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ORIGINAL RESEARCH ARTICLE

Sustainable groundwater management in northwestern and west-central Bangladesh: Variability, human impacts, and food security implications

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Abstract: Groundwater in Bangladesh exhibits significant spatial and temporal variability, driven by monsoon recharge, lithologic heterogeneity, and human extraction. Integrating long-term monitoring data with recent field and Geographic Information Systems analyses (2021–2023), this study quantifies groundwater responses across northwestern and west-central Bangladesh. Seasonal drawdowns in solar irrigation pump (SIP) wells averaged 4.38 ± 1.74 m, followed by full post-monsoon recovery, confirming a recharge–discharge balance. The Theis analytical model, applied with a pumping rate of 2,500 m^3/day (representing the upper operational range of SIPs), an average aquifer material transmissivity of 1,800 m^2/day, and a storage coefficient of 0.1, predicted maximum drawdowns of 0.68 m at a distance of 10 m from the pumping wells—well below the 5 m critical threshold for maintaining domestic water-supply sustainability. Data also reveal that transmissivity and storage coefficients vary by up to two orders of magnitude among physiographic regions, emphasizing the need for site-specific management. The relatively high transmissivity and storage coefficients of the aquifer materials enable the functioning of the Bengal Water Machine, in which irrigation-induced recharge enhances groundwater storage and helps maintain stable water levels. By applying the United States Geological Survey's safe-yield concept alongside the Mandel–Shiftan sustainability framework, this study demonstrates that current SIP groundwater withdrawals remain well within sustainable limits. These findings support regionally adaptive groundwater governance that aligns pumping rates with recharge capacity. Such alignment is essential for maintaining irrigation viability and food security under changing climatic and hydrologic conditions. Overall, the results emphasize the importance of region-specific management strategies rather than generalized depletion narratives.

Keywords: Groundwater; Aquifer recharge; Safe-yield framework; Bengal Water Machine; Solar irrigation pumps; Food security

1. Introduction

This study originated from a project commissioned by the Global Center on Adaptation to support the Infrastructure Development Company Limited (IDCOL) of Bangladesh in preparing a Green Climate Fund Concept Note titled "Scaling Up Solar-Powered Irrigation to Ensure Food Security and Enhance

Resilience in Drought-Prone Areas of Bangladesh."[1] The proposal sought to expand solar irrigation pumps (SIPs) as a sustainable alternative to diesel-based pumping (Figure 1). SIPs provide multiple benefits: they operate using renewable solar energy, reducing dependence on fossil fuels and cutting greenhouse gas emissions, while strengthening food security, thereby aligning with interlinked global sustainability goals.[2,3]

SIPs powered by photovoltaic systems are increasingly used in groundwater-based irrigation, particularly in regions of South Asia and Sub-Saharan Africa. Once installed, SIPs have minimal running costs since solar energy is free, unlike diesel-based systems that require continuous fuel purchases.[4] In off-grid or poorly electrified rural areas, SIPs ensure reliable daytime irrigation, improving crop yields and enhancing the livelihoods of smallholder farmers.[5] However, their adoption also presents both opportunities and challenges that must be managed through careful policy and water governance. Case studies from western China and South Asia have shown that SIPs significantly reduce operational costs and deliver environmental co-benefits compared to diesel-powered systems.[3] When combined with site-specific considerations of hydrologic conditions and appropriate regulatory frameworks, SIPs have the potential to transform the traditional energy-groundwater system by integrating solar energy incentives with sustainable groundwater management.[2]

During the review of the concept note, the Green Climate Fund requested evidence that SIP expansion would not exacerbate groundwater over-abstraction. This concern reflects a broader dilemma: while groundwater supports Bangladesh's food security, aquifer dynamics are spatially heterogeneous, influenced by recharge variability, lithology, and irrigation demand.[6]

Figure 1. A solar irrigation pump well system from the study area. The solar panels supply power to the submersible pump housed within the shed located behind them. Photo by Shafiul Chowdhury.

Oversimplifying the situation as uniform "groundwater mining" obscures these differences and risks deterring climate-smart irrigation investments where they remain viable.

This study addresses these concerns by providing a nuanced, evidence-based understanding of groundwater variability across northwestern and west-central Bangladesh. The findings aim to inform both national water policy and international climate finance decisions while contributing to broader debates on sustainable groundwater management in South Asia.

1.1. Study area

Bangladesh hosts one of the most productive groundwater provinces in the world (Figure 2). The Ganges–Brahmaputra–Meghna (GBM) river system has been depositing vast sediment sequences in the Bengal Basin, forming Cretaceous to Recent deposits up to 15 km thick and covering an area of about 100,000 km^2.[7,8] Derived mainly from the Himalayas and Indo-Burman ranges, the GBM system carries the world's largest sediment load,[9] with roughly 1.5×10^6 million m^3 of sediment accumulating across the basin's floodplain and delta since ~7,000 years Before Present.[10] The Himalayan uplift resulting from the India–Eurasia collision continues to supply sediments to the delta.[11]

Most parts of the Bengal Basin are covered by Pleistocene and Holocene fluvio-deltaic sediments collectively referred to as alluvium. These sediments are composed of clay, silt, sand, and gravel deposited by streams within river valleys and incised floodplains.[8,13] Aquifer systems within these deposits are commonly classified by depth, with shallow aquifers occurring at depths of <100 m and deep aquifers extending below 100 m.[7,14]

