is to unite the separate fields under a broader umbrella of research and to improve their collective application (Lucertini & Musco, 2020). The circular city or region thus requires a reevaluation of the way infrastructure is implemented and governed, as it forces a reassessment of the optimal scales upon which resources should be managed (Giezen, 2018). A circular economy requires restructuring of not just infrastructure but also institutional and regulatory frameworks. It aims to create local cycles of material movement to reduce the burden on the larger environment (Van Broekhoven & Vernay, 2018).

In Indian cities, there is a physical disconnect between the three urban water streams, namely, freshwater, drinking water, and wastewater, which are often managed by different agencies, creating a discontinuity in decision-making and institutional collaboration (Tsatsou *et al.*, 2023). This generates insufficient information and gives rise to lack of standard methodologies for assessing water accounts and identifying water uses (Bassi *et al.*, 2020). A more cyclic system can help water managers and administrators improve water-use efficiency to address water shortages and promote optimum utilisation of water resources to sustain the resource long-term. Thus, to move towards the circular economy paradigm, there is a need to rethink the water and wastewater systems in a more holistic and integrated manner, i.e. from an economic, environmental, social, and technical approach (Kakwani & Kalbar, 2022). Although increasing awareness of wastewater reuse will help, a strong policy that includes the principles of a circular economy towards recycling and reusing resources is needed to efficiently utilise wastewater as a resource. The current study proposes an approach to assess water-use efficiency at the local level of a city for enhancing wastewater reuse.

4. STUDY AREA AND DATA COLLECTION

A core prerequisite for using the indicators of the urban water metabolism framework at the local level is to define a spatial boundary to segregate internal and external resources for the study area. This helps in analysing whether the study area is self-sufficient in utilising its resources. This research also aims to assess the temporal element of water-use efficiency of a study area by including the timeline of expansion of the water supply network. In the absence of availability of a pipeline network, location of the supply reservoirs and their distribution zones were identified. Surface runoff calculations were done to calculate the ratio of runoff change using the Strange Table method for assessing the hydrological performance of the study area and to deduce the change due to urbanisation. In developing countries like India, infrastructure often does not match the pace of population growth. By including a temporal element for analysis, this study improves upon the work done by Atkins and Farooqui and refines the understanding of linkages between development and society.

Bhopal, a city in central India, is taken as a case example for this study. It is the capital of the state of Madhya Pradesh and had a population of 1.9 million according to the 2011 census. Bhopal is a rapidly growing metropolis in central India. The estimated population of the city is 2.3 million in the year 2023. The city has been identified as one of the 20 cities in India that may face pressure due to water stress in the near future (Clisby, 2019; NITI Aayog, 2019). The city was selected for the purpose of this study because of its unique socioecological and hydrological system. The city has 18 lakes within its urban boundary, making it well known as the 'City of Lakes'. Bhoj Wetland is a freshwater lake ecosystem designated as a Ramsar site in Bhopal. The system consists of two lakes known as Upper Lake (*Bhoj taal*) and Lower Lake (*Chota talab*), both of which are man-made. The water of Upper Lake was of good quality until 1947 and was directly provided to approximately 0.1 million residents of the city (TCPO, GoMP, 1975, 2023). The identification of Bhopal as the capital of Madhya Pradesh in 1956 brought a huge influx of population into the city. A dam was constructed across the Kolar River, a tributary of the Narmada River that led to an impoundment known as Kolar Dam in 1984, around 50 km from Bhopal. However, the expanding population required that other resources be explored, as shown in Figure 5. The Narmada River was identified as a feasible resource and a water treatment plant (WTP) was built at Shahganj, District Sehore, about 72 km from Bhopal. Kerwa, a reservoir near Bhopal, is also being used for water supply since the year 2015.

Bhopal city gets its water from these different resources through a network of many Elevated Service Reservoirs (ESRs) and GSRs connected within a supply zone of the individual resources. This study also aims to include a temporal element to assess the evolution and expanse of the water supply system of the city. To assess the water-use efficiency of Bhopal city, water supply data were collected for all ESRs/ GSRs constructed across the city. Their source and year of first operation or year of the project under which the ESR/GSR was constructed were identified and mapped as shown in Figure 4. The city undertook development works under various schemes of the Government of India as detailed in Table 2 and that has improved the network coverage to nearly 67% of the current population as of 2022 (TCPO, GoMP, 2023).

