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Ensuring Water Justice and Achieving Sustainable Development Goals in Megacities Through Cooperative Bargaining Solutions

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Abstract
Water scarcity and insecurity remains a critical challenge for the megacities of Global South, disproportionately impacting vulnerable and low-income communities. In Karachi, one of Pakistan's largest cities, almost 45 percent of domestic water demands are unmet due to governance failures and infrastructural inefficiencies. Our study applies a novel integrated Water Evaluation and Planning (WEAP)-Nash Bargaining Solution (NBS) framework that simulates future water demands and optimizes fair and equitable allocation of water among the seven administrative divisions of the city. Under WEAP, the projected satisfaction ratio with no intervention declined from 60 percent in 2023 to 30 percent in 2040, whereas the integrated strategy improved the demand satisfaction to 100 percent for all seven districts by 2036. Our results also indicate that water allocation under NBS, weighted by the Multidimensional Poverty Index (MPI), would enhance equity at the district level with Karachi East's allocation increasing from 60 to 96 percent in addition to the allocation improvements for other marginalized areas. These results highlight the importance of embedding socio-economic considerations within technical water allocation models. This would also directly contribute to achieving Sustainable Development Goals (SDGs) 6 and 10, ensuring access to water and reducing inequality, respectively.

Keywords Global South · Karachi · Water Evaluation and Planning (WEAP) · Nash Bargaining Solution: Water Justice · Sustainable Development Goals (SDGs) · Water Security · Urban Water Management

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1 Introduction

Ensuring equitable and sustainable distribution of water to domestic households remains a significant challenge for the majority of cities in developing countries. Many cities in the Global South experience acute water scarcity, making low-income populations highly vulnerable to water shortage (Weststrate et al. 2019). The combined forces of climate change, poor water governance and rapid urbanization in many South Asian megacities have resulted in severe water shortage, disproportionately affecting marginalized and poor communities. The disproportionate allocation of water and poor quality of service has resulted in urban water insecurity, hindering economic growth and exacerbating economic disparities (Ekmekcioğlu et al. 2022; Fukuda et al. 2019; Liu et al. 2024; Weststrate et al. 2019).

In almost all metropolitan cities of developing and underdeveloped countries, low-income domestic households not only incur higher relative costs for obtaining water but also face increased health risks due to unequal access to clean water. Morales-Novelo et al. (2018) showed that water subsidies provided in large metropolitan cities disproportionately benefit high-income households, which, in turn, leads to water wastage and exacerbates the overall water shortage for the wider population.

The majority cities in the Global South are highly vulnerable to severe water scarcity (Adams et al. 2020). Densely populated and low-income neighborhoods of these cities are subjected to extremely low water supply (Beard and Mitlin 2021; Mahama et al. 2014). Residents in these neighborhoods face a disproportionate impact, not only in terms of direct consequences of scarcity but also in overall measures of wellbeing (Fontana and Elson 2014; Gimelli et al. 2018). The poor and marginalized population of these cities spend several hours daily in the collection and transportation of water causing emotional distress (Anwar et al. 2020), compromising personal hygiene (Crow and Odaba 2010) and hampering education and economic activities (Crow et al. 2012). According to Lund (2015), societies with unequal water distribution, where residents dedicate substantial time and resources to securing water access, are"always poor". Obstacles in accessing water, which demand excessive time, energy, and expenses from the poor and socially marginalized, effectively prevent them from achieving a desirable quality of life. Lu et al. (2014) conclude that the urban water utilities in these cities are unable to serve their most vulnerable populations.

The Sustainable Development Goals (SDGs) proposed by the United Nations (UN) “are a universal call to action to end poverty, protect the planet and ensure that all people enjoy peace and prosperity” (Bexell and Jönsson 2017). Various researchers have assessed the components making up the SDGs (Casini et al. 2019; Lehner et al. 2018; Saladini et al. 2018; Siksnelyte et al. 2018). Access to water is not only essential for healthy living and economic development, but also for maintaining peace and security (Cernev and Fenner 2020; Zhang et al. 2024).

This paper addresses SDGs 6 and 10, both of which hold significant importance. Goal 6 seeks to “ensure availability and sustainable management of water and sanitation for all” while goal 10 aims to “reduce inequality among and within countries” (Cai et al. 2021; Hoekstra et al. 2017). Achieving a balance in managing water resources requires equitable distribution among all individuals and consideration of competing needs.

To develop water-resilient systems and strengthen responsible institutions, a focus on social/ecological justice is crucial (Lund 2015). Considering the magnitude and seriousness of the water crisis and inequitable distribution of water in the cities of the Global South,

studies that quantify and address water insecurity for various groups in developing countries are vitally important.

In this study, we propose a novel integration of the Nash Bargaining Solution (NBS) and Water Evaluation and Planning (WEAP) framework, incorporating key socio-economic indicators relevant to Karachi, Pakistan, such as the Multidimensional Poverty Index (MPI) and household size, into the bargaining process, to address the research gap identified above. Firstly, we simulate the future water demands for the seven administrative divisions of the city of Karachi under various scenarios using WEAP. Secondly, we use the NBS game theoretic approach to ensure equitable water allocation among the districts (administrative divisions) of Karachi.

This study integrates predictive modeling (WEAP) with fairness-based bargaining theory (Nash Bargaining Solution) to provide a context-sensitive framework for equitable water allocation in Karachi. As such, the study aims to provide a practical, evidence-based approach to inform equitable water resource management and allocation policy, both in Karachi and similar cities in the Global South, aimed at improving water security and addressing core SDGs.

2 Previous Related Work in Global South Metropolitan Cities

Various researchers have used different models and decision support tools for the assessment of available water resources. These include system dynamics models (e.g. STELLA, integrated assessment models, optimization-based approaches (e.g., linear and non-linear programming, multi-objective optimization), agent-based models (e.g., NET-LOGO), simulation tools (e.g., SWAT, MODFLOW). Each of these has contributed uniquely to understanding complex water systems under changing climatic, economic, and policy conditions. WEAP is one of the tools that has been widely used to simulate future water demands based on various 'what if' scenarios, including climate change, socio-economic expansion, water conservation strategies and population growth (Ahmed et al. 2018; Al-shutayri 2019; Mohammed et al. 2020; Mehboob et al. 2020; Saketa 2022; Zhang et al. 2023). These studies all highlight the ever-increasing pressure on our water resources and the need for improved water management strategies. For instance, Al-shutayri (2019) modelled the future water demands for Jeddah City, Saudi Arabia and proved that, despite various water conservation strategies and desalination, the water shortages would increase in future, emphasizing the need for stronger water management policies. Similarly, Zhang et al. (2023) enhanced WEAP by incorporating regional and industrial priorities. The study concluded that the modified model led to more equitable water allocation and improved user satisfaction in the Guangdong-Hong Kong-Macao Greater Bay Area, especially in times of water shortage. These findings highlight the importance of refining water allocation frameworks to effectively address future challenges. A three-stage model combining bankruptcy rules, Nash bargaining, and TOPSIS was applied to the Indus River basin in Pakistan to allocate water among provinces under scarcity scenarios (Janjua et al. 2025). Also, an integration of WEAP with Nash bargaining theory has been developed for the Kabul River transboundary basin under future demand scenarios (Khalid et al. 2024).

