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Research Article

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Shortfalls and Challenges in Groundwater Regime Monitoring

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Abstract
Groundwater is exploited un-relentlessly worldwide, leading to severe resource shortages, reflected through a sharp decline in water levels and deterioration of water quality. Groundwater, a dynamic and renewable resource, needs continuous monitoring for its effective utilization and to meet the ever-increasing demand for water. Many non-government and government agencies have measured groundwater levels and their chemical quality over the past five decades. However, a cursory scan of the data, reports, and publications reveals that many countries still follow primitive practices of groundwater monitoring. Scant research publications and little R&D efforts are noticed in this domain. Lack of modernization in monitoring mechanism led to a paucity of real-time and accurate data. There is an urgent need to draw the attention of monitoring agencies toward updating monitoring strategies using the latest technology. System analysis is required for process standardization and the design of protocols to revitalize groundwater regime surveillance. Efforts are made to identify the areas of weakness which need immediate attention and explore the possibilities of engaging new techniques by adopting an out-of-box approach in collecting, analyzing, and disseminating the information on quantitative and qualitative indicators of groundwater to the end users in actionable form.

Keywords: Monitoring; Water level; Water quality; Assessment; Rainfall; Change in Storage; Extraction.

1. Introduction

Looking at the water in a well is as primitive as using groundwater. By a casual observation of water level disposition, a farmer or user estimates the availability of water to meet his needs. He makes arrangements for lifting devices and plans future crops based on the water level condition. Groundwater monitoring has been practiced for ages using simple and viable techniques to manage the resource effectively. As the water demand is increased to meet the rising population requirements, the need for regular and systematic monitoring of essential water parameters is also growing. International organizations and various countries felt the necessity for continuous monitoring of water levels and quality to guide the public on the utilization of groundwater. Though it was initiated in early 1970 at the government level, the process of monitoring groundwater took a giant leap in mid-1990 with the intervention of the World Bank and UNDP and push by the water users to focus on resource conservation. It has become all the more imperative as groundwater utilization has taken a quantum jump due to the onset of the green revolution and power subsidy, forcing the statutory agencies to pay attention to demand-side management shifting from supply-side management. As the measurement is the key to management, many countries initiated the modernization of monitoring mechanisms. The economic liberalization and revolution in the IT and communication sector gave imputes to data acquisition, analysis, and dissemination for the betterment of humanity.

However, developments in Ground Water Monitoring (GWM) developments are not in tune with its demand or utilization, which has created rapid spatiotemporal variations in water levels. The impact is significant in developing countries that lag in using efficient monitoring models compared to developed countries. International Groundwater Resources Assessment Centre (IGRAC 2020), in its report 'A global overview of quantitative groundwater monitoring networks,' stated - Groundwater is monitored worldwide by measuring groundwater levels, groundwater abstraction rates, spring discharge, and groundwater quality. Globally, there is no sufficient knowledge about the state and trends of groundwater resources, primarily due to: insufficient monitoring and limited accessibility to monitoring data/outcomes. Chandan and Yashwant opinioned that - In many developing countries, optimized groundwater level monitoring networks are rarely designed to build a robust groundwater level database and to reduce operation time and cost [1]. Many Asia-African countries, including the Indian sub-continent, regard the water levels and water chemistry data as simple information, confined to their database or put up in the form of reports for bureaucratic fulfillment. The parametric data is rarely converted into actionable information. Many shortcomings at different levels of monitoring mechanisms can be noticed by observing the database and reports or visiting the data dissemination platforms (websites). For years, many organizations have regarded groundwater monitoring as routine work and accorded minor importance. This lackluster approach of departments, domain experts, and the scientific community failed to convince the governments to invest in the GWM program. Though much hue and cry are made on depleting water levels and deteriorating water quality, seldom are remedial measures initiated due to a lack of specific action plans in GWM reports except propagating the need to boost the recharge by adopting various artificial recharge options.

The water levels reflect quantitative changes that occur in an aquifer. If recorded periodically and information is analyzed in conjunction with other hydrological parameters, timely action can be initiated to manage the groundwater resource effectively. However, short-term rise and fall in water levels due to variations in rainfall or other input components pose a problem in convincing the bureaucrats for strategic actions on groundwater monitoring. Presenting the water level measurements as mere numerical data by the monitoring organizations and limiting its use mainly for administrative or academic purposes is one of the reasons for losing the sanctity of GWM. Paradoxically the water level data is used in estimating the groundwater resource of an area and also to evaluate the stage of groundwater development. In addition, it is used in assessing drought conditions and releasing financial aid by respective governments.