Through repeated cycles of deposition and progradation, fluvio-deltaic deposits develop upward-coarsening successions—from basal clays and silts of the prodelta to overlying sands of the delta front and mixed deposits on the delta top.[8] This vertical and lateral heterogeneity produces aquifer systems that are typically confined to semi-confined types, where sand and gravel act as permeable aquifer units bounded above and below by relatively impermeable silts and clays. As a result, deltaic deposits form productive yet hydraulically complex aquifers with variable transmissivity (T), storativity (S), and connectivity across fine spatial scales.[15] These fluvio-deltaic deposits, exceeding 300 m in many places, form extensive multi-layered aquifer systems that are recharged annually by monsoon rainfall and seasonal flooding.[16,17] The combination of

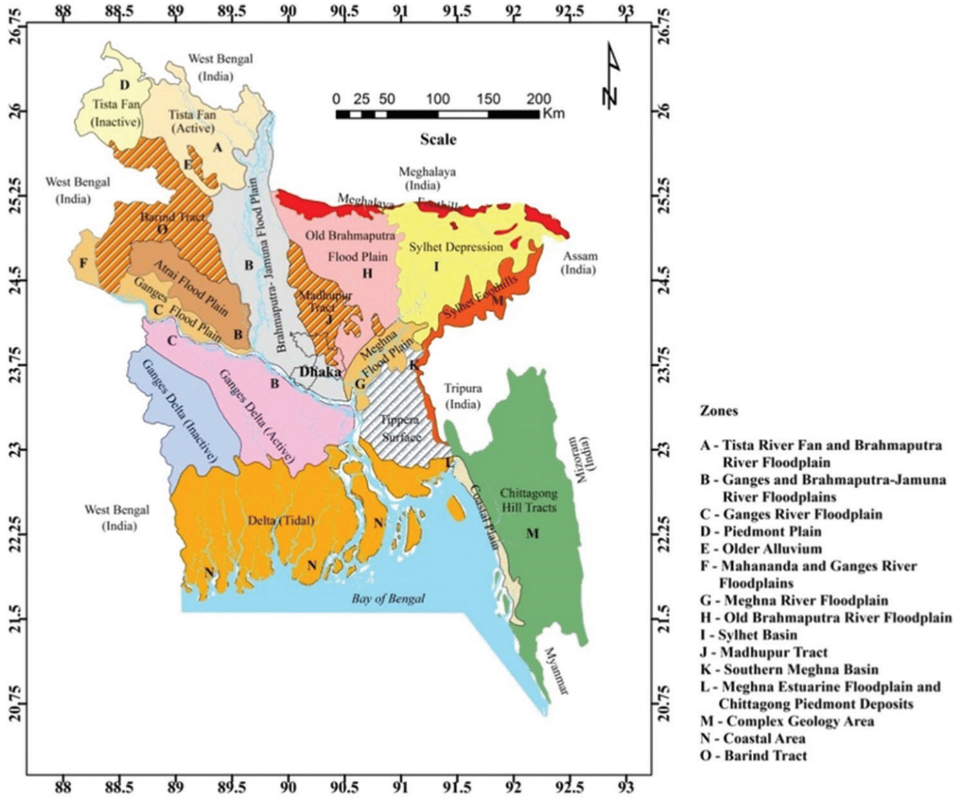

Figure 2. National-scale map showing the principal groundwater development and aquifer zones across Bangladesh, based on the Bangladesh Water Development Board and United Nations Development Program zoning framework (1982).[12] The map delineates 15 development zones (A-O), each associated with differing aquifer potential and physiographic settings.

high rainfall (1,500–3,000 mm/year), low topographic relief, and permeable deltaic sand sequences supports intensive irrigation and domestic water supply, which together sustain national food security.[18,19]

Groundwater recharge occurs primarily through vertical percolation and bank infiltration during the monsoon. The GBM system can be viewed as three hydraulically interconnected domains: (i) a shallow, actively recharged aquifer with dynamic water-table fluctuations; (ii) an intermediate transition zone with mixed recharge sources; and (iii) a deep confined aquifer containing older, more mineralized groundwater[20] (Figure 3). Subsurface temperature and isotopic studies indicate that regional groundwater flow paths extend from the northern piedmont fans toward the Bay of Bengal, with evidence of submarine discharge offshore.

Average groundwater flow velocities in northwestern Bangladesh are 5,900–7,300 m/year, reflecting high T and strong seasonal head gradients.[21] Remote-sensing analyses using Gravity Recovery and Climate Experiment (GRACE) data reveal groundwater storage declines of ~5.5 mm/year, particularly in some areas of the northwestern and central floodplains, corresponding to zones of intensive irrigation abstraction.[22] However, SIPs installed in shallow aquifers provide high groundwater yields and rapid recharge, making them suitable for small-scale irrigation and domestic supply. The overall water quality of the shallow aquifers in the study area remains well within acceptable standards and is notably free from arsenic and heavy metal contamination.[7,23] Although arsenic and heavy metal contamination pose a major challenge to the use of shallow aquifers,[24,25] arsenic concentrations in SIP wells remain below the maximum contaminant level.[23]

