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Innovating Groundwater Recharge using a BoreCharger Technology in Khalad Area, Pune District, India

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Abstract

Groundwater is absolutely vital for sustaining over 80% of agricultural irrigation in India, underscoring its critical importance in food production. However, ensuring groundwater sustainability remains a pressing challenge, particularly in regions with hard rock, such as the Deccan basalts. Formed millions of years ago through volcanic eruptions, this terrain is characterized by complex geological formations with variable basaltic layer thicknesses, classified into two types: 'simple' and 'compound'. Effective groundwater management in such settings requires integrated hydrogeological studies that rely on rainfall patterns, geological structures, and hydrographic data. To address these challenges, innovative approaches, such as BoreCharger, have been introduced. BoreCharger technology involves detailed hydrogeological investigations and perforation of borewell casings to enable recharge of deeper aquifers with freshwater from unconfined aquifers. This process enhances groundwater availability, improves quality, and revitalizes low-yielding or failing borewells, paving the way for sustainable water management. The present study, conducted at Khalad, Purandar, Maharashtra, demonstrates the positive outcomes of the BoreCharger application. Results show that BoreCharger-equipped borewells consistently sustain water levels until late March, ensuring a reliable supply for both agriculture and drinking purposes. Water quality has also shown significant improvement, with no adverse effects observed on groundwater levels or in nearby wells and water bodies. BoreCharger emerges as a powerful solution to combat the challenge of groundwater sustainability in basaltic terrains. Its ability to enhance both quantity and quality of groundwater highlights its potential for wider application beyond the study area.

Keywords: Artificial Recharge, BoreCharger, Impact, Water Level, Khalad Area, Pune District

Introduction

Water is fundamental to sustaining life, supporting agricultural practices, and driving economic growth (USGS, 2024). Despite covering approximately 71% of the Earth's surface, a mere fraction is accessible as usable freshwater. Of the total global water supply, less than 2.5% constitutes freshwater, with only about 1% available for direct human consumption (USGS, 2024; IAEA, 2012). The increasing demand for water, coupled with mismanagement and the impacts of climate variability, has precipitated a significant global water scarcity crisis that affects billions of individuals (EPA, 2015). In India, the situation is particularly dire, with the agricultural sector consuming nearly 80–90% of the nation's total water resources (CGWB, 2023). Groundwater has emerged as the predominant source for irrigation, sustaining over four-fifths of the cultivated area. However, unregulated extraction practices have led to widespread aquifer depletion and degradation of water quality (CGWB, 2023; Bhanja *et al.,* 2017, 2019). Projections indicate that per capita water demand in India may escalate from the current average of 99 liters per day to approximately 167 liters per day by 2050, which is poised to exacerbate the ongoing crisis (ADRI, 2024). The complexity of water resource management is further amplified in basaltic terrains, such as those found in the Deccan Traps of Maharashtra. These volcanic formations are characterized by alternating simple and compound flows, exhibiting considerable variability in thickness and fracturing patterns (Kulkarni *et al.*, 2000; Krishnamurthy, 2020). In these geological contexts, aquifer storage and transmission are significantly influenced by secondary porosity stemming from weathering, jointing, and fracturing processes (Mishra *et al.*, 2023; Dongare *et al.*, 2024). This intrinsic heterogeneity presents formidable challenges for groundwater management, rendering conventional recharge techniques often ineffective (Saha *et al.*, 2022; Sufyan *et al.*, 2024). In response to these challenges, innovative solutions such as BoreCharger technology have emerged. BoreCharger encompasses a comprehensive hydrogeological assessment and the strategic perforation of borewell casings at suitable geological depths. This process facilitates the recharge of deeper, confined aquifers using freshwater from shallow sources (Sufyan *et al.*, 2024). The implementation of this method not only enhances groundwater availability but also has the potential to rejuvenate underperforming