Nevertheless, the information must be systematically collected, analyzed, and shared. Observing data focusing on anomalies and above-threshold values helps identify the black spots. Then, preemptive action can be suggested to minimize the damage to the hydrosphere and hardship to people. It will also provide opportunities for detailed studies and open a gateway to new research. Huayao et al. noted that ‘To date, groundwater overexploitation has mainly been evaluated using the groundwater quantity balance and the effect of groundwater exploitation on the environment However, determining groundwater exploitation for an agricultural irrigation area is challenging due to the need for detailed environmental monitoring data' [2]. Monitoring groundwater input and output components are required to frame guidelines and regulate water extraction sectors (domestic, irrigation, and industry). These measures will enable executives to initiate action to control overexploitation and rapid fall in water levels.

Surface water is visible and can be easily measured by installing graduated poles or flow meters. In contrast, groundwater, hidden in the echelons of the Earth, needs to be monitored cautiously. Sinha, in his report 'State of Groundwater in Uttar Pradesh says- 'Since it is not visible, the biggest challenge is making it visible [3]. Therefore, a scientific approach is needed for its comprehensive understanding. Water level measurements obtain information on groundwater in the wells and indirect methods like surface geophysics, remote sensing, geological and geomorphological mapping, drilling/ exploration, parameter tests, yield tests, Etc.' (https://cdn.cseindia.org/). Monitoring groundwater is more challenging than monitoring surface water (rivers and lakes; IGRAC, 2020). Rapidly depleting shallow aquifers, exploited through open wells, led to the development of bore wells, leaving measuring water levels a problematic task. Multi-layered aquifer system requires exclusive wells or Multi-Depth Groundwater Monitoring Systems to monitor the fluctuations in different aquifers (https://en.wikipedia.org/). Pragnaditya et al. also suggest ‘groundwater abstraction to be the dominant influencing factor in most of the basin, particularly at the greater depth of the aquifer, thus highlighting the importance of understanding multi-depth groundwater dynamics for future groundwater management and policy interventions' [4]. The GWM has become complex and requires trained personnel and special equipment. Monitoring generates huge bits of numerical information that need to be managed and analyzed by engaging domain experts. Sharing the data with end users in comprehensible mode is another area that demands at most attention. The ever-increasing groundwater requirement may lead to a water crisis. GWM activity has to be broadened, strengthened, and modernized to provide user-friendly holistic information for timely intervention. It has become necessary due to the steady decline in water levels and geogenic contamination in deeper aquifers. Condon et al. stressed that additional work would be needed to achieve a consistent global groundwater framework that interacts seamlessly with observational datasets and other earth system and global circulation models [5].

Scientists using data from NASA's Gravity Recovery and Climate Experiment (GRACE) have found that the groundwater beneath Northern India has been receding by as much as one foot per year over the past decade [6]. As per Central Ground Water Board (CGWB), Punjab's groundwater in the first 100 meters will get exhausted by 2029 and drop below 300 meters by 2039 [7]. Almost two-thirds - 63 percent - of India's districts are threatened by falling groundwater levels [8]. Climate change ushering with unseasonal rains, cloud bursts, continuous droughts, and uneven peak atmospheric temperatures impact the groundwater severelly, necessitating the intensifying the monitoring activity for better crisis management [9]. Brutsaert observed, ' As of yet, despite its importance, very few reliable records of underground water storage are long or comprehensive enough to allow meaningful diagnoses for water resource planning or climate change purposes' [10]. Kumar, also agrees that ‘the relationship between the changing climate variables and groundwater is more complicated and poorly understood' [11]. Lisbeth and Jens, in their research article "Groundwater monitoring in Denmark: Characteristics, perspectives, and comparison with other countries," discussed strategic considerations for monitoring design, the link between research and monitoring, and adopting responses to climate change [12].

Despite five decades of monitoring, excluding a few developed countries, the program is yet to be reviewed for its efficiency and effectiveness in many countries. Except for expanding the monitoring area, developing stand-alone observation wells, automation of measurements in some regions, and revising the monitoring cycle on a pace-meal level, concrete steps still needed to be taken to evaluate the monitoring mechanism in terms of scientific, technical, and financial validity. Mike stressed the need for upgrading groundwater monitoring networks in low-income countries [13]. Groundwater monitoring in Denmark has been continuously adjusted to incorporate new knowledge from research programs and meet new policy demands, currently the European Union Water Framework Directive, particularly concerning an increased focus on quantitative aspects and the groundwater/ surface water interaction [12].

India is one of the significant consumers of groundwater and extensively monitors the resource involving multiple agencies, but it is lagging in data analysis and dissemination. Integration and validation