Revamping India's groundwater monitoring network

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Groundwater level is the most important parameter in any study involving the evaluation, development and management of groundwater resources. Systematic monitoring of groundwater levels, which commenced with the establishment of the Central Ground Water Board (CGWB), has been of immense use in addressing several challenges like prioritization of areas for groundwater recharge, delineating areas prone to waterlogging, estimation of storage change in the aquifers, estimation of groundwater flow, etc. In a major boost to strengthen groundwater monitoring in the country, the Government of India has sanctioned a special project under which CGWB has envisaged to construct 9000 purpose-built wells (piezometers) in identified priority areas, which will be equipped with digital water-level recorders (DWLRs) and telemetry devices for acquisition and transmission of groundwater levels at increased frequency. The intended uses of the long-term high-frequency data include monitoring short-term and long-term changes in the groundwater levels, groundwater storage and recharge to the aquifers, monitoring the effects of climatic variability, estimating transboundary flow, assessing regional effects of groundwater development, quantifying impacts of water conservation and artificial recharge projects, and improved understanding of groundwater and surface water interactions. High-frequency groundwater level data also have the potential for steering multi-institutional collaborative research projects in the country, particularly for studying the impact of groundwater extraction on land subsidence, the relationship between groundwater levels and tectonic disturbances, and climate change impacts on the groundwater regime.

Keywords: Aquifers, climate change, groundwater level, high-frequency data, monitoring networks.

GROUNDWATER level is the most important parameter that describes the health of an aquifer. Long-term data acquired through regular monitoring of groundwater levels provide an opportunity to understand the behaviour of the aquifers to changing stress regimes[1]. Systematic monitoring of groundwater levels in the country began in 1972 with the establishment of the Central Ground Water Board (CGWB) by the Government of India (GoI)[2]. Representative monitoring stations, based on factors such as geology, hydrogeology, geomorphic features, land-use patterns and administrative divisions, were strategically placed across the country to acquire consistent baseline data on groundwater levels and quality[3]. At present, CGWB carries out national-level groundwater monitoring through nearly 23,000 wells spread across different parts of India[3].

The decline in groundwater levels due to an increase in groundwater extraction, along with a gradual shift in groundwater abstraction structures from open wells to borewells/tubewells over the years, has resulted in the drying up of open wells in various parts of the country. These have led to discontinuity in the availability of long-term water-level data. Further, the current practice of manual groundwater monitoring carried out four times a year[3] is also limited in its ability to capture short-term fluctuations in groundwater levels, assess the effects of delayed monsoon or climate change[4], evaluate the influence of tides[5] and natural disasters, analyse anthropogenic impacts on the groundwater regime[6], and conduct a comprehensive assessment of the impacts of artificial recharge structures on the groundwater system[7].

To address the above concerns, CGWB has taken up a major project to strengthen the water-level monitoring infrastructure in India. The project aims to strengthen the existing monitoring infrastructure through the establishment of 9000 piezometers (purpose-built wells for water-level monitoring) throughout the country, which will be equipped with digital water-level recorders (DWLRs) and telemetry devices for the acquisition of long-term, high-frequency water-level data[2].

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Existing groundwater level monitoring systems in India

Groundwater levels in India are currently monitored by CGWB and the State Government Departments. Nearly 65,000 wells are being monitored throughout the country, of which about 23,000 are being monitored by CGWB[3] and nearly 42,000 by the various State Government Departments. Data acquisition from the majority of the wells is presently being carried out through manual monitoring mode.

Among the nearly 23,000 monitoring wells of CGWB, dugwells (open wells) constitute about 16,000 (70%); purpose-built wells (piezometers) constitute nearly 6300 (23%)[3], and the remaining are handpumps and springs. During the initial phase of monitoring, dug wells were the most commonly used groundwater abstraction structures. Therefore, they were the natural choice for monitoring the behaviour of the phreatic aquifers and studying the ambient groundwater quality. However, in recent years, piezometers have been used by CGWB for monitoring the groundwater levels/piezometric levels.

The collected water-level data from these stations are utilized for preparing various maps, such as the seasonal distribution of depth to water levels, water-table contour maps (referenced to mean sea level), seasonal fluctuations in water levels/piezometric levels, etc. The depth-to-water-level maps, depicting the relative position of groundwater level with respect to the ground surface, have been instrumental in addressing waterlogging, prioritizing areas for artificial recharge, and in preparing strategy for energization of the wells based on water levels and well yields. The water-level fluctuation maps (showing rise and fall in groundwater levels) are of utmost significance in studying the storage changes in the aquifers, while water-table contour maps are useful in estimating the groundwater flow through an area and studying the interconnections of the aquifers. Using data from the monitoring wells, CGWB regularly publishes groundwater Year Books for India as well as for different states, and shares the findings with the state agencies.

