Research Article

Assessment of Water Scarcity Across Pakistan Using Machine Learning Techniques and Novel Water Stress Indicators

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Abstract | Global warming has altered global hydrological cycles, intensified population growth, and diminished groundwater recharge. Urbanization has significantly impacted the level of water stress in Pakistan, resulting in a rise in water scarcity in the country. In present study, employing ISIMIP 2a and 2b data from WaterGAP2 hydrological model, we assessed the current (2005 to 2020) as well as future (2040) levels of water stress in Pakistan utilizing two novel water stress indicators, the Falkenmark Index and the Withdrawal to Availability Ratio. In our analysis, we employed machine learning algorithms (K-Nearest Neighbors, KNN) and polynomial regression to develop predictive water scarcity models for the future. Our analysis has demonstrated a rising trend of water scarcity over time, as the Falkenmark Index falls below 500 m^3/person/year and the Water Withdrawal to Availability Ratio surpasses 0.4, thereby predicting a heightened level of water scarcity by 2040. The findings directly derived from Falkenmark Indicator and Withdrawal to availability ratio provided quantitative spatial distribution of water scarcity across Pakistan highlighting substantial portions of the Balochistan province, with Gwadar and Sibbi ranking among the most impacted, alongside several districts in Punjab, Sindh, and Khyber Pakhtunkhwa, with the capitals of each province being highly vulnerable to the rising water stress. To our knowledge, limited research has been conducted in Pakistan utilizing machine learning algorithms to forecast water scarcity over time. We anticipate that the results of this study will constitute a significant resource for policymakers, researchers, and organizations seeking to implement UN Sustainable Development Goals and sustainable water management strategies in Pakistan.

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Keywords | Falkenmark indicator, Machine learning, Pakistan, Water GAP2, Water withdrawal to availability ratio, Water scarcity

Introduction

Water resources are essential for human existence, economic advancement, and ecological balance. Over the past several decades, human-induced water withdrawal has significantly increased, driven mainly rapid global population growth and improved living standards (Huang *et al.*, 2021). The urbanization process is continuing at an unprecedented rate globally, with projections indicating an escalation to 6.7 billion (68.4%) by the year 2050 (He *et al.*, 2021).

During the last century, human water demand has surged eightfold, a trend closely associated with the fourfold increase in global population. Pakistan's population is expected to rise to 400 million by 2040 as a consequence of rapid urbanization with major cities expanding at an unprecedented speed (Arif *et al.*, 2019). As concluded by Huang *et al.*, (2021), major cities like Karachi and Lahore have become seasonal and perennial water scarce regions because of population growth. Additionally, due to the prevailing water scarcity situation, only 29 million hectares (Mha) of land out of a total of 80 Mha is deemed arable; however, merely 17 Mha is currently under significant canal irrigation (Khan *et al.*, 2022). Consequently, the necessity to import food grains exerts further pressure on the economy, as Pakistan, being primarily an agrarian nation, heavily depends on its agricultural sector (Ali and Usman, 2025). Together with increasing food import dependency this restriction undermines national goals aligned with UN SDG 01 (No Poverty) and SDG 02 (Zero Hunger). At the same time, it is anticipated that climate change will significantly influence both the spatial and temporal distribution of water resources (Rahman *et al.*, 2023; Wu *et al.*, 2020). Consequently, urban water scarcities along with groundwater depletion are expected to emerge as a pressing concern in the near future (Ashraf *et al.*, 2022; Liu *et al.*, 2017). Hence, the concept of water scarcity warrants analysis through both physical and economic perspectives (Rosa *et al.*, 2020).

