

# Quantifying the Role of Groundwater, Agriculture, and Climate on India's Water Security: A Grey Relational Model Based on the Falkenmark Index

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## Abstract

Currently, India is experiencing a prominent and serious water crisis characterised by extreme regional disparities which is essentially an outcome of the rising population growth, rampant urbanisation, and unsustainable extraction practices. This study employs the Falkenmark Index (2012–2024) alongside Grey Relational Analysis (GRA) to identify and rank the systemic drivers of per capita water decline. The findings of the study have reported a fall in water availability from 1,517 m<sup>3</sup>/person/year in 2012 to 1,318 m<sup>3</sup>/person/year in 2024, thereby pushing several geographical territories into water-stressed or water-scarce categories. GRA rankings indicate population growth (0.95) as the most influential driver, followed by groundwater extraction (0.85) and agricultural use (0.80), while pollution (0.70), infrastructure deficit (0.60), and monsoon variability (0.50) show moderate to lower impacts. Case studies from the states of Punjab and Haryana highlight the over-exploitation of groundwater for irrigation, while recurring water dispute between/among various states indicate governance challenges. These findings highlight the dominance of chronic stressors; population pressure, groundwater misuse, and irrigation intensity, over episodic climatic variability. The study contends that policy interventions must prioritise groundwater budgeting, crop diversification, micro-irrigation, wastewater reuse, and basin-scale governance to address the issues of per capita decline. By integrating GRA diagnostics with the Falkenmark framework, the analysis provides a decision-support tool for Integrated Water Resource Management (IWRM), aligning with national priorities and the Sustainable Development Goals (SDGs-6).

**Keywords:** Grey relation analysis, falkenmark, climate, environment, water scarcity.

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## 1. Introduction

The severe exploitation of the groundwater resources has been a central concern amidst the water crisis of India. Rodell et al. (2009) unravelled the serious depletion of groundwater especially in the northern parts of India, thereby highlighting these withdrawal to be of highly unsustainable in nature. Scanlon et al. (2012) exhibited that India ranks at the apex in terms of depletion of groundwater, basically due to the withdrawal of groundwater for agricultural requirements and also due to the lack of policy rigour to safeguard the same. Shah (2009) and Hira (2009) have stated that extensive subsidies provided for availing the pump sets and also for the electricity facilitates excessive extraction of the groundwater. Giordano (2009) also reiterates the lack of institutional mechanisms in addressing the groundwater governance, thereby recommending for participatory approaches that are region specific in nature. Prathapar and Reddy (2014) have put forward conjunctive use models that integrate both groundwater and surface water to ensure effective management and variations in the supply in semi-arid landscapes.

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Highest share of India's freshwater is used by agricultural sector, which further stresses the need for an urgent reform. Molden et al. (2007) prescribed for parameters which are essentially based on performance such as "crop per drop" to reduce wastage and thereby increase the degree of efficiency. Hoekstra and Mekonnen (2012) have highlighted that India is exporting water intensive crops like rice at the cost of magnifying scarcity of the water at the domestic level. Zhong et al. (2023) and Varis et al. (2017) have reiterated the vulnerabilities integrated in global trade dependencies, which externalize and overlook the significant crisis of water at the local level. Furthermore, Jain et al. (2020) propose decentralized irrigation systems and micro-irrigation technologies as alternative practices which are highly sustainable as compared to the traditional practices.

The climate change is further exacerbating the already existing serious issues of water crisis in India. Various scholarly studies (Mall et al., 2006; Lal, 2001) have highlighted as how the variations in the rainfall (with regards to intensity and geographical distribution), significantly impact the soil moisture availability in the areas which are dependent on rainfall. Studies by Mishra and Tiwari (2023) have advocated that glacier retreat, evapotranspiration anomalies, and aquifer stressors intersect are a byproduct of the human actions and interventions which basically affect the environment. Rockström et al. (2010, 2024) and Falkenmark (2020) advocate the integration of blue (surface/groundwater) and green (soil moisture) water strategies to ensure that ecological thresholds are maintained, which is quite essential for sustainable agriculture. Porporato et al. (2001) contribute a stochastic modeling approach to understand vegetation responses under uncertain climatic regimes, highlighting the significance of various water management reforms.

Advanced hydrological modeling and systems-based approaches enrich the knowledge and understanding of India's water crisis. Veettil and Mishra (2018), as well as Veettil et al. (2022), employed tools such as SWAT (Soil and Water Assessment Tool) and AgES (Agricultural Ecosystems Services) to provide granular assessments of water footprints across regional and crop-specific dimensions. Similar research studies (Srinivasan et al., 2017; Ram & Irfan, 2021) highlight the need for systems thinking, leveraging feedback loop analysis to trace the co-evolution of water use, energy demands, and land use changes. The relevance of Grey Relational Analysis is emphasised by Liu et al. (2012), who demonstrated its efficacy in evaluating complex, multidimensional stress scenarios, thereby justifying its integration with the Falkenmark Index in this study.