Digital maps for micro watersheds required for the hydrological performance indicator were procured from the online portal of Soil and Land Use Survey of India (SLUSI) as done in a previous study (SLUSI, 2017), wherein a micro watershed is the smallest hydrological unit of about 500–1,000 hectares in area (Taneja *et al*., 2019). Average monthly precipitation data were collected for identifying the magnitude and ratio of change of surface runoff from the base year to the current year of analysis.

Among the four resources for the city of Bhopal, only one, Upper Lake, lies within the administrative boundary of the city and was considered as an internal resource, while the other three are within 100 km of the periphery of the city and were considered as external resources for the purpose of this study. Groundwater, owing to its nature

Table 2 | Details of water supply projects carried out in Bhopal city

S. No	Project	Launch year	No. of ESRs/GSRs constructed
1	Base year	Till 2000	76
2	Gas Rahat Programme	2007	10
3	Asian Development Bank	2009	10
4	JNNURM	2012	62
5	AMRUT 1.0	2017	23[a]
6	AMRUT 2.0 (ongoing)	2019	36[a]

[a]Some old ESRs dismantled and reconstructed at the same location.
Source: Compiled from ADB, JNNURM, AMRUT project reports, and Municipal Corporation, Bhopal.

as an underground resource, was considered as an external resource. Degree of Supply Internalisation is the amount of water met by internally harvested/recycled water. To assess this indicator, analysis was done to assess the amount of water supplied from within the urban boundary or recycled or harvested within the city. There is very limited data available on rainwater harvesting done within the city on a localised level and the stormwater drainage system is not independent of the sewage drainage system. Therefore, only the water supplied from the Upper Lake is taken as a measure for this analysis. Urban water efficiency is an indicator of the overall efficiency of 'environmental' water use for the whole urban system and expressed as a rate of environmental water withdrawal per inhabitant per year (kL/capita/yr). It is an outcome of both the urban water demand, and the degree of supply internalisation (rainwater and stormwater collection, or wastewater recycling). The indicator uses freshwater removed from the environment as the measure of efficiency. However, in Bhopal, the water treatment plants are located within the premises of the water intake points, and the backwash is disposed of within the same reservoir. Therefore, for the purpose of this study, the Urban Water Efficiency has been assessed as 'Per capita treated water supplied to the city'.

The hydrological performance indicator is used to assess how urbanisation has affected the hydrology of the region. Surface runoff is a measure to assess the change in permeability of the urban catchment as increased built-up tends to reduce percolation and decreases the water table. The study uses the Strange Table method to assess the quality of the watershed and assigns a runoff yield value to it based on the type of catchment, the process is listed in Figure 3. The method was developed by W. L. Strange in 1892 by studying rainfall and runoff and developing yield ratios as indicators of catchment characteristics. This method is suitable to use where daily rainfall data and antecedent moisture conditions are not available (Subramanya, 2013). Yield is calculated by multiplying the area of catchment with cumulative monthly runoff volume calculated through an equation based on a yield ratio specific for a particular type of catchment and rainfall volume. The catchment which gives higher runoff (a highly impervious built-up surface – typically found in urban areas) would be termed as a good catchment whereas a pervious catchment (typically bare soil or agricultural lands) would be termed as poor catchment. An average catchment is the one that does not fall into either of the categories.

5. RESULTS

The study assessed the water-use efficiency of Bhopal city through the analysis of its existing resources and their spatial locations within or outside the city limits. By including a temporal aspect to the study, the analysis helped in understanding the change in the water use of the city over the years. The hydrological performance was analysed through a comparative analysis of a change in surface runoff in the context of increasing built-up in the city.