However, continuous groundwater level data are limited due to the abandonment of monitoring wells, often caused by declining water levels. Current challenges in groundwater management, influenced by global climate change and anthropogenic activities, emphasize the crucial need for monitoring long-term water-level trends nationwide[4].

Strategy for improving monitoring networks

The location of the proposed piezometers has been strategically planned to cover the areas falling under over-exploited, critical, semi-critical (OCS) assessment units of the country (categorized on the basis of dynamic groundwater resource assessment by CGWB and the states), large urban agglomerations, industrial clusters, coastal areas, canal command areas, along international boundaries, seismic zones, etc. A normative requirement of one piezometer in every 50 km^2 area has been considered suitable for monitoring water levels; however, the density of the proposed networks has been kept flexible in certain areas requiring higher density of monitoring, like in urban areas and those requiring a low density like deserts/high slopes in hilly areas. Apart from the OCS areas, the locations have been prioritized on the basis of other criteria like areas with scarce groundwater information/data, those falling in the command areas of irrigation projects, areas near international boundaries, seismic areas, mining areas, industrial clusters, urban areas, etc. In coastal areas where continuous monitoring of vital groundwater quality parameters like EC and temperature are required to keep a check on the inland sea-water ingress in the aquifers, DWLRs with water-quality probes have been proposed to be installed in the piezometers.

The depth of the piezometers has been planned so that maximum emphasis is given to the depth zones witnessing intensive groundwater extraction. A few deep piezometers (depth of more than 200 m) have also been planned to generate long-term records of deeper aquifers. Among the 9000 piezometers, depth-wise distribution is as follows: 6450 piezometers up to 100 m depth, 2550 between 100 and 200 m depth, and 50 beyond 200 m depth. Apart from the addition by CGWB, intensification of the monitoring networks is also being taken up under the National Hydrology Project (NHP), Atal Bhujal Yojana (ABHY), GoI, and by the State Government agencies under state-specific schemes. Figure 1 shows the distribution of all the monitoring stations for groundwater levels in India under various schemes.

Considering the 25 lakh km^2 area is worthy of groundwater recharge in the country[8], the present density of groundwater level monitoring stations of CGWB is one monitoring well for every 108 km^2 area. After installing an additional 9000 piezometers, the overall monitoring density of CGWB will improve to nearly one well for every 85 km^2.

Presently, CGWB has an automated monitoring facility at 60 locations in the coastal aquifers of Tamil Nadu. The installation of DWLRs in 5200 existing piezometers is in process under NHP. With an additional 9000 DWLR-equipped piezometers, the total automated monitoring stations of CGWB will increase to 14,260. Similarly, State Governments have proposed the installation of ~17,000 DWLRs under NHP/ABHY/other schemes, bringing the total to ~31,000 automated monitoring systems in India.

Why frequency and continuity of monitoring are important

The non-availability of long-term continuous records of groundwater levels significantly affects the evaluation, development and management of groundwater resources.