In the Global Risks 2015 Report disseminated by the World Economic Forum (WEF, 2015), the crisis regarding freshwater supply was recognized as the foremost high-impact risk of contemporary significance. In this study, our primary focus is centered on blue water scarcity. Given that the phenomenon of water scarcity represents a substantial threat to food security, public health, socioeconomic progress, and ecosystem services. It is imperative to comprehend the spatial and temporal dynamics of water scarcity (Liu *et al.*, 2017; Rosa *et al.*, 2020). Physical water scarcity can be further categorized into green water scarcity and blue water scarcity. Green water scarcity denotes the deficiency of root-zone soil moisture that is essential for agricultural output (Gao *et al.*, 2024). On the other hand, blue water scarcity refers to the lack of freshwater resources within both surface water and groundwater systems necessary to satisfy human consumption requirements (Liu *et al.*, 2017). Economic water scarcity is characterized by a scenario in which renewable freshwater resources are accessible. However, the absence of adequate socioeconomic and institutional frameworks obstructs public access to these water resources (Yin *et al.*, 2020). In the past, indicators like Falkenmark Indicator (Falkenmark *et al.*, 1989) and Withdrawal to Availability Ratio (Alcamo and Henrichs, 2002) have widely been used to access water stress at both regional and global scales.

Machine-learning techniques have been proven to be satisfactory (Fatima and Rahimi, 2024; Kausar *et al.*, 2023; Nguyen *et al.*, 2023). The future climatic impacts of water scarcity in a data-scarce region like Pakistan can be efficiently modeled using advanced machine-learning techniques like KNN (Asghar *et al.*, 2016). Both algorithms provide a powerful approach for water scarcity modeling, with KNN being better at short-term and polynomial regression being better at long-term forecasting (Hussain and Jan, 2019). Moreover, KNN has been found highly efficient in data-scarce regions (Zhang and Liu, 2018) and possesses the capacity to discern patterns and generate forecasts based on both historical data and latent trends that may not be readily distinct through conventional statistical approaches (Eed *et al.*, 2024; Shaheen *et al.*, 2024). Hence, the KNN algorithm along with polynomial regression was applied in this study owing to his robust performance in earlier studies (Ali *et al.*, 2024; Zhang and Liu, 2018).

Prior to our research most of the studies were at a global scale (coarser scale)(Modi *et al.*, 2022; Huang *et al.*, 2021; Liu *et al.*, 2017) and none of them conducted detailed investigations in water stress analysis. Therefore, using novel water stress indicators, this study aims to assess and forecast water scarcity in Pakistan at a much finer scale, i.e., 0.5-degrees, with the aim to provide a deeper insight into the water scarcity situation. In addition, climate change (RCP) and socio-economic scenarios (SSPs) are involved as such factors drive water stress trends at national, regional, and local scales to facilitate the sustainable management of water resources are considered (Sheikh *et al*., 2024; Yin *et al*., 2020), including sustainable practices (Al-Musabbir *et al*., 2022; Falkenmark and Rockström, 2004). Predicting how this blue water scarcity will evolve over the period of time is essential for proactive planning and such understanding is crucial, as it may potentially undermine the achievement of the United Nations Sustainable Development Goals (SDGs), particularly SDG 01 (No Poverty), SDG 02 (Zero Hunger) and SDG 11, which addresses Sustainable Cities and Communities (UN, 2015).

Materials and Methods

Study area

Pakistan is situated within the latitudinal coordinates of 23.5°–37.5° N and longitudinal coordinates of 62°–75° E, encompassing a total terrestrial expanse of 803,940 km^2 (Figure 1). The extensive climatological profile of the country is primarily characterized by regions of aridity and semi-aridity. This diversity in climatology can be attributed to the prevailing monsoonal patterns and various seasonal phenomena, leading to chilly and wet conditions in December, extremely arid and high-temperate weather in April, and hot, excessively humid conditions during September (Hussain *et al*., 2023; Almazroui *et al*., 2021).