India is witnessing rapid and extensive urbanisation leading to complications in the already contested landscape of water. Su et al. (2020) stated that urban water insecurity is translating to the triad of scarcity, pollution, and hazard vulnerability, a framework extended by Zhao et al. (2017) to capture peri-urban dynamics critical to India's rapidly expanding metropolitan borders. Patel and Karmakar (2018) have clearly demonstrated the linkage between population explosion and decline of groundwater and surface water, thereby revealing acute vulnerabilities in densely populated regions. Lal (2015) enriches the conceptual toolkit by delineating water types, blue, green, grey, and virtual; offering a broad lens for integrated urban-rural water planning. Scholarly studies (Biswas, 2004; Sivakumar, 2011; Biswas & Seetharam, 2008) have argued that it is the deficiencies at the institutional front which needs to be addressed rather than only focussing on the absolute physical scarcity. Srinivasan et al. (2012) introduced the concept of "institutional syndromes", which is essentially a combination of systemic breakdowns in policy coherence, regulatory enforcement, and inter-agency coordination. However, the recent policy developments like Jal Shakti Abhiyan and Jal Jeevan Mission mark a significant departure towards the decentralized form of water governance. Studies have also highlighted the significant inclusion gaps on the basis of caste, class and gender (Narain, 2018; Mukherjee et al., 2025). Abdullah et al. (2023), employing the IF-DEMATEL technique, to map the causal network of vulnerabilities in India's water governance infrastructure, highlights the importance of decision-support systems. Levorio et al. (2025) explain a strategy for the convenience of linking piggy farming with agriculture practices to accomplish sustainable management. Jegathishkumar et al. (2025) shows an experimental research study on passive cooling of photovoltaic panel in the context of harvesting atmospheric water using hygroscopic salt India's water crisis also surrounded by various geopolitical and transboundary concerns. Sahu and Mohan (2022) stated that the Brahmaputra basin as a securitized hydro-political space, cautioning that excessive militarization of water discourse may undermine regional cooperation. Amarasinghe et al. (2008) emphasized long-term water demand projections and the imperative of transitioning towards the demand side management, underpinned by robust, transparent data systems. Similarly, the socio-cultural and psychological dimensions of water insecurity is also huge. Mehta (2005) exhibits how caste and class hierarchies shape accessibility to water, thereby further exacerbating the structural inequities within hydro-social relations. Studies (Brewis et al., 2020; Stoler et al., 2020; Rhue et al., 2023) link household water insecurity to nutritional deficiencies and mental health stress. Various studies have also documented gendered vulnerabilities (Tallman et al., 2023; Adams et al., 2022; Wutich et al., 2022), and traced how the burden of water collection and exposure to violence disproportionately affect women in marginalized areas. Young et al. (2022) employ the IWISE

(Individual Water Insecurity Experiences) scale to demonstrate how intersecting factors; income, geography, and social identity tend to worsen household water outcomes during crises such as the COVID-19 pandemic. Methodological advances support the development of hybrid water stress indicators. Pereira et al. (2009) critiqued the limitations of traditional parameters, urging for composite indicators that integrate water quantity, quality, and socio-ecological needs. Seminal contributions by Gleick (1998) and Seckler et al. (1998) emphasize threshold-based approaches that balance basic human requirements with sustainable ecological limits, thereby complementing Falkenmark's per capita index with demand-side considerations. India's intensifying water stress reflects a complex interplay of hydrogeological, ecological, socio-economic, and institutional variables, warranting a multi-dimensional analytical approach. This review synthesizes interdisciplinary scholarship to support the integration of Grey Relational Analysis (GRA) with the Falkenmark Index, melding a dynamic, data-driven methodology with a foundational per capita water availability threshold, to offer a robust diagnostic of India's water stress. The reviewed literature confirms that India's water stress is a huge and cross-sectoral phenomenon embedded in socio-political structures, ecological transitions, and technological interfaces. The proposed hybrid framework, coupled with GRA's multi-variable sensitivity analysis with the Falkenmark Index's simplicity and policy resonance offers a comprehensive lens to evaluate India's evolving water security and to inform resilient, context-sensitive planning interventions. Table 1 shows a summary of various research studies using the Falkenmark Index, outlining its approach, time period, and findings. This synthesis helps in explaining existing research and identifying research gaps for this study.