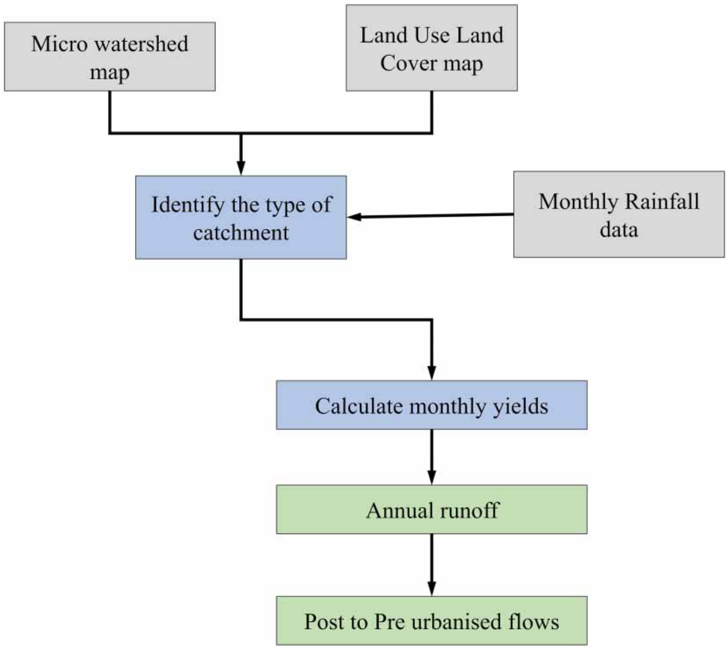


Fig. 3 | Process diagram for using the Strange Table method for surface runoff.

5.1. Degree of supply internalisation

As described earlier, Bhopal city has water supplied from four different sources, as shown in Figure 4. The locations of all the ESRs/GSRs were marked per the assessment years considered in this study to map the growth and expansion of the supply network. The Upper lake, which is within the city limits, is still being used for supply; however, it is now limited to only certain localities of the city as shown in Figure 4. Since agriculture is the primary land use towards the north and northwest of the city under the areas served by the Upper lake and uses groundwater resource for its irrigation needs, the Upper Lake is being used only for domestic needs as of now. Per information provided by the local administration, the uptake has reduced over the years and the supply to the localities is supplemented by other resources on alternate days. The Upper Lake, which was a primary resource a few decades ago, is now a dwindling asset (KPMG, 2018). The lake has reduced storage capacity due to the inflow of silt from urban and rural catchments, dumping of municipal wastes, and other anthropogenic activities. This has led to the deteriorating quality of water and the growth of invasive species and even traces of toxic metals (Gupta, 2008; Pani, 2008; Madgare *et al*., 2012; Upadhyay *et al*., 2013; Bhat *et al*., 2014). Understanding its ecological importance, various measures have been taken to preserve the lake and its ecology throughout the years, including desilting and dredging, construction of sewage drains, and plantations in the catchment area (Nakamura *et al*., 2004).

The analysis suggests that over the years the city has managed to expand its water supply coverage network through various schemes as detailed in Table 2. Using the same assessment years considered for this study, it can be seen from Figure 4 that until 2001 only core areas of the city were connected to the municipal supply network, but the work done under the JNNURM project was an extensive expansion of the network. The ongoing AMRUT project is further augmenting the supply network to the peripheral areas. However, on closer