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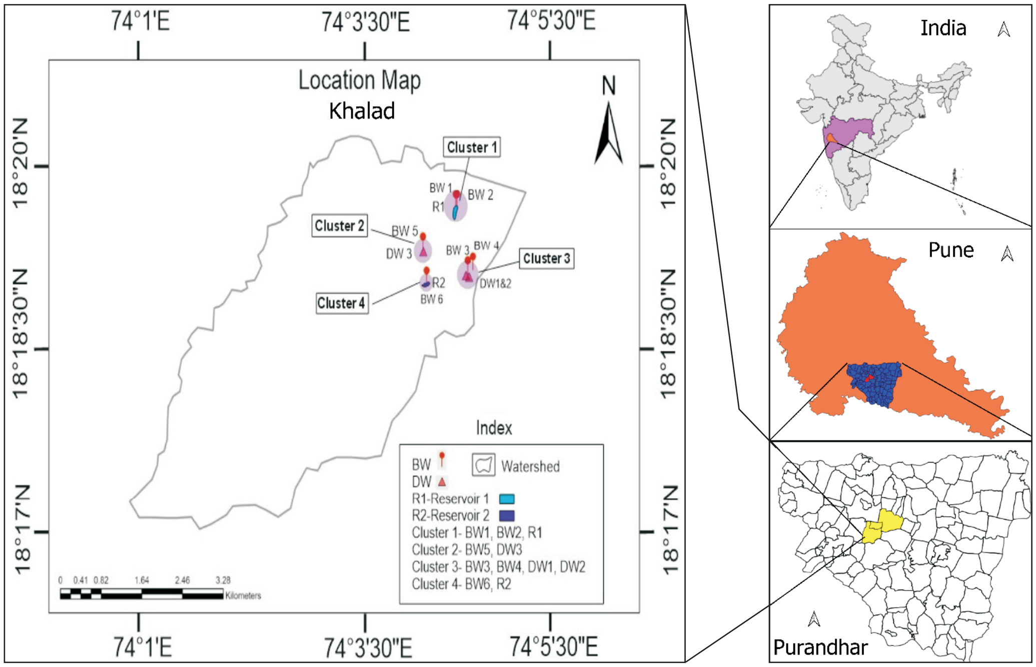

Fig.1. Location Map of Study Area

borewells and ameliorate water quality when appropriately monitored (Adhikari *et al.*, 2013; Wagh *et al.*, 2025). The objective of this study is to assess the application of BoreCharger technology in Khalad village, Purandar Taluka, Maharashtra, situated within the Deccan Volcanic Province. Specifically, this investigation aims to evaluate the technology's impact on groundwater levels and quality, as well as its effects on adjacent wells and water bodies. The findings of this research aim to support the establishment of BoreCharger as a viable and sustainable groundwater management tool for the hard-rock regions of India (CGWB, 2017, 2023; APN-GCR, 2024).

Study Area

The study area focuses on Khalad Village and its surrounding region within Purandar Taluka, Pune District, Maharashtra. This region is positioned between the latitudes of 18.316693°N and 18.328470°N, and the longitudes of 74.068310°E to 74.079551°E, with an average elevation ranging from 730 meters to 835 meters above mean sea level, demonstrating a relative relief of approximately 105 meters (Fig.1). The topography exhibits a gentle eastward slope, characterized by a relatively flat central portion of the watershed. Seasonal drainage is marked by a dendritic pattern, predominantly featuring short ephemeral streams that flow during the southwest monsoon season, which spans from June to September. Climatically, the area experiences a subtropical to tropical monsoon climate, characterized by three distinct seasons. The summer season, from February to May, experiences maximum temperatures ranging from 30°C to 40°C, with a peak in May. The monsoon, which occurs from June to September, brings moderate rainfall, with approximately 40 rainy days each year. Winter, from October to January, is marked by cool and dry conditions. The region receives an average annual rainfall of about 518 mm, with approximately 80-85% of this precipitation concentrated during the southwest monsoon (IMD, 2024). Soils in this region are derived from Deccan Trap basalts and primarily consist of black cotton soils (vertisols) in the low-lying areas, while red lateritic soils are found at higher elevations and slopes. Soil thickness varies with the topographic features, generally being thicker in valley regions and thinner over basaltic ridges. Land use in the area is predominantly agricultural, with common crops including sugarcane, pomegranates, jowar, bajra, wheat, and pulses (Deshpande *et al.*, 2006). The population mainly consists of marginal farmers, and the landscape features intermittent patches of fallow land and wasteland, with scrub vegetation prevalent in the hilly areas. The built-up area is concentrated mainly within Khalad village and nearby hamlets. To facilitate the study, the area is mapped using the Survey of India Toposheet No. E4313 (47J/3) at a scale of 1:50,000, which serves as the foundational map for delineating watershed boundaries, drainage patterns, and well locations.