**Table 1.** Summary Table of Review of Literatures.

| Author(s)                                      | Focus Area                               | Methodology / Contribution                          | Key Insights / Relevance to India                                    |
|------------------------------------------------|------------------------------------------|-----------------------------------------------------|----------------------------------------------------------------------|
| Veettil & Mishra (2018); Veettil et al. (2022) | Water footprint modeling                 | Use of SWAT, AgES for blue/green/grey water mapping | Highlights spatial heterogeneity in semi-arid water stress zones     |
| Srinivasan et al. (2017); Ram & Irfan (2021)   | Systems thinking in water governance     | Feedback loops and causal diagrams                  | Enables dynamic, cross-sectoral water analysis                       |
| Porporato et al. (2001)                        | Climate-induced agricultural stress      | Stochastic modeling under climatic uncertainty      | Supports rainfed and drought-prone agriculture strategies            |
| Patel & Karmakar (2018)                        | National vulnerability mapping           | Integration of hydrology and demographics           | Identifies emerging hotspots of water stress                         |
| Damkjaer & Taylor (2017)                       | Critique of scarcity metrics             | Alternative freshwater storage-based indicators     | Challenges static indices like Falkenmark in monsoon regions         |
| Su et al. (2020)                               | Urban water insecurity                   | Multidimensional (scarcity, hazard, pollution) lens | Advocates hybrid water governance in Indian cities                   |
| Zhao et al. (2017)                             | Peri-urban water stress (China)          | Urban sprawl and virtual water reliance             | Mirrors India's peri-urban expansion and agricultural displacement   |
| Hira (2009)                                    | Agricultural water use in Punjab-Haryana | Policy critique of irrigation incentives            | Links free electricity and paddy incentives to groundwater depletion |
| Pradhan & Srinivasan (2022)                    | Participatory planning                   | Call for post-evaluated, inclusive planning         | Proposes shift from dam-centric to community-driven models           |
| Zhong et al. (2023)                            | Virtual water trade                      | Global trade flow analysis                          | India's exports worsen local water stress; policy contradiction      |
| Varis et al. (2017)                            | Global water-food nexus                  | Trade and conflict linkages                         | Pushes for transboundary, intersectoral governance reforms           |
| Mishra & Tiwari (2023)                         | Climate-water vulnerability              | Synthesis of monsoon, glacier, and aquifer risks    | Identifies compound climatic stressors for Indian water systems      |
| Sabater et al. (2018)                          | Biodiversity impacts                     | Flow modifications and freshwater species loss      | Reveals ecological trade-offs in infrastructure development          |
| Rockström et al. (2024); Falkenmark (2020)     | Ecological water frameworks              | Emphasis on green water and soil moisture           | Offers sustainability lens for rainfed agriculture                   |

| Author(s)                                   | Focus Area                 | Methodology / Contribution                       | Key Insights / Relevance to India                        |
|---------------------------------------------|----------------------------|--------------------------------------------------|----------------------------------------------------------|
| Biswas & Seetharam (2008); Sivakumar (2011) | Governance critique        | Systemic failure over physical scarcity          | Mismanagement as root cause of Asia's water crisis       |
| Srinivasan et al. (2012)                    | Governance syndromes       | Pattern-based diagnosis of institutional failure | Framework to analyze recurring governance issues         |
| Mukherjee et al. (2025)                     | Jal Jeevan Mission (JJM)   | Evaluation of digital rural supply model         | Points to need for inclusive implementation              |
| Abdullah et al. (2023)                      | IF-DEMATEL analysis        | Causal vulnerability mapping                     | Diagnoses over-abstraction and infrastructure gaps       |
| Sahu & Mohan (2022)                         | Geopolitics of water       | Securitization theory on Brahmaputra             | Warns against militarizing transboundary water issues    |
| Brewis et al. (2020); Stoler et al. (2020)  | Household water insecurity | Empirical link to food insecurity and stress     | Even affluent households affected by water stress        |
| Rosinger & Young (2020); Rhue et al. (2023) | Developmental outcomes     | Links to child and caregiver health              | Shows hidden psychosocial costs of water insecurity      |
| Tallman et al. (2023)                       | Gendered water violence    | Exposure to gender-based violence                | Water access deficits worsen women's vulnerability       |
| Adams et al. (2022)                         | Urban informal settlements | Embodied water burden documentation              | Reveals gender, class, and infrastructure inequalities   |
| Wutich et al. (2022); Hidalgo et al. (2017) | Structural marginalization | Studies from U.S. colonias and Latin America     | Comparative lens for India's rural and tribal exclusions |
| Lal (2015)                                  | Water typology & SDGs      | Framework of blue, green, gray, virtual water    | Promotes integrated, SDG-aligned management approach     |
| Young et al. (2022)                         | IWISE scale across LMICs   | Household-level water stress indicators          | Aligns with India's digital governance shift under JJM   |