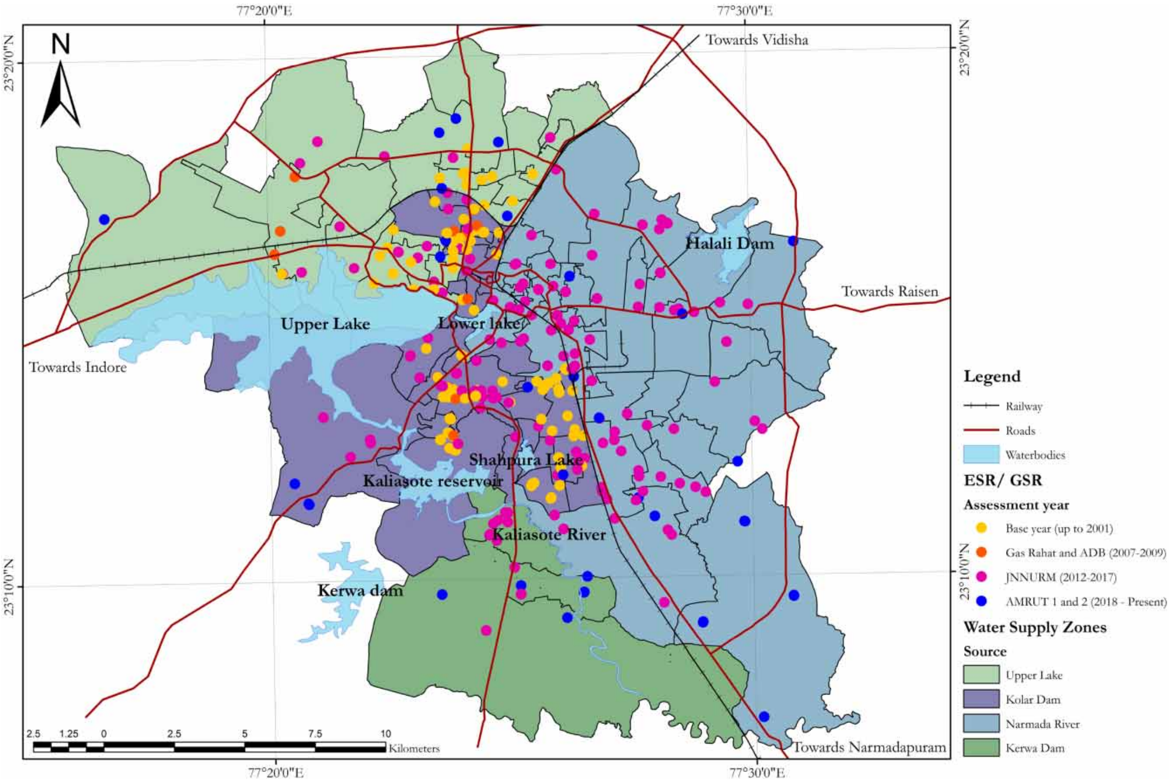


Fig. 4 | Water supply zones in Bhopal city (*source*: generated by authors in ArcMap).

examination it was found that the dependence on the Upper Lake has reduced drastically and is now only at 4.63% of the total average per capita supply to the city, as shown in Table 3. The resource from within the urban boundary therefore may not be usable in future and the possibility of total dependence on an external resource cannot be overlooked. The city should thus relook at reusing its available resources more efficiently and adopting practices that conserve and reuse water.

Total reliance on an external resource can be a cause for concern for rapidly growing cities like Bhopal. However, improving their inherent capacity by collecting and storing rainwater for use in dry months, directing it towards Groundwater Recharge, will improve the water table and enhance the hydrological regime of the area. Promoting wastewater reuse by raising awareness and building the trust factor among residents by

Table 3 | Upper lake and its supply

S. No.	Year	Upper lake (LPCD)	Total Municipal Supply (LPCD)	% met
1	2001	5.87	60	9.79
2	2011	5.31	58	9.22
3	2015	10.13	217	4.67
4	2023	9.04	195	4.63

LPCD, Litres per Capita per Day.

implementing small-scale localised projects can increase the acceptability of the idea. Using technologies such as bioswales and rain gardens, authorities can increase stormwater collection while simultaneously reducing the flooding during peak precipitation events.

5.2. Urban water efficiency

Bhopal city receives water supply from four different resources as described earlier. The Upper lake is the only resource that lies within the municipal limits of the city. Apart from this, the city draws water from Kerwa Dam, Kolar Dam, and Narmada River, approximately 50–100 km away from the city as shown in Figure 5. While the Upper lake and Kerwa Dam are part of the Ganga River basin, Kolar Dam and Narmada are part of the Narmada River basin, which means the city receives inter-basin water transfer, bringing a change in the hydrological regime of the region.

The results shown in Table 4 suggest that over the years the city has been able to improve its per capita water supply. It is also notable that the dependence on groundwater resources is decreasing. If all the available resources are added, the city received an average of 200 litres per day (LPCD) of water per person in 2023 (for an estimated 2.3 million population). Per the population projections for the year 2031 and resource augmentation, average supply of 146 litres/day/person (TCPO, GoMP, 2023) is ensured, which is less than the per capita water supplied as of 2023 but will still be more than the standards laid by the Government of India of 135 litres/day/person. As of now, Kolar Reservoir and Narmada River by themselves contribute nearly 80% of the total

