Volume 3, Number 3, 2026 Pages 2086-2104

Bioscience Insights

ISSN: 3080-3489 (Print)
ISSN: 3080-3497 (Online)

BioSciInsights.com

THE FRESHWATER CRISIS: WATER SCARCITY, GROUNDWATER DEPLETION AND THE GLOBAL CHALLENGE OF SAFE WATER ACCESS

Maryam khalid[*1], Dr. Tauseef Imtiaz[2], Ghulam Ghous[3], Dr. Imran Khan Swati[4], Junaid Ullah[5]

[*1] *Institute of Geography, University of the Punjab, Lahore.*
[2] *Faculty of Pharmacy and Pharmaceutical Sciences, University of Karachi, Karachi, Pakistan*
[3] *Government Sadiq Egerton Graduate College, Bahawalpur*
[4] *Department of Chemical Engineering, University of Engineering and Technology Peshawar, Pakistan*
[5] *Department of Chemistry, Government Postgraduate College Mandian, Abbottabad; Department of Chemistry, Hazara University, Mansehra, Pakistan*

[*1]maryamkhalid.geog@pu.edu.pk, [2]timtiazksa@gmail.com, [3]ghous.edu15@gmail.com, [4]imranswati@uetpeshawar.edu.pk, [5]junaidhamid2004@gmail.com

ORCID: [4]0009-0008-6314-1392

https://doi.org/10.5281/zenodo.24462133

Article Information

Article History

Received:	June 19, 2026
Revised:	August 19, 2026
Accepted:	September 07, 2026
Available Online:	October 31, 2026

Keywords:
Freshwater scarcity; groundwater depletion; safe drinking water; SDG 6; Falkenmark indicator; economic water scarcity; climate change; WASH; Pakistan.

Abstract

Background: *The world was experiencing a water problem in three respects: availability of freshwater per capita was inadequate, pumping of aquifers was exceeding recharge, and the drinking water was not safe. Typically, these dimensions were examined independently and the notion that safe water scarcity was due to physical scarcity was not often tested on a country-by-country basis.*
Methods: *This global country dataset is created by compiling FAO AQUASTAT (SDG indicator 6.4.2), the WHO/UNICEF Joint Monitoring Programme (JMP; SDG indicator 6.1.1), UN World Population Prospects 2024, income and governance indicators from the World Bank, and a global synthesis of 1,693 aquifer systems which are monitored. We estimated the future renewable water availability per capita in 179 countries that account for 99.4% of the global population for 2050 under population-only baseline and two climate scenarios. The availability of water is regressed on water systems that were safely managed in 125 countries, four robustness checks are conducted, and robust standard errors are used. The results were mapped on a world tile-grid map and a case study of Pakistan is analysed.*

Results: *The population increase alone increased the population of countries with less than 1 m³ per person from 1.08 billion (36 countries) in 2026 to 2.35 billion (46 countries) in 2050. Three-quarters of the rise was due to the situation in Africa and ten countries moved into scarcity. The population in absolute scarcity (less than 500 m³) increased from 0.76 billion to 1.01 billion with the uniform 10% loss of renewable water. 72% of the world's groundwater withdrawn by eight countries. The variation in safe-water coverage could be explained almost entirely by water availability (R^2 = 0.01), but the variation in income could explain 78%: a GDP per capita 10 times greater was associated with 54 percentage points higher coverage ($p < 0.001$). Government effectiveness was a good predictor of coverage alone, and the effect was small after controlling for income. In Pakistan the official scarcity statistic had been shifted to a different basis without informing anybody, on a constant basis, water per person was approximately 695 m³ in 2025 while the official was 899 m³.*

Conclusion: *The problems of physical scarcity and unsafe drinking water were separate crises and of different causes. The driving factors for scarcity were population growth and over-pumping of the aquifers and climate, while the factors for the safe-water deficit were income and infrastructure and institutions that income allows. A governance framework for groundwater and investments in water, sanitation and hygiene (WASH), targeted in sub-Saharan Africa and South Asia, was needed to enable effective policy. The keywords are: freshwater scarcity, groundwater depletion, safe drinking water, SDG 6, falkenmark indicator, economic water scarcity, climate change, WASH, Pakistan.*

1. INTRODUCTION

Freshwater supported food production, public health, energy generation and ecosystems and threatened by mid-2020s on every continent inhabited. According to World Resources Institute, approximately 4 billion people, or half of the world's population, were potentially under high water stress for at least one month of the year, while 25 countries with a quarter of the global population were extremely high water stress every year (WRI, 2023). The renewable resource usage in those countries was almost 100% of the renewable resource. The same assessment estimated a further billion people would be living in extreme stress by 2050, and in the Middle East and North Africa the entire population would be (WRI, 2023).
The problem of the lack of freshwater seemed to have three dimensions and we studied them together.

Scarcity: In 2021, global water stress, or the proportion of freshwater withdrawn compared to available freshwater, was 18.6% and had been increasing since 2015 (FAO & UN-Water, 2024). In Northern Africa, the average global gap of concealed extremes is 120% of renewables, in Southern Asia 83% of renewables (UN-Water, 2024).

Groundwater depletion: Approximately a quarter of all freshwater abstracted globally was from groundwater, and the amount of groundwater abstracted worldwide was estimated at 959 km³ in 2017 (UNESCO, 2022). It provided about half of the water drawn for domestic use and about a quarter of irrigation water. Aquifers were reloaded slowly: over-pumping used a long-term storeman as an accumulated store of over one hundred years.

Unsafe water: In 2024, there were still 2.1 billion people – 106 million of them using untreated surface water – without safely managed drinking water (WHO/UNICEF JMP, 2025). At least 1.4 million people

died in 2019 due to inadequate water, sanitation and hygiene, including 395,000 children under five (WHO, 2023; Wolf et al., 2023).
The three problems were sometimes taken for granted that they would be the same: countries experiencing water scarcity were presumed to be unable to produce safe water. Assuming that was the case, the answer would be principally hydrological in nature, with increased storage, increased inter-basin transfers, and increased desalination. If it didn't hold, unsafe water was predominantly an issue of infrastructure, governance and financing and needed a different set of policies.

Research gap: Each SDG indicator was assessed separately in a global assessment. There are few studies that have directly compared demographic scarcity estimates to groundwater trends and access information in the same countries; fewer still that have controlled for income and governance to see if physical scarcity predicts access. National figures that supported the scarcity claims made in the headlines were also seldom audited. It was important to differentiate between these explanations because the amounts involved were significant and the time frame until the 2030 deadline was short. Without investment targeting the wrong constraint, both crises would have remained unsolvable: new reservoirs would not have provided safe water to households without pipes, and new pipes would not have put water into the depleted aquifers. The setting up of a clearer picture of what problems exist in which countries was thus a prerequisite for an efficient allocation of limited public and donor finance.

Objectives: In this study we (i) projected renewable water per person to 2050 for 179 countries under population and climate scenarios; (ii) quantified how concentrated, and how fast-falling, global groundwater use was; (iii) estimated the pace of progress needed to reach universal safe drinking water; (iv) tested, with income and governance controls, whether scarcity predicted access; and (v) examined Pakistan as a case study in which all three dimensions of the crisis met. In Section 2, we examined the literature, in Section 3, we outlined the data and methods, and in Section 4, we presented the results of the global study, while in Section 5 we presented the results of the Pakistan case study. We then discussed the findings, their policy implications, the limitations of the study and conclusions in section 6 to 9.

2. Literature Review

2.1 Measuring Scarcity and Stress

There were two sets of water scarcity indicators that were prevalent. The Falkenmark indicator relates a country's renewable water to its population size, and considers countries consuming less than 1,700 m^3 per person per year as water-stressed, less than 1,000 m^3 as water-scarce and less than 500 m^3 as in absolute scarcity (Falkenmark, 1989). It was simple and comparable and became the most popular scarcity measurement, but it did not consider how much of the water supply was actually used or that it could be stored or routed. The use to availability ratios rectified that. For SDG indicator 6.4.2, total freshwater withdrawal by renewable water resources was calculated after subtracting the environmental flow requirement, and classified as high stress (above 75%) and critical (above 100%) (UN, 2024). Seasonal and sub-national detail were added to the same logic in the Aqueduct atlas of the World Resources Institute (WRI, 2023). The problem was described in two ways, from each family's perspective an unique dimension of the problem was captured.