### 1.1. Problem of Identification

The water security of India is plagued by climate change, intensive agriculture and depletion of groundwater. Plenty of studies have tried to address these concerns, however a significant challenge still persists in estimating the impact of these factors from a holistic perspective. Traditional tools like the Falkenmark Index, while offering a broad-brush indication of per capita water availability, fail to account for the disparities at the regional level alongside the disparities, seasonal variability, and the challenges emanating from the demand-side such as irrigation intensity, over utilisation of groundwater, and the severe degradation of quality due to pollution. Groundwater, is often underrepresented in national-level assessments, despite its contribution in sustaining agriculture and rural livelihoods. In addition to that, India's extreme degree of dependence on rainfall makes it highly prone to intra-seasonal and inter-annual climate variability, yet such temporal patterns are insufficiently reflected in existing water stress indicators. Moreover, while various studies have addressed individual dimensions, such as hydrological modeling, water footprints, or vulnerability mapping, there still remains a lack of a unified framework capable of assessing the relative importance of various factors simultaneously. This leads to a methodological gap in understanding how these factors interact to shape India's water security outcomes. In light of these issues, there is a serious need for a relational and diagnostic approach that can quantitatively assess the influence of multiple, interrelated variables. This study seeks to fill this gap by employing a Grey Relational Model based on the Falkenmark Index to systematically analyze and rank the influence of key stressors; groundwater availability, agricultural dependence, and climate variability on India's water security trajectory. The assessment of climate vulnerability has gained attention, yet synthesis remains limited. Shehzad et al. (2026) highlighted the dominance of single-event studies and sociodemographic indicators in CVIs, with insufficient focus on structural factors and neighbourhood-scale analysis. Elling et al. (2026) proposed an impact-driven framework for evaluating climate models relevant to societal outcomes. Alvarez et al. (2026) demonstrated seasonal contrasts in agricultural vulnerability in semi-arid regions, where groundwater access and adaptive capacity shape outcomes. Opdyke et al. (2026) showed nature-based solutions deliver more equitable benefits than grey infrastructure. Hilmar (2026) emphasized integrating meritocracy beliefs into climate justice research. These gaps underscore the need for integrated models like the Grey Relational Model based on the Falkenmark Index to assess India's water security.

## 2. Methodology & Data

India's total renewable water resources are estimated to be approximately 1,911 km<sup>3</sup> per year. However, due to a significant rise in population from 1.26 billion in 2012 to 1.45 billion in 2024, the Falkenmark Index, which measures per capita water availability, has declined from 1,517 cubic meters to just 1,318 cubic meters. This is a direct testimony of the water scarcity experienced by people in the country. Moreover, the water resources in India are not evenly distributed, which is further accentuated by geographic conditions, rainfall variability, and population density. The total renewable water resources were assumed to be constant at 1,911 km<sup>3</sup> per year, based on the long-term average for consistency of estimates (FAO and World Bank Data). The population data are based on the Indian census and UN projection and interpolations.

### 2.1. Falkenmark Index

Falkenmark and Lindh first articulated a quantitative connection between freshwater availability and population at the Third World Population Conference in Bucharest (1974). Formal measurement of water scarcity took shape in the early 1980s with Falkenmark's Water Stress Index (WSI), which explicitly linked food security to per-capita freshwater (Falkenmark 1986, 1989). Developed amid famines in the Sudano-Sahel, the WSI was conceived as an early-warning tool to guide strategies for food self-sufficiency under expected drought and rapid population growth. Since then, it has become one of the most widely applied scarcity metrics. Although its limitations have been well documented (e.g., Savenije 1999; Chenoweth 2008; Taylor 2009; Brown & Matlock 2011; Jarvis 2013; Wada 2013; Brauman et al. 2016), the WSI continues to be used from regional to global scales (Vörösmarty et al. 2000; Alcamo et al. 2003; Arnell 2004; Wada et al. 2011; Wada 2013; Schewe et al. 2013)

$$\text{Falkenmark Index} = \frac{\text{Total Renewable Freshwater Resources (m}^3\text{/yr)}}{\text{Population}}$$

### 2.2. Grey Relational Analysis

Grey System theory, an interdisciplinary approach, was introduced in 1982 (Ju-Long, 1982). The Grey system proposition establishes a connection between black with white. Grey Relational Analysis which used for analyzing relations between the discrete data sets is one of the popular methods. Grey Relational Analysis is also used for decision-making in multi-attribute cases. This approach contacts establish relations among the factors based on level of similarity and variability. Grey Relational Analysis uses Grey Relational grade to measure relation degree of factors

### 2.3. Data Preprocessing

In the data preprocessing step, in order to compare correctly the data that have different measurement units, a transformation operation is made, and after this process, the data values are obtained in the 0-1 interval.

The decision matrix for the data set is as follows:

$$x_i^*(k) = \begin{bmatrix} x_{(1)} & 1x_{(1)}2 & \dots & x_{(1)}m \\ \vdots & \ddots & \ddots & \vdots \\ x_{(n)} & 1x_{(n)}2 & \dots & x_{(n)}m \end{bmatrix} \dots \dots \dots (1.1)$$

The normalisation process can be done in four ways:

After data preprocessing, Grey Relational Coefficient is calculated based on normalized sequences.

### 2.4. Min-Max Normalization Formula

If the criteria is larger better

$$x_i^*(k) = \frac{x_i^{(O)}(k) - \min x_i^{(O)}(k)}{\max x_i^{(O)}(k) - \min x_i^{(O)}(k)} \dots \dots \dots (1.2)$$

If the criteria is larger better

$$x_i^*(k) = \frac{\max x_i^{(O)}(k) - x_i^{(O)}(k)}{\max x_i^{(O)}(k) - \min x_i^{(O)}(k)} \dots \dots \dots (1.3)$$

If the criteria is target value to be reached for the original data (OB means target value)

$$x_i^*(k) = 1 - \frac{|x_i^{(O)}(k) - OB|}{\max(\max x_i^{(O)}(k) - OB, OB - \min x_i^{(O)}(k))} \dots \dots \dots (1.4)$$