1.2. Groundwater irrigation in Bangladesh: Context and misconceptions

1.2.1. Historical development

Groundwater has been central to Bangladesh's agricultural transformation and food security over the past five decades. The introduction of high-yielding variety rice in the late 1960s sharply increased water demand during the dry season. In response, the Government of Bangladesh initially promoted deep

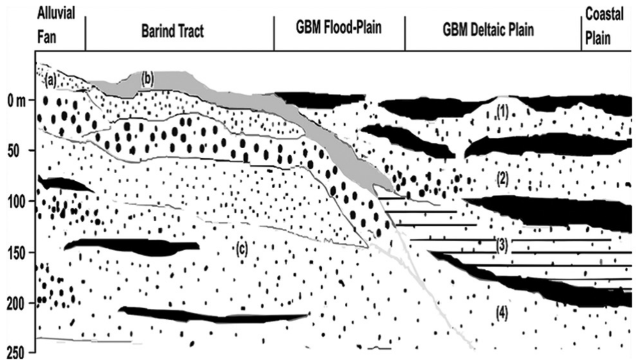

Figure 3. Generalized hydrostratigraphic cross-section of the Bengal Basin aquifer system (Bangladesh Water Development Board–United Nations Development Program, 1982)[12]

Notes: (a) Surface clay and silt layers of the Pleistocene upland (Barind clay); (b) Oxidized and weathered Pleistocene deposits (red-brown clay, mottled zone) forming the upper confining layer; (c) Fine to medium sand with interbedded clay—deep confined aquifer within Pleistocene/Holocene transition; (1) upper shallow aquifer—unconfined to semi-confined Holocene alluvium (sands and silts); (2) second aquifer—semi-confined fine- to medium-grained sand (local aquitard interlayers); (3) third aquifer—regionally confined, medium to coarse sand/gravel, high transmissivity; and (4) deep confined aquifer—fine to coarse sand and gravel within Pleistocene to late tertiary deposits other textures: Large black lenses—coarse sand and gravel aquifer zones; dotted zones—fine-grained silts and clays (aquitards); and gray shaded bodies—oxidized or weathered zones separating aquifer units.

Abbreviation: GBM: Ganges–Brahmaputra–Meghna.

tubewells in the mid-1970s but soon shifted focus to shallow tubewells (STWs). STWs became dominant due to their lower installation and maintenance costs, farmer-led financing, and minimal reliance on subsidies. By the 1980s, STWs accounted for most of the irrigation expansion, particularly benefiting smallholders who had been largely excluded from state-managed water development projects.[6,26-28]

1.2.2. Current status of groundwater irrigation

Today, Bangladesh cultivates ~8.13 million ha (Mha) of land, of which 5.7 Mha are irrigated. Nearly 4 Mha of this irrigated land is supplied by minor irrigation systems, primarily STWs.[6,29,30] Groundwater irrigation has enabled farmers to overcome seasonal surface-water scarcity—abundant during the monsoon but scarce in the dry season. Most importantly, it facilitated the expansion of *Boro* rice cultivation, now the dominant dry-season crop. By 2023, *Boro* rice contributed ~20 million metric tons, accounting for more than half (55%) of national rice production.[30] The combined use of groundwater, high-yielding variety seeds, and fertilizers has been pivotal in achieving near self-sufficiency in staple food production.

1.2.3. Misconceptions and evidence

Despite these achievements, Bangladesh's groundwater use is often portrayed as unsustainable "mining," a narrative that overlooks the country's unique hydrogeologic setting. Bangladesh overlies one of the world's largest and most complex deltaic aquifer systems, where recharge is strongly influenced by river networks, ponds, irrigated fields, and heterogeneous sedimentary deposits. In many regions, pumping-induced recharge has partially offset drawdown, preventing the persistent long-term declines typically associated with groundwater mining.

The frequent application of a uniform depletion rate (e.g., 2.5–10 mm/year) obscures substantial spatial and temporal heterogeneity. While localized over-abstraction and declining water levels are real concerns in parts of northwestern Bangladesh, these conditions are not representative nationwide. Across much of the country, aquifer recharge—both natural and pumping-induced—maintains irrigation withdrawals within sustainable limits and contributes to groundwater-level stability.

1.2.4. Policy and media narratives

Oversimplified representations of groundwater depletion carry serious policy implications.[31,32] Framing the situation as uniformly unsustainable risks discourages international development agencies from investing in groundwater-based irrigation, even where it remains viable and essential for food security. Media reports often amplify this perception. For example, a widely read newspaper, the Daily Star (Dhaka), claimed that Bangladesh is "losing 2.5–10 mm of freshwater annually," reinforcing public fears about irrigation sustainability.[33]

At the same time, emerging remote-sensing evidence provides a broader but more generalized view. A recent study in Science Advances, led by Arizona State University, used GRACE Follow-On satellite data (2003–2024) to track total water storage in 101 countries.[34] Within the GBM, which includes much of Bangladesh, the study reported consistent 21-year declines, with total water storage losses of −1 to −2 cm annually in the northwest and north-central regions.[35] While such findings highlight important regional stress, they must be interpreted alongside finer-scale, ground-based measurements to avoid overstating generalized depletion trends.