Geology and Hydrogeology of the Study Area

The study area is situated on Deccan basalts, also known as the Deccan Traps, which were formed by extensive lava eruptions approximately 65 million years ago. The thickness of these lava flows varies significantly, from a few meters to hundreds of meters, and can be subdivided into various units. Deccan basalts are classified into 'simple' and 'compound' types based on lava viscosity (Deshmukh, 1988; Kale and Kulkarni, 1992). Simple flows are typical of flood basalts, characterized by the effusive eruption of low-viscosity lava. In contrast, compound flows result from explosive activity with more viscous lavas or occur at the edges of simple flows, where viscosity increases due to cooling and the loss of gas. The project area primarily features compound basalts from the Ambenali Formation of the Wai Subgroup (Subbarao and Hooper, 1988) and the Purandhargad Formation of the Diveghat Subgroup in the Sahyadri Group (Godbole *et al.*, 1996). These compound flows lose significant volatile gases prior to extrusion, resulting in high viscosity (Fig. 2). This trapped gas can cause rubbly textures on both upper and lower surfaces, with some flows lacking a clearly defined compact layer. Mapping in this area

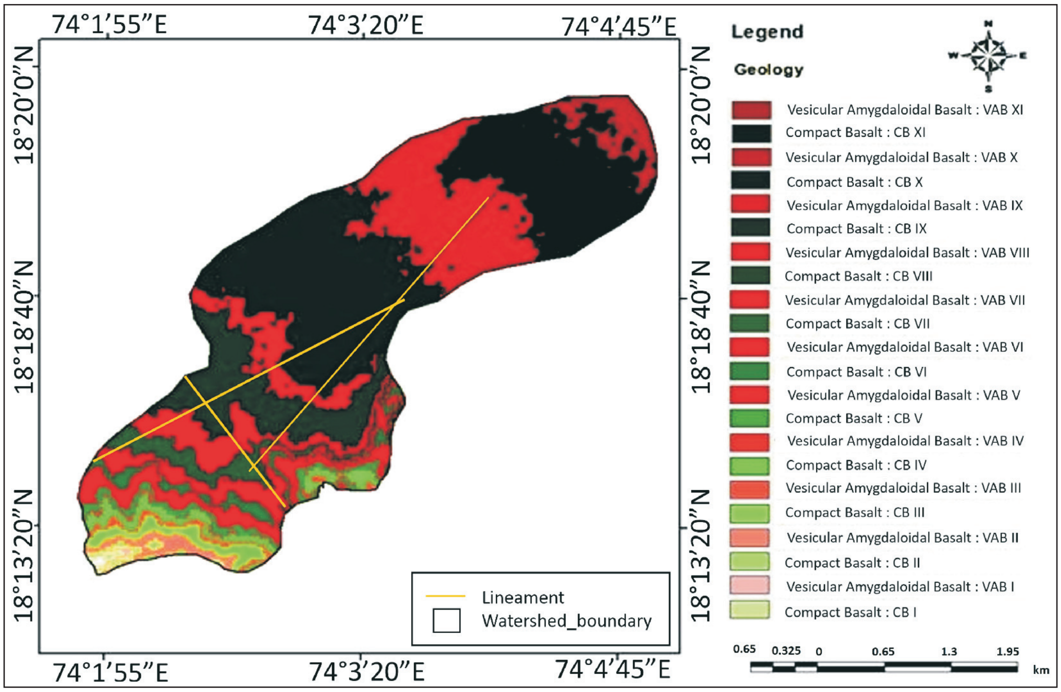

Fig.2. Geological map of Khalad Watershed

involves distinguishing units, including vesicular-amygdaloidal and compact basalts, both of which are overlaid by 2 to 5 meters of black cotton and sandy loamy soils. Figure 3 shows weathered Compact Basalt (CB) along the roadside, while Figure 4 presents the Vesicular Amygdaloidal Basalt unit in a stream. Additionally, Figure 5 offers an inferred geological map categorizing compound flows into Compact Basalt (CB) and Vesicular Amygdaloidal Basalt (VAB), with 22 distinct units identified (11 of each type).

The hydrogeology of the region is primarily characterized by Deccan Traps and intertrappean beds from the Upper Cretaceous to Lower Eocene (Subbarao, 1999; Widdowson *et al.*, 2000). The lava formations, ranging from 620 to 1080 meters AMSL, consist of 22 basalt units classified as Compact and Vesicular Basalt (Deshmukh and Sehgal, 1988). Well yields are influenced by aquifer permeability, transmissivity, location, diameter, and depth (CGWB, 2020). While basalt flows have negligible primary porosity, secondary porosity from fractures and weathered zones (5–12 meters thick in low-lying areas) enhances yields (Kulkarni, 2000; Gale, 2006). These fractured basalt layers, though discontinuous, serve as the main aquifers.