If the criteria is dividing sequence values by the first value of sequence

$$x_i^*(k) = \frac{x_i^{(O)}(k)}{x_i^{(O)}(1)} \dots \dots \dots (1.5)$$

## 2.5. Calculating of Grey Relational Coefficient and Grey Relational Grade

After data transforming in to comparable form, Grey Relational Coefficient is calculated using (Yang, 2006).

$$\gamma[(x_0^*(k), x_i^*(k))] = \frac{\Delta_{\min} + \xi \Delta_{\max}}{\Delta_{0i}(k) + \xi \Delta_{\max}}, 0 < \gamma[(x_0^*(k), x_i^*(k))] \leq 1 \dots \dots \dots (1.6)$$

where  $\Delta_{0i}(k)$  is the deviation sequence between  $x_0^*(k)$  reference values and  $x_i^*(k)$  comparable values and the term  $\xi$  is a distinguishing coefficient in [0 and 1](note- that usually takes a value of 0.5 in literature).

deviation sequence is calculated as the biggest deviation and the smallest deviation are

calculated as

$$\Delta_{01}(k) = |x_0^*(k) - x_i^*(k)| \dots \dots \dots (1.7)$$

The largest and the smallest deviations are calculated using

$$\Delta_{\max} = \max_{j \in i} \max_{\nabla k} |x_0^*(k) - x_j^*(k)| \dots \dots \dots (1.8)$$

$$\Delta_{\min} = \min_{j \in i} \min_{\nabla k} |x_0^*(k) - x_j^*(k)| \dots \dots \dots (1.9)$$

## 2.6. Calculation of Grey Relational Grades

Grey relational grade is simply the weighted sum of grey relational coefficients and is calculated using:

$$\sum_{k=1}^n \beta_k = 1. \dots \dots \dots (1.10)$$

where:

$$\gamma(x_0^*, x_i^*) = \sum_{k=1}^n \beta_k \gamma[x_0^*(k), x_i^*(k)] \dots \dots \dots (1.11)$$

The grey relational grade represents the level of correlation between the reference sequence and comparable sequence. In equation,  $\gamma[x_0^*(k), x_i^*(k)]$  Grey Relational grade represents the level of correlation between the reference sequence and comparable sequences. Grey Relational grade also shows the level of influence applied to reference sequence by comparable sequence.

**Table 2.** Descriptive Statistics of Falkenmark Index (2012–2024)

| Year | Population (in billion) | Falkenmark Index Formula      | Result (m <sup>3</sup> /person/year) |
|------|-------------------------|-------------------------------|--------------------------------------|
| 2012 | 1.26                    | $(1,911 / 1.26) \times 1,000$ | 1,517                                |
| 2013 | 1.28                    | $(1,911 / 1.28) \times 1,000$ | 1,493                                |
| 2014 | 1.29                    | $(1,911 / 1.29) \times 1,000$ | 1,481                                |
| 2015 | 1.31                    | $(1,911 / 1.31) \times 1,000$ | 1,458                                |
| 2016 | 1.32                    | $(1,911 / 1.32) \times 1,000$ | 1,447                                |
| 2017 | 1.34                    | $(1,911 / 1.34) \times 1,000$ | 1,426                                |
| 2018 | 1.36                    | $(1,911 / 1.36) \times 1,000$ | 1,405                                |
| 2019 | 1.37                    | $(1,911 / 1.37) \times 1,000$ | 1,394                                |
| 2020 | 1.39                    | $(1,911 / 1.39) \times 1,000$ | 1,374                                |
| 2021 | 1.4                     | $(1,911 / 1.40) \times 1,000$ | 1,365                                |
| 2022 | 1.42                    | $(1,911 / 1.42) \times 1,000$ | 1,346                                |
| 2023 | 1.43                    | $(1,911 / 1.43) \times 1,000$ | 1,336                                |
| 2024 | 1.45                    | $(1,911 / 1.45) \times 1,000$ | 1,318                                |

The table 2 discuss the Falkenmark Index to population data per year to calculate available freshwater per person. The results highlight how increasing population reduces per capita water availability over time.

**Table 3.** National Falkenmark Index (2012–2024)

| Year | Population (Billions) | Renewable Water Resources (km <sup>3</sup> /year) | Falkenmark Index (m <sup>3</sup> /person/year) | Category     |
|------|-----------------------|---------------------------------------------------|------------------------------------------------|--------------|
| 2012 | 1.26                  | 1,911                                             | 1,517                                          | Water Stress |
| 2013 | 1.28                  | 1,911                                             | 1,493                                          | Water Stress |
| 2014 | 1.29                  | 1,911                                             | 1,481                                          | Water Stress |
| 2015 | 1.31                  | 1,911                                             | 1,458                                          | Water Stress |
| 2016 | 1.32                  | 1,911                                             | 1,447                                          | Water Stress |
| 2017 | 1.34                  | 1,911                                             | 1,426                                          | Water Stress |
| 2018 | 1.36                  | 1,911                                             | 1,405                                          | Water Stress |
| 2019 | 1.37                  | 1,911                                             | 1,394                                          | Water Stress |
| 2020 | 1.39                  | 1,911                                             | 1,374                                          | Water Stress |
| 2021 | 1.4                   | 1,911                                             | 1,365                                          | Water Stress |
| 2022 | 1.42                  | 1,911                                             | 1,346                                          | Water Stress |
| 2023 | 1.43                  | 1,911                                             | 1,336                                          | Water Stress |
| 2024 | 1.45                  | 1,911                                             | 1,318                                          | Water Stress |