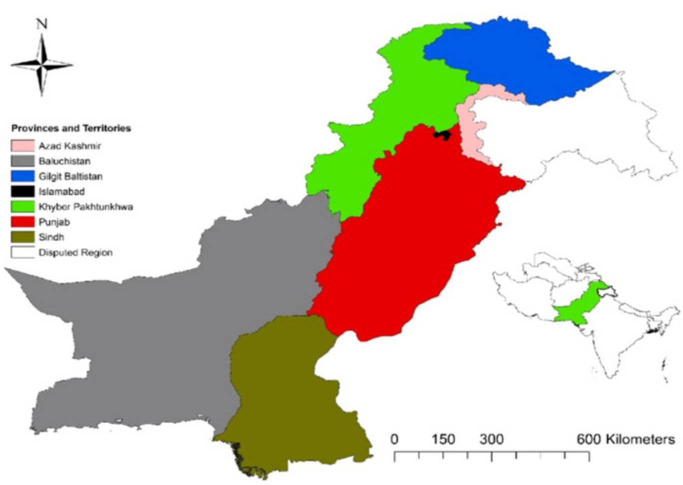

Figure 1: *Study area map including four provinces, federally administered areas, and capital Islamabad (Ahmad et al., 2025).*

Methodology

This study utilizes the hydrological simulation data from The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP 2a and 2b, Gosling *et al*., 2017) for 2005–2040 which was obtained using the Global Hydrological Model (GHM) Water Global Assessment and Prognosis (WaterGAP2, Kupzig *et al*., 2024), which features a distinctive spatial resolution of 0.5° × 0.5°. WaterGAP2 climate change scenario RCP 8.5 along with socioeconomic data for SSP2 scenarios was employed to evaluate water usage in different economic sectors in Pakistan. Current GHM simulations incorporated hydrological (surface water discharge) and socioeconomic (water withdrawal) variables from the Hadley Centre Global Environment Model version 2 (HadGEM2-ES) and Model for Interdisciplinary Research on Climate (MIROC5). Global Climate Models (GCMs) are acknowledged for their effectiveness in climate science and in assessing the consequences of climate change on water resource systems (de Souza Costa *et al*., 2021). The preprocessing of the dataset included managing temporal alignment to bring down the population data and water availability variables to a common annual interval (2005-2040); spatial alignment to ensure consistent resolution (0.5° × 0.5°) for hydrological and population data. Furthermore, gap-filling or interpolation was performed to address missing data. In the absence of in-situ discharge or withdrawal records across Pakistan's basins, model calibration and validation were performed using indirect yet robust approaches using coefficient of determination as a main statistical tool for the calibration of model. Although there exists a few global and regional water stress studies by Modi *et al*., 2022, Huang *et al*., (2021) and Liu *et al*., (2017), but we were unable to validate our results owing to difference in spatial-temporal scales as well as datasets used.

A multitude of indices have been formulated and employed to evaluate the current and prospective global water resources across catchment, national, and international frameworks (Liu *et al*., 2017). This study utilized two novel water stress indicators, namely the Falkenmark indicator (FI) and the Water Withdrawal to Availability Ratio (WTA). Details of both water stress indicators are provided below:

Falkenmark indicator

The FI is a widely utilized method for measuring water scarcity. It requires data on the population and the volume of available blue water in a specific area. Per capita water availability is expressed in (m^3/cap/year) (Falkenmark *et al*., 1989).

$$FI = \frac{Surface\ runoff}{Population}$$

Where, Surface runoff is measured annually in (m^3/year) and population in numbers.

Water withdrawal to availability ratio

The WTA is another recognized metric for evaluating water scarcity, linking water usage to renewable resources. This ratio effectively measures the amount of water extracted from available resources.

A criticality ratio exceeding 40% indicates significant water stress as defined by Alcamo and Henrichs, (2002).

$$WTA = \frac{Total\ water\ withdrawal}{Total\ water\ availability}$$

In this context, water withdrawal (m^3/day) is defined as the volume of water extracted for residential consumption, agricultural irrigation, and commercial applications. On the other hand, water availability (m^3/day) encompasses the total quantity of water present in a specified region, which includes both surface and groundwater sources.