Fig.3. Weathered Compact Basalt

Groundwater structures include dug wells, bore wells, and dug-cum-bore wells. Shallow aquifers, tapped by dug wells at depths between 8 and 28 meters, exhibit water levels ranging from 2.0 to 17.5 meters below ground level (bgl), with yields typically ranging from 20 to 90 m^3/day, occasionally reaching 100–250 m^3/day in optimal locations. This groundwater primarily supports

Fig.4. Vesicular Amygdaloidal Basalt

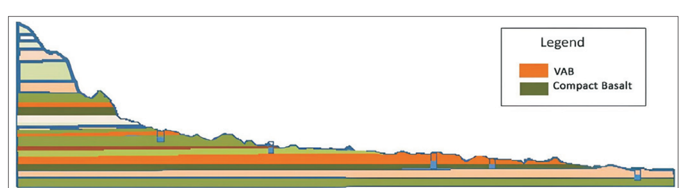

Fig.5. Cross-section of Khalad Watershed

irrigation for cash crops like sugarcane and pomegranates, with additional supply from government-drilled bore wells (500–3000 lph) for rural drinking water (Government of Maharashtra, 2018; GSDA, 2019).

Aquifer-I, at depths of 5.6–28 m, shows pre-monsoon water levels of 2.0–17.5 m bgl and post-monsoon levels of 0.2–12.0 m bgl, yielding 5–100 m^3/day (CGWB, 2021). Aquifer-II, from 20 to 174 m deep, has pre-monsoon levels between 2.3 and 60 m bgl and post-monsoon levels from 2 to 41 m bgl, mainly accessed by bore wells (Kulkarni and Deolankar, 1995; CGWB, 2021).

The basalt aquifer system is inherently complex, requiring a general overview due to the varied flow paths and limited data available for precise mapping. The unconfined aquifer comprises Compact Basalt and the Vesicular Amygdaloidal Basalt Unit, averaging around 10 meters in thickness. The Deccan lavas serve as a key example, where the distinct lithologies function together as a unified hydrogeological system. Hydraulic gradients are influenced by secondary recharge and discharge, with spatial variations in hydraulic properties leading to diverse conductivity ranges. Areas with high conductivity often correspond to geological features or thick interflow zones, while low values result from offset interflow zones or reduced porosity from secondary mineral deposits (Deolankar, 1980). Water movement through these basaltic formations is affected by topography, interbeds, and tectonic activity, resulting in variable lateral continuity and composition. Typically, only 5% to 10% of a basalt flow's thickness is the interflow zone, which significantly enhances water transmission. While lateral flow primarily occurs through fractures, it is less significant than the flow through interflow zones, which utilize features like flow vesicles (Krishnamurthy and Patil, 2005). Vertical movement of groundwater in interflow zones, though lower per area, can be substantial overall due to their unpredictable nature (Mishra *et al.*, 2023). Investigations reveal an upward trend in groundwater flow among aquifers, driven by recharge from precipitation in higher elevation areas. Deeper aquifers represent an underutilized source of non-monsoon water accessed mainly via bore wells, while dug wells have exposed the water table surface (Kulkarni *et al.*, 2015; CGWB, 2017).

Materials and Methods

Recharge of a borewell occurs only during rainfall. The recharge rates of borewells do not match the stormwater generated, leading to significant amounts of stormwater being wasted and flowing away.

The study thus employed a systematic methodology that began with site selection based on accessibility and measurement feasibility. After finalizing the site, water structures were identified, including borewells (BWs), dug wells (DWs), and nearby water bodies. One borewell was chosen for BoreCharger implementation, while observation borewells (OBWs) were selected for monitoring, along with dug wells and surface water bodies to assess potential impacts. A baseline data collection phase recorded initial water levels and spatial attributes, followed by a hydrogeological and lithological investigation that punctured the borewell casing at strategic depths for filtered water entry from the upper aquifer to deeper zones. During the BoreCharger implementation phase, water levels in the observation borewells, dug wells, and other wells were measured, with seasonal recharge changes monitored for efficiency. In the post-implementation phase, pre- and post-water levels were compared to evaluate improvements in recharge and overall water availability, alongside an assessment of cost-effectiveness and sustainability. The methodology concluded with the documentation of results and the formulation of recommendations for future recharge interventions.