### 3. Results & Discussion

By 2025, 1800 million people are expected to be living in countries or regions with “absolute” water scarcity (<500 m<sup>3</sup> per year per capita), and two-thirds of the world population could be under “stress” conditions (between 500 and 1000 m<sup>3</sup> per year per capita) (FAO, 2025). Falkenmark Index has declined from 1,517 m<sup>3</sup> in 2012 to 1,318 m<sup>3</sup> in 2024, indicating that population growth is rapidly outpacing freshwater availability in India (Table 3). Although the country still falls within the “water stress” range (1,000–1,700 m<sup>3</sup>), it is gradually approaching the critical “water scarcity” threshold of 1,000 m<sup>3</sup>. Ghosh (2021) and Narain (2000) warn of India’s urban water crisis, now visible nationally. Alcamo et al. (2000) show withdrawals falling in industrialized countries but rising in developing ones, increasing stress. Cativo et al. (2025) note the Amazon’s seasonal flows shape planting, fishing, and mobility. These serious developments underscores the immediacy to rethink how the precious resource is utilised especially in the context of groundwater and agriculture. The Central Water Commission (2024) has estimated India’s annual renewable water availability at 2,115.95 BCM, slightly higher than the 1,911 km<sup>3</sup> figure used in this analysis. Using the CWC data, the recalculated Falkenmark Index for 2024 would be 1,459 m<sup>3</sup>, still within the stressed zone but somewhat higher. Ningi et al., (2025) recommends water saving techniques to address water scarcity, and Cheng et al., (2025) address water scarcity and soil degradation.

**Table 4.** Regional Disparity Falkenmark Index

| Region    | Population 2012 (Millions) | Water Resources (km <sup>3</sup> /year) | Falkenmark Index 2012 (m <sup>3</sup> /person/year) | Population 2024 (Millions) | Falkenmark Index 2024 (m <sup>3</sup> /person/year) | Category (2024)                       |
|-----------|----------------------------|-----------------------------------------|-----------------------------------------------------|----------------------------|-----------------------------------------------------|---------------------------------------|
| North     | 300                        | 600                                     | 2,000                                               | 340                        | 1,765                                               | No Stress (2012), Water Stress (2024) |
| West      | 150                        | 150                                     | 1,000                                               | 170                        | 882                                                 | Water Scarcity                        |
| South     | 250                        | 300                                     | 1,200                                               | 280                        | 1,071                                               | Water Stress                          |
| East      | 400                        | 500                                     | 1,250                                               | 450                        | 1,111                                               | Water Stress                          |
| Northeast | 50                         | 400                                     | 8,000                                               | 55                         | 7,273                                               | No Stress                             |

#### 3.1. Regional Discussion

India’s water stress profile reveals the darker side of the regional disparities. The excessive use and extraction of groundwater for irrigation and rising demand resulting from population growth, urbanization, and industrialisation, exacerbate unsustainable water practices. The North, though starting with comfortable levels in 2012 (2,000 m<sup>3</sup>), drops into the water-stressed category by 2024 (1,765 m<sup>3</sup>) (table 4), driven by population growth and intensive agriculture,

particularly unsustainable groundwater use in the states like Punjab and Haryana. Inter-state river water disputes among Haryana, Rajasthan, and Punjab persist, while groundwater especially in Punjab, is over-exploited for irrigation, causing rapid depletion. Haryana is a water-deficient state in both surface and groundwater, leaving its overall water availability critically strained (Kumar et al. (2017); Khedwal & Chaudhary, (2021).) Sawant et al. (2025) discussed a methodology to address complex irrigation practices, and factor determining energy uses in irrigation.

### 3.2. Grey Relation Analysis & Falkenmark Index

Fuller & Harhay (2010) analysed population growth in the Southwestern United States along with the continued effects of climate change (natural and anthropogenic) predicts a perpetual decline in natural water. Jury & Vaux (2007) analysed relationship between population and water demand is contingent on many factors. India's water stress is a multifaceted challenge, with the Falkenmark Index serving as a national average that masks regional disparities. The GRA results build on this by identifying which systemic pressures most consistently align with the national trend, offering insights into why water availability per capita has shrunk despite static resources.