For future analysis, we adopted the KNN technique due to its effectiveness in handling large datasets and its ability to model nonlinear relationships between predictor and response variables. It was also found useful in classifying the areas into different water stress categories based on the historical patterns (Eed *et al*., 2024). Hence, it can effectively model both the current and projected patterns of water scarcity in Pakistan. By combining the KNN and polynomial regression, we validated the predicted water stress levels across Pakistan with respect to time and space. Furthermore, the statistical parameter, coefficient of determination (R^2) was used to assess the accuracy for both algorithms, predicting the observed and simulated water stress levels across Pakistan. Remote sensing imagery was then processed and analyzed using ArcGIS to visualize spatial and temporal trends. Such high-quality remote sensing spatial maps provide valuable insights into water scarcity dynamics across Pakistan (Aslam *et al*., 2024, Zahoor *et al*., 2023).

Results and Discussion

Spatial analysis

Falkenmark indicator

Spatial plots depict the progression of water stress throughout Pakistan spanning the years 2005 to 2040. The FI, derived from surface discharge datasets produced by the MIROC5 and HadGEM2-ES climate models in conjunction with population data from ISIMIP2a and 2b (RCP 8.5 and SSP2) (Schewe *et al*., 2014), elucidates the changing spatial configuration of water deficiency.

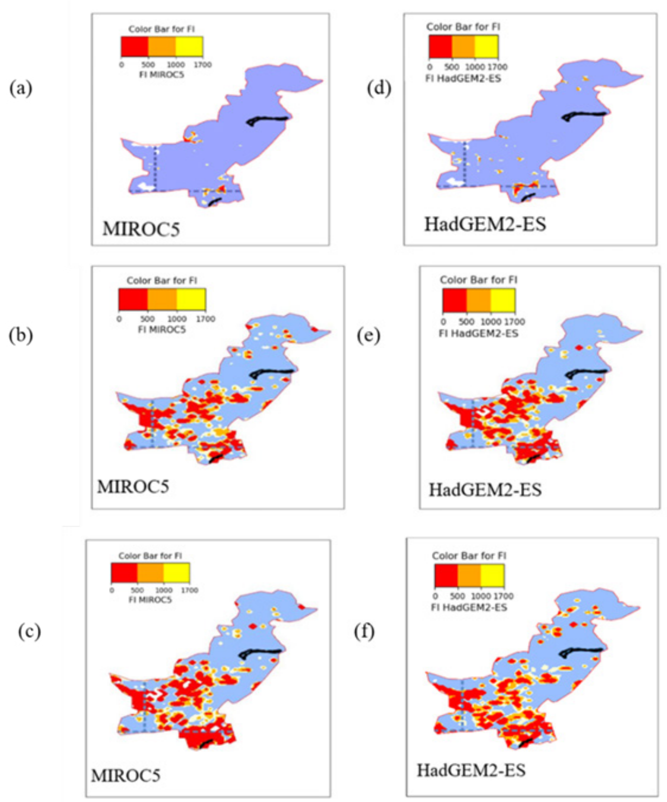

Figure 2: *Falkenmark Indicator for (a) MIROC5 for the year 2005 (b) MIROC5 for 2020 (c) MIROC5 for the year 2040 (d) HadGEM2-ES for the year 2005 (e) HadGEM2-ES for the year 2020 (f) HadGEM2-ES for the year 2040.*

Spatial analyses from Figure 2(a to f) indicate an alarming trend; from 2005 onwards (Figure 2(a)) the per capita availability of freshwater is diminishing as Pakistan's population continues to increase. Figure 2(c and d) also illustrates similar patterns of increasing water stress. Currently, a considerable proportion of the country faces severe or absolute water scarcity. The water scarcity situation is expected to worsen as evidenced by the FI dropping below the threshold of

500m^3/person/year as illustrated in Figure 2(e and f) (Table 1, Falkenmark *et al*., 1989). Major urban areas such as Lahore, Rawalpindi, Faisalabad, Karachi, Sukkur, Thatta, Peshawar, Nowshera, Quetta, Karachi, Chaghi, and Panjgur are especially susceptible to water stress and diminished access to freshwater resources which align with the earlier findings of Huang *et al*., (2021) and Aslam *et al*., (2024).