BoreCharger Technique

This patented Innovative approach (patent No. 397449, granted on May 24, 2022) developed by the authors helps enhance both groundwater quantity and quality. This approach revitalizes failing or low-yielding borewells, contributing to sustainable water management. A Borewell scanning camera system is used for thorough hydrogeological investigations and lithological mapping. By integrating primary field observations with geological and groundwater data, we gain insight into groundwater aquifer systems. This enables the BoreCharger to make precise perforations in the borewell's impervious casing at optimal depths, allowing water from the upper aquifer to replenish deeper layers during and after the monsoon. This enhances groundwater quantity and provides a sustainable water supply, rapidly reviving failed or low-yielding borewells. The innovation lies in puncturing the casing in situ, avoiding the need for excavation and reducing costs and time associated with yield improvements. This deeper puncturing ensures that only naturally filtered water enters the borewell, encouraging the unconfined aquifer to supply water during dry seasons and allowing more time for recharging confined aquifers. The process increases borewell yield and prolongs water supply. Figure 6 illustrates the borewell's condition after the BoreCharger procedure.

Other Instruments Used for the Study

Water Level sounder, borehole camera system, measuring staff for water level measurements in borewells/dugwells, and pH, Conductivity and TDS meters, along with a field test kit for measurement of Hardness.

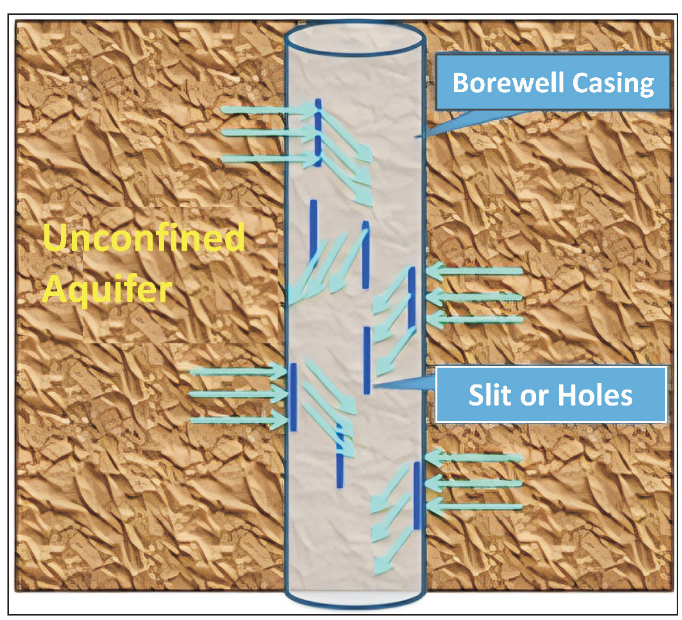

Fig.6. Borecharger activity

Results

Hydrogeochemical Observations

Hydrochemical analyses were conducted on water samples collected from six borewells, three dug wells, and two surface water bodies to evaluate the influence of BoreCharger-induced recharge on water quality. Pre-implementation pH values ranged from 7.8 to 8.25, total dissolved solids (TDS) varied between 363 and 1220 mg/l, electrical conductivity (EC) ranged from 542 to 1820 µS cm^{-1}, and total hardness was between 96 and 890 mg/l (Table 1). Post-implementation monitoring revealed pH values between 7.7 and 8.15, TDS values from 341 to 1243 mg/l, EC values between 509 and 1855 µS cm^{-1}, and total hardness ranging from 91 to 785 mg/l (Table 2). These marginal yet consistent improvements indicate the potential of induced recharge to stabilize or slightly improve groundwater quality parameters (Wagh *et al*., 2025; Shinde *et al*., 2022).

Water Level Analysis

A three-dimensional conceptual model of the Khalad watershed has been created to enhance understanding (Fig. 7). Based on the hydrogeological characteristics of the Khalad watershed, four monitoring clusters were delineated to assess groundwater dynamics and variations in water quality before and after the BoreCharger implementation. Each cluster comprised different combinations of borewells, dug wells, and surface reservoirs to facilitate a comparative evaluation of water levels and quality responses. Cluster 1 included Borewells BW1 and BW2 along with Reservoir 1; Cluster 2 comprised Borewell BW3, Dug Wells DW1 and DW2, and Borewell BW4; Cluster 3 consisted of Borewell BW5 and Dug Well DW3; and Cluster 4 incorporated Borewell BW6 and Reservoir 2.