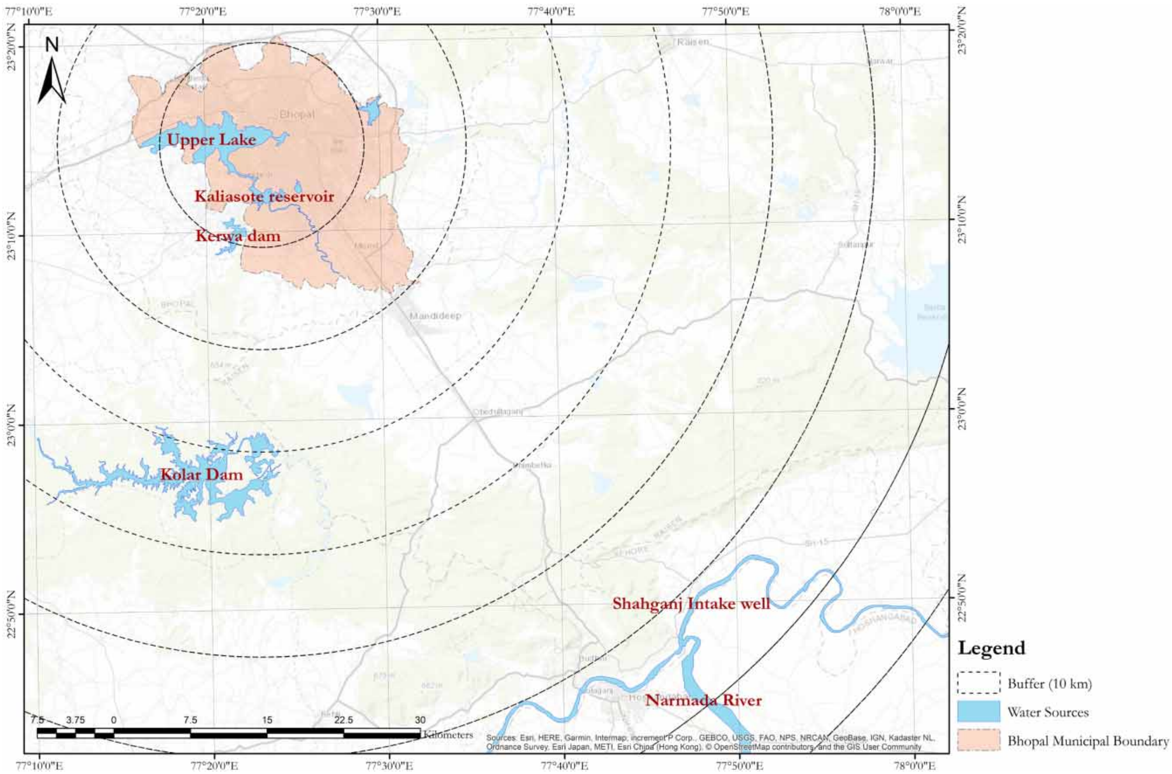


Fig. 5 | Water resources for Bhopal city (*source:* generated by authors in ArcMap).

Table 4 | External water resources for Bhopal city

S. No.	Year	External (LPCD)	Groundwater (LPCD)	Total
1	2001	54.13	3.4	57.56
2	2011	84.45	17.0	101.41
3	2015	206.75	16.7	223.42
4	2023	186.13	13.8	199.97

LPCD, Litres per Capita per Day.
Source: Compiled from ADB, JNNURM, AMRUT project reports, and the Municipal Corporation, Bhopal.

water supply. However, it is important to note that both these resources are external resources and the city lacks incentive to conserve and use water judiciously for future use.

The resources currently in use except for the Upper lake are external and have been augmented to their highest capacity as reported. In addition, all resources are rainfall dependent and any deficit due to external factors can affect the availability of the resource. In the scenario where the resource dwindles and population increases, the resource availability may even be affected more. The city should therefore look at making optimum use of the available resource by raising awareness about safe and efficient use of water, incentivising businesses and organisations that conserve water, and encouraging and promoting mechanisms and systems that use less water, thereby reducing demand for potable water.

5.3. Hydrological performance

To assess the change in the study area due to urbanisation and its impact on the hydrological performance, a process as shown in Figure 3 was used. A micro watershed layer was intersected with the Land use and Land cover (LULC) map in ArcMap to identify the type of catchments in the study area. A multiplicand factor was assigned to each micro watershed using the monthly rainfall data and type of catchment. Using the equations given in the W. L. Strange method, cumulative monthly yields were calculated, which gave annual runoff when multiplied with area of the catchments. This process was repeated once each for year 2001 and year 2022 to assess the ratio of pre- to post-urbanised flows as shown in Figure 6.

A ratio of change was calculated for the pre- to post-urbanised surface runoff to deduce the difference in flows. On analysing the results, micro watersheds towards the south/southwest showed a ratio of less than 1, ranging from 0.475 to 1, suggesting that the runoff has decreased, whereas those on the south, southeast, and northwest showed a fivefold increase. Since the precipitation has not varied much, the results suggest that micro watersheds on the northern and southern peripheries have undergone a decreased permeability and have higher runoff as compared to pre-urbanised levels as shown in Figure 6. This is in concurrence with the growth of the city in those areas and implies higher built-up/impervious cover across the city, which has also increased the surface runoff during rainfall events. The city underwent rapid urbanisation in the past few decades and the built-up area increased from over 0.35% in 1977 to 7.31% of total city area in 2014. This has also led to drastic reduction in vegetation cover from 92% in 1977 to just 21% in 2014 on an average (Aithal *et al.*, 2016) and led to significant drop in the water table (Wadwekar & Wadwekar, 2018).