As discussed, WEAP has been very effective in simulating future demand and supply under various scenarios; however, it fails to inherently address the issues of equity and fair-

ness in the allocation of water among the contending agents, such as in those megacities facing stark intra-urban disparities. In order to overcome this limitation, researchers have applied cooperative game theory to facilitate equitable resource sharing among competing stakeholders (Chessa et al. 2023; Janjua et al. 2024). NBS has been used in various river basins and agricultural settings to resolve conflicts and allocate water fairly based on negotiation dynamics and stakeholder priorities. Despite this, its application to complex urban contexts—particularly megacities in the Global South—remains limited. This study bridges that gap by integrating WEAP's predictive capabilities with the equity-focused strengths of NBS. We apply this innovative approach, using a case study methodology, to predict and simulate future water scenarios at the district level in Karachi, one of the largest cities in Pakistan that is suffering from a water shortage.

3 Methodology

3.1 Case Study Area Description and Key Water Resources Distribution Challenges

The paper presents a case study of Karachi, Pakistan, which is one of the world's largest cities with a population of almost 25 million. The city is located in the south-west of Pakistan and occupies an area of about 3,530 km^2. The city is divided into seven 'districts' or 'administrative divisions', as shown in Fig. 1.

The city hosts 60 percent of Pakistan's industry and contributes almost 15 percent annually to the national gross domestic product. As a major contributor to Pakistan's economy, Karachi is experiencing a rapid influx of people migrating from rural areas. For example, the number of households in the city in 1990 was about 2.1 million; by 2020, this had

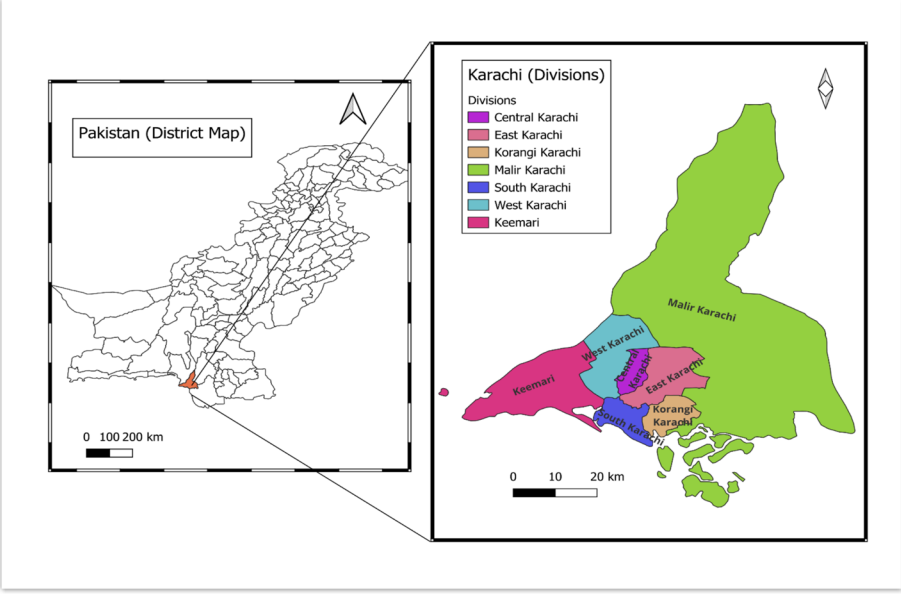

Fig. 1 Study area (District-wise map of Pakistan and administrative divisions of Karachi)

increased to 3.9 million, the majority of which are categorized as poor and low-income households. This rapid surge in population has placed immense pressure on the available water resources of the city. At the same time, the local administration has failed to accommodate the increased domestic water demand driven by demographic change, resulting in increasing water scarcity, especially during the hot summer season. Much like other South Asian cities (e.g., Mumbai), Karachi's population also suffers from a lack of equitable access to water. The improper and inequitable distribution of water in Karachi is such that only 28 percent of the population has a reliable and continuous supply of water (Beard & Mitlin 2021).

The Karachi Water and Sewerage Board (KWSB) is the government organization responsible for the management and allocation of water in Karachi. Unfortunately, mismanagement, corruption, and political interference have led to a precarious financial situation for KWSB (World Bank 2018). According to a study by Toppa (2016), the city fails to meet almost 45 percent of its overall water demand. Poor management and planning have resulted in revenue shortfalls and hindered improvements in the water supply system. The city's water infrastructure has deteriorated with time due to inadequate maintenance, resulting in sewage mixing and posing serious public health risks (Khalil et al. 2023). According to Pappas (2011), this sewage mixing problem results in almost 30,000 deaths each year in the city. In addition, due to inefficient water infrastructure, Karachi also suffers a loss of 30 percent of domestic water due to theft and leakages (Khan & Arshad 2022a; Nabi et al. 2019).

Disparities in access to water contribute further to socio-economic inequalities, with low-income households getting a lower share of water compared to high-income households. According to Khan and Arshad (2022a, b), people living in areas of low-income spend nearly 10–20 percent of their monthly income to procure water from non-piped sources such as private water tankers. Karachi's water crisis is expected to worsen due to climate change causing extreme weather events, frequent droughts and altered precipitation patterns (Khan et al. 2024; Zeb et al. 2023). Rising temperatures with higher evapotranspiration rates will result in reductions in groundwater resources and surface water supply (Baocheng et al. 2024). Furthermore, rising sea levels pose a significant threat to water availability in Karachi, as saltwater intrusion into freshwater resources could degrade water quality, subsequently reducing the supply of potable water (Irfan et al. 2018).

Low-income communities, already facing inadequate water supply, will be severely affected by these climate-induced changes (Morales-Novelo et al. 2018). A sustainable solution is urgently needed to ensure the fair and equitable distribution of water to all citizens of Karachi, especially as water stress increases due to projected climate change.

3.2 Current Water Resources in Karachi

The main water sources for Karachi are surface water resources from the Indus River, via Kalri Baghar Feeder Upper Canal (KBFU) and Keenjhar Lake, with a small contribution from the Hub Dam (Irfan et al. 2018). Until recently, a small quantity of groundwater was also supplied to the city through the Dumlottee wells (Ghazal et al. 2021). The cumulative domestic water supply to the city from the above resources is about 3.023 Mm^3/day or 665 million gallons per day (MGD) against a current demand of almost 5 Mm^3/day or 1100 MGD (Anwar et al. 2020; Irfan et al. 2018). Overall, the per capita water demand is 246 L

(54 gallons) per capita per day (KWSB, 2018). Details regarding the district-wise population of the city, along with water demands and availability, are presented in Table 1.

3.3 Problem of Improper and Inefficient Water Allocation

While we could not ascertain the inequalities in water allocation amounts related to the current distribution among the districts of Karachi due to a lack of available data, various reports and publications suggest that the current water allocation by the KWSB is neither fair nor equitable. Low-income areas receive significantly lower allocations (Ghazal et al. 2021; JICA 2021; Khan et al. 2023; Khan & Arshad 2022b, a). In 2008, the total water availability for the domestic households of Karachi's 20 towns was reportedly 1.89 Mm^3/day; however, due to leaks, the actual supply available to the towns was just 1.33 Mm^3/day (293 million Gallon Per Day, MGD) (KWSB 2008). The percentage column (% Quota Received) is calculated by dividing the actual supply by the required amount (i.e., Actual ÷ Required × 100). Seven of these towns – namely, Gulshan, North Karachi, Site, Jamshed, Baldia, Gadap and Orangi – received only 30–57% of their allocated quota, while others received between 60–100% of their quota (Table 2). In contrast, some of the high-income and influential areas, such as DHA and Landhi, received well over 100% of their quota. This inequitable distribution of water persists to this day (Khan et al. 2023; Tayyab et al. 2022).

3.4 Study Design

As described, our study involves two stages (Fig. 2). Data were collected from various authorities, including the Karachi Water and Sanitation Board (KWSB) and the Population Census of Pakistan (Statistics, 2023), and used to determine the current domestic water supply and demand for different administrative divisions of Karachi. The findings were then incorporated into the WEAP model, where future water demands were simulated under various scenarios (Part A of Fig. 2). The results from these scenario analyses were subsequently imported into MATLAB, where the NBS was applied to ascertain a fair and equitable allocation of water among the administrative divisions of Karachi (Part B of Fig. 2).