Cluster 1 (BW1, BW2, and Reservoir 1)

Reservoir 1 remained largely stable from October to December 2023 despite above-normal rainfall, reflecting the efficiency of check dams in maintaining storage. BW1 (control borewell) and BW2 (BoreCharger-implemented) showed high water levels through most of the monitoring period. BW2 recorded a temporary decline on 28 November due to BoreCharger pumping but recovered rapidly. From mid-January to March, reservoir levels declined naturally due to evaporation and infiltration. BW1 exhibited the greatest drawdown, whereas BW2 experienced only minor reductions, underscoring the positive impact of BoreCharger in sustaining borewell levels (Fig. 8a; Adhikari *et al*., 2013; Raj *et al.*, 2024).

Cluster 2 (BW3, DW1, DW2, and BW4)

BW3, fitted with BoreCharger, is located near DW1 and DW2 (30 m) and BW4 (100 m). BW3 showed a temporary drawdown during BoreCharger pumping on 28 November but returned to pre-implementation levels shortly thereafter. DW1 and DW2 remained stable throughout, with no discernible influence from BW3. Seasonal drawdown became evident by late January, when BW3 dropped below BW4; both equalized by March. DW1 and DW2 consistently maintained higher levels than the borewells. Post-implementation, BW3 displayed hydraulic behavior more aligned with DW1 and DW2, suggesting enhanced connectivity with the unconfined aquifer (Fig. 8b; Saha *et al.*, 2022; Sufyan *et al.*, 2024).

Cluster 3 (BW5 and DW3)

Both BW5 (BoreCharger-implemented) and DW3 maintained high water levels between October and December. BW5 experienced a temporary decline on 27 November due to BoreCharger pumping, but it quickly recovered. After mid-December, DW3 began to decline gradually due to irrigation withdrawals, while BW5 showed only minor drawdown. This resilience suggests improved recharge conditions in BW5, while DW3 remained unaffected (Fig. 8c; Sharma *et al.*, 2025; Dijksma *et al.*, 2025).

Cluster 4 (BW6 and Reservoir 2)

Reservoir 2 remained stable from October to December, supported by above-normal rainfall. BW6, located 5 m away, recorded a temporary decline on 27 November due to pumping but rapidly recovered. Even under sustained irrigation withdrawals, BW6 maintained stable water levels, while reservoir levels remained unaffected, confirming BoreCharger's effectiveness without adverse impacts on surface water bodies (Fig. 8d; Khalique and Singh, 2025; APN-GCR, 2024).

Table 1: Water quality parameters before BoreCharger implementation

WELL-ID	BW1 (m)	BW2 (m)	BW3 (m)	BW4 (m)	BW5 (m)	BW6 (m)	DW1 (m)	DW2 (m)	DW3 (m)	Reservoir 1 (m)	Reservoir 2 (m)
pH	8.12	7.93	7.85	8.25	7.8	7.9	8.1	8.1	8.2	7.9	7.8
TDS	610	714	363	1220	754	1174	950	660	625	1120	1085
EC	910	1065	542	1820	1125	1752	1418	1015	977	1671	1619
Total Hardness	490	405	266	890	477	96	86.4	160	132	238	189

Table 2: Water quality parameters after BoreCharger implementation

WELL-ID	BW1 (m)	BW2 (m)	BW3 (m)	BW4 (m)	BW5 (m)	BW6 (m)	DW1 (m)	DW2 (m)	DW3 (m)	Reservoir 1 (m)	Reservoir 2 (m)
pH	8.1	7.96	7.75	8.15	7.7	7.78	8.2	8.15	8.15	8.1	8.02
TDS	620	655	341	1235	628	1071	965	684	639	1243	1136
EC	925	971	509	1843	937	1599	1440	1021	953	1855	1695
Total Hardness	478	197	142	785	312	91	94.5	178	127	264	204