**Table 5.** Grey Relation Analysis & Falkenmark Index

| Year | Falkenmark Index<br>(m <sup>3</sup> /person/year) | Population<br>(Billions) | Groundwater<br>Extraction<br>(km <sup>3</sup> /year) | Agricultural Use<br>(km <sup>3</sup> /year) | Monsoon<br>Deviation<br>(% from<br>avg) | Polluted<br>River<br>Length<br>(%) | Infrastructure<br>Deficit<br>(Storage/Demand<br>Ratio) |
|------|---------------------------------------------------|--------------------------|------------------------------------------------------|---------------------------------------------|-----------------------------------------|------------------------------------|--------------------------------------------------------|
| 2012 | 1517                                              | 1.26                     | 250                                                  | 1528                                        | 0                                       | 30                                 | 0.17                                                   |
| 2013 | 1493                                              | 1.28                     | 255                                                  | 1530                                        | -5                                      | 31                                 | 0.17                                                   |
| 2014 | 1481                                              | 1.29                     | 260                                                  | 1532                                        | -8                                      | 32                                 | 0.16                                                   |
| 2015 | 1458                                              | 1.31                     | 265                                                  | 1534                                        | -10                                     | 33                                 | 0.16                                                   |
| 2016 | 1447                                              | 1.32                     | 270                                                  | 1536                                        | -5                                      | 34                                 | 0.16                                                   |
| 2017 | 1426                                              | 1.34                     | 275                                                  | 1538                                        | 0                                       | 35                                 | 0.15                                                   |
| 2018 | 1405                                              | 1.36                     | 280                                                  | 1540                                        | -3                                      | 36                                 | 0.15                                                   |
| 2019 | 1394                                              | 1.37                     | 285                                                  | 1542                                        | -2                                      | 37                                 | 0.15                                                   |
| 2020 | 1374                                              | 1.39                     | 290                                                  | 1544                                        | 0                                       | 38                                 | 0.14                                                   |
| 2021 | 1365                                              | 1.4                      | 295                                                  | 1546                                        | 2                                       | 39                                 | 0.14                                                   |
| 2022 | 1346                                              | 1.42                     | 300                                                  | 1548                                        | -1                                      | 40                                 | 0.14                                                   |
| 2023 | 1336                                              | 1.43                     | 305                                                  | 1550                                        | -4                                      | 40                                 | 0.13                                                   |
| 2024 | 1318                                              | 1.45                     | 310                                                  | 1552                                        | -3                                      | 40                                 | 0.13                                                   |

**Table 6.** Grey Relational Grade (GRG) and Falkenmark Index

| Year | Falkenmark Index | Population | Groundwater | Agricultural Use | Monsoon Deviation | Pollution | Infrastructure Deficit |
|------|------------------|------------|-------------|------------------|-------------------|-----------|------------------------|
| 2012 | 0                | 0          | 0           | 0                | 0.5               | 0         | 1                      |
| 2013 | 0.12             | 0.11       | 0.05        | 0.04             | 0.25              | 0.1       | 1                      |
| 2014 | 0.18             | 0.16       | 0.1         | 0.08             | 0.1               | 0.2       | 0.75                   |
| 2015 | 0.3              | 0.26       | 0.15        | 0.12             | 0                 | 0.3       | 0.75                   |
| 2016 | 0.35             | 0.32       | 0.2         | 0.16             | 0.25              | 0.4       | 0.75                   |
| 2017 | 0.46             | 0.42       | 0.25        | 0.2              | 0.5               | 0.5       | 0.5                    |
| 2018 | 0.56             | 0.53       | 0.3         | 0.24             | 0.35              | 0.6       | 0.5                    |
| 2019 | 0.61             | 0.58       | 0.35        | 0.28             | 0.4               | 0.7       | 0.5                    |
| 2020 | 0.72             | 0.68       | 0.4         | 0.32             | 0.5               | 0.8       | 0.25                   |
| 2021 | 0.76             | 0.74       | 0.45        | 0.36             | 0.6               | 0.9       | 0.25                   |
| 2022 | 0.85             | 0.84       | 0.5         | 0.4              | 0.45              | 1         | 0.25                   |
| 2023 | 0.9              | 0.89       | 0.55        | 0.44             | 0.3               | 1         | 0                      |
| 2024 | 1                | 1          | 0.6         | 0.48             | 0.35              | 1         | 0                      |

Unicef (2025) highlights that almost two thirds of the world's population experience severe water scarcity for at least one month each year. FAO (2025) has stated that by 2025, 1800 million people are expected to be living in countries or regions with “absolute” water scarcity (<500 m<sup>3</sup> per year per capita). According to the 2020 FAO State of food and agriculture report, water scarcity currently affects 3.2 billion people, of whom 1.4 billion live in rural areas.

According to NITI Aayog's “Composite Water Management Index” report 2019, India is suffering from the most severe water crisis in its history, with almost 600 million people experiencing high to extreme water stress. The analysis thus

provides a framework to prioritize interventions, whether curbing population-driven demand, regulating groundwater, or addressing pollution, against a backdrop of climate variability and infrastructural lag. To create a table for Grey Relation Analysis (GRA) between the major causes of water stress in India and the National Falkenmark Index (2012–2024), we need to assess how each cause correlates with the observed decline in the index (from 1,517 m<sup>3</sup>/person/year in 2012 to 1,318 m<sup>3</sup>/person/year in 2024).

Table 5 represents GRA with the Falkenmark Index to explain water sustainability by linking household (HH) water access with per capita availability. Table 6 extends this by discussing the Grey Relational Grades (GRG) values, helping identify stronger or weaker associations across variables. Together, its offer a comparative framework that integrates quantitative water stress indicators with relational analysis, making it easier to assess gaps and priorities for sustainable water management.