2.2 Groundwater Depletion

The first continental scale detection of regional aquifer loss was from satellite gravimetry from the GRACE and GRACE-FO missions, beginning with north-western India, where Rodell et al. (2009) linked a large and persistent decrease in TWS to irrigation pumping. Gleeson et al. (2012) suggested that the extent of the groundwater footprints of some of the world's largest irrigated aquifers, such as the Indus Basin and the High Plains of the USA, are larger than the area in which they are recharged. The 170,000 monitoring wells in 1,693 aquifer systems analysed in this largest synthesis of in situ measurements represent roughly 75% of global groundwater withdrawal, in countries (Jasechko et al., 2024). That study indicated that 36% of the groundwater systems were experiencing declines greater than 0.1 m per year and 12% greater than 0.5 m per year. A reduction in all ODRs became more rapid in 30% of systems in

the 21st century, particularly in dry, intensively cropped systems. The effects of depletion were land subsidence, salt water intrusion, and dry wells and reduced river flows.

2.3 Access To Safe Water and Water Quality

The indicator of 'safely managed' drinking water from JMP comprised drinking water from an improved source located on premises with no faecal and priority chemical contamination, and available on demand when required (WHO/UNICEF JMP, 2025). The standard was designed to be demanding and removed the previous 'improved source' indicator under the Millennium Development Goals which only indicated the type of infrastructure but not the quality of the water provided. Between 2015 and 2024, global coverage increased from 68% to 74%, but the JMP found that coverage would have to improve by many factors to achieve SDG target 6.1 by 2030. There was an additional threat of geogenic contamination. An estimate of the population exposed to arsenic contamination in groundwater has been made using a machine learning risk map, which suggests 94% of the population, or between 94 and 220 million people, is in Asia (Podgorski & Berg, 2020).

2.4 Health burden

According to the 2019 WHO burden-of-disease assessment, unsafe water, sanitation and hygiene contributed to the death of at least 1.4 million people and 74 million disability-adjusted life years (DALYs) (WHO, 2023; Wolf et al., 2023). Over one million of those deaths were due to diarrhoeal disease. Over three-quarters of the deaths were in the WHO African and South-East Asia regions and 89% in low- and lower-middle-income countries.

2.5 Physical Versus Economic Scarcity

Two types of scarcity had been isolated in a long line of investigation. Oki and Kanae (2006) and Vörösmarty et al. (2010) mapped the global water stress and detected the threats to human water security in many of the populated parts of the world. Mekonnen and Hoekstra (2016) calculated that approximately 4 billion people experienced extremely high water scarcity for at least one month per year, instead of using yearly data. The many localities that have been classified as "water-scarce" did not lack in water, but in access to water, stated Rijsberman (2006). The Comprehensive Assessment of Water Management in Agriculture defined this as economic water scarcity, where water was available in nature but human, institutional or financial capital was insufficient to provide the water (Molden, 2007).

Two additional areas of research were in support of that distinction. For one thing, simple human necessities were not very large. Gleick (1996) estimated them at around 50 litres per person per day, or under 20 m^3 per year, a far cry from even the absolute-scarcity line for 500 m^3 per year. Secondly, the primary impediment to universal access seems to have been financial, with costing exercises suggesting the cost to achieve SDG targets 6.1 and 6.2 is approximately US$114 billion per year (Hutton & Varughese, 2016). There may be an overestimate of safety, as a meta-analysis revealed that a large proportion of sources labeled as "improved" were contaminated with faeces (Bain et al., 2014).

2.6 Groundwater And Climate Change

Global models were the first to quantify non-renewable groundwater use and its contribution to groundwater depletion (Wada et al., 2010; Bierkens & Wada, 2019). Famiglietti (2014) presented a global groundwater crisis, and Rodell et al. (2018) found many hotspots of freshwater loss with many attributed to irrigation. De Graaf et al. (2019) reported that numerous watersheds were already already exceeding environmental flows limits due to pumping, and Dalin et al. (2017) determined that a portion of groundwater depletion was being exported through international food trade. Climate was also interacting with aquifers: they were moderating droughts but also recharge rates were dependent on changing rainfall regimes (Taylor et al., 2013; Scanlon et al., 2023).

The added stress of climate projections. The IPCC Sixth Assessment indicated greater streamflow in northern high latitudes, and forecasted droughts in areas like the Mediterranean (Caretta et al., 2022; IPCC, 2021). In addition to the impact of population growth, a multi-model study estimated an additional absolute scarcity increase of around 40% at +2 °C (Schewe et al., 2014). Greve et al. (2018)

highlighted the high level of uncertainty in future scarcity in their models, thereby supporting the ranges of scenarios over the single projections.

2.7 Gap Addressed

While the idea of economic water scarcity was well known, it has not been widely tested quantitatively, across almost all countries, while controlling for income and governance, using the latest SDG data. Scarcity estimates were also rarely reported with access estimates from the same countries in the same time period. We examined both gaps, and added an audit of one national scarcity statistic to illustrate the potential differences in headline statistics across definitional choice.

3. Data And Methods

3.1 Data Sources

All data were public data and no new field measurements were taken. All the datasets were summarized in Table 1, and the variables that we selected from each dataset, the reference year, the country coverage and the source of each dataset. Using the country names in each record, they were matched to the ISO 3166 codes held in the various databases. National agencies and published national studies were used as a source of data for Pakistan case study.

Table 1. Datasets used in the study

Dataset	Variables used	Year(s)	Countries	Source
FAO AQUASTAT (SDG 6.4.2)	Total renewable water resources (TRWR) and total freshwater withdrawal, km^3/yr	2020	179 with TRWR > 0	FAO & UN-Water (2024), via UN-Water SDG 6 Data Portal
WHO/UNICEF JMP (SDG 6.1.1)	Population using safely managed drinking water, %	2024 (latest)	134 matched	WHO/UNICEF JMP (2025), via UN-Water SDG 6 Data Portal
UN World Population Prospects 2024	Population 2026 and 2050, medium variant	2026, 2050	194	UN DESA (2024)
World Bank World Development Indicators	GDP per capita, PPP (international $)	2024	191	World Bank (2025)
Worldwide Governance Indicators	Government effectiveness estimate (about −2.5 to +2.5)	2023	190	Kaufmann & Kraay (2024)
UN World Water Development Report 2022	Global groundwater withdrawal; withdrawal by country	2017–2022	Top 8 users	UNESCO (2022)
Global well synthesis	Groundwater-level trends in 1,693 aquifer systems	2000–2022	> 40	Jasechko et al. (2024)
WHO burden of disease	Deaths and DALYs attributable to unsafe WASH	2019	183	Wolf et al. (2023)
Global arsenic model	Population at risk of arsenic above 10 µg/L	2020	Global	Podgorski & Berg (2020)
World tile grid	Country tile positions for mapping	–	191	Schwabish (2017)
Pakistan national data	Census, official per-capita water, tubewells, water quality	1951–2025	Pakistan	PBS (2023); PCRWR (2026); PIDE (2026)

3.2 Water per Person and Scenarios

The amount of renewable water available per capita in year t for each country i was computed as:

$$A(i, t, s) = TRWR(i) \times f(i, s) \times 10^9 \div P(i, t) \quad (1)$$

In which, TRWR(i) was the total renewable water resources at i (km3/year), and P(i, t) was the population and climate factor was f(i, s). A was in m^3 per person per year when it was multiplied by 10^9 to convert cubic kilometres to cubic metres. We classified each country on the Falkenmark scale as being in absolute scarcity (below 500 m^3), scarcity (500 to 1,000 m^3), stress (1,000 to 1,700 m^3) or no stress (1,700 m^3 or more), and we compared the classification in 2026 with three scenarios for 2050:

1. Population only (f = 1): This was a baseline that maintained values of renewable resources at 2020 levels and separated the impact of demographic change.

2. Directional climate scenario: For countries in the wetter regions of the world (northern high latitudes, East Africa and the South Asian Monsoon belt) and drier regions (the Middle East and North Africa, Mediterranean Europe, southern Africa, Mexico and Central America), we set f = 1.10 and f = 0.85, respectively. In all other countries, f was set at 1. Groupings were based on the direction of change as stated in the Sixth Assessment of the IPCC (Caretta et al., 2022) and the magnitudes were illustrative.

3. A uniform stress test (f = 0.90 for all countries): This was a very simple sensitivity bound.

The scenarios were developed to bound reasonable changes, rather than to replicate model outputs. A simple withdrawal ratio, which is a ratio of total withdrawal to TRWR, was also calculated. This ratio was not equal to the official SDG 6.4.2 value due to the lack of the deduction of environmental flow requirements in this ratio.