1.2.5. Toward a nuanced approach

Bangladesh's groundwater cannot be reduced to a single narrative of nationwide depletion. Rather, it represents a dynamic and regionally variable system in which localized risks coexist with opportunities for sustainable irrigation. Addressing these complexities requires an evidence-based approach that incorporates hydrogeologic variability, differentiates areas of stress from those of resilience, and balances immediate concerns with the long-term imperative of food security.

1.3. Objectives

Recognizing the fact that Bangladesh's groundwater systems exhibit significant spatial and temporal variability, this study applies an evidence-based approach to quantify the regional sustainability of irrigation withdrawals. The objectives of this study are to:

1. Compile and analyze long-term groundwater level records from different hydroecological settings across northwestern and west-central Bangladesh to evaluate seasonal fluctuations and drawdown patterns due to irrigation.
2. Apply the Theis analytical method to estimate drawdown around SIP wells under projected pumping scenarios to assess safe yield.
3. Conduct targeted field investigations to identify aquifer properties consistent with "safe abstraction zones," where shallow aquifers can sustain irrigation demands without compromising long-term water availability or domestic supply.

These objectives support an evidence-based understanding of groundwater variability and provide actionable insights for sustainable irrigation policy and climate finance decisions.

2. Methods

2.1. Field data collection and SIP analysis

Groundwater pumping data from 975 SIP wells (2016–2023), provided by IDCOL, included Global Positioning System locations, pumping rates (Q), monthly water-level measurements, and infrastructure details (Figure 4). Representative field sites were selected to capture hydrogeologic variability. These data were complemented by the Asian Development Bank's Geographic Information Systems (GIS)-based multi-criteria analysis for SIP rollout,[36] which was expanded here by incorporating safe yield principles.

2.2. Safe yield framework and critical threshold determination

The concept of safe yield, also referred to as perennial yield or basin yield, is fundamental to groundwater management. The United States Geological Survey defines safe yield as "the amount of groundwater that can be withdrawn from a basin annually without causing undesirable results," which includes depletion of storage, deterioration of water quality, infringement of water rights, excessive economic costs due to declining water levels, depletion of baseflow, or land subsidence.[37]

While the safe yield concept provides an important guideline, modern groundwater management recognizes that aquifer sustainability depends on dynamic, system-specific responses to pumping.[38-40] Accordingly, this study applied the framework developed by Mandel and Shiftan[41] for estimating sustainable groundwater yield.[39] The framework emphasizes identifying the most stringent constraint governing groundwater use within a given socio-hydrologic context (Figure 5). The legal prioritization of water use is outlined in the Bangladesh Water Act 2013 (Section 18), as published in the *Bangladesh Gazette* on December 29, 2013.[42] The act ranks water-use priorities in water-stressed regions as follows: (i) potable water, (ii) household use, and (iii) agricultural irrigation. This hierarchy underscores the necessity of protecting drinking-water supplies during conditions of water scarcity.

Field assessments in the study area revealed that hand tube wells, which supply drinking and household water, become non-functional when groundwater levels decline beyond approximately 7 m below ground surface. To ensure a conservative margin of safety, this study adopted a 5 m drawdown threshold as the critical constraint for evaluating pumping impacts around SIP wells. Drawdowns exceeding this 5 m limit were considered indicative of unsustainable groundwater withdrawal.

2.3. Application of the Theis (1935) equation

Drawdown refers to the decline in hydraulic head caused by groundwater withdrawal, leading to the lowering of the water table in an unconfined aquifer or the potentiometric surface in a confined aquifer. Groundwater pumping from a well causes surrounding water levels to form a characteristic cone-shaped

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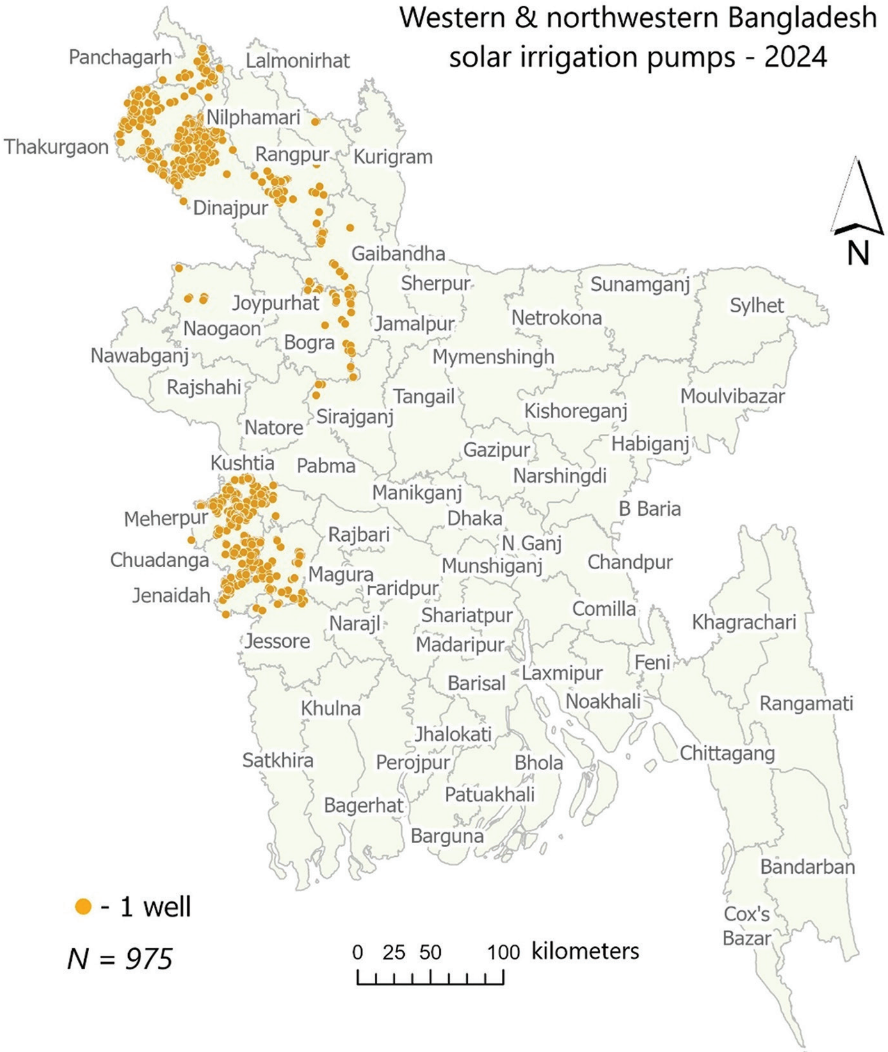