Table 1 Current (2023) water demand and supply for districts in Karachi city, Pakistan

Name of administrative unit	Population* (2023)	Population growth rate*	Water demand @ 245 L per capita per day or 54 GPCD (000 m^3/day)	Minimum survival demand @ 47 L per capita per day or 10.2 GPCD (000 m^3/day)	Total water supply** (000 m^3/day)
Karachi Central	3,822,325	4.3	937	177	3023
Karachi East	3,950,031	5.45	968	182	
Karachi South	2,329,764	4.71	573	109	
Karachi West	2,679,380	4.35	659	123	
Keemari	2,068,451	2.07	509	96	
Korangi	3,128,971	3.29	768	146	
Malir	2,403,959	3.79	591	114	
Total	20,382,881	-	5005	946	

* Government of Pakistan. *Pakistan Bureau of Statistics*, Feb. 2023, https://www.pbs.gov.pk/sites/default/files/population/2023/Sindh.pdf (Statistics, 2023)

** (Irfan et al. 2018)

Table 2 Water supply in various towns within the city of Karachi, Pakistan

Sr. No	Town	Water requirement ($\times 1000\ m^3$/day)	Actual water received ($\times 1000\ m^3$/day)	% Quota
1	Lyari	63.6	54.6	85
2	Saddar	145.5	136.4	93
3	Kemari	45.5	36.4	80
4	Jamshed	136.4	63.6	46
5	Gulshan	159.1	90.9	57
6	Shah Faisal	54.6	40.9	75
7	Malir	90.9	54.6	60
8	Landhi	72.7	90.9	125
9	Korangi	109.1	95.5	87
10	Bin Qasim	63.6	63.6	100
11	Gulberg	100.0	77.3	77
12	North Nazimabad	90.9	63.6	70
13	Liaquatabad	81.8	81.8	100
14	North Karachi	159.1	90.9	57
15	Orangi	181.8	54.6	30
16	Baldia	90.9	36.4	40
17	Site	81.8	45.5	55
18	Gadap	36.4	13.6	37
19	Cantonment	100.0	100.0	100
20	DHA	27.3	40.9	133
	Total	1891.2	1332.0	

Source: Karachi Water and Sanitation Board (KWSB), 2008

3.5 The Water Evaluation and Planning Model (WEAP)

WEAP is a water planning and evaluation model that can be used at both temporal and spatial levels. The software has the ability to build and compare different scenarios (Amin et al. 2018; Mehboob et al. 2020; Yao et al. 2021). These scenarios can relate to a wide range of 'what if' questions; for example, what if the population growth rate increases? What if a water conservation strategy is applied? What if combinations of the scenarios are implemented?

Typical scenario modelling in WEAP consists of three steps: (i) a current account year is chosen to serve as the base year of the model; (ii) a reference scenario is established from the current accounts that simulates the evolution of the system without any intervention; and (iii) various"what-if"scenarios are developed to modify the reference scenario and assess the impact of changes in policies and/or technologies.

3.5.1 Scenario Development for WEAP

Scenarios have been defined as self-consistent storylines that show how the future system will behave under a set of technology conditions or policy changes and under certain socio-economic conditions (Sieber and Purkey 2015). They enable us to answer various 'what if' questions. For our case study, the future demands of the city may be affected by changes in socio-economic factors including population growth, living standards of people, water

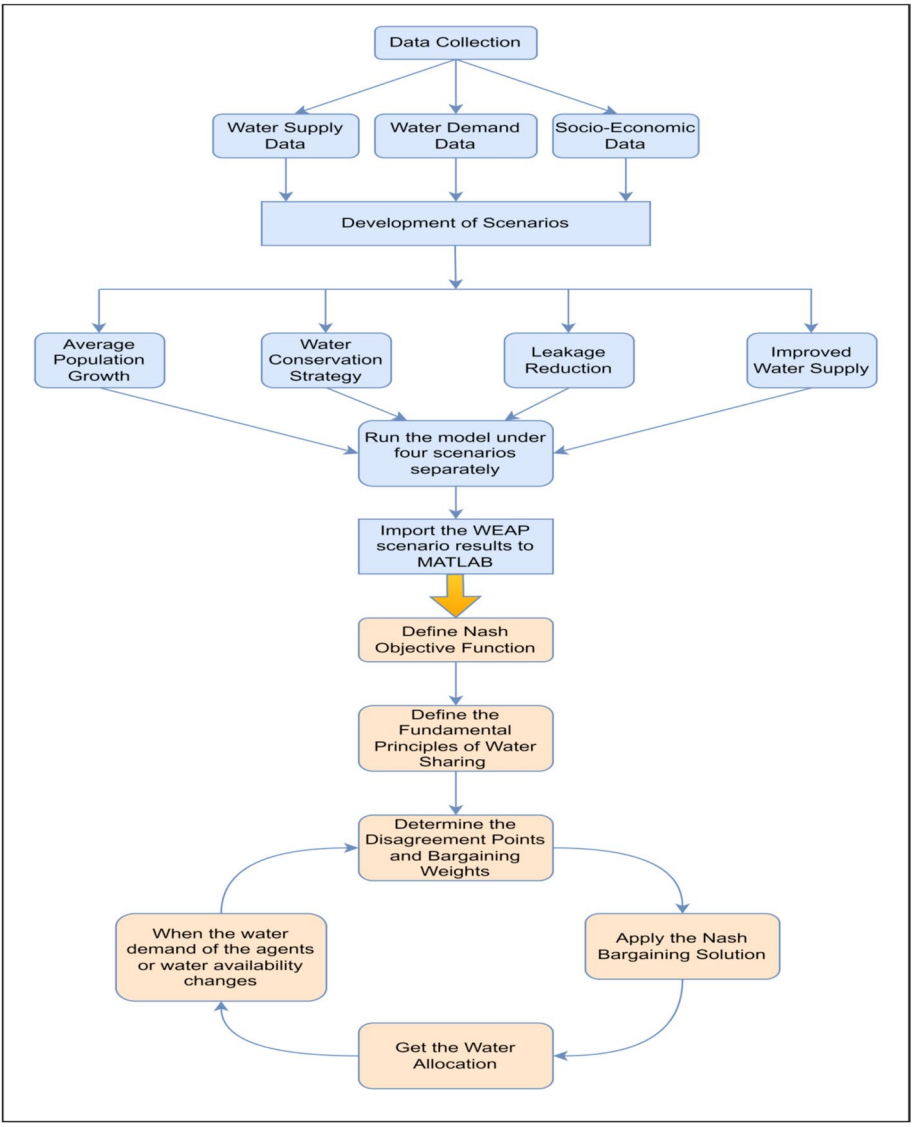

Fig. 2 Sequential steps of the adopted methodology integrating WEAP for demand simulation and NBS for equitable water allocation. Part A (in blue) shows WEAP-based scenario modeling; Part B (in orange) applies NBS with socio-economic weights (household size and MPI) for fair distribution among districts

losses and others. Different assumptions are proposed for our case study in the light of two detailed reports. The first of these is a report prepared by the Japan International Cooperation Agency (JICA) entitled "Data Collection Survey on Water Supply and Sewerage Sector of Pakistan" (JICA 2021). The second is "Transforming Karachi into a Livable and Competitive Megacity" (World Bank 2018). Both present a comprehensive attempt to collect and present detailed data on the economy, livability and planned urban infrastructure of the

city. These reports also highlight the challenges faced by the Karachi Metropolitan Sector, focusing on water scarcity.