3.3 Regression model

To assess if physical scarcity was a predictor of access to safe drinking water, the following model was estimated using ordinary least-squares:

$$SM(i) = \beta_0 + \beta_1 \times \log_{10} A(i) + \beta_2 \times \log_{10} GDP(i) + \beta_3 \times GE(i) + \varepsilon(i) \quad (2)$$

where SM(i) denoted the population percentage that accessed safely managed drinking water in country i, A(i) represented the renewable water available per person in 2026, GDP(i) was the GDP per capita at purchasing-power parity (PPP) and GE(i) was the government effectiveness estimate, and $\varepsilon(i)$ was the error term. Both water and income were highly skewed, which meant β_1 and β_2 could be interpreted as changes in coverage, in percentage points, for a tenfold increase in each variable.

We used heteroskedasticity-robust (HC1) standard errors, and all variance inflation factors were at or below 3.0, which indicated that multicollinearity was moderate. The core sample consisted of 125 countries that had all four variables. Six specifications (M1 to M6) were run. Water only was used in model M1, water and income in model M2, and water, income and full model in model M3. Three other tests of robustness were also conducted: M4 used the log of the withdrawal ratio, M5 used only countries with over 1 million people and M6 used water and governance without income. The full model was also re-estimated using a logit transformation of the outcome, which maintained the range of the outcome variable between 0 and 100, and standardised predictors were calculated to facilitate comparisons of relative weights of the predictors.

3.4 Data quality and validation

Three checks were performed on the merged data set. The first comparison was between the population estimate in our sample who did not have access to safely managed water and the JMP's published global total; the figures agreed reasonably well (with a difference of approximately 3%) suggesting that the estimates for the country had been matched well. Second, we checked that the 179 countries in the scarcity analysis taken collectively accounted for 99.4% of the UN's estimate of the world population in 2026. Third, in the Pakistan case study, we have tested our extrapolated trend in Lahore against an independent estimate which was not used in fitting the trend. A per-capita value could not be calculated

for the countries with a renewable-resource value equal to zero in AQUASTAT (mostly small island states), and these countries were therefore not included in the scarcity analysis.

3.5 Other analyses

We calculated the proportion of global groundwater use by the eight largest users from the total global use of 959 km³ per year (UNESCO, 2022), and we used aquifer-level trends directly from Jasechko et al. (2024). A rate of progress for achieving universal safe drinking water coverage was calculated, using the global trend of achieving safe drinking water coverage between 2015 and 2024 (WHO/UNICEF JMP, 2025), where 99% is defined as universal coverage. We plotted the findings on a world tile-grid map, where each country was assigned an equal-sized square and placed in the vicinity of the country's geographical location (Schwabish, 2017). The effect of this design was that countries were given the same visual impact regardless of their size and that it did not create distortion as is found on traditional choropleth maps, where large countries with small populations were prominent. The water volume implied by each of the official per capita figures has been calculated by multiplying each by the population from the same year for the Pakistan case study and the official series has been re-expressed on a constant 1951 basis. The water-table decline rates in Lahore were recorded during the periods and a linear trend by ordinary least squares was fitted to them. All analyses were carried out in Python 3 with the NumPy and SciPy libraries.

4. Results

4.1 Population growth more than doubled the number of people in water-scarce countries

Population growth alone led to an increase in the number of people living in countries below the 1,000 m³ scarcity line from 1.08 billion in 2026 to 2.35 billion in 2050 across the 179 countries (Table 2), accounting for 99.4% of the world's population. During the same period, the population in absolute scarcity (less than 500 m³) increased more than doubling from 0.32 billion to 0.76 billion, while the population below the stress line of 1,700 m³ increased from 3.31 to 4.50 billion.

Table 2. Population (billion) and number of countries below each Falkenmark threshold, 2026 and 2050

Threshold (m³ per person per year)	2026	2050, population only	2050, directional climate	2050, uniform −10%
Absolute scarcity (< 500)	0.32 (19)	0.76 (25)	0.76 (26)	1.01 (30)
Scarcity (< 1,000)	1.08 (36)	2.35 (46)	2.35 (47)	2.43 (49)
Stress (< 1,700)	3.31 (56)	4.50 (63)	4.50 (63)	4.55 (68)

Numbers of countries in brackets; 179 countries with renewable-resource data. Sources: FAO AQUASTAT (2020); UN WPP 2024; authors' calculations.

This growth was in Africa alone, as indicated in Table 2. Three-quarters of the world's population increase was in the African population, from 0.64 to 1.59 billion, while the population increase in Asia was from 0.43 to 0.74 billion. In Africa, population growth alone saw the numbers of ten countries cross the 1,000 m³ threshold by 2050, namely Comoros, Niger, Nigeria, Tanzania, Togo, Uganda and Zimbabwe, as well as Afghanistan and Uzbekistan in Asia and Haiti in the Caribbean.

The scenarios in Table 2 further accentuated this picture primarily at the edges. The directionally applied drying scenario of the Middle East, North Africa, Mediterranean and southern Africa only included one country in the small category (Lesotho), as most of the drying areas were already below the category. It was thus its chief impact to exacerbate preexisting scarcity. The more drastic 10 per cent loss had a more significant impact: it increased the number of people in the absolute-scarcity group by 250 million, or 33 per cent compared with the population-only case. This rise was comparable to the climate-induced rise of approximately 40% found by a multi-model study (Schewe et al. 2014) for a 2 °C warming. We thus decided that the major future scarcity was of the demographic kind, and that the effect of climate change was primarily to accentuate the scarcity of countries that were already scarce.

In a number of countries, withdrawals have already surpassed the renewable supply. The larger ones, most of which were simple withdrawal ratios, ranged in Saudi Arabia at 1,083%, in Yemen at 170%, in Egypt at 135% and in Uzbekistan at 121%, the remaining gap being filled by fossil groundwater, desalination or by inflows from upstream countries. In 2023, Northern Africa and Western Asia removed 78% of the water they could get, while Central and Southern Asia removed 68%, and sub-Saharan Africa removed 10%, of its water (UN-Water, 2025). These results were displayed on a tile-grid map of the world in figure 1. The countries in black projected to have less than 1,000 m³/person by 2050, and the shading represents the percentage of each country's population that is expected to have access to safely managed drinking water in 2024. The countries outlined are grouped into 2 clusters. The first was in North Africa, the Middle East and the Gulf, and was shaded dark, which indicated that the vast majority of this region was already supplying safe water to the majority of its population, despite the scarcity of water. The second, in East and West Africa, was mostly a light shade of scarcity, and was a poor access match to the other parts of the world. Low access, but good water, was indicated in large areas of central Africa, the South and South-East Asia and in the Pacific. The map was therefore predicted to show the statistical result described in Section 4.4.