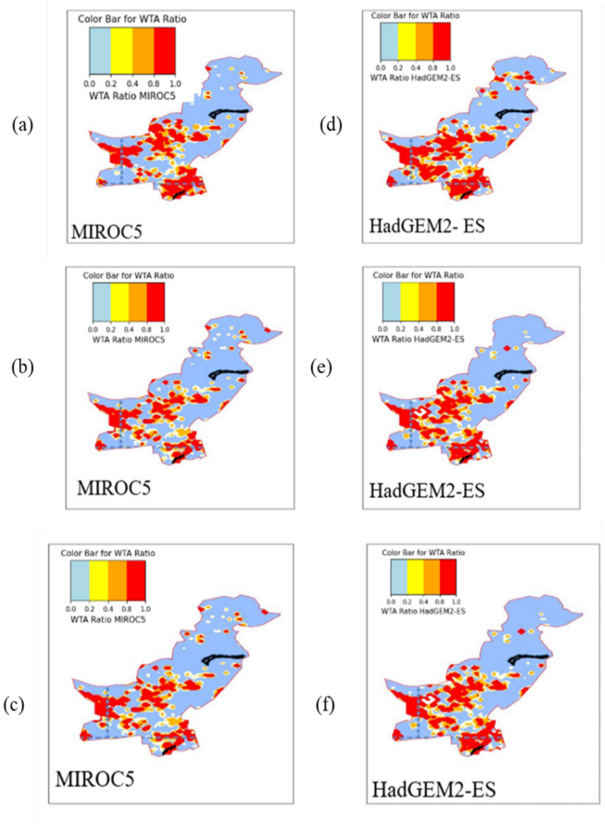

Figure 3: *WTA ratio for (a) MIROC5 for the year 2005 (b) MIROC5 for the year 2020 (c) MIROC5 for the year 2040 (d) HadGEM2-ES for the year 2005 (e) HadGEM2-ES for the year 2020 (f) HadGEM2-ES for the year 2040.*

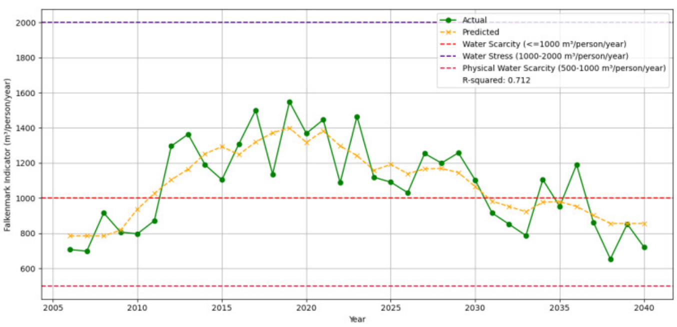

Figure 4: *Falkenmark Indicator time series for years 2005-2040*

Water withdrawal to availability ratio

Spatial analyses reveal a concerning trend of increasing water scarcity in Pakistan from 2005 to 2040. The WTA, derived from MIROC5 and HadGEM2-ES climate models, highlights the spatial distribution of water stress nationally. Initial studies identify eastern urban areas as critical hotspots, while the frequency of flash droughts has increased nationwide (Ali *et al*., 2024). The increase in withdrawal to availability ratio beyond 2015 period coincides with rapid urbanization, increased irrigation demands, and higher industrial consumption (Ashraf *et al*., 2022). This trend, combined with rising water withdrawals and population growth (Dalstein *et al*., 2022), has intensified water scarcity in various regions as evident from Figure 3 (c and d). Major urban centers such as Karachi, Thatta, Sukkur, Lahore, Rawalpindi, Faisalabad, Dera Ghazi Khan, Quetta, Panjgur, Gwadar, and Peshawar are notably vulnerable to these challenges as the values of WTA are approaching absolute scarcity (Table 2, Liu *et al*., 2017) and are frequently situated in areas characterized by aridity and semi-aridity (Ashraf *et al*., 2022), typically defined by low rainfall and high evaporation rates, and face heightened water stress as a consequence of limited water supply and not that fails to meet demand. Our findings corroborate prior research by Veldkamp *et al*., (2017) and Wada *et al*., (2011), emphasizing the significant impact of increasing water withdrawals and urban population growth on water scarcity in Pakistan.