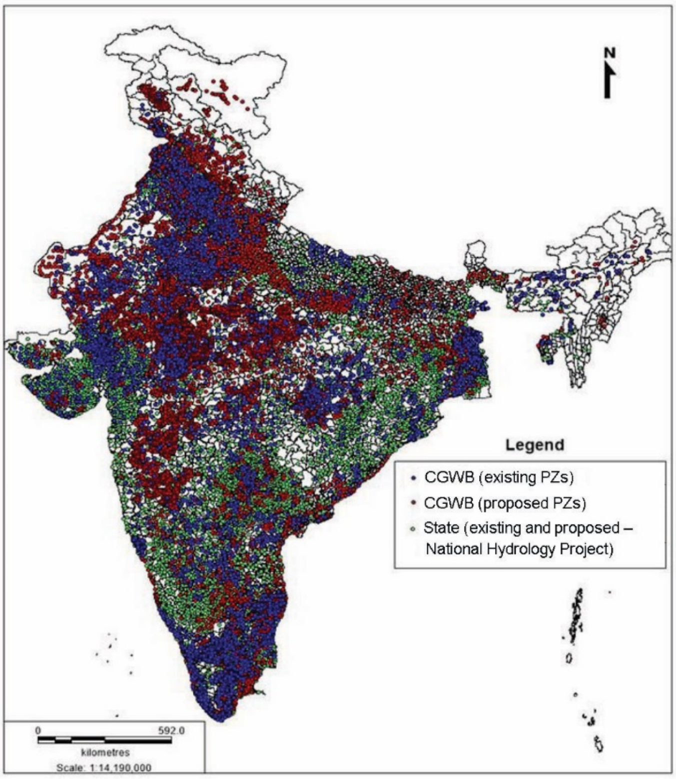

Figure 1. Distribution of the existing and proposed piezometers (PZs) for groundwater monitoring in India (CGWB and State Governments under various schemes).

Frequency and continuity of monitoring are decided on the basis of the intended purpose for which monitoring networks are designed. Inadequate monitoring frequency often leads to underestimation of the rise and fall in groundwater levels, which directly affects the estimation of recharge and discharge. The prevailing system of monitoring is mainly aimed at assessing the changes in groundwater storage. Such changes depend upon factors like rainfall, pumping, irrigation, evaporation, urbanization, etc. As India has a monsoonal climate regime with a well-defined rainy season, the frequency of monitoring selected as four times in a year for most parts of the country, i.e. May (pre-monsoon), August (mid-monsoon), November (post-monsoon) and January (*rabi* season) may be considered as adequate to study the generalized behaviour of groundwater levels in large basins. Also, rainy days during the monsoon period were well spread in the past.

However, in recent years, several studies have documented the changes in rainfall regime with an interlude of long, dry spells during the monsoon months[9]. The onset and withdrawal of the monsoon is also not synchronous in different parts of India. Further, large areas of the country are now being brought under irrigation, thereby necessitating monitoring of groundwater levels to be aligned with the periods during which water is made available for irrigation to distinguish the impacts of rainfall and irrigation on groundwater levels.

We present a typical well hydrograph of a piezometer from Nagla Hukumpur, G. B. Nagar district, Uttar Pradesh, India (source: Uttar Pradesh Ground Water Department) to emphasize the advantages of increasing the monitoring frequency. Figure 2 shows four hydrographs for the same station prepared for quarterly, monthly, weekly and daily frequencies.

A typical well hydrograph consists of a rising limb corresponding to a period of build-up in groundwater storage (recharge) and a recession limb marking storage loss from the aquifers[10]. The hydrograph in Figure 2 exhibits a gradual ascent during May–June, a sharp recession in July, and a dual rising phase up to August in daily frequency. This is mirrored as a single ascending limb in the quarterly hydrograph. Likewise, the recession limb manifests three distinct segments: a gradual decline from August to December, a stabilization phase from December to March, and a subsequent decline from March to May, as evident in the daily frequency. However, the quarterly and monthly frequencies only reveal two segments in the recession limb. It can be seen that with the change in frequency from daily to three-monthly, there is a compromise in the peaks and troughs of the hydrographs. The actual peaks and troughs are not captured in the quarterly hydrograph, while the daily hydrograph captures them. Further, it can be seen that the quarterly hydrograph averages the recharge over a three-month period; however, the monthly hydrograph is