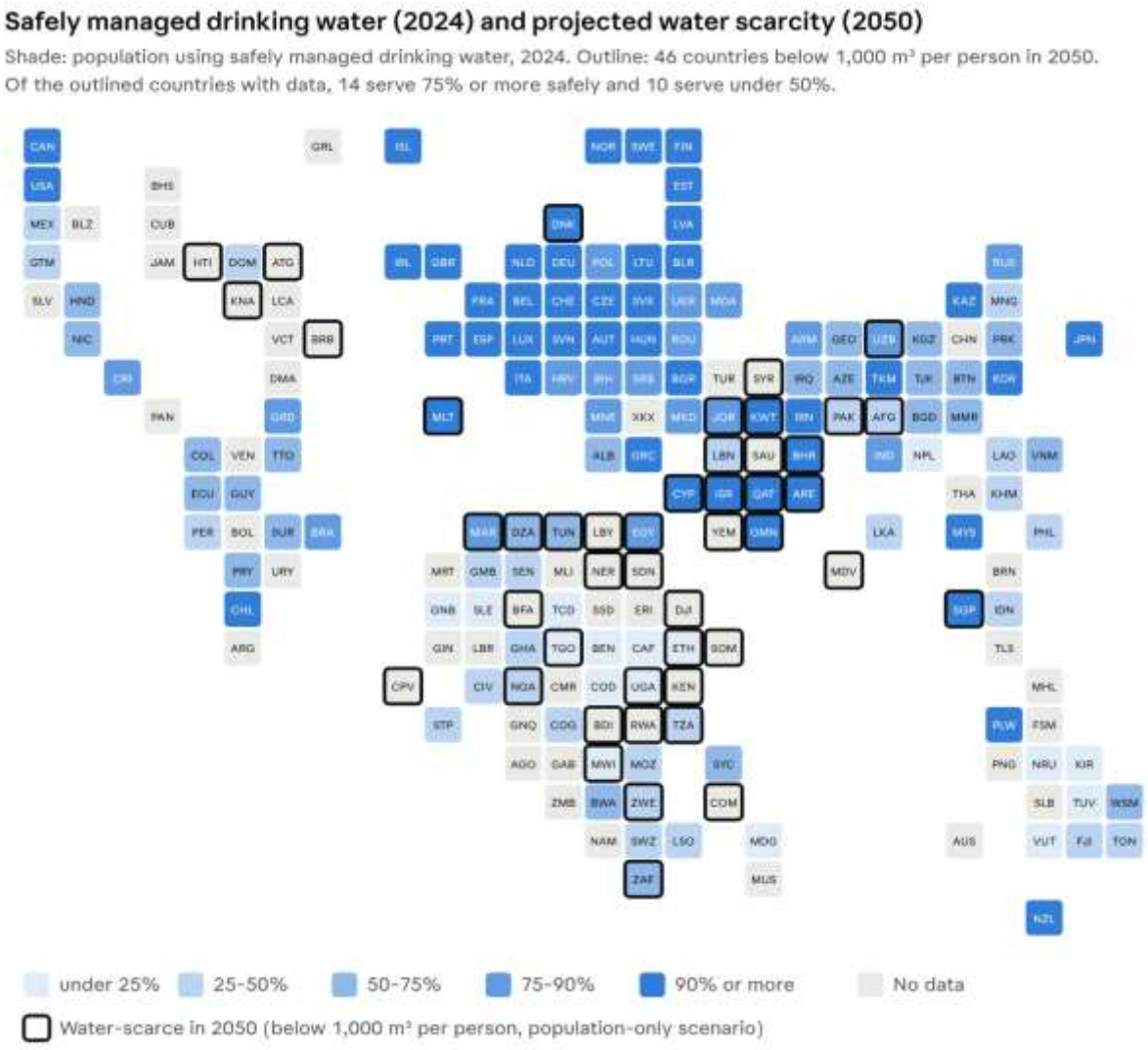

Figure 1. Safely managed drinking-water coverage in 2024 and countries projected to be water-scarce in 2050, shown on a world tile-grid map.

Each square is a country and is located in the geographic location which is determined by its location in the world (Schwabish, 2017). Shading indicates proportion of population using safely managed drinking water; grey squares are areas where no JMP estimate was available. The countries expected to have less than 1,000m³ of renewable water per person in 2050 under the population-only scenario are shaded in black. Data from WHO/UNICEF JMP, FAO AQUASTAT (UN-Water SDG 6 Data Portal), UN WPP 2024, and authors' calculations.

In Figure 1, the pattern across the country was similar to the regression. Ten countries forecast to be water-stressed in 2050 provided less than half of their population with safe drinking water, including Pakistan, Nigeria, Ethiopia, Tanzania, Uganda and Afghanistan. But at least three-quarters of their residents had access to safely managed water in 14 countries, such as Egypt, Morocco, Jordan, Israel and the Gulf states. In the other side of the distribution, there were seven countries with high water availability (more than 1,700 m³/capita in 2050) that provide less than 25% of their population safely, including the Democratic Republic of the Congo, Central African Republic, Madagascar, Nepal and Sierra Leone.

4.2 Groundwater use was concentrated and levels were falling widely

Groundwater use was very concentrated globally. From Table 3, it is seen that the eight largest users withdrew 687 km³ per year, representing 72% of the global total of 959 km³ per year. 56% of the total was contributed by four countries – India, China, United States, and Pakistan.

Table 3. The eight largest groundwater users

Country	Withdrawal (km³/yr)	Share of global total	Share used for irrigation
India	251	26%	89%
China	112	12%	54%
United States	112	12%	71%
Pakistan	65	7%	94%
Iran	64	7%	87%
Bangladesh	30	3%	86%
Mexico	29	3%	72%
Saudi Arabia	24	3%	92%
Top eight	**687**	**72%**	

Source: UNESCO (2022), as tabulated in PIDE (2026); shares calculated by the authors against the global total of 959 km³.

As displayed in the last column of Table 3, all countries, except China, had more than 70% of groundwater withdrawn used for irrigation. Thus, groundwater depletion was the chief problem of agriculture. The groundwater monitoring evidence showed widespread decline: in 36% of 1,693 aquifer systems, groundwater levels declined by more than 0.1 m per year; in 30% of aquifer systems, groundwater levels accelerated in the 21st century; and in 12%, groundwater levels declined by more than 0.5 m per year (Jasechko et al., 2024). Those with the most severe symptoms were extreme. The Rashtkhar aquifer in Iran fell by a median of 2.6 m per year and the Chowchilla sub-basin in California by about 1 m per year. In 80% of the aquifers that showed accelerated declines, rainfall had also been declining, indicating that climatic drying and pumping both contributed to the accelerated declines (Jasechko et al., 2024).

4.3 Slow and uneven progress in improving safe drinking water

The rate of global safe managed coverage increased from 68% in 2015 to 74% in 2024, an average increase of 0.67% per year. If this rate of progress continues, universal coverage (99%) would be achieved in the year 2061, which is 30 years after the SDG target. A universal coverage of 4.2 points per year would have been needed to reach universal coverage by 2030. The JMP's own estimate, which also included population growth, was eightfold (WHO/UNICEF JMP, 2025).

Table 4. Water stress and safe drinking water by SDG region

SDG region	Water stress, 2023 (% of available water withdrawn)	Safely managed drinking water, 2024 (%)	Drinking surface water, 2024 (%)
Northern Africa and Western Asia	77.7	76.2	0.8
Central and Southern Asia	67.8	77.0	0.6
Eastern and South-Eastern Asia	30.3	75.3	0.4
Europe and Northern America	11.4	94.2	0.04
Sub-Saharan Africa	9.8	31.7	5.6
Latin America and the Caribbean	5.4	78.1	1.8
World	**17.6**	**73.7**	**1.3**

Source: UN-Water SDG 6 Data Portal, indicators 6.4.2 and 6.1.1 (UN-Water, 2025).

The major result of the study at the regional scale has already been revealed by the Table 4. One of the least water stressed regions, in terms of water stress, was Sub-Saharan Africa (9.8%) but in terms of safe-water coverage, it was the lowest (31.7%). In contrast, Northern Africa and Western Asia was the most stressed region (77.7%) yet provided safely managed water to three-quarters of its people. SSA also had the largest proportion of people drinking untreated surface water (5.6%) which was well above the world average.

4.4 Income, not water, predicted safe drinking water

The results of the regression are presented in Table 5. Renewable water per person was one of the least important variables, accounting for almost no variance in safely managed coverage when alone (M1: R^2 = 0.01; Spearman $\rho = -0.05$; $p = 0.60$) in the 125 countries. The explained variance increased to 78% (M2) with the addition of GDP per capita. In the full model (M3), a tenfold higher income was associated with 54 percentage points higher coverage ($p < 0.001$). The coefficient for water endowment per person was slightly negative: an increase by one order of magnitude in water endowment was correlated with a decrease in coverage by 2.8 points ($p = 0.049$). This was similar to the situation found in a large number of tropical African and Asian countries that are water abundant but low-income.

Table 5. OLS regressions of safely managed drinking water (% of population) on water availability, income and governance

Variable	M1 Water only	M2 + Income	M3 Full	M4 + Withdrawal ratio	M5 Countries > 1 million	M6 Water + governance
$\log_{10}$ water per person	−3.48 (2.70)	−2.75 (1.42)	−2.79* (1.40)	2.25 (3.06)	−1.58 (1.46)	−1.77 (1.84)
$\log_{10}$ GDP per capita (PPP)		52.90*** (2.37)	54.04*** (4.97)	48.86*** (5.69)	56.56*** (4.98)	
Government effectiveness			−0.70 (2.45)	0.67 (2.50)	−1.70 (2.45)	21.28*** (1.71)
$\log_{10}$ withdrawal ratio				5.40 (2.99)		
Observations	125	125	125	124	115	125
R^2	0.01	0.78	0.78	0.78	0.79	0.51

Robust (HC1) standard errors in brackets. * $p < 0.05$; *** $p < 0.001$. Variance inflation factors ≤ 3.0. Sources: JMP 2024; AQUASTAT 2020; UN WPP 2024; World Bank WDI 2024; WGI 2023; authors' calculations.

Government effectiveness was a strong predictor alone: Coverage increased by 21 points with each point added to the governance scale (M6, $p < 0.001$). When income was added, however, the coefficient was reduced to close to zero (M3). There was a strong positive correlation between the two variables ($r = 0.81$), so they were unable to be clearly separated. When the outcome was specified using the logit model (which respected the bounds of the outcome), governance was also significant ($p = 0.003$) in addition to income. The main result, the income coefficient between 49 and 57 points and highly significant in each specification, was not altered by the robustness checks in Table 5, while the water coefficient was small and insignificant when the withdrawal ratio was added (M4) or small states were excluded (M5). The standardised coefficients of the full model explicitly highlighted the contrast, at 0.90 for income, −0.08 for water and −0.02 for governance. The difference was vividly presented in figure 2. The countries were distributed throughout the entire spectrum of coverage at each level of water availability (left panel), and the fitted line was almost flat ($R^2 = 0.01$). The same countries are plotted as an equally steep and tight gradient in the right panel as income ($R^2 = 0.77$). Pakistan was shaded in blue which was near the income line, which meant that Pakistan's coverage of 45% was about the level that one would predict from its income and not below average for its water supply.