Certain areas of the city especially to the southwest saw a growth in vegetation cover in recent years due to their ecological importance. The catchment area of the Upper lake towards southwest and areas surrounding Kerwa and Kaliasote Dams saw an increase in plantation under the city forest scheme, in part to create a buffer for the Ratapani Wildlife Sanctuary that abuts it while also to protect the catchment of the reservoirs (NGT, India OA

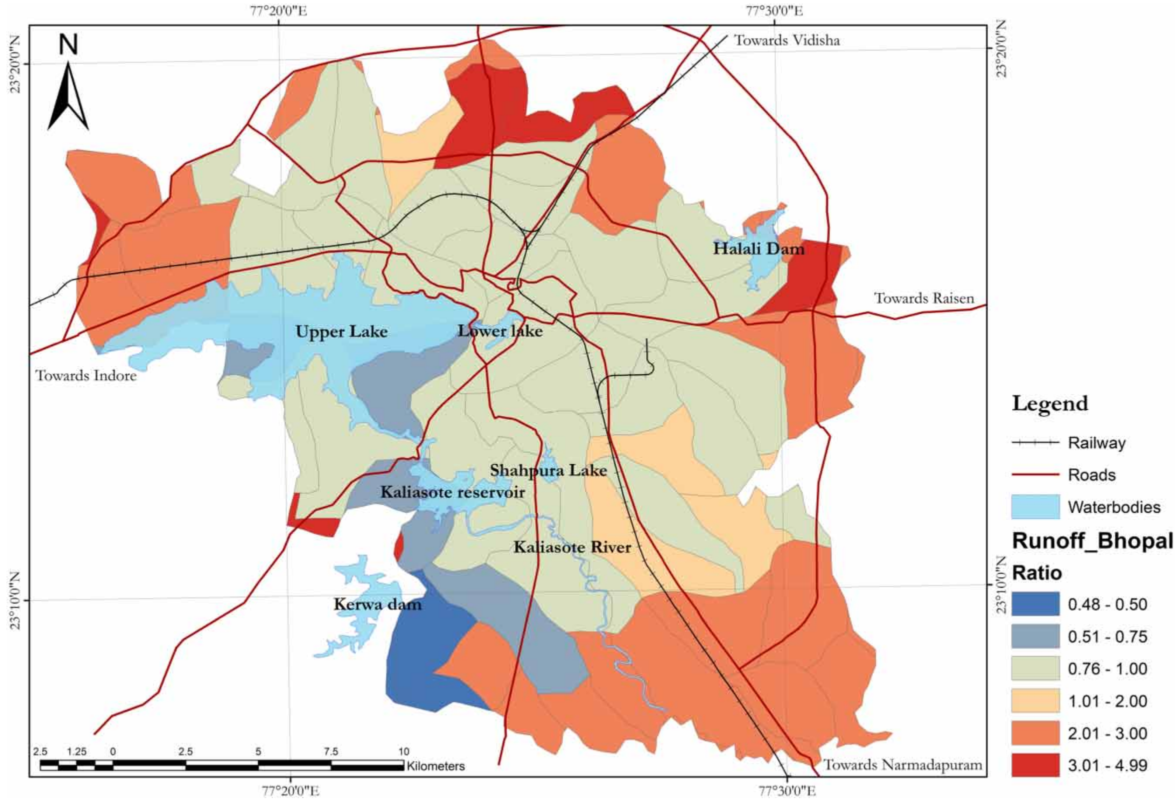


Fig. 6 | Annual runoff volume – 2001 to 2022 (*source:* generated by authors in ArcMap).

07/2022 (CZ), 2023, TCPO, GoMP, 2023). These areas observe reduction in runoff by almost 50% as compared to the previous assessment year as shown in Figure 6. It can be deduced that areas that saw an increase in plantation demonstrate a reduction in runoff and increased permeability. This suggests that even small measures can yield positive results if implemented with sound understanding of the localised spatial context.