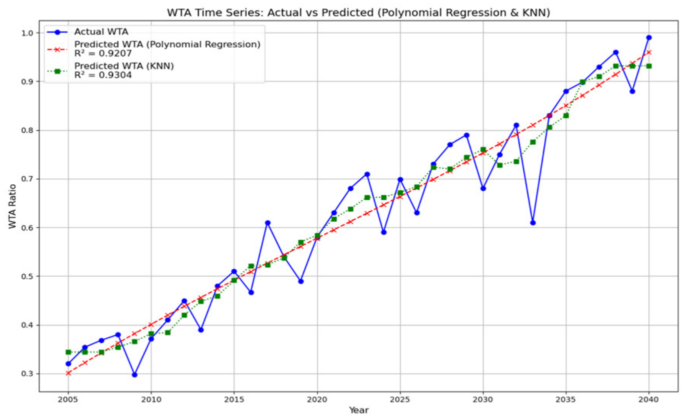

Figure 5: *WTA time series for the years 2005-2040 using KNN and polynomial regression.*

Time series analysis

Falkenmark indicator

Figure 4 delineates the progression of water scarcity phenomena in Pakistan from 2005 to 2040. FI is a widely recognized metric employed to evaluate water scarcity and is quantified in cubic meters per capita annually. This time series encompasses both empirical and projected values of the FI, in addition to thresholds for various degrees of water scarcity: water scarcity (<1000 m^3/capita/year), water stress (1000-2000 m^3/capita/year), and physical water scarcity (500-1000 m^3/capita/year) (Table 1, Falkenmark *et al*., 1989; Halder *et al*., 2024).

Table 1: *Threshold for Falkenmark indicator (Falkenmark et al., 1989).*

Sr. No	FI (m^3/capita/year)	Stress Level
1	>1,700	No Stress
2	1,000-1,700	Stress
3	500-1,000	Scarcity
4	<500	Absolute Scarcity

This time series depicts an alarming trajectory of diminishing water availability in Pakistan during the past decade (Aslam *et al*., 2024).The actual values of the FI have persistently remained beneath the threshold indicative of water stress, signifying a continual condition of water scarcity. The projected values, derived from the analytical model, imply that the scenario is poised to deteriorate in the subsequent years. The FI is anticipated to decline further below the threshold of water scarcity. This suggests an escalating risk of water scarcity and its associated repercussions especially after 2030, ultimately causing diminished agricultural yield, restricted access to potable water, and heightened susceptibility to flash droughts and floods (Ali *et al*., 2025; Ali *et al*., 2024). A slight difference observed in the current and future forecasts in case of FI might be due to the lack of a detailed census in the country for many years. Since population stats from government agencies are reliable and are a very important parameter in computing the FI, the results show a strong sensitivity to the accuracy and constancy of population data.

Water withdrawal to availability ratio

Figure 5 illustrates the evolution of water scarcity in Pakistan from the year 2005 to 2040, with a particular emphasis on the WTA ratio, which is a widely recognized metric for evaluating water stress. This time series encompasses both empirical and projected figures, thereby illuminating the changing landscape of water scarcity over the specified timeframe. The overall trend shows an increasing trend, which means water scarcity is going to worsen in the future (Aslam *et al*., 2024; Veldkamp *et al*., 2017). WTA value is continuously increasing showing heightened water stress level in the country and such phenomenon is significant after 2020, i.e., where WTA>0.6. The reason could be an increase in population as predicted by FAO and many other studies (Ahmad *et al*., 2025; Van Dijk *et al*., 2021). Besides changes in water availability (m^3) owing to variability in hydrological cycles could be a reason to such increased WTA values in the country (Habib, 2021).