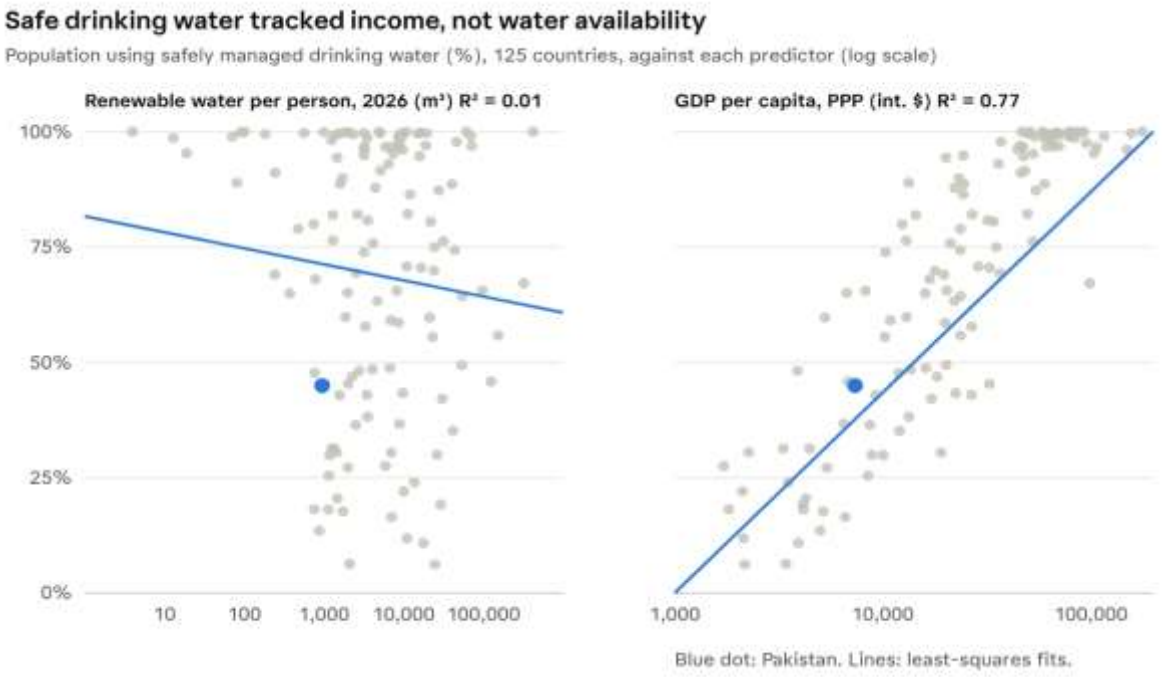

Figure 2. Safely managed drinking-water coverage against renewable water per person (left) and GDP per capita (right), 125 countries

The X and Y axes are on a log scale. Lines are least-squares fits and the area of Pakistan is highlighted in blue. Data sources: WHO/UNICEF JMP 2024, FAO AQUASTAT 2020, UN WPP 2024, World Bank WDI 2024, authors' calculations.

4.5 Health and Chemical Contamination

The toll of the access deficit was high. At least 1.4 million people died in 2019 due to unsafe water, sanitation and hygiene. Over one million of these deaths were attributed to diarrhoea, and over 356,000 were attributed to acute respiratory infections related to poor hand hygiene (WHO, 2023; Wolf et al., 2023). Unsafe WASH led to 395,000 child deaths aged under 5 years, accounting for 7.6% of all child deaths in this age group. The burden of chemical hazards was also a hidden one: up to 220 million people were potentially ingesting arsenic contaminated groundwater above the WHO guideline value, with 94% of those in Asia (Podgorski & Berg, 2020). This arsenic was geogenic, and the more the wells are pumped,

the deeper and more intense they are, the greater the amount of this arsenic can be found in the groundwater.

5. Case Study: Pakistan, Where All Three Dimensions of the Crisis Met

Pakistan is the country which showed the global results. It was the fifth most populous country in the world in 2025 with 255 million inhabitants and the fourth largest groundwater user in the world (Table 3) with 372 million projected in 2050. Approximately 140 million of its inhabitants did not have safe drinking water. It receives virtually all its surface water from one river system, the Indus, and agriculture withdrawal is around 94% of the total withdrawals (Maqbool, 2022). The country thus has the demographic stress, depletion of aquifers and scarcity of access highlighted by the global analysis.

5.1 Scarcity was deeper than the official statistic showed

The water available per capita dropped from 5260 m^3 in 1951 to 899 m^3 in 2025 (Ministry of Water Resources, 2025). By multiplying the water volume from each official value by the population in each year, the implied water volume increased from 177.5 km^3 in 1951 to approximately 229 km^3 from 2017 onwards. This 29% decrease in the underlying resource estimation was not reported with the series, and is most likely due to transitioning from a river-flow to a more resource-based definition. The figure was around 695 m^3 per person in 2025 on a constant 1951 basis and the country crossed the 1,000 m^3 scarcity line around 2010, not after 2016.

The two series were compared and are presented in figure 3. The official line (grey) and the constant-basis line (blue) began at the same level in 1951, but diverged in 2017 due to the change in the official line's base value in the intervening years. The constant-basis line crossed the 1,000 m^3 threshold about a decade earlier than the official line. If projected for 2050 using the UN medium-variant population, it would rise to 477 m^3, which is still below the absolute-scarcity threshold, whereas the official basis would rise to 616 m^3. Pakistan has 968 m^3 per capita in 2025 based on the 3rd, wider base which was FAO's estimate of 246.8 km^3 of total renewable resources for the world. The same country might thus be found at 695, 899 or 968 m^3 depending on which definition is applied. This was of global significance as the statistics of scarcity were not frequently audited nationally, and headline statistics elsewhere have been understated.

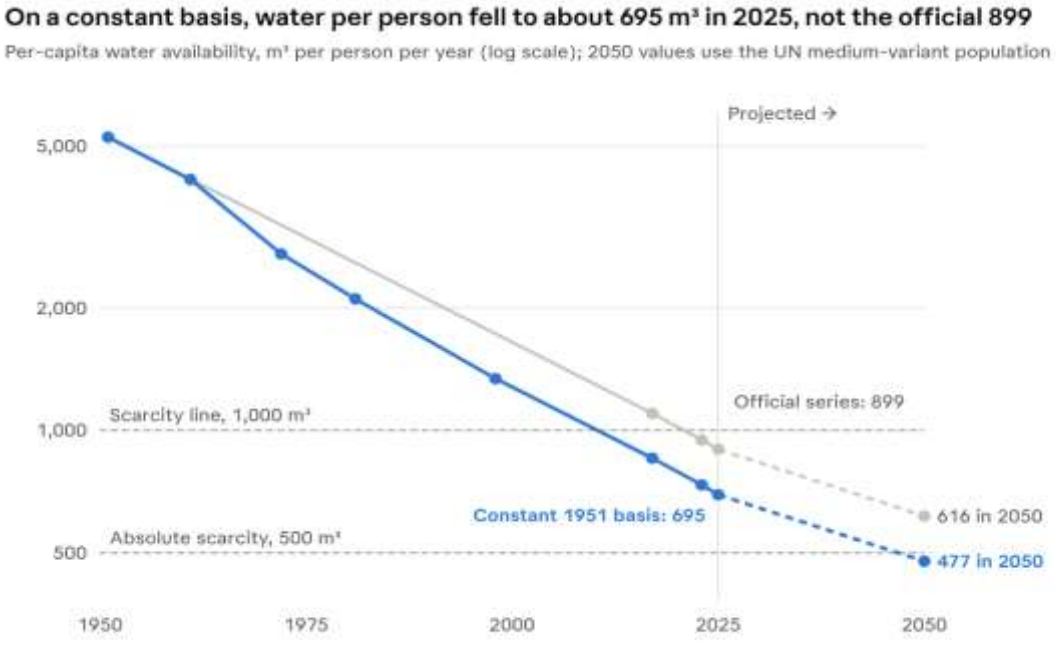

Figure 3. Water Availability Per Person In Pakistan, 1951–2050: Official Series And Constant-Basis Series

The resource estimate for the constant-basis series remained constant (177.5 km³) in 1951. The vertical axis is plotted on a log scale, dashed lines indicate the 1,000 m³ and 500 m³ levels, and dashed segments beyond 2025 are projections based on the UN medium-variant population. The data sources are the Ministry of Water Resources (2025), PBS censuses 1951-2023, UN WPP 2024, and authors' calculations.