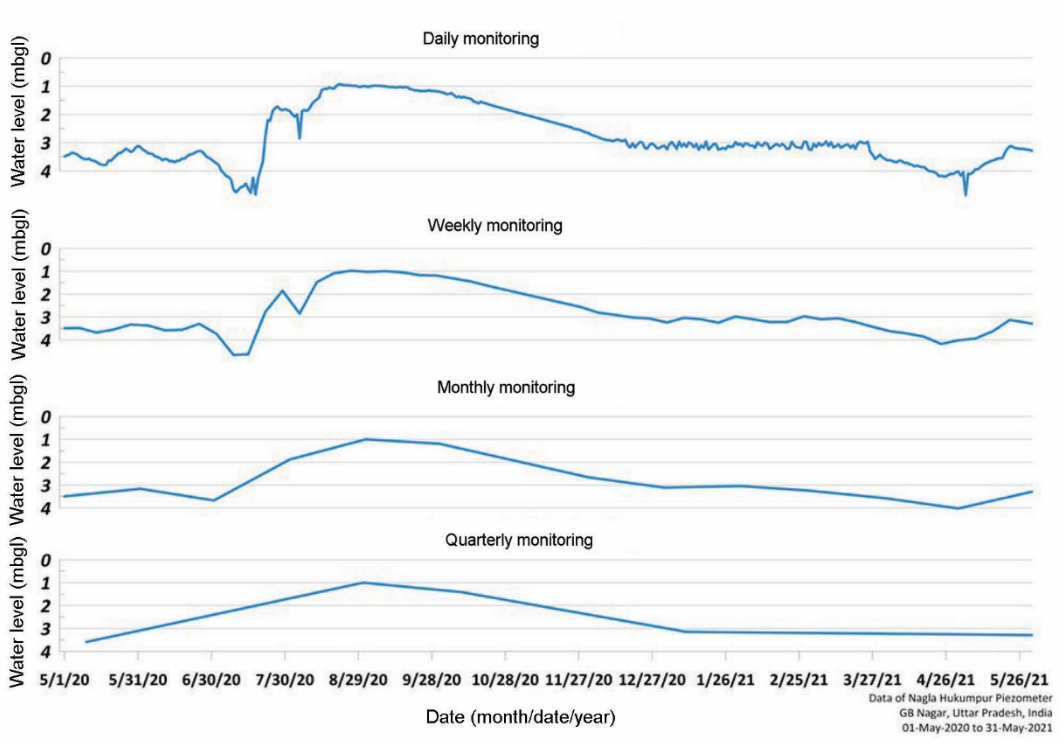

Figure 2. Well hydrograph with different frequencies of data capturing.

able to capture the impacts of the dry spell during the monsoon months.

The hydrographs with daily and weekly frequencies can also be used to determine the recession coefficient of the limb, which is governed by the hydrogeological characteristics of the basin and the rainfall infiltration factor[11]. Further, daily hydrographs in relation to the stream discharge can also be used to estimate the contribution of groundwater to the run-off or base flow at representative sites[11].

A few control stations with monitoring at hourly or even better frequency may also be set up in each basin to study the barometric efficiency, build-up of bank storage during high river stage along the major rivers, effects of tides on salinity in the coastal areas, and to study the pattern and duration of groundwater pumping in intensely irrigated areas or urban/industrial areas with high groundwater dependence.

Multiple piezometers with DWLRs at a few control stations, which are also envisaged, will further provide the time window during which leakage takes place from phreatic to semi-confined aquifers or vice versa, thereby improving our understanding of the inter-aquifer interactions.

Intended benefits

Systematic monitoring records of groundwater levels generated over a long term are fundamental to resolving several complex issues to ensure sustainable management of groundwater resources[12]. Important issues related to groundwater that are expected to be addressed through the generation of high-frequency systematic records of water levels over a long period are enumerated in the following:

(i) The piezometers with DWLRs and telemetry will play a pivotal role in providing continuous data from groundwater extraction hotspots, such as the urban agglomerations and industrial areas, and would help ascertain the regional impacts of concentrated groundwater extraction in such areas.
(ii) Data collection along international borders would help quantify the transboundary flow through the aquifers.
(iii) In coastal areas, it will provide opportunities for estimating submarine groundwater discharge, besides formulating strategies for the prevention of saline water ingress and the maintenance of a safe head for the sustainability of fresh groundwater resources in coastal areas witnessing high groundwater extraction.
(iv) High-frequency data from multi-layered aquifers will help in studying the inter-aquifer interactions. Further, the delineation of areas with piezometric heads at shallow levels would facilitate strategic planning and efficient utilization of such aquifers in an energy-efficient manner.
(v) The impact of groundwater withdrawal on surface-water resources is becoming a growing concern in groundwater studies. Numerous researchers have expressed apprehensions regarding the diminishing water availability in major rivers of India, linking it to the

depletion of groundwater storage in the aquifers. This depletion subsequently leads to a reduction in baseflow from the aquifers into the major rivers of the country. Intensified monitoring will provide opportunities for in-depth studies based on high-frequency water level data, especially in the proximity to stream-gauging stations.

(vi) High-density water-level data would also form a critical input to water budgeting and planning for groundwater interventions in groundwater-stressed areas besides providing inputs in planning under the Jal Jeevan Mission, Pradhan Mantri Krishi Sinchayee Yojana-Har Khet Ko Pani-Ground Water (PMKSY-HKKP-GW), Atal Bhujal Yojana (ABHY), and other programmes of GoI and the State Governments. The continuous data series generated by these piezometers will furnish a clearer understanding of recharge mechanisms and the efficiency of artificial recharge structures implemented under various Government schemes.