Figure 4. Map of Bangladesh depicting the locations of 975 solar irrigation pump wells

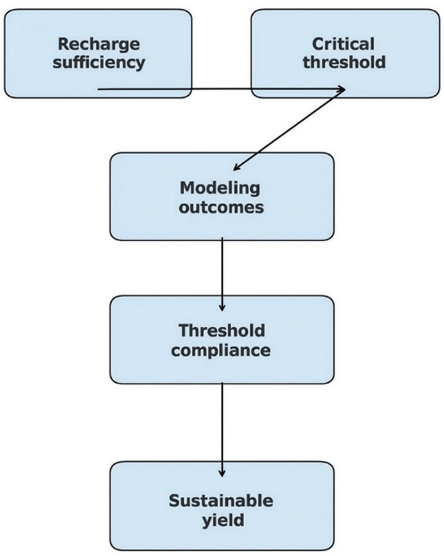

Figure 5. Conceptual flow diagram of safe yield analysis

depression known as the cone of depression, the extent and magnitude of which depend on the aquifer's hydraulic properties, Q, and duration of pumping.[15] Quantifying drawdown is essential for understanding aquifer behavior, evaluating sustainable yield, and predicting potential interference or resource depletion under varying abstraction scenarios.

In this study, aquifer drawdown was estimated using the analytical solution developed by Theis (1935), which describes transient radial flow toward a fully penetrating well in a confined, homogeneous, and isotropic aquifer of infinite extent.[43] The Theis model assumes constant discharge and instantaneous release of water from storage, enabling the hydraulic response to be expressed as a function of T and S.[43] Despite these limitations, the Theis method remains one of the most widely used analytical approaches for evaluating aquifer response to pumping. It can be applied to estimate drawdown when aquifer parameters (T and S) are known, or conversely, when drawdown data are available, T and S can be calculated. Recent work by De Filippi *et al*.[44] further demonstrated that even low-flow pumping tests can yield reliable estimates of hydraulic conductivity and related parameters using the Theis analytical solution.

3. Results and discussion

3.1. Summary of groundwater trends in Bangladesh

Groundwater processes in Bangladesh exhibit substantial regional variation, influenced by both natural and anthropogenic factors that shape hydrogeologic conditions.[45-50]

A comprehensive study on the Bengal Basin examined how extensive groundwater pumping for irrigation affects water-level behavior and aquifer recharge. The research introduced the concept of the Bengal Water Machine, a system in which large-scale groundwater withdrawal creates additional subsurface storage capacity, enabling enhanced infiltration of monsoon rainfall during high-precipitation events. Over a 30-year period (1988–2018), the study quantified the extra freshwater captured beyond predevelopment recharge levels, driven by the collective activity of roughly 16 million smallholder farmers operating shallow wells (<100 m). Drawing on more than 1 million weekly piezometric observations from 465 monitoring sites, with time series spanning 24–54 years (median of 43 years), the findings provided a robust empirical basis for understanding the reciprocal relationship between groundwater extraction and recharge in the Bengal Basin, emphasizing how human activity can augment natural aquifer processes.[47]

In the Barind Tract of northwestern Bangladesh, long-term hydrogeologic monitoring revealed pronounced spatial variation in groundwater behavior. Over a 25-year period, increasing numbers of deep tube wells and higher abstraction rates caused greater fluctuations in water levels, particularly across the high Barind, level Barind, and flooded terrace landforms. The high Barind area experienced the most severe and persistent declines in groundwater levels.[50] However, more recent investigations challenge the generalized perception of unsustainable groundwater mining in this region. A 2023 study by Rushton *et al*.[48] demonstrated that groundwater responses differ considerably across physiographic sub-units and that earlier analyses often failed to account for crucial surface–subsurface flow interactions. Using data from a representative groundwater well (<100 m) in the high Barind, the researchers discovered a deeper water table beneath the Barind Clay aquitard. This deeper layer supports steady vertical flow into the aquifer, remaining largely unaffected by seasonal rainfall variability or irrigation pumping. The study concluded that the vertical hydraulic conductivity of the aquitard plays a vital role in maintaining sustainable groundwater availability, a mechanism likely present in other multi-layered aquifer systems.[48]