5.2 An Aquifer in Structural Deficit

The annual groundwater pumpage in Pakistan is approximately 65 km³, while the recharge was approximately 55 km³, resulting in an annual groundwater overdraft (PIDE, 2026) of 10 km³. The number of tubewells rose from 984,000 in 2004–05 to 1.55 million in 2023–24, and it rose by 154% in Sindh. The rate of groundwater storage loss in the Indus basin increased from 0.65 cm/yr prior to 2015 to the current value of 2.16 cm/yr (Dharpure et al., 2025). In Quetta water table dropped from 50m to over 150m below ground between 2000 and 2023.

The water-table decline rate in Lahore for the 6 periods from 1960 to 2013 is presented in Figure 4. The rate rose from 0.30 m per year in 1960–67 to 0.91 m per year in 2011–13. Our linear fit showed the rate was about 0.01 m per year for 50 years (R^2 = 0.88) and it predicted a reduction of about 1.0 m per year until 2025. The estimated value of about 1 m per year by Arshad et al. (2023) which was not used in the trend fitting was on the extrapolated line and was in agreement with our projection. At the city level, Lahore was a reflection of the acceleration of 30% of the world's aquifers as documented by Jasechko et al. (2024).

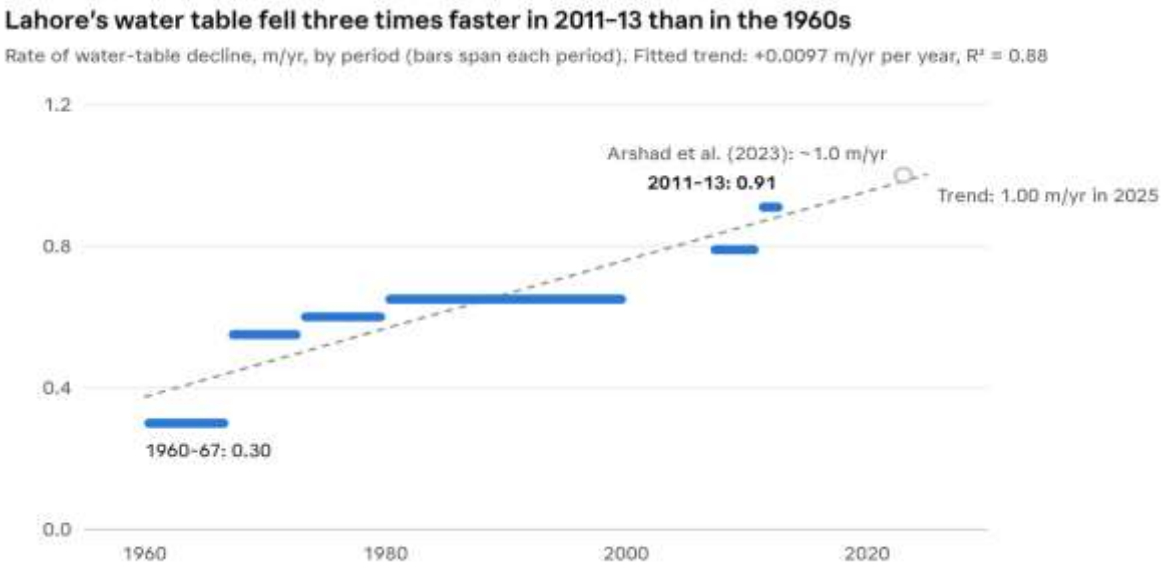

Figure 4. Rate of water-table decline in Lahore, Pakistan, by period, 1960–2013

Each recording period is covered by horizontal bars. The dashed line is a least-squares trend extrapolated to 2025 and the hollow marker represents an independent estimate which was not included in the trend. The data presented are from State Bank of Pakistan (2017) and Arshad et al. (2023), as sourced by PIDE (2026), and involve the authors' calculations.

5.3 Unsafe Drinking Water

In 2025, the Pakistan Council of Research in Water Resources (PCRWR) conducted a sampling campaign in 70 cities across the country, testing 2,205 drinking-water samples. Only 32% of these samples fulfilled the national standard and of the 59% samples that did not meet the standard, 59% were found to have microbial contamination (PCRWR, 2026). In Punjab, 14% of the sources had arsenic more than 10 µg/L, whereas in KP (13%) and Sindh (10%) the proportion was less (PIDE 2026).

Figure 5 presented the proportion of unsafe samples by province/region. Sindh recorded the highest share (89%) while Azad Jammu and Kashmir (85%) and Gilgit-Baltistan (69%) had a higher share compared to the national share (68%). Punjab at 61% and Balochistan at 59% were slightly ahead and KP at 40% was the lowest. The ranking was not water dependent, with some of the worst outcomes in water poor areas like Gilgit-Baltistan and Azad Jammu and Kashmir, both of which are located in the upper Indus catchment which has abundant water. This pattern was repeated in one country, in keeping with the worldwide observation that access and quality was more related to the quality of service delivered than to the quantity of water supplied.

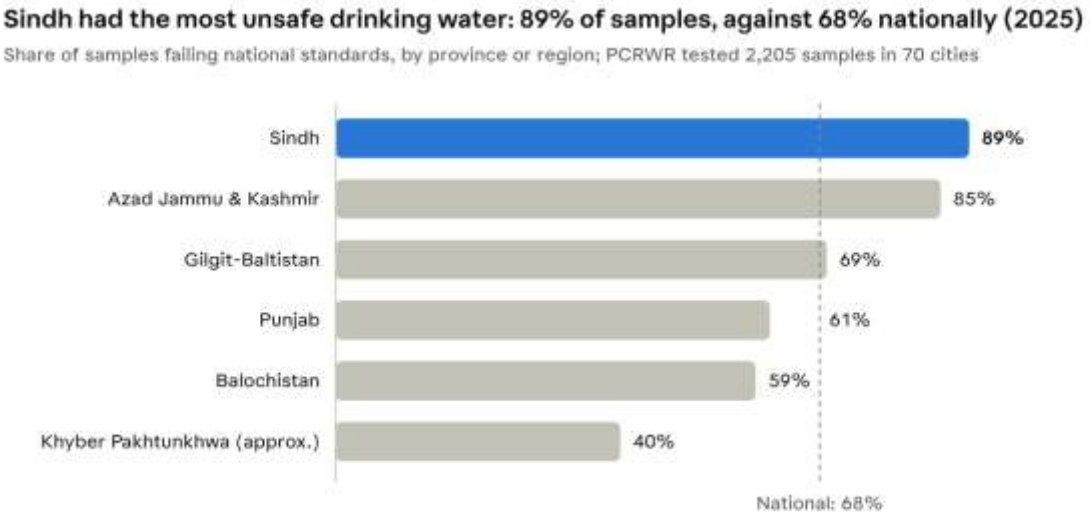

Figure 5. Share Of Drinking-Water Samples Failing National Standards By Province Or Region Of Pakistan, 2025

The dashed line marks the national figure of 68% (2,205 samples from 70 cities). The Khyber Pakhtunkhwa value was derived from the reported 60% of samples meeting standards. Source: PCRWR (2026).

5.4 What the case study added

The Pakistan case has validated the international trend at the national level and also provided three lessons. Population was the primary cause of scarcity in Pakistan as an increase in population accounted for the entire decrease in water per person since 1951, when the resource base was kept constant. Secondly, it was being overdrafted by irrigation and the overdraft was increasing. Third, unsafe water was primarily a service delivery problem, as microbial contamination was the predominant source. The case also illustrated a transboundary risk which could not be identified in the global analysis. From April 2025, India had kept the Indus Waters Treaty "in abeyance" and in May 2025, the river flow in the Chenab at Marala reduced to about 3,100 cusecs from up to 35,000 (WAPDA river-flow data, reported in Dawn, 2025). Pakistan had limited buffer against such shocks as it only stores around 30 days of demand (Maqbool, 2022).

6. Discussion

6.1 Two Crises, Not One

We found that the situation of physical scarcity and safe-water deficit were two distinct issues that had different causes. The coverage of safe water, in 125 countries, accounted for 1% of the variation in water availability, while income accounted for 78% (Table 5). These findings lent quantitative support, using current SDG data, for the concept of economic water scarcity, which has been around for a long time (Rijsberman, 2006; Molden, 2007). Even in the face of significant physical scarcity, Egypt, Morocco and Jordan brought safely managed water to the majority of their people and Saudi Arabia, which did rely on

desalination, ensured access to at least basic water for 99%. However, the Democratic Republic of the Congo (12%), Ethiopia (14%) and Madagascar (22%) did not despite having so much more water per person. It was demonstrated by Figure 1, Figure 2 and Table 4 geographically, statistically and at regional scale.