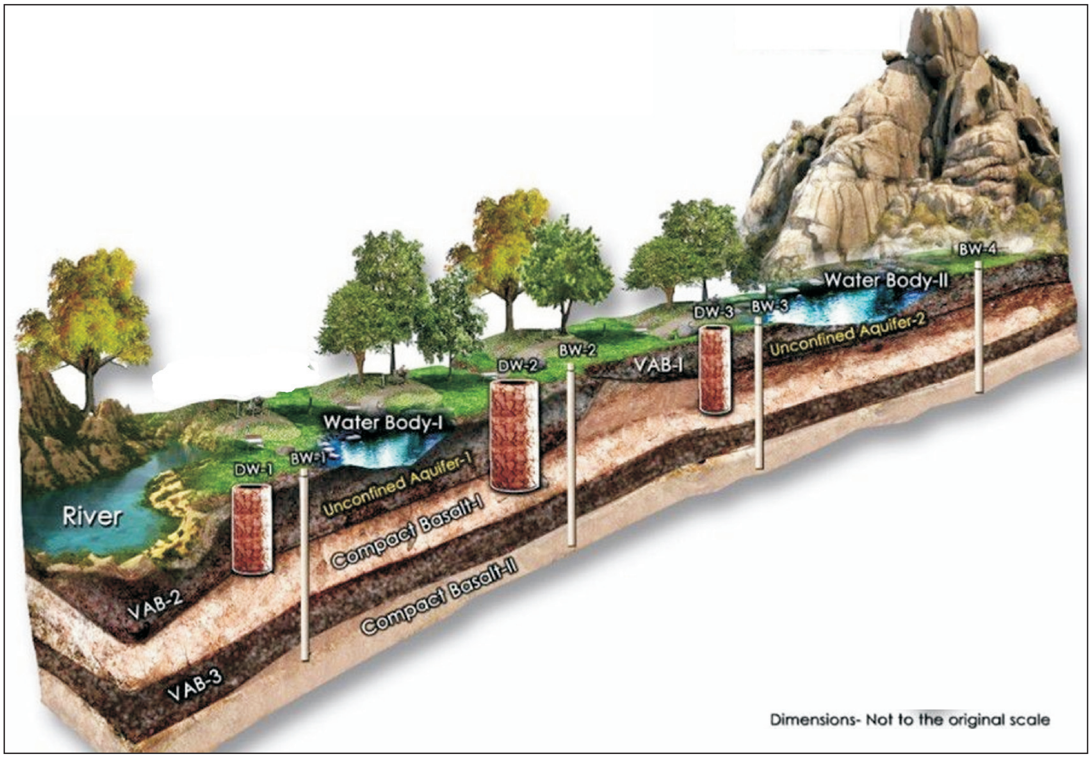

Fig.7. Conceptual model of Khalad Watershed

Discussion

The combined hydrogeochemical and water-level monitoring results demonstrate that BoreCharger technology effectively enhances borewell recharge in Deccan basalt terrains without negatively influencing nearby dug wells or reservoirs. The stabilization of TDS and hardness values post-implementation suggests that induced recharge promotes aquifer flushing and dilution, thereby contributing to gradual water quality improvement, consistent with recent hydrogeochemical studies in basaltic aquifers (Wagh *et al.*, 2025).

Across clusters, borewells equipped with BoreCharger consistently exhibited faster recovery after pumping and smaller seasonal declines compared to control wells. For instance, BW2 and