Using the WEAP model, we evaluated the water requirement, the supply delivered and the unmet water demands for each scenario. The basic parameters in WEAP include district-wise population of the city, per capita daily water consumption in liters per day, the population growth rate and pipeline losses (in percentages). For our case study, the year 2023 was used as the base year for the model (Table 3, Scenario 1). In 2023, the city's population was nearly 20 million, with an estimated per capita water demand of approximately 246 L (54 gallons) per person per day. Additionally, as reported by various sources, current water losses in the distribution networks are around 25 percent (JICA 2021; World Bank 2018). Based on these reports, we developed three potential future scenarios (Table 3, Scenarios 2–4). We then ran the WEAP model for a period of 16 years, from 2023 to 2040.

3.6 The Nash Bargaining Solution and Water Bankruptcy

Where two or more water agents are competing for a limited source of water, the allocation of water amongst the agents can result in a 'water bankruptcy' situation (Khaneiki et al. 2024), where the combined demand of agents involved in a water dispute exceeds the total

Table 3 Description of future water demand scenarios and key assumptions for Karachi city, Pakistan

Scenarios	Main assumptions
Scenario 1 (Reference Scenario)	This scenario represents the current account. This was set up based on the latest population census (2023) and the latest system conditions, including water supply and demand zones. It represents an average population growth rate for every division of Karachi with existing water supply and allocation policies
Scenario 2 (Water Conservation Strategy)	At present, the water conservation concept is not applied by the Karachi Water and Sanitation Board (KWSB) due to a lack of awareness about the economic benefits of water conservation. However, the KWSB plans to implement a water conservation strategy to reduce water consumption per capita by 20 to 30 percent (JICA 2021)
Scenario 3 (Improved Supply)	The K-IV project, initiated by the Karachi Water and Sanitation Board, envisages a supply of 2.95 Mm^3/day or 650 million gallons per day (MGD) to Karachi from Keenjhar Lake. The project will be completed in two phases. Water and Power Development Authority (WAPDA), Pakistan, is currently constructing Phase I, which is scheduled to be completed in 2025 and to bring 1.19 Mm^3/day or 260 MGD to Karachi. Phase II of the K-IV water project, to be completed and become operational by 2030, will supply an additional 1.77 Mm^3/day or 390 MGD of water (JICA 2021; World Bank 2018)
Scenario 4 (Improved Supply + Leakage Reduction + Water Conservation Strategy)	Scenario 4 combines Scenarios 2 and 3. Together, these strategies aim to enhance water availability, reduce losses, and lower demand for a sustainable water management approach

available water resources. In accordance with these conditions, the water bankruptcy problem can be formulated as:$\{N, E, c_i, x_i^-\}$. Here, '*N*' is a finite set of agents, which in our case will be the administrative divisions of the city, competing for limited water. '*E*' is the limited water resource that is insufficient to satisfy the demand of all the competing stakeholders/agents. Here, $i \in N$ and c_i is the amount of water claimed by any agent. The amount of water allocated to an agent is denoted by x_i^- and the total amount of water available to each agent *i* is a_i. As per this condition, the available water resources within the city are $E = \sum_{i=1}^{n} a_i$. In our study, asymmetric Nash Bargaining Theory is combined with the bankruptcy theory to ensure fair and equitable allocation of water among the agents. Bargaining weights $\{b_1, b_2, b_3, \ldots, b_n\}$ of the agents are considered to ensure self-enforceability and equity. Disagreement water allocation points $\{m_1, m_2, m_3, \ldots, m_n\}$ of the water sharing agents are also taken into account to ensure equity and self-enforceability in a closed and bounded feasibility space. Nash (1950, 1953) proved that a certain set of desirable properties could be satisfied using such optimization approaches. The solution optimizes the area between the pareto-optimal frontier $\{x_i^-\}$ and the disagreement point $\{m_i\}$.

The minimum water allocation to each agent is then defined using a bankruptcy theory concept. In this case, the vector of disagreement points $\{d_1, d_2, d_3, \ldots, d_n\}$ is defined as the minimum water allocation to the agents and represents the minimum that water agents are willing to accept. It is, therefore, necessary that the individual rationality requirements are reflected prior to the cooperation of the agents so that the maximal (upper bound) and minimal (lower bound) solutions are satisfied. Here, the respective water claims of the agents serve as the upper bound and the disagreement points serve as the lower core bound. For each agent, the disagreement point formula is defined by,

$$d_i = U_i(m_i) \tag{1}$$

where U_i are the utility functions.

In order to solve the problem of minimal water allocation to each agent, bankruptcy theory can be used when the total available water is less than the total water demand. The minimal water allocation formula for each agent is given by,

$$m_i = \max\{0, E - \sum_{k \neq i} c_i\} \tag{2}$$

subjecting to $E \leq C$, where $C = \sum_{i=1}^{n} c_i$ is the total water demand.

The minimum water allocation to any agent, especially to those with smaller claims, may become zero if the above method of Bankruptcy Theory is used to define the minimum water allocation. However, each agent will demand a minimum amount of water λ_i in the process of water resource allocation. Using the above Theory of Bankruptcy, the minimum water allocation may be less than the minimum water requirement of each agent. Therefore, in order to avoid the case of unreasonable minimum water allocation by bankruptcy theory, we have proposed Eq. (3), which determines the minimum water allocation and considers the minimum requirement for each agent:

$$z_i = \max\{\lambda_i, E - \sum_{k \neq i} c_i\} \tag{3}$$

where λ_i is the minimum water requirement of each agent, based on the population living within the division, which in our case is defined as the survival demand and is taken as 47 L per capita per day (LPCD) as per World Bank report (World Bank 2018).

The optimization problem for the fair allocation of water under the water bankruptcy scenario is given by,

$$\text{Maximise } \mathrm{N}^w = \prod_{i=1}^{n} \left(x_i^- - z_i\right)^{w_i} \tag{4}$$

which becomes

$$\text{Maximise } \mathrm{N}^w = \prod_{i=1}^{n} \left(x_i^- - \max\{\lambda_i, E - \sum_{k \neq i} c_i\}\right)^{w_i} \tag{5}$$

where $\sum_{i=1}^{n} w_i = 1$.

For the above model, the water claims and disagreement points serve as the upper and lower core bounds, respectively, whereas the model itself is constrained by feasibility and individual rationality.

The selected model, the Nash Bargaining Solution, was preferred over other game-theoretic approaches due to its axiomatic fairness properties, ability to manage feasibility spaces using upper and lower constraints, as well as its features of symmetry and Pareto Efficiency. These attributes make the Nash Bargaining Solution well-suited for allocating scarce water resources among different agents while also considering factors like social equality through the use of bargaining weights. In our case, the bargaining weights were derived from two socio-demographic indicators including household size and Multidimensional Poverty Index (MPI). Each of these indicators represents a unique aspect of water vulnerability. Additionally, the disagreement points calculated from Eq. 3 help ensure the enforceability and individual rationality of the outcomes.

For the water sharing problem facing the city of Karachi, the city is divided into seven administrative divisions/districts ($n = 7$) and thus x_i^-, z_i, w_i are, respectively, the optimized water allocation, the lower core bound, and the bargaining weight for each of the districts.