A direct consequence of the policy was that. Supply-side megaprojects like dams, inter-basin transfers, and desalination plants corrected physical scarcity, but little was done about the 2.1 billion people facing scarcity because there was no money, infrastructure, or institutions to achieve the transfer of water. The amounts of material moved were relatively small. Basic domestic needs of approximately 50 litres per person per day (LPD) (Gleick, 1996) equivalent to less than 20 m^3 per person per year (pPY) were less than 5% of the absolute scarcity threshold of 500 m^3 pPY. Unlike, however, in other parts of the world, like Pakistan, Egypt and Yemen, where water withdrawals were almost equal to the renewable supply even in their absence, the extension of piped networks did not end scarcity.

The governance outcome needed some special handling. The government effectiveness measure alone made a strong prediction of access, as it was closely associated with income, making it impossible to disentangle the two effects from cross-sectional data. We took the result to mean that income and state capacity were complementary; i.e., that a wealthy state could pay for water services and a good state could ensure they are provided and maintained. This was confirmed by the logit specification where governance was still important. The small negative coefficient of water also needed to be commented. It was likely due to geographic distribution of poverty and not to the impacts of water availability, because the poorest countries were in humid tropical areas that had high levels of renewable water.

6.2 Demography First, Climate Second

In the case of scarce countries, the population increase was more than doubled by 2050 due to population growth, since the renewable resources were assumed to remain constant in the baseline (Table 2). The change in the number of scarce countries under our climate scenarios was very small as the areas that the IPCC projected to become drier were mostly already scarce. A consistent three-third of the population was in absolute scarcity due to climate change, which mainly increased existing scarcity.The absolute scarcity due to climate change was consistent and amounted to a third of the population, which was in line with multi-model estimates (Schewe et al., 2014). The transition from scarcity was the highest in 2023 in Sub-Saharan Africa (Table 4) which was the least water stressed region. The two crises could merge in that region later in the century if investment fails to keep up with population growth, where the rate of access was the lowest.

6.3 Groundwater Was The Link Between The Two Crises

Scarcity and access were linked with groundwater. It protected from drought and provided approximately half the world's domestic water, hence its primary role in ensuring that many water-stressed farmers and towns had water at all. But it was being extracted just where it was most needed: as can be seen from Table 3 and the Lahore record in Figure 4. One-third of sampled aquifers were declining, with almost one-third of those declining at a greater rate than in prior years. As water levels dropped, wells were deepened, pumping expenses increased, salty water or water tainted by arsenic was extracted, and the lowest quality water was tapped first, from shallow hand pumps by the poorest users. Groundwater depletion was thus, not only a scarcity issue, but an access and health issue in the future. Cheap solar pumps, which in Pakistan power just 2% of tubewells in 2023–24 (PIDE, 2026), posed a threat to eliminate the final economic constraint on abstraction in many countries.

6.4 Statistics Mattered

The Pakistan audit (Figure 3) revealed that the headline scarcity figure could undergo a change of definition at any time without notice. Reporting data had to be collected from a national level, and many countries made infrequent and inconsistent revisions to resources estimates. To set reliable targets credible water accounting was therefore a prerequisite, and cost-effectiveness is low compared to infrastructure decisions that rely on water accounting.

6.5 Comparison With Previous Studies

The groundwater results were consistent with the results of the other studies – Rodell et al. (2009), Gleeson et al. (2012) and Jasechko et al. (2024) – regarding the speed and location of aquifer declines. Our population-level projection of 2.35 billion people living in water-scarce countries in 2050 was more modest than the monthly-scale estimates of people living in severe water scarcity (Mekonnen & Hoekstra, 2016; WRI, 2023), as these figures masked shortages at a sub-national and seasonal level. The key finding of the study was the test of the economic-scarcity hypothesis in 125 countries with income and governance controls as well as the comparison of that test with scarcity projections for 179 countries.

6.6 Implications for SDG 6 Monitoring

Progress towards SDG 6 was also affected by our results in terms of monitoring. Both indicators, water stress (SDG 6.4.2) and safe drinking water (SDG 6.1.1), were reported in the SDG framework, implying that there was a close relationship between the two. Our analysis revealed that they acted more or less autonomously on the inter-country level, and improvement in one country could not be interpreted as progress in the other. There was a risk that countries with low stress, but poor access (mostly sub-Saharan Africa) would be neglected in the arguments dominated by scarcity, and a risk that countries with high stress, but good access (mostly Middle East and North Africa) would be considered success stories with their aquifers drained. To this end, we recommended that the monitoring reports provide a nation-by-nation ranking of countries by scarcity and access as in figure 1, so that the countries can be identified by their binding constraints. We also advocated for including groundwater levels as a regular indicator, since neither 6.4.2 nor 6.1.1 included an indicator of the depletion of non-renewable groundwater storage that buffered so many water-scarce economies.

7. Policy Implications

Since they were caused by scarcity, they needed different instruments; because they were caused by unsafe water. We organized the recommendations by theme, according to the problem each addressed.

For physical scarcity

1. **Control the demand of agriculture first:** Most of the water was being withdrawn for irrigation in all of the countries with scarce water resources in our data. Possible changes in crop mix, implementation of drip and sprinkler irrigation, and the mitigation of conveyance losses would yield more water than most new dams.
2. **Plan for the growth of population:** The ability to account for demographic projections in national water plans should be included in water ministries in rapidly growing countries, particularly sub-Saharan Africa, South Asia and Central Asia, as was done in this study.
3. **Cooperate across borders:** Most major riverbanks were shared and treaties with mechanisms for dispute resolution and data-sharing minimized the potential for scarcity to become a source of conflict.

For groundwater depletion

4. **Register, meter and license wells.** The vast majority of the 8 largest users did not have any enforceable rights to private pumping and initiating the licensing of high-capacity wells was an obvious next step.
5. **Link energy subsidy to water caps:** The cost barrier of pumping was eliminated by free or 'flat rate' electricity, and more recently by relatively inexpensive solar pumps, and therefore subsidies should be linked to abstraction limits or to efficient irrigation.
6. **Recharge aquifers deliberately:** Flood flows, treated wastewater, and urban stormwater could be used to managed aquifer recharge and transform aquifers into a strategic storage.

For safe water access

7. **Focus coverage on finances where it was the lowest.** The biggest need for WASH investment in Sub-Saharan Africa followed by the large South and South-East Asian countries with the majority of people not having safe water.

8. **Operating and construction of funds.** The Pakistan data presented in Figure 5 indicated that if pipes are subject to continuous pressure, regular chlorination and testing, the microbial contamination that often contributed to water-quality problems eliminated.
9. **Suitable tests for geogenic contamination**. The cost of the screening wells for arsenic and fluoride in high risk aquifers is minimal relative to the health cost that they helped to avoid

In all three aspects

10. **Improve water accounting.** To measure honestly progress towards SDG 6, governments should establish regular and reliable national time series on renewable resources, withdrawals and groundwater levels.

8. Limitations

• **Secondary data:** The information in all figures was taken from published databases and reports. Even though the date of reference was not exactly the same, renewable resources and withdrawals were referred to 2020, access to 2024, income to 2024, governance to 2023 and the population to 2026 and 2050. Data from the countries were retrieved from portal tables and were matched by name; a small amount of mismatch was possible.

• **Sample coverage:** The scarcity projections included 179 countries (99.4% of the world's population) while the regression included 125 countries due to the absence of safely managed estimates in several larger countries, such as China, Kenya and Saudi Arabia. Had these countries been different systematically from the others, the coefficient might have been biased.

• **Cross-sectional design:** The regression was a measure of association, not causation. Income, governance and access might all have been determined by a shared history, and improved access could have, in turn, boosted income via health outcomes.

• **Climate scenarios**: The scenarios were illustrative and directional and did not represent a product of the hydrological models, and national values masked significant sub-national variation in both water availability and access.

• **The Falkenmark indicator:** The indicator included renewable water that may not have been available to use, and considered shared rivers as entirely available to every riparian country.

A case study of Pakistan. Many of the limitations of national data are passed down to the case study: the time series used for the official per-capita figure is unknown.