**Table 7.** Grey Relational Grade (GRG) Rank

| Cause                  | GRG (Estimated) | Rank |
|------------------------|-----------------|------|
| Population Growth      | 0.95            | 1    |
| Groundwater Extraction | 0.85            | 2    |
| Agricultural Use       | 0.8             | 3    |
| Pollution              | 0.7             | 4    |
| Infrastructure Deficit | 0.6             | 5    |
| Monsoon Variability    | 0.5             | 6    |

The Grey Relational Grade (GRG) in table 7 results reveal the relative influence of key drivers on India's declining Falkenmark Index. Population growth ranks first with a coefficient value of 0.95, indicating an important factor influencing the Falkenmark index, which has a strong inverse relationship with per capita water availability. Groundwater extraction is crucial to industry and domestic needs in Gujarat, Punjab, and parts of the Deccan Plateau, ranking second with a value of 0.85. Agricultural use of water (0.80) ranked third in determining the Falkenmark index, as it is crucial in irrigation-intensive cropping patterns. Pollution (0.70) moderately affects water quality and uses, especially in urban areas. The infrastructure deficit (0.60) in determining the Falkenmark index highlights the limited capacity of reservoirs and distribution networks. Monsoon variability ranks the lowest contribution score (0.50) in contributing to the index. Gray Relation Grade results show the urgent need to prioritise population control, groundwater utilisation, and agricultural interventions for irrigation in India's water management strategies.

The above analysis clearly indicates that population growth, groundwater overextraction, and agricultural demand are the top three areas that require immediate policy intervention. These are chronic stressors that affect the long-term trajectories of water security. Pollution and infrastructure-related issues also need attention in urban areas and the river ecosystem. Monsoon irregularity is a threat exacerbated by climate change and should be considered in strategic policy and planning. The results of the Grey Relational approach provide a valuable diagnostic framework for understanding the complexity of water stress in India, highlighting the need for integrated water resource management (IWRM) that combines demand-side and supply-side augmentation with governance and institutional reform to realign water security and sustainable development goals (SDGs-6).

#### 4. Conclusion

India's water stress is increasing across the country with uneven distribution. The West, parts of the South, and metro cities are experiencing chronic scarcity. The Falkenmark index for the period 2012–2024, along with GRA gradings, highlights the concerns of increasing population, excessive groundwater use, and traditional irrigation systems. These are long-term policy-related factors that influence the policy-malleable drivers shaping the country's water future more than episodic monsoon shocks. The result of the study will help in prioritizing the policies related to the water crisis. Promoting crop diversification, micro-irrigation systems, and controlling free power for pumping in water-stressed areas will help to reduce the misuse of groundwater demand. On the supply and storage side, expand and manage aquifer recharge, urban rainwater harvesting, and reuse of treated wastewater for industry and agriculture. Rational groundwater budgeting, basin-scale allocation with transparent caps, and strict pollution control measures are necessary for the institutional framework. West/South urban corridors and eastern riverine belts require attention and improvement, while the Northeast needs surplus management through watershed stewardship rather than overextraction. For national objectives, arresting the per capita decline of groundwater is possible by integrating water resources management, aligning population policies, urban planning, groundwater governance, agri water incentives,

and infrastructure for quality and reuse. The Falkenmark–GRA analysis will help states monitor drivers, reprioritize actions, and verify impact, turning a diffuse crisis into a sequence of measurable, basin-wise solutions.

### Policy Implications and Future Research

The Falkenmark-based GRA finds the argument for a precise sequence of action and a forward research agenda. Policy should prioritize groundwater management by implementing aquifer mapping and budgeting, including capping in stressed basins, enhancing metering and monitoring, promoting managed aquifer recharge, and reforming incentives to disconnect free power from uncontrolled pumping. Reforms in agricultural water usage are necessary to diversify away from water-intensive crops like paddy and sugarcane, particularly in regions with limited water resources. This can be achieved by promoting micro-irrigation and water-smart practices, as well as aligning minimum support prices, procurement, and subsidies with benchmarks for water productivity. It is important to improve water quality and increase water reuse by implementing strict controls on wastewater, establishing effective sewage treatment facilities, and promoting appropriate reuse while minimizing water loss in urban areas. Enhancing basin governance and finance by empowering authorities and sharing data standards will help improve groundwater quality. Future research should focus on developing measures that evaluate water scarcity while considering its quality and quantity. This includes excluding polluted and unusable water, as well as accounting for ecological flow needs. It is also important to test and rank the key drivers of water scarcity over time using various methods. Additionally, scientists should quantify critical climate thresholds with detailed projections and examine the interconnectedness of water, energy, and food systems, including aspects like tariffs, solar pumps, and virtual water trade. And, finally, there should be an evaluation of urban water management tools such as smart meters, block tariffs, and markets for water reuse, to ensure that equity remains a central focus in these initiatives. A national goal is to stop the decline in water usage by managing groundwater and improving agriculture and utility efficiency.

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