The optimization model is subject to following constraints:

1. The final water allocation to each agent should be equal to or greater than the lower core bound.

$$x_i^- \geq z_i, i = 1, 2, 3, \ldots\ldots, n \tag{6}$$

2. The final allocated water must be less than the amount of water claimed for each agent.

$$z_i \leq x_i^- \leq c_i \tag{7}$$

3. The total allocated water should be less than or equal to the amount of water available for division.

Table 4 Average household size and bargaining weights of all districts in the Karachi city, Pakistan

District	Household size*	Bargaining weight
Karachi Central	5.86	0.144
Karachi East	5.94	0.143
Karachi South	5.47	0.155
Karachi West	5.76	0.147
Keemari	6.47	0.131
Korangi	6.34	0.134
Malir	5.77	0.147

*Commissioner Karachi Division. *Economic Indicators*. Commissioner Karachi, 12 Feb. 2025, https://commissionerkarachi.gos.pk/. (Division 2025)

Table 5 Multidimensional poverty index (MPI) and bargaining weights of all districts in the city of Karachi, Pakistan

District	Percentage of MPI* (poor people)	Bargaining weight
Karachi Central	10.5	0.111
Karachi East	23.3	0.249
Karachi South	10.9	0.115
Karachi West	17.7	0.187
Keemari	6.7	0.071
Korangi	7.6	0.080
Malir	17.7	0.187

Data source: (Planning and Initiatives, 2022)

$$\sum_{i=1}^{n} x_i^{-} \leq E \tag{8}$$

3.6.1 Determination of Bargaining Weights

The allocation of water resources should be done to ensure fairness and efficiency due to limited availability and intense competition. The optimization problem stated in Eq. (4) is applied to the metropolitan city of Karachi, where there are seven administrative divisions competing for a limited amount of water.

Three cases were analyzed. Firstly, available water was allocated using equal weights. However, in reality, the water-sharing agents differ in terms of their socio-economic status. Therefore, to show the significance of bargaining weights, the agents were assigned different weights in the second case. These weights were based on their average household size. As found in other studies, total water consumption rises with household size, but per capita water usage decreases due to the sharing of water-intensive activities such as dishwashing or laundry (Arbués et al. 2010; Hussien et al. 2016). Therefore, a district having a smaller average household size will have higher bargaining weight and will be preferred in the allocation. Average household sizes for each district and their bargaining weights are shown in Table 4 below.

In the third case, weights were given to agents based on their Multidimensional Poverty Index (MPI), as shown in Table 5. The MPI shows the areas and levels of deprivation that people in a certain region experience, and it helps identify where funds are most needed. We

assume that agents with higher MPI scores are poorer and have a reduced ability to afford water. As a result, these agents were given priority in the water allocation process.

4 Results

4.1 WEAP Results

Figure 3 represents the unmet water demands and the satisfaction ratios of Karachi city under various scenarios. The satisfaction ratio indicates the percentage of total water demand that is successfully met or fulfilled in a given scenario. The demand priorities for all districts were kept the same in all scenarios. The results show that supply exceeds demand in all scenarios except for Scenario 4, where there is no shortfall for the years 2031 to 2036. The specific water demands for all scenarios are discussed below.

4.1.1 Scenario 1

Scenario 1 assumed the average population increase rates for all districts (Table 3). These district-level growth rates were incorporated into the WEAP model and future water demands were simulated for the years 2023 to 2040. The results show that the aggregate unmet water demand for the city increases from 1649×10^3 cubic meters in 2023 to 5852×10^3 cubic meters in 2040 (Fig. 3a). Similarly, the satisfaction ratio decreases from 60 percent in 2023 to 30 percent in 2040 (Fig. 3a).

4.1.2 Scenario 2

Scenario 2 considers the water conservation strategy that the Karachi and Water Sanitation Board (KWSB) plans to implement to minimize per capita water consumption by 20

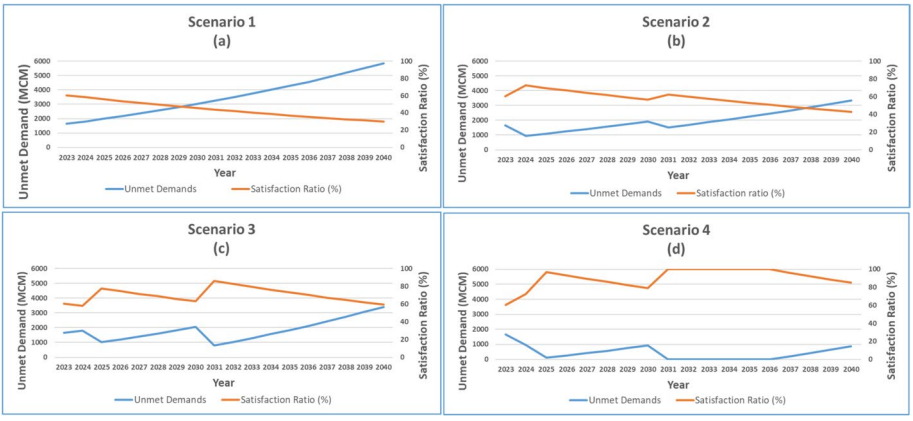

Fig. 3 Scenario-based analysis of future unmet water demand and satisfaction ratios for the city of Karachi, Pakistan (2023–2040). Scenario 1 (Plot a) represents modelling based on average population growth rate for all districts; Scenario 2 (Plot b) shows the impact of water conservation strategies to minimize water consumption for all districts; Scenario 3 (Plot c) represents an increased water supply; and Scenario 4 (Plot d) is a combination of Scenario 1 and Scenario 2. (Table 6, Annex-A, provides scenario details)

to 30 percent. The results of implementing this scenario in the WEAP model are shown in Fig. 3(b). Unmet water demand in this scenario increased from 1649×10^3 cubic meters in 2023 to 3341×10^3 cubic meters in 2040. This shows that despite the implementation of water conservation strategies, the supply–demand gap still exists, although it is considerably less than in Scenario 1. Satisfaction also fell but to a lesser extent compared to Scenario 1.

4.1.3 Scenario 3

Scenario 3 represents an improved water supply to the city. The Karachi Water and Sewerage Board (KWSB) has initiated the K-IV Project, which will supply 2.95 Mm^3/day or 650 million gallons of water per day (MGD) to Karachi from Keenjhar Lake. The project will be completed in two phases. Currently the Water and Power Development Authority (WAPDA) is constructing Phase I, which is scheduled to be completed in 2025 and will bring 1.19 Mm^3/day or 260 MGD to Karachi. The second phase of the K-IV water project aims to supply an additional 1.77 Mm^3/day or 390 million gallons per day of water and is planned to be completed and become operational by 2030 (World Bank 2018; JICA 2021).

Adopting this scenario in WEAP, predicted future water demand still shows a similar increase (to Scenario 2) in aggregate unmet water demand for the city from 1649×10^3 cubic meters in 2023 to 3392×10^3 cubic meters in 2040 (Fig. 3c). Similarly, while there was little change in the satisfaction ratio over time, this was considerably improved (at ~ 60% in 2040) compared to that indicated in Scenarios 1 and 2, which were around 30% and 40%, respectively (Fig. 3c).

4.1.4 Scenario 4

Scenario 4 in WEAP combines Scenario 2 and Scenario 3, which together aim to deliver a more sustainable water management situation with enhanced water availability and reduced losses and demand. It can be seen in Fig. 3d that the unmet water demand of 1649×10^3 cubic meters in 2023 decreases to 933×10^3 cubic meters in 2030. From 2031, Phase-II of the K-IV water project becomes operational, supplying 1.77 Mm^3/day or 390 million gallons per day of water to the city, resulting in a water shortfall of zero from 2031 to 2036, after which it increases to reach 881×10^3 cubic meters in 2040; satisfaction peaks at 100%, then falls to around 85% over this same time period (Fig. 3d).