9. Conclusion

There was no single crisis of the global water, the water problem was growing and unequal. However, the increase of population alone between 2026 and 2050 put three quarters of the population growth in Africa, from 1.08 to 2.35 billion. The impact of climate change was primarily to exacerbate scarcity, and an additional 250 million people became 'absolutely scarce' due to the 10% reduction in renewable water supply. Groundwater, the world's primary buffer against scarcity, was tied up in a small number of heavy users, and in over a third of aquifers studied, groundwater levels were declining.

The provision of safe drinking water was based on a different logic. Water availability accounted for nearly none of the variation in safe-water coverage across 125 countries, while income accounted for most of the variation and governance was closely correlated with income. Before they were water-scarce, the 2.1 billion people without safely managed water were poor. Policy should therefore seek to tackle scarcity by regulating demand, by responding to scarcity in water use with a policy on groundwater management and adaptation to climate change, and by responding to the lack of access by a policy on finance, utilities and institutions. The Pakistan case illustrated the possibility of both crises coming together in a single nation and the potential for these crises being underreported even in official figures.

Panel data should be used in future research to control for the effect of income and governance and to substitute our illustration of climate with an ensemble of hydrological models, as well as to connect access and health outcomes to sub-national water availability.

REFERENCES

Peer-Reviewed Literature

Bain, R., Cronk, R., Wright, J., Yang, H., Slaymaker, T., & Bartram, J. (2014). Fecal contamination of drinking-water in low- and middle-income countries: a systematic review and meta-analysis. PLoS Medicine, 11(5), e1001644.

Bierkens, M. F. P., & Wada, Y. (2019). Non-renewable groundwater use and groundwater depletion: a review. Environmental Research Letters, 14, 063002.

Caretta, M. A., Mukherji, A., et al. (2022). Water. In Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the IPCC Sixth Assessment Report (pp. 551–712). Cambridge University Press. doi:10.1017/9781009325844.006.

Dalin, C., Wada, Y., Kastner, T., & Puma, M. J. (2017). Groundwater depletion embedded in international food trade. Nature, 543, 700–704.

de Graaf, I. E. M., Gleeson, T., van Beek, L. P. H., Sutanudjaja, E. H., & Bierkens, M. F. P. (2019). Environmental flow limits to global groundwater pumping. Nature, 574, 90–94.

Dharpure, J., Howat, I., & Kaushik, S. (2025). Declining groundwater storage in the Indus Basin revealed using GRACE and GRACE-FO data. Water Resources Research. doi:10.1029/2024WR038279.

Falkenmark, M. (1989). The massive water scarcity now threatening Africa: why isn't it being addressed? Ambio, 18(2), 112–118.

Famiglietti, J. S. (2014). The global groundwater crisis. Nature Climate Change, 4, 945–948.

Gleeson, T., Wada, Y., Bierkens, M. F. P., & van Beek, L. P. H. (2012). Water balance of global aquifers revealed by groundwater footprint. Nature, 488, 197–200.

Gleick, P. H. (1996). Basic water requirements for human activities: meeting basic needs. Water International, 21(2), 83–92.

Greve, P., Kahil, T., Mochizuki, J., et al. (2018). Global assessment of water challenges under uncertainty in water scarcity projections. Nature Sustainability, 1, 486–494.

Jasechko, S., Seybold, H., Perrone, D., Fan, Y., Shamsudduha, M., Taylor, R. G., Fallatah, O., & Kirchner, J. W. (2024). Rapid groundwater decline and some cases of recovery in aquifers globally. Nature, 625, 715–721. doi:10.1038/s41586-023-06879-8.

Mekonnen, M. M., & Hoekstra, A. Y. (2016). Four billion people facing severe water scarcity. Science Advances, 2(2), e1500323.

Oki, T., & Kanae, S. (2006). Global hydrological cycles and world water resources. Science, 313, 1068–1072.

Podgorski, J., & Berg, M. (2020). Global threat of arsenic in groundwater. Science, 368, 845–850.

Rijsberman, F. R. (2006). Water scarcity: fact or fiction? Agricultural Water Management, 80, 5–22.

Rodell, M., Velicogna, I., & Famiglietti, J. S. (2009). Satellite-based estimates of groundwater depletion in India. Nature, 460, 999–1002.

Rodell, M., Famiglietti, J. S., Wiese, D. N., Reager, J. T., Beaudoing, H. K., Landerer, F. W., & Lo, M.-H. (2018). Emerging trends in global freshwater availability. Nature, 557, 651–659.

Scanlon, B. R., Fakhreddine, S., Rateb, A., et al. (2023). Global water resources and the role of groundwater in a resilient water future. Nature Reviews Earth & Environment, 4, 87–101.

Schewe, J., Heinke, J., Gerten, D., et al. (2014). Multimodel assessment of water scarcity under climate change. Proceedings of the National Academy of Sciences, 111(9), 3245–3250. doi:10.1073/pnas.1222460110.

Taylor, R. G., Scanlon, B., Döll, P., et al. (2013). Ground water and climate change. Nature Climate Change, 3, 322–329.

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., et al. (2010). Global threats to human water security and river biodiversity. Nature, 467, 555–561.

Wada, Y., van Beek, L. P. H., van Kempen, C. M., Reckman, J. W. T. M., Vasak, S., & Bierkens, M. F. P. (2010). Global depletion of groundwater resources. Geophysical Research Letters, 37, L20402.

Wolf, J., Johnston, R. B., Ambelu, A., et al. (2023). Burden of disease attributable to unsafe drinking water, sanitation, and hygiene in domestic settings: a global analysis for selected adverse health outcomes. The Lancet, 401(10393), 2060–2071. doi:10.1016/S0140-6736(23)00458-0.

Reports and Datasets

FAO & UN-Water (2024). Progress on the level of water stress: mid-term status of SDG indicator 6.4.2 and acceleration needs. Rome: FAO.

Hutton, G., & Varughese, M. (2016). The costs of meeting the 2030 Sustainable Development Goal targets on drinking water, sanitation, and hygiene. Washington, DC: World Bank, Water and Sanitation Program.

IPCC (2021). AR6 Working Group I regional fact sheet: Europe. Geneva: IPCC.

Kaufmann, D., & Kraay, A. (2024). The Worldwide Governance Indicators: methodology and 2024 update. Policy Research Working Paper 10952. World Bank. Data.

Molden, D. (Ed.) (2007). Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. London: Earthscan; Colombo: International Water Management Institute.

Schwabish, J. (2017). The world tile grid map. PolicyViz. Coordinates.

UN (2024). The Sustainable Development Goals Report 2024. New York: United Nations.

UN DESA (2024). World Population Prospects 2024, medium variant. Country projections accessed via populationpyramids.org and INED.

UNESCO (2022). The United Nations World Water Development Report 2022: Groundwater – Making the invisible visible. Paris: UNESCO.

UN-Water (2024). Summary brief: mid-term status of SDG 6 global indicators and acceleration needs.

UN-Water (2025). UN-Water SDG 6 Data Portal: indicator 6.1.1 and indicator 6.4.2.

WHO (2023). Burden of disease attributable to unsafe drinking-water, sanitation and hygiene: 2019 update. Geneva: WHO.

WHO/UNICEF JMP (2025). Progress on household drinking water, sanitation and hygiene 2000–2024: special focus on inequalities. Geneva and New York: WHO and UNICEF.

World Bank (2025). World Development Indicators: GDP per capita, PPP. Values accessed via Worldometers.

WRI (2023). Aqueduct 4.0: updated decision-relevant global water risk indicators. Washington, DC: World Resources Institute.

Pakistan Sources

Arshad et al. (2023), as cited in PIDE (2026, Section 4.2), reporting a consistent decline of about 1 m per year in Lahore's water table. [Full bibliographic details were not given in the citing source; the authors should confirm the original before submission.]

Maqbool, N. (2022). Water crisis in Pakistan: manifestation, causes and the way forward. Islamabad: PIDE.

Ministry of Water Resources, Government of Pakistan (2025). Report on per-capita water availability submitted to the National Assembly. As reported by Dunya News.

Pakistan Bureau of Statistics (2023). 7th Population and Housing Census: press release.

PCRWR (2026). National Water Quality Monitoring Programme 2025–26: drinking water quality in 70 cities. Islamabad: Pakistan Council of Research in Water Resources. As reported by The News and Nukta.

PIDE (2026). Pakistan's groundwater crisis: policy lessons and a framework for sustainable resource use. Working Paper 2026:07.

State Bank of Pakistan (2017). Water sustainability in Pakistan: key issues and challenges. Chapter 7 (from p. 93) in The State of Pakistan's Economy: Annual Report 2016–17. Karachi: State Bank of Pakistan. Lahore decline rates as tabulated in PIDE (2026, Table 4.2).

WAPDA (2025). Daily river-flow report, Chenab at Marala, May 2025. As reported in Dawn.