Between 2005 and 2015, the WTA exhibits variability within the range of 0.3 to 0.4 (Table 2, Liu *et al*., 2017), signifying a state of moderate water stress. This interval is characterized by relatively stable hydrological conditions, but still under pressure. From 2015 to 2035, the ratio escalates to a range of 0.4 to 0.8, indicating a shift towards acute water stress, attributable to escalating demand, demographic expansion, and environmental challenges. After 2035, the WTA ratio attains a level of 1.0 (Table 2), signifying a condition of exceedingly high water stress. This upward trend indicates the cumulative repercussions of human activities, rapid urban development, and the adverse effects of climate change (Huang *et al*., 2021; Modi *et al*., 2022).

Table 2: *Threshold for water withdrawal to availability ratio (Liu et al., 2017).*

Sr No.	Water Withdrawal to availability ratio	Stress Level
1	>0-0.2	Low water stress
2	>0.2-0.4	Moderate water stress
3	>0.4-0.8	High water stress
4	>0.8-1.0	Very high –water stress

FI and WTA were examined on a grid cell level (0.5-degrees) for Pakistan using outputs provided by WaterGAP2 hydrological model. To determine high–risk zones, e.g., where FI < 1,700 m^3/cap/year; WTA > 40% within administrative or catchment boundaries; both indices were computed annually using future projections, i.e., 2025–2040 under RCP 8.5 and SSP2. This allowed tracking the changes over time in FI, and WTA with the help of polynomial regression models.

Conclusions and Recommendations

This study provides the first fine-scale (0.5-degrees) machine learning-based forecast that reveals a notable escalation in water scarcity within Pakistan, attributed to urbanization, climate change, and population growth. The application of the Falkenmark Index and Water Withdrawal to Availability combined with the climate change scenario RCP 8.5 and socioeconomic data for SSP2 scenarios indicates that water stress is expected to escalate by 2040, especially in regions like Baluchistan and major urban areas in Punjab, Sindh, and Khyber Pakhtunkhwa. These results highlight the immediate necessity for integrated and sustainable water management approaches to alleviate the projected consequences on food security, public health, and economic viability. This study uniquely employed machine learning algorithms to predict water scarcity in Pakistan. The KNN algorithm achieved 71% accuracy in predicting the Falkenmark Index. For the Water Withdrawal to Availability ratio, both KNN and polynomial regression effectively projected the upward trend and escalating water stress. In WTA time series, polynomial regression was observed to be smooth which could imply that it can be employed for long-term forecasting. The KNN model, with its higher R-squared value, captured the short-term fluctuations better and can be considered more effective for near-term predictions, presenting an innovative framework for policymakers and researchers confronting this critical issue. The implementation of proactive strategies based on our results is essential for promoting resilient water resource management and achieving the objectives outlined in the UN SDGs, particularly those related to clean water and sustainable cities.

For future research, areas identified as high-risk by spatial plots should prioritize immediate groundwater recharge. Population and runoff data with a spatial resolution of 0.5° x 0.5° does not comprehensively describe the water variability in heterogeneous regions like mountains and urban zones. Hence, we recommend using a higher-resolution datasets in the future analysis. Moreover, inclusion of climate change and socio-economic scenarios can lead to detailed investigations. Lastly, looking for field data for model validation is important. Despite limitations regarding spatial scale, datasets, and indices, our study offers a pathway for improved water resources management in Pakistan. It emphasizes methods such as efficient irrigation, community-based water conservation, rainwater harvesting, and urban infrastructure development to mitigate future resource scarcity.

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Novelty Statement

High resolution water scarcity mapping in Pakistan using novel water stress indicators and in-corporating SSP and RCP scenarios.

Author's Contribution

Mustajab Ali and Usman Ali: Conceptualization, methodology, data collection, re-sources, writing, review and editing, supervision.
Hammad Akhtar and Muhammad Bilal: Conceptualization, methodology, data collection, re-sources, software, writing.
Muhammad Imtinaan Ibraaz and Muhammad Abad Arif: Conceptualization, methodology, data collection, re-sources.
Momna Asghar, Syed Hasnain Gillani, Hassam Ahmed and Tasleem Kausar: Writing, review and editing.

Generative AI or AI assisted technology statement
Generative AI or AI assisted tools are not use while preparing this document.

Conflict of interest
The authors have declared no conflict of interest

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