4.2 Nash Bargaining Solution results

As stated in the previous sections, the Nash Bargaining Solution is a method used in cooperative game theory to determine the optimal outcome for two or more parties when they negotiate a compromise. In this section, we calculated the water satisfaction ratio for all seven districts under all four scenarios. First, we simulated the Nash Bargaining Solution (NBS) using equal weights. Next, we incorporated household size into our calculations when considering a modified version known as NBS-1. This approach adjusts the bargaining power based on the number of individuals in each household. After estimating the water satisfaction ratios under both NBS and NBS-1, we compared these results with those obtained from the WEAP model (Fig. 4). We also examined the water satisfaction ratio

based on the Multidimensional Poverty Index (Fig. 5). Figure 6 shows the year-wise water satisfaction levels for seven administrative divisions of Karachi under WEAP, Nash Bargaining Solution (equal weights) and Nash Bargaining Solution (based on household size) across Scenario 1, 2 and 3; Fig. 7 shows the same for Scenario 4.

From Figs. 4, 5, 6 and 7, it can be seen that the water allocation using WEAP yields different results than the water allocation using Nash Bargaining Solution (under homogenous and heterogenous weights). When weights were based on household size, districts with smaller households received higher allocations, reflecting their greater need. When using the Multidimensional Poverty Index (MPI), poorer districts were prioritized, ensuring a more pro-poor and equitable distribution. These weighted approaches allowed the model to account for intra-city disparities that more traditional proportional allocation approaches

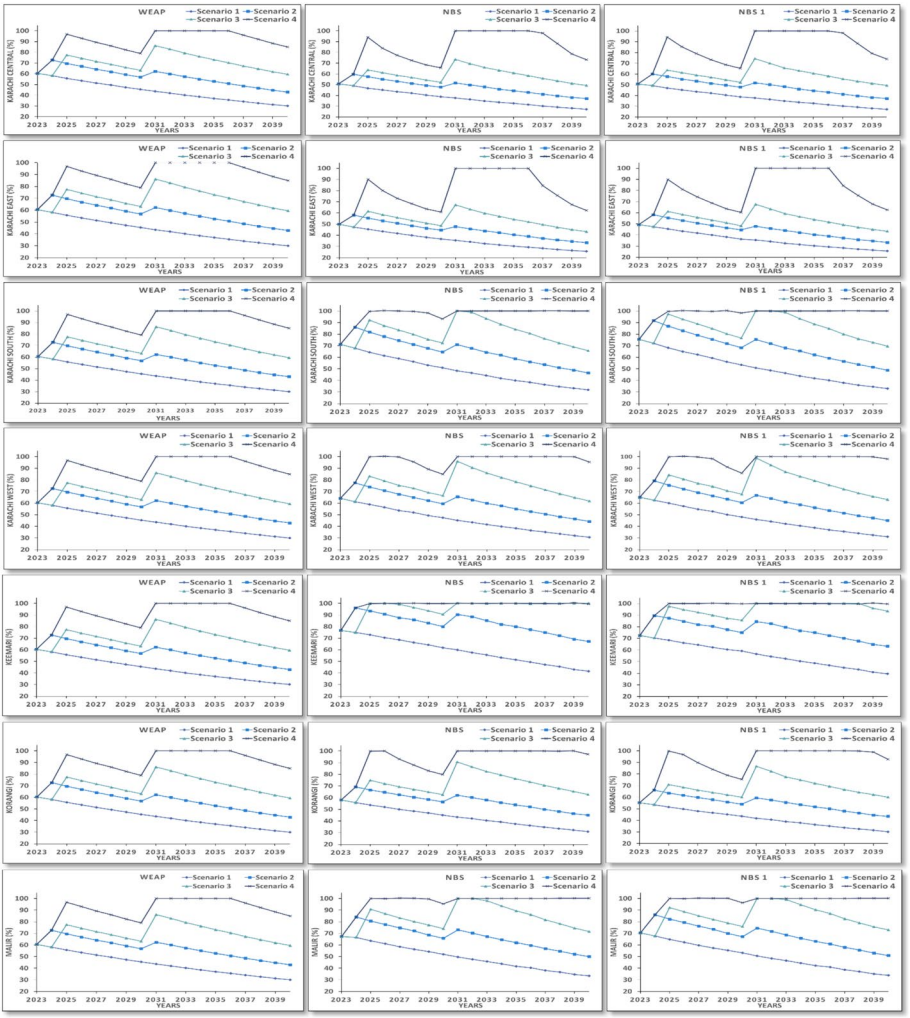

Fig. 4 Water satisfaction under WEAP, Nash Bargaining Solution (equal weights) and Nash Bargaining Solution (based on household size) by district in Karachi, Pakistan, as a percentage of water demand met (demand coverage), for Scenarios 1–4 (2023–2040). Each graph shows scenario-wise comparison

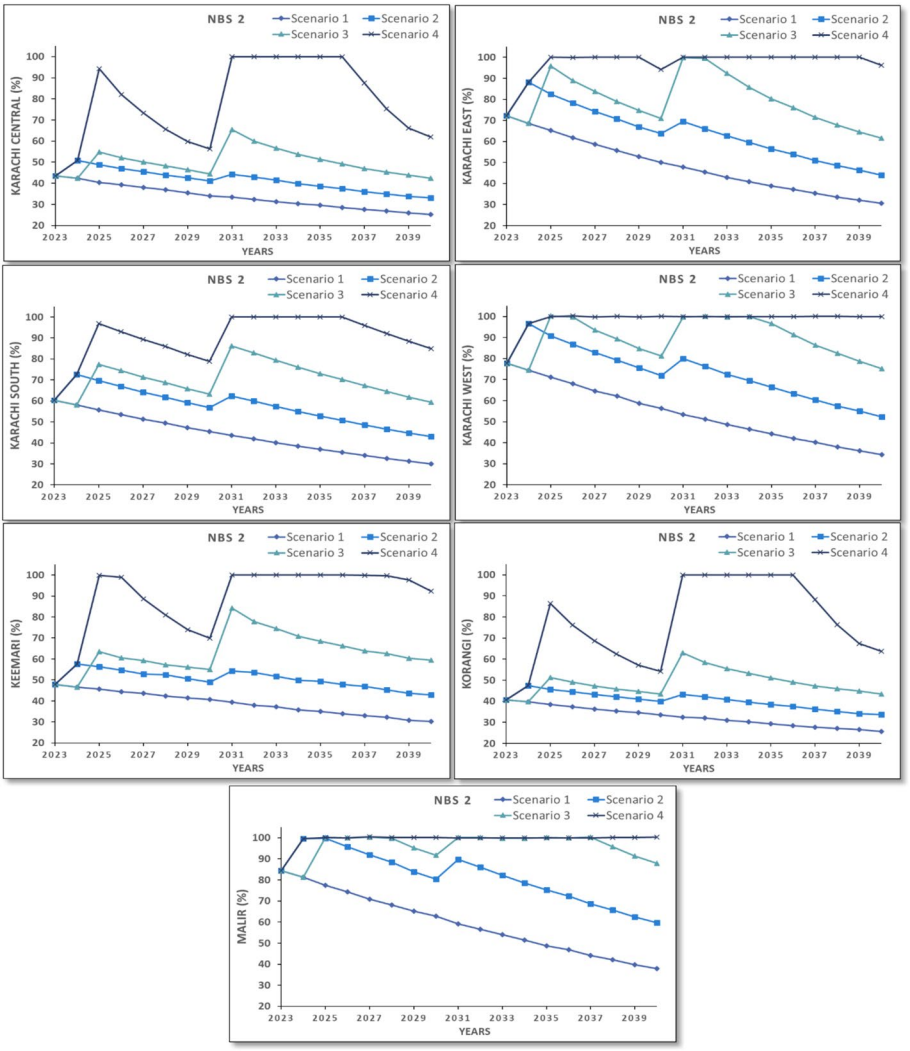

Fig. 5 Water satisfaction under Nash Bargaining Solution (Based on the Multidimensional Poverty Index) by district in Karachi, Pakistan, as a percentage of water demand met (demand coverage), for Scenarios 1–4 (2023–2040). Each graph shows scenario-wise comparison

(e.g., WEAP) overlook. For instance, WEAP allocates water proportionally among the agents and cannot resolve the heterogeneity among water agents (districts) in terms of their cooperation, household sizes and poverty levels. NBS solutions, on the other hand, consider these factors, resulting in fair water allocations and more nuanced water satisfactions among the agents. Thus, these NBS results reflect the distinct characteristics of the districts in Karachi city in terms of water security.