A broader regional analysis by the Bangladesh Rural Advancement Committee (1981–2011) documented significant long-term groundwater declines across northwestern Bangladesh, with the most severe depletion observed in Rajshahi, followed by Pabna, Bogura, Dinajpur, and Rangpur districts.[51] In addition, localized anthropogenic impacts, such as those from the Barapukuria Coal Mine in Bogura district, have contributed to groundwater depletion and land subsidence. Mining operations and associated sand extraction have increased subsurface void ratios, promoting water infiltration into mine pits that may have evolved into permanent lakes. Since 2006, surface subsidence has led to productivity losses, prompting government acquisition of 2.61 km^2 of affected land for compensation.[52]

By contrast, hydrograph data from the Bangladesh Water Development Board (2008–2018), covering 211 observation wells in eastern regions bordered by the Jamuna, Padma, and Meghna Rivers, indicate generally stable groundwater conditions. Seasonal fluctuations in these areas suggest sufficient recharge and limited long-term decline.[53] Complementary hydrogeologic studies conducted by the Department of Public Health and Engineering (DPHE) and the British Geological Survey (BGS) in 2001 confirmed that most shallow aquifers (<100 m) across Bangladesh are fully recharged during the monsoon season (August–October). Beyond this period, additional rainfall is largely rejected once aquifers reach storage capacity. Although interannual variability in peak groundwater levels exists, the onset levels at the beginning of each irrigation season (January) remain relatively consistent, underscoring the resilience of shallow aquifers under current climatic and abstraction regimes.[7]

3.2. SIP well analysis

Statistical analysis of pumping data from 975 SIP wells provided by IDCOL indicates that groundwater responses are highly consistent across the study region. The difference between the mean peak drawdown and mean peak recovery is only 1.74 m, with a standard deviation of 0.71 m, reflecting limited variability. The low standard deviations for both drawdown and recovery underscore minimal spatial heterogeneity, suggesting that the aquifer behaves as a relatively homogeneous and isotropic system. This uniformity provides strong justification for applying the Theis analytical solution to estimate drawdown and recovery across the study area.

Equally important, all 975 wells consistently returned to their pre-pumping static water levels at the end of each growing season. This finding indicates that seasonal pumping stresses are offset by a combination of natural recharge from the monsoon and pumping-induced recharge through enhanced infiltration. Spatial interpolation of IDCOL water-level data highlights clear seasonal fluctuations across western and northwestern Bangladesh. During peak irrigation (March–May), depth-to-water ranged from ~2.5 to >8 m, with localized drawdown hotspots aligned with intensive abstraction zones (Figure S1). Post-monsoon recovery (October–December) shows widespread rebound, with water levels improving to 0.6–7.5 m (Figure S2).

The maximum average drawdown across all monitored wells was 4.38 m, with a standard deviation of 1.21 m. No measurable decline in water levels was detected relative to the initial baseline between 2021 and 2023, suggesting that groundwater abstraction is effectively offset by natural recharge. This trend indicates localized stress yet overall regional stability, supporting the conclusion that the groundwater budget remains sustainable under current solar irrigation practices.

Although this study was carried out more than two decades ago, the 2021–2023 SIP database confirms that its conclusions remain valid: groundwater levels at the onset of the irrigation season in January are stable across years, and aquifers reliably recover before the next pumping cycle begins. The SIP database is provided in Supplementary File 1.

Taken together, the new SIP evidence provides a long-term validation of the DPHE–BGS findings, demonstrating that shallow aquifers in Bangladesh continue to be resilient and capable of sustaining irrigation withdrawals under current recharge and management conditions.

3.3. Safe yield assessment

Table 1 summarizes the logical progression of the safe yield analysis. Beginning with evidence of recharge sufficiency, the analysis accounts for regulatory obligations under the Bangladesh Water Act (2013) and field-identified sustainability thresholds. These thresholds were operationalized through Theis-based drawdown modeling, which showed compliance under worst-case pumping scenarios (described in detail in the next section). The framework concludes that current SIP abstractions are within sustainable yield limits, ensuring protection of shallow drinking-water supplies while supporting irrigation demand.

Table 1. Summary of safe yield analysis and sustainability evaluation

Criterion	Key findings	Implications for sustainability
Recharge sufficiency	Both natural and irrigation-induced recharge are adequate to support current abstraction levels	Ensures that the regional water balance is maintained
Regulatory constraints	The Bangladesh Water Act (2013) prioritizes potable > domestic > irrigation uses. Field reports note public concern when hand tube wells fail	Legal and social safeguards emphasize the protection of shallow drinking-water sources
Critical threshold	Field assessments show drawdown ≥ 7 m causes most hand tube wells (<7 m depth) to fail	A 5 m drawdown limit is adopted as the sustainability threshold
Abstraction–impact linkage	The 5 m threshold applied as benchmark for unacceptable pumping impacts.	Provides a measurable criterion for sustainability assessment
Modeling outcomes	Theis-based simulations (site-specific T and S; SIP pumping rates) show maximum drawdown < 5 m even under worst-case scenarios	Modeled drawdowns remain within safe limits
Threshold compliance	Simulated drawdowns stay below the 5 m threshold	Hand tube wells remain functional; no adverse impacts detected
Sustainable yield conclusion	Recharge–abstraction balance and model results confirm that current SIP pumping rates are within sustainable yield limits	Groundwater use is sustainable under present conditions

Abbreviations: S: Storativity; SIP: Solar irrigation pump; T: Transmissivity.