(vii) Automation of the monitoring network would also address the challenges of groundwater monitoring in areas that are often inaccessible due to weather conditions or other local reasons during monitoring.

Potential for fostering collaborative research

The wealth of the high-density and high-frequency data flowing from the automated monitoring stations would steer an environment for collaborative research both at the level of the institutions and individual researchers. Three important areas with significant potential for collaborative research at the institutional level are discussed below.

Mapping, modelling and impact assessment of land subsidence

Alluvial basins are vulnerable to land subsidence due to excess withdrawal of groundwater. In the past, several authors have reported land subsidence due to over-extraction of groundwater from different parts of the world, e.g. in the United States[13], Mexico City[14], Bangkok[15], Shanghai[16], San Joaquin Valley[17], National Capital Territory of India[18], Kolkata[19], etc. Even though land subsidence may occur in several alluvial areas, the ability to detect small changes in subsidence and its corroboration through continuous records of water levels might have constrained research in this field. In recent years, there has been increasing use of satellite-based geodetic signatures for delineating areas witnessing land deformation, which are further studied using precision levelling surveys and groundwater levels to ascertain the causal mechanism of land subsidence. The advancement in surveying, along with the availability of high-frequency groundwater levels, will further propel research in the field of land subsidence in India.

Studying the relationship between tectonic disturbances and groundwater levels

Seismic waves released during earthquake events can cause dilatation/compression of the subsurface materials through which they pass. These waves can travel large distances and may cause abnormal fluctuations in water levels. The response of a well to seismic waves depends on several factors, including the hydraulic characteristics of the formation, nature, duration and amplitude of the wave, etc. This aspect has been studied for a long time by various researchers in several instances[20]. Groundwater level is an important parameter often studied by researchers in tectonically active areas for its use as a precursor to an earthquake[21]. Thus, high-frequency groundwater-level data have the potential for steering collaborative research among the institutions dealing with groundwater, geology and disaster management in India and may help establish the branch of seismic hydrogeology.

Studying the impacts of climate change on groundwater regime

Climate change is projected to significantly impact water resources**.** The projected climate change impacts, though fraught with uncertainties of various magnitudes, echo concerns on both the quantitative and qualitative aspects of water. Understanding climate variability and change is vital for society and ecosystems, particularly with regard to complex changes affecting the availability and sustainability of surface-water and groundwater resources. The well-recognized potential effects of climate variability and change on water resources have been identified as a major issue in the availability of groundwater resources[4]. The dynamic or renewable groundwater resources which are directly connected to near-surface hydrological processes could be directly affected by climate change. In areas with significant dependence on groundwater resources, the effects of climate change could threaten the sustainability of these resources[22]. Although recent research has begun to focus more on understanding the effects of climate variability and change on groundwater quantity and quality, these remain poorly understood. Understanding the potential effects of climate variability and change on groundwater is more complex than with surface water. Groundwater residence time can range from days to tens of thousands of years or more, which delays and disperses the effects of climate and challenges efforts to detect responses in the groundwater to climate variability and change. Furthermore, human activities such as groundwater pumping and the resulting loss of storage and capture of natural discharge are often on the same timescale as some climate variables and change, which makes it difficult to distinguish between human and climatic stresses on groundwater. High-frequency monitoring of groundwater levels and the availability of continuous monitoring records would provide avenues to better understand and distinguish the impact of human activities on the groundwater regime from climate change.

Conclusion

The non-availability of long-term continuous records of groundwater levels greatly affects the evaluation, development and management of groundwater resources. The current practice of manual groundwater monitoring conducted four times a year is limited in its ability to capture short-term fluctuations in groundwater levels, assess the effects of delayed monsoons or climate change, evaluate the influence of tides and natural disasters, analyse anthropogenic impacts on the groundwater regime, and conduct a comprehensive assessment of the impacts of artificial recharge structures on the groundwater system.

The increased density of groundwater monitoring networks with a greater percentage of wells equipped with DWLRs and telemetry would enable groundwater professionals, researchers and academicians to precisely account for the short-term and long-term changes in groundwater levels, groundwater storage and recharge to the aquifers, monitoring the effects of climatic variability, estimating trans-boundary flow, assessing regional effects of groundwater development, artificial recharge interventions and surface–groundwater interactions. It would also meet the requirements for assessing the impact of groundwater extraction on land subsidence and in studying the relationship between tectonic disturbances and fluctuation in groundwater levels.

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