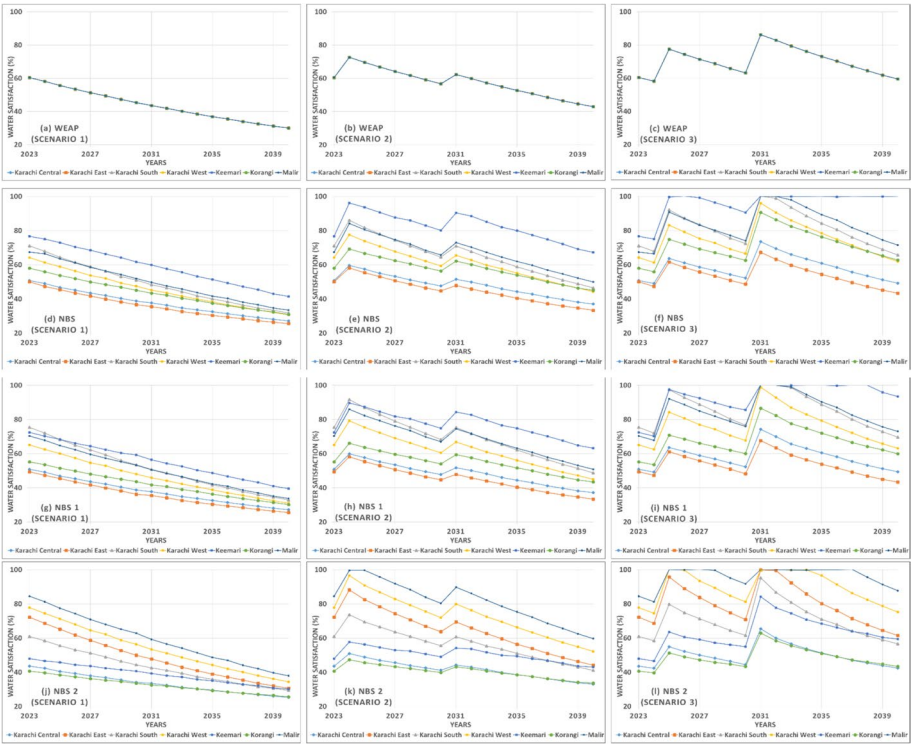

Fig. 6 Year-wise water satisfaction levels for seven administrative divisions of Karachi under WEAP, NBS, and NBS1 across Scenario 1, 2 and 3. Each graph shows district-wise comparison

4.2.1 Water Allocation Under WEAP

Water satisfaction was consistent across all districts when WEAP was used to allocate water (Fig. 4, left hand panel). This is also clearer in Figs. 6(a), (b), (c) and 7(a) where it can be seen that the satisfaction lines of all the districts overlap due to the same satisfaction ratio. This is due to the fact that WEAP allocates water proportionately among the agents, resulting in the same water satisfaction rate (based on % of water demand met) for all districts.

4.2.2 Water allocation under Nash Bargaining Solution (equal weights)

Figures 4, 5, 6 and 7 illustrate that water allocation under the NBS yields quite different results compared to WEAP. WEAP allocates water proportionally among the agents, whereas NBS maximizes the collective utility of all agents while considering agents' demands, thereby ensuring fairness. In essence, WEAP is a deterministic planning tool, while NBS incorporates negotiation dynamics and economic principles, potentially yielding more equitable or efficient outcomes based on agents'bargaining power and priorities (Janjua et al. 2024, 2025).

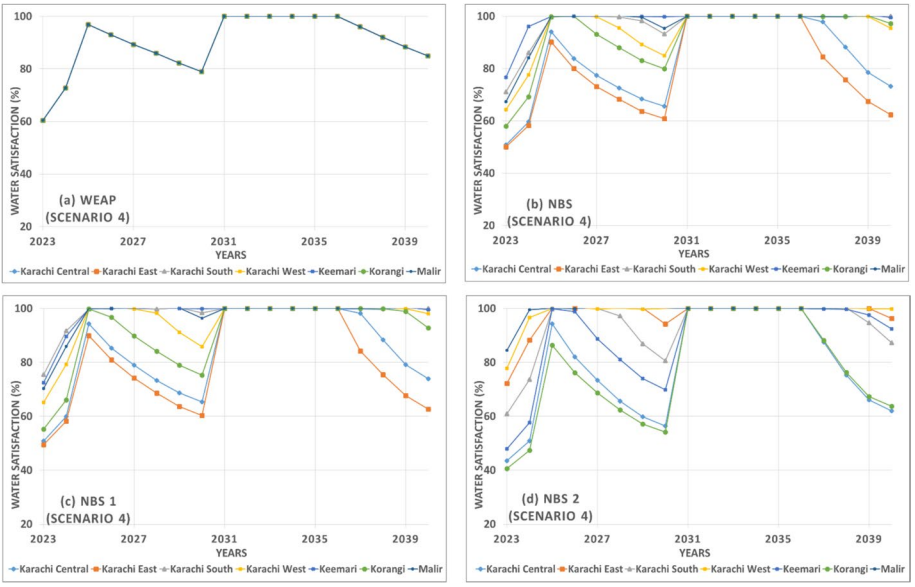

Fig. 7 Year-wise water satisfaction levels for seven administrative divisions of Karachi under WEAP, NBS, and NBS1 across Scenario-4. Each graph shows district-wise comparison

4.2.3 Water Allocation Under Nash Bargaining Solution NBS-1 (based on household size)

As explained above, the NBS under equal weights assumes that all the seven districts have the same bargaining power. In this way, no district is given priority based on demographic factors, resulting in a uniform allocation approach. This allocation ensures equitable distribution solely based on maximizing collective utility without accounting for any other socio-economic dynamics. In this case, water allocation was modelled using the NBS under unequal (heterogenous) weights based on the average household size. As stated earlier, districts with smaller household sizes are given higher weights, as they are presumed to have greater per capita water needs despite lower total water consumption due to shared activities like dishwashing or laundry. Under these assigned weights, districts with smaller households are favoured resulting in more context-sensitive allocation, as is evident in Figs. 4 and 6.

4.2.4 Water Allocation Under Nash Bargaining Solution, NBS-2 (based on Multidimensional Poverty Index)

In this instance, water allocation was based on the Multidimensional Poverty Index (MPI). The MPI highlights the areas and levels of deprivation experienced by people in a specific region, assisting in identifying where funding is most urgently needed (Ahmed et al. 2023). We assumed that districts with higher MPI scores are poorer and have a lower ability to purchase water. As a result, these districts were prioritized in the water allocation process.

When we compare the allocation results using WEAP, NBS (Equal Weights), and NBS (Based on Household Size), we find that districts with higher MPI scores, such as Karachi East, Malir, and Karachi West, now experience relatively greater water satisfaction, as shown in Figs. 5, 6(j, k, and l), and 7(d). The power of the Nash Bargaining Solution lies in its ability to incorporate agents'priorities through bargaining weights, allowing for context-sensitive and equitable allocations. The importance of these weights and their influence on final water distribution outcomes are further explored in the discussion section.