3.3.1. Theis (1935) analytical solution for drawdown estimation

For this study, the Theis equation was applied using representative aquifer parameters and pumping conditions. A Q of 2,500 m^3/day was selected to represent the upper range of SIP operation. T was set at 1,800 m^2/day, and S at 0.1, consistent with values reported for Bangladesh aquifers.[54] Drawdown was calculated at a radial distance of 10 m from the pumping well after one day of continuous operation. An open-source Theis calculator provided by the Utah Division of Water Rights was used for computation.[55] Details of the Theis derivation, governing equations, and parameter definitions are provided in Section S1.

The simulated drawdown at 10 m after 24 h of continuous pumping was 0.68 m, well below the 5 m critical threshold often associated with loss of functionality in shallow domestic wells Section S1. In practice, SIPs typically operate for ~7 h/day rather than continuously. Thus, the calculated drawdown should be considered a conservative upper bound, and actual daily drawdowns would likely be substantially lower. Typically, hand tube wells used for domestic purposes are installed at least 10 m away from SIP wells. Figure 6 illustrates an exception from the study area, where a hand tube well is located adjacent to a SIP well. The well is regularly used by pump operators for their water needs and has consistently maintained water availability, even during peak pumping seasons.

Figure 6. A hand tube well located adjacent to a solar irrigation pump well in the study area. Photo by Shafiul Chowdhury

3.3.2. Regional variability of aquifer properties

Aquifer T and S vary widely across Bangladesh, reflecting diverse hydrogeologic settings. Table 2 summarizes regional ranges of aquifer properties based on aquifer test analyses.[54]

3.3.3. Interpretation

The data highlight significant hydrogeologic contrasts across Bangladesh. T values range from <200 m^2/day in the southeast to >4,000 m^2/day in the northwest, while S values vary from <0.001 in the southeast to >0.2 in the northwest. These differences underscore the importance of site-specific aquifer characterization when estimating drawdown and assessing safe yield for irrigation expansion.

Theis-based analytical modeling (Figure 7) was performed to simulate drawdown under representative SIP pumping conditions; this time using aquifer properties estimated from field investigations. T values of 2,500–3,800 m^2/day and S values ranging from 1×10^{-3} to 5×10^{-3} were adopted, consistent with the shallow alluvial aquifer system of northwestern Bangladesh. As demonstrated by the simulation, the maximum drawdown reached only 0.68 m at 10 m from the pumping well after 24 h of continuous operation, far below the 5 m sustainability threshold for shallow domestic wells. Under more realistic SIP operating conditions (~7 h/day), the effective drawdowns are considerably smaller, highlighting the aquifer's strong capacity for rapid recovery between pumping cycles.

The cone of depression was shown to dissipate radially within ~200 m, beyond which drawdown became negligible, ensuring minimal hydraulic interference with neighboring wells (Figure 7). Importantly, the T values derived for this aquifer are one to two orders of

Table 2. Regional ranges of aquifer properties in Bangladesh

Region	T_min (m^2/day)	T_max (m^2/day)	S_min	S_max	K_min (m/day)	K_max (m/day)
Northeast	200	3,000	0.002	0.10	3	90
Northwest	300	4,000	0.003	0.23	12	114
Southwest	900	3,200	0.01	0.15	11	65
Southeast	140	1,900	0.0007	0.07	5	23

Notes: Transmissivity (T) and hydraulic conductivity (K) values demonstrate strong regional variability, while the storage coefficient (S) spans several orders of magnitude, reflecting heterogeneous aquifer conditions.