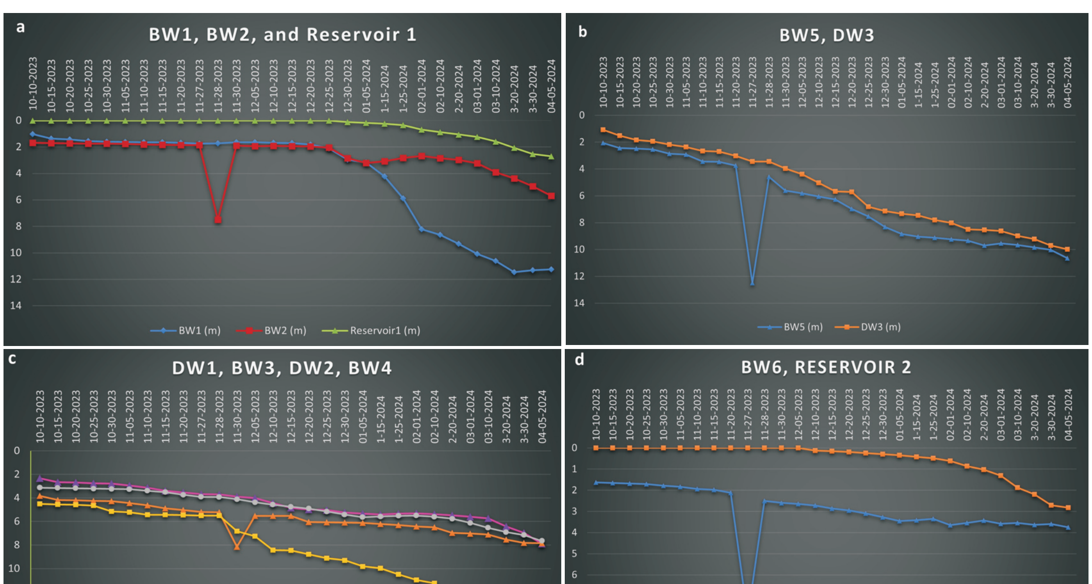

Fig.8. a. Water Level Observations at Cluster 1; **b.** Water Level Observations at Cluster 2; **c.** Water Level Observations at Cluster 3; **d.** Water Level Observations at Cluster 4

BW3 displayed sustained levels despite being subjected to pumping stress, reflecting their hydraulic connection to unconfined aquifers facilitated by the intervention. These observations align with recent findings that artificial recharge structures and subsurface interventions improve aquifer sustainability in hard-rock regions (Shinde *et al.*, 2022; Raj *et al.*, 2024). Equally important, dug wells (DW1, DW2, DW3) and reservoirs (Reservoirs 1 and 2) exhibited negligible variations during and after BoreCharger operation, confirming that the intervention does not compromise surrounding shallow water resources. This outcome corroborates earlier case studies showing that recharge interventions in basaltic terrains can augment localized groundwater availability without reducing community access to traditional water sources (Adhikari *et al*., 2013; Saha *et al.*, 2022).

Overall, the findings emphasize BoreCharger's role as a low-cost, scalable groundwater management solution in basaltic terrains. By enhancing recharge efficiency, stabilizing water quality, and ensuring minimal impacts on nearby sources, the technology demonstrates strong potential for improving irrigation sustainability and rural water security in semi-arid India (Raj *et al*., 2024; Sufyan *et al*., 2024; Khalique and Singh, 2025).

Conclusions

This study presents compelling evidence regarding the implementation of BoreCharger technology in enhancing groundwater management within basaltic terrains, particularly its impact on surrounding shallow water sources, which are crucial for agricultural irrigation. The data indicate that borewells equipped with BoreCharger systems not only mitigate the risk of exacerbating local water scarcity but also enhance overall groundwater availability. Notably, the BoreCharged borewells maintain stable water levels under significant pumping stress, particularly evident through to the end of March, during peak agricultural demand periods. Sustained water availability is vital in semi-arid regions, where irrigation needs intensify concurrently with declining groundwater supplies. Notably, the results show that BoreCharger technology does not negatively impact the water levels of adjacent borewells, dugwells, or reservoirs, thereby promoting equitable resource distribution among stakeholders. By averting excessive drawdown and stabilizing groundwater levels, BoreCharger emerges as a pragmatic solution for fostering irrigation sustainability while concurrently safeguarding community water security. Preliminary observations also suggest potential improvements in water quality metrics associated with this technology, likely due to enhanced recharge dynamics and increased intermixing between aquifer zones. While these findings were derived from a limited observation period, they suggest that the long-term application of BoreCharger could yield substantial benefits in terms of groundwater quality. Collectively, this case study underscores the broader implications of BoreCharger technology as a sustainable approach to groundwater management in hard-rock aquifer settings. By prolonging water availability during critical agricultural phases, minimizing the negative impacts on proximate water sources, and potentially enhancing groundwater quality, BoreCharger represents a viable pathway towards climate-resilient agricultural water management. Ongoing long-term monitoring and broader application are crucial for validating these findings and optimizing the integration of BoreCharger technology to enhance groundwater sustainability in regions experiencing water stress.

Authors' Contributions

VP: Conceptualization, Investigation, Design, Material Preparation, Data Generation and Analysis, Writing-original Draft. RB: Conceptualization, Investigation, Design, Material Preparation, Writing-original Draft. AS: Conceptualization, Investigation, Design, Data Generation and Analysis, Supervision, Writing-original Draft, Reviewing and Editing.

Conflict of Interests

The authors declare that they have no conflict of interests.

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Declaration of Generative AI and AI-assisted Technologies

During the preparation of this work, Vinit Phadnis, Rahul Bakare, and Ashwini Supekar used (Grammarly) in order to enhance the language. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

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