Overall, the analysis suggests that Bhopal city, in spite of being blessed with a large water resource within its municipal limits, is dependent on external resources. This can be attributed to various factors such as high population growth, urbanisation, and deterioration of the existing resource. To meet the water demand, the city is procuring resources external to not just its physical but also hydrological boundary. The impact of urbanisation can also be seen in increasing runoff and the concurrently low percolation leading to the depleting water table.

The results indicate that Bhopal city is rapidly growing and that the city fulfils its water needs from resources outside of its administrative boundary. Over the years, the city improved its per capita supply of water while also expanding the availability of the resource for its peripheral areas. The analysis in Table 4 suggests that the resource availability is ensured and planned for the future, but the increased reliance on these resources implies that the resources within the city are not only insufficient for current needs but are also getting ignored. An increase in population in the future and with threats such as climate change, which have been estimated to affect the water resources negatively, the city needs to identify measures and practices that make judicious use of the available resource.

6. DISCUSSION

A scaled decentralised Urban Water Infrastructure is generally considered to promote sustainability and resilience and works out lower in economic costs (Giezen, 2018; Kalbar & Lokhande, 2023). While water resources differ in temporal and spatial distribution, water quality, and availability across the years, treated wastewater as a resource is less affected by seasonal and temporal variations and is a constant source (Song *et al.*, 2020). Bhopal city has a system of decentralised sewage treatment due to its topography, but the use and reuse of treated wastewater for non-potable needs has not caught the attention of the authorities. For effective deployment of wastewater post treatment, data and information about potential uses and users, their spatial location across the urban area, water quality and quantity requirement per standards are needed to identify and estimate the intended uses and users. Wadwekar & Kapshe (2023) have identified a Dasymetric spatial method to estimate wastewater generated in various locations across the city. The total wastewater estimated for Bhopal using this method is 143.32 MLD, while the treatment capacity is only 105 MLD. Using this method and identifying deployment points/localities, such decentralised systems can then be used to reuse treated wastewater for non-potable uses. Building a dual-piping network infrastructure that can transport treated wastewater to other areas for reuse will however be needed. This would involve co-ordination and planning at the local level by identifying and linking the generation points to the reuse locations. In a system like this, the Decentralised Wastewater Treatment Plants would be the resource instead of an endpoint, thereby making the linear water supply and disposal system a more cyclic one.

A more cyclic and sustainable approach is needed where waste from one end of the system can become a resource by bringing it back into the cycle. This will bode well with the circular economy principles that make reuse of materials their core principle. In the water cycle in particular, preserving and conserving existing waterbodies and improving the specific functional use of water is needed. Regenerating more uses from the same resource will enhance its efficiency and will be a more sustainable approach in the long run. Wastewater is one such resource where certain alternate needs that do not require potable quality water such as toilet flushing and municipal irrigation can be supplemented.

Measures to maintain and protect the existing resources from encroachments and external threats due to urbanisation should be prioritised. Identifying and adopting systems that promote judicious use of water and reuse of wastewater should be looked into. Including and promoting rainwater harvesting and giving monetary benefits will give impetus to individuals and organisations to design and use it within their premises. Solutions such as these can improve the ecological value and increase the resilience of the system in general. Urban authorities should look into identifying such localised systems that can improve the hydrological regime of the city and work towards a more circular approach towards a sensitive resource within the urban system.

Wastewater reuse, although a known option as a resource, does not find a wide range of applicability due to the potential risks it can cause to humans and the environment in its unrestricted and untreated form. There are social and cultural apprehensions about its reuse, and the economic costs associated with treatment are higher. However, treated wastewater is rich in nutrients that can reduce the need for fertilisers if it is used for irrigation. It can also be used for non-potable purposes in industries and for domestic uses, for groundwater recharge, aquaculture, and so on. The primary reason for the lack of reuse of urban wastewater is the apprehension among the users regarding the thought that 'drinking recycled water is disgusting', known as the 'yuck factor' in contemporary discourse (Russell & Lux, 2009). With time, research has shown that it is due to the fear of 'offensive products' mixing into pure resources, the 'fear of contagion' (Russell & Lux, 2009), and the distrust towards the system for the health issues that may result in case of system failure. Research by Wester (Wester *et al.*, 2015) found that the 'yuck factor' is not simply an emotional aversion but a disgust towards pathogens.