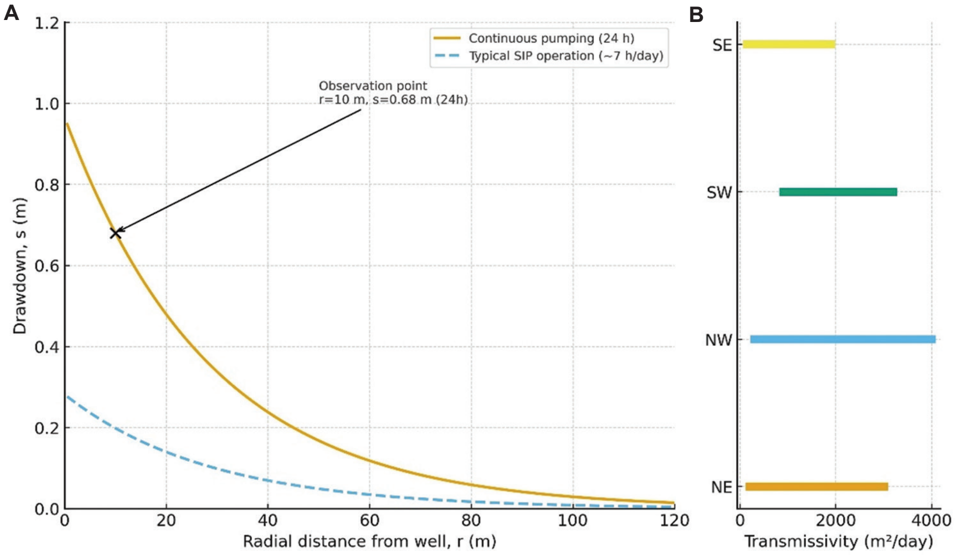

Figure 7. Drawdown around solar irrigation pump (SIP) wells and regional aquifer variability in Bangladesh.[43] (A) Conceptual schematic of drawdown around an SIP well based on the Theis (1935) analytical solution. The pumping well (pumping rate = 2,500 m^3/day) induces a cone of depression, with an observation well at 10 m showing a calculated drawdown of 0.68 m after 24 h of continuous pumping. The pumping-induced drawdown reached 0.87 m after 24 h, relative to the initial static water level (0 m), with the solid curve illustrating the decline in water level away from the pumping well. Because SIPs typically operate for ~7 h/day, the actual initial water level and the subsequent drawdown are expected to be smaller than the simulated 24-h value. Parameters used: T = 1,800 m^2/day and S = 0.1. (B) Regional ranges of aquifer T across Bangladesh, showing substantial hydrogeologic variability from <200 m^2/day in the southeast to >4,000 m^2/day in the study area.

Table 3. Summary of selected solar irrigation pump (SIP) sites and key operational characteristics

District	Upazila	Year SIP installed	STWs replaced	Well depth (ft)	Groundwater-level status	Farmer subscription trend	Key implications
Serajganj	Tarash	2021	13	110	No change since installation	Strong interest	Stable water levels; suitable for SIP scaling
Gaibandha	Gobindaganj	2018	14	195	No change since installation	Strong interest	Demonstrates long-term stability under SIP use
Rangpur	Badarganj	2020	15	200	No change since installation	Strong interest	Confirms aquifer resilience despite multiple SIPs
Rangpur	Badarganj	2016	12	150	No change since installation	Strong interest	Oldest installation; evidence of sustained recovery
Rangpur	Peerganj	2018	11	200	No change since installation	Strong interest	Consistent stability; indicates safe abstraction
Gaibandha	Sadullahpur	2017	15	Not available	No change since installation	Strong interest	Despite missing well depth data, recovery is evident
Kushtia	Kushtia Sadar	2018	13	202	No change since installation	Strong interest	Deeper well with stable water table; supports scalability
Jhinaidaha	Kaliganj	2021	16	200	No change since installation	Strong interest	Newly installed SIP; early evidence of resilience

Abbreviation: STW: Shallow tubewells.

magnitude higher than those of the well-studied Ogallala Aquifer in the United States, which typically range from 46.45 to 1,096.26 m^2/day.[56] This contrast underscores the exceptionally high capacity of the Bengal alluvial aquifer to transmit water, enabling it to accommodate localized irrigation withdrawals with limited long-term impacts on groundwater storage.

Regional aquifer properties exhibit wide variability (T = 140–4,000 m^2/day; S = 0.0007–0.23), underscoring the need for site-specific assessments.[54] Nevertheless, all modeled drawdowns remained within sustainable limits.

The Theis-based analysis provides a useful first-order diagnostic of SIP well drawdown under different scenarios and demonstrates that, under representative conditions, drawdowns remain modest relative to thresholds of concern. However, its limitations underscore the importance of coupling such analytical estimates with updated aquifer testing, long-term monitoring, and numerical modeling to refine safe yield thresholds.

3.3.4. Field study findings

The results from the field investigations are summarized in Table 3, which presents the operational characteristics of the selected SIP sites, including installation year, number of STWs replaced, well depth, groundwater-level status, and user demand. Across all sites, no measurable decline in groundwater levels has been observed since SIP installation. In addition, farmers expressed strong interest in expanding participation, as reflected in new subscription requests. Field evidence indicates stable groundwater levels across sites and strong farmer demand, supporting the case for sustainable SIP expansion.

The findings demonstrate that current SIP operations are functioning well within safe yield limits. Integrating recharge sufficiency, legal constraints, and drawdown thresholds provides a rigorous framework for sustainable irrigation expansion.

4. Conclusion

Field investigations and analyses of SIP wells indicate that shallow aquifers in northwestern and west-central Bangladesh remain hydrogeologically resilient under current irrigation practices. Water levels consistently recover to nearly pre-pumping levels after each irrigation cycle, and seasonal drawdowns remain modest across multiple years of monitoring. These findings align with earlier DPHE–BGS studies, providing long-term evidence that shallow aquifers are being sustainably recharged and can support controlled irrigation without significant depletion.

Safe-yield assessments and GIS-based spatial analyses confirm that SIP systems represent a climate-smart and environmentally sound irrigation option. By matching pumping intensity with natural recharge, SIPs promote sustainable groundwater use while reducing dependence on diesel pumps, thereby lowering greenhouse gas emissions. Incorporating safe-yield thresholds into groundwater management helps maintain withdrawals within replenishment limits and secures water for domestic and ecological needs. When informed by data-driven management and site-specific hydrogeologic conditions, solar irrigation can enhance agricultural productivity, improve rural livelihoods, and contribute to Bangladesh's long-term goals of climate resilience and sustainable groundwater management.

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

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Availability of data

The datasets generated and analyzed during this study are available in Supplementary File 1.

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