5 Discussion

In this novel framework, NBS was chosen for its ability to incorporate fairness and negotiation dynamics, addressing equity challenges not captured by WEAP. We first applied WEAP under several different scenarios to model future water demands in the case of Karachi, Pakistan – one of the world's largest and most water-insecure cities. The results show that under the scenario which combines water security adaptation and that allocates water based on principles of equity and social justice (Scenario 4), Karachi Central's demand coverage (water satisfaction) was 73 percent under NBS (Equal Weights) by the year 2040. This was similar at 74 percent under NBS 1 (based on household size) but reduced to 62 percent under NBS 2 (based on the Poverty Index, MPI). The lower allocation under NBS 2 is attributed to the district's relatively lower bargaining weight, as indicated by its mid-range MPI.

In comparison, results for Karachi East indicate that the demand coverage for Scenario 4 in the year 2040 is 62 percent under the NBS (Equal Weights) and 63 percent under NBS 1 (based on household size). However, it increases significantly to 96 percent under NBS 2 (based on the Multidimensional Poverty Index; MPI). The reason for the much higher demand coverage under NBS 2 is that the Karachi East district has the highest MPI weight, leading to a substantial increase in its allocation. On the other hand, District Keemari, being near to the sea has a greater proportion of wealthy residents and the lowest MPI weight, hence its allocation reduces from 100 percent (for Scenario 4, Year 2040), under the NBS (Equal Weights) to 92 percent under NBS 2 (based on the MPI). Similarly, bargaining weights played a crucial role in influencing water allocations in other districts.

The various water allocation methods, including WEAP, NBS (using equal weights), NBS-1 (based on household size), and NBS-2 (based on the Multidimensional Poverty Index, MPI), produce significantly different results due to their unique methodologies. WEAP allocates water deficits proportionally, without considering socioeconomic factors. In contrast, the NBS method with equal weights aims to maximize overall utility, but it does not take demographic or poverty disparities into account. When weights are adjusted based on household size in NBS-1, districts with smaller households receive a larger share of water, reflecting their higher per capita needs. On the other hand, NBS-2 employs MPI-based weights, which prioritize poorer districts, recognizing their lower economic power and greater vulnerability.

These differing approaches underscore the importance of aligning water allocation methods with specific equity and efficiency goals, which can significantly impact the final distribution of water resources. The proposed integrated WEAP and Nash Bargaining Solution approach has broader relevance for other megacities of the world facing water stress, particularly for the cities of Global South where urban inequality and huge disparities in the

water allocation among districts occur. The framework can help policy makers to design a more transparent water allocation mechanism that is socially just and technically sound. However, the study has some limitations, including that practical implementation of the proposed approach requires more detailed and disaggregated data and stakeholder involvement, while institutional coordination for the city of Karachi is lacking due to limited technical and governance capacity. Another major barrier might be political interference from more influential or wealthier areas that may lose their relative water share under a more equitable allocation framework. Our current model focuses on socio-economic equity using Multi-dimensional Poverty Index (MPI) and Household Size. Future development of the framework would likely benefit by including demographic and technical parameters such as population age structure, elevation and building types. These inclusions would allow a detailed understanding of infrastructure constraints and water usage patterns across the city.

The results presented in Figs. 4, 5, 6, and 7 are derived from model simulations rather than experiments or survey data based on random samples. In this paper, our inputs are fixed, which makes traditional statistical tests, such as p-values or confidence intervals, inappropriate. The main objective of our study is to compare how different water allocation strategies (specifically, NBS vs. WEAP) respond to various factors, such as poverty levels and household size. In our study, we employed realistic weighting methods, including equal weights, the Multidimensional Poverty Index (MPI), and household size, without conducting a formal sensitivity analysis. Our approach illustrates how different priorities can influence outcomes. This provides a clear understanding of how water allocation changes when the bargaining power of districts shifts.

For future research, we acknowledge that a more detailed sensitivity analysis would be beneficial, particularly in the context of uncertainty or changing inputs. In summary, due to the deterministic nature of our model outputs, traditional significance testing is not applicable. Instead, our comparative framework serves as an implicit sensitivity analysis, demonstrating how equity-based assumptions can shape distributive outcomes.

6 Conclusions

With a population of more than 20 million, the metropolitan city of Karachi is the 12th most populous city in the world. The city faces numerous challenges, such as rapid urbanization, water scarcity and population growth. Located in an arid climatic region where the rainfall pattern is highly erratic, water scarcity is considered a serious (and growing) problem. Policymakers and government officials must take a holistic approach to address the water sector, considering critical factors such as population increase, climate change, and rapid urban development. The Karachi Water and Sanitation Board (KWSB), along with local government authorities, are under pressure to implement best practices and regulations to address the ever-increasing water shortage. New developments planned by the provincial and federal governments on the outskirts of the city must consider the available water resources or future residents will face serious water supply problems.

Various methodologies were explored in this paper to ensure fair water allocation, comparing WEAP's proportional approach with that of the NBS under different weighting schemes. Equal weights, household size-based weights, and MPI-based weights were applied to analyze their impact on fairness and efficiency in water distribution. By incorpo-

Table 6 WEAP modeling results for unmet water demand (in thousand cubic meter) and satisfaction ratios (in % age) for scenarios 1–4 (Table 2) for Karachi, Pakistan (2023–2040)

Year	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	Satisfaction Ratio (%)	Unmet demand ('000 m^3)	Satisfaction ratio (%)	Unmet demand ('000 m^3)	Satisfaction Ratio (%)	Unmet demand ('000 m^3)	Satisfaction Ratio (%)	Unmet demand ('000 m^3)
2023	60	1649	60	1649	60	1649	60	1649
2024	58	1810	73	944	58	1810	73	944
2025	56	2001	70	1098	77	1017	97	113
2026	53	2189	67	1248	74	1205	93	263
2027	51	2385	64	1404	71	1401	89	420
2028	49	2575	62	1557	69	1591	86	573
2029	47	2803	59	1739	66	1818	82	754
2030	45	3025	57	1917	63	2041	79	933
2031	44	3258	62	1525	86	798	100	0
2032	42	3485	60	1684	83	1024	100	0
2033	40	3755	57	1873	79	1294	100	0
2034	39	4019	55	2058	76	1559	100	0
2035	37	4296	53	2252	73	1836	100	0
2036	36	4566	51	2441	70	2105	100	0
2037	34	4887	49	2665	67	2426	96	205
2038	33	5202	47	2886	64	2741	92	426
2039	31	5531	45	3117	62	3071	88	656
2040	30	5852	43	3341	59	3392	85	881

rating socio-economic factors such as household size and poverty levels, we demonstrated how tailored weighting approaches can aid in addressing equity concerns and better reflect the needs of diverse districts. The findings provide valuable insights into achieving equitable water allocation in resource-scarce settings. We believe that our developed framework will inspire new ideas and be used in other populated cities around the world facing water shortages.

Annex-A

Authors Contributions Conceptualization: Shahmir Janjua; Methodology: Shahmir Janjua, Shahbaz Mushtaq; Formal analysis and investigation: Shahmir Janjua, Shahbaz Mushtaq, Kathryn Reardon Smith, Duc-Anh An-Vo; Writing—original draft preparation: Shahmir Janjua; Writing—review and editing: Kathryn Reardon Smith, Shahbaz Mushtaq; Funding acquisition: N/A; Resources: Shahmir Janjua; Supervision: Shahbaz Mushtaq, Kathryn Reardon Smith, Duc-Anh An-Vo.

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Declarations

Ethical Approval N/A

Consent to Participate N/A.

Consent to Publish N/A

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