People have been more accepting of treated wastewater if the human contact is minimal and the water is used for non-potable purposes (Hartley, 2006; Duong & Saphores, 2015; Akpan *et al.*, 2020). This trust factor for the administrative authorities is important since another issue is the absence of policy guidelines and inadequate coordination among implementation agencies. There have been few success stories like Canada, Singapore, and Hong Kong where public trust in the authorities and publicity campaigns changed the public perception and improved acceptability (Duong & Saphores, 2015). In India, residents of New Delhi had increased acceptance for treated wastewater after awareness campaigns and information for improved treatment technologies (Neha & Kansal, 2022). As urban areas continue to grow, the generation of wastewater will also increase and thus has immense potential as an alternative resource for non-potable use. There are various policies laid out by the Government of India to promote the reuse of treated wastewater for non-potable uses such as irrigation, industrial use, and as a recharge for groundwater. However, current policies do not include urban wastewater reuse as one of its potential uses.

Thus, a more holistic approach that can bring together various subcomponents of the larger water resource system is required. To facilitate this, current policies should be integrated and accountability identified from top to bottom that considers all components of water use equally and allocates resources as needed. This system has to ensure flexibility towards different end-uses and users where the treated wastewater may be reused in the individual households. The policies currently in practice need to be clubbed together and analysed instead of dealing with individual components by themselves.

6.1. Limitations

Data and information related to groundwater abstraction, wastewater generation, and stormwater collection were unavailable with the local authorities at Bhopal and were excluded from the study. For most of the cities in India, such data are not collected on regular intervals and it may not be possible to generate city-scale data from the broader spatial contextual data available. We acknowledge that this may influence the results of the study and it can improve if the required data are available in future.

7. CONCLUSION

The study analysed the performance of Bhopal city by assessing its water-use efficiency. This has in turn also helped in taking a closer look at the problems being faced by cities in India in general. The likely policy options to address these problems have also been discussed.

Our assessment for Bhopal shows that the city has improved its water availability and distribution; however, it lacks a more sustainable and resilient approach towards the resource. The study evaluated performance indicators and identified that increasing urbanisation and population growth have exacerbated the demand for resources and the insufficient availability within the urban limits is putting pressure on the faraway resources. The city also lags in practicing stormwater collection and storage as well as wastewater recycling. Implementing measures that preserve and conserve water on a local level is therefore needed to improve the resilience of Bhopal city.

The study also identified that reuse of treated wastewater may be hindered due to mismatch of the magnitude and frequency and the intended use of the resource generated. Urban areas generate huge amounts of wastewater on a daily basis whereas the potential uses proposed in the existing policies, such as agricultural irrigation and industrial use, need intermittent supply. Conversely, horticulture and urban uses such as watering of parks and gardens, toilet flushing, car washing, and municipal cleaning, have a more regular and frequent requirement. These can therefore be included in the current policy directives as potential options for using treated wastewater. Using and reusing treated wastewater within the same urban area reduces the cost of transporting it to the outskirts and minimises the pollutant load on water resources where it would otherwise be drained. It can also be recommended to adopt a more decentralised system by identifying clusters that have specific needs and demand. This will be helpful in monitoring the system, its performance and management, and help the city be more efficient in managing its own resources. A system like this would shorten and close the loop of the overall system, making it more sustainable.

These policy initiatives should focus on identifying and assessing the need to reuse treated wastewater in the immediate vicinity of the city instead of deploying it for uses away from the city, thus reducing its cost for transportation and laying out of the infrastructure. A solution such as this will ensure that the water is recirculated within the system at a faster pace more efficiently.

Certain general policy measures that can be suggested on the basis of this study are as follows:

- Relook into wastewater as a resource than as a by-product.
- Improve and modify existing policies to include treated urban wastewater reuse.
- Identify the spatial context of different users and the functional uses in an urban area for potential users of treated wastewater.
- Create awareness and build trust towards reusing wastewater for non-potable uses.

The Circular Economy approach advocates for such principles and intends to bring in a more cyclic reuse of resources while relooking into experimentation and letting go of the traditional methods of consumption. The policies can thus be made more flexible towards identifying a variety of potential users. With time and improved acceptance towards treated wastewater and assurance about the techniques of purification, the residents may be willing to accept treated wastewater for drinking water use. To implement this, key data and information about different resources, their capacity and frequency, and seasonal and temporal variation are necessary for analysis. An organisation or an agency that can collect temporal and spatial data and information is needed to effectively implement this system. Data and information that are constantly updated will ensure that the supply remains unaffected and the established system works in an efficient manner. A robust policy that incorporates all the elements of the overall system and a strong implementation agency can lead urban India to look towards a more sustainable and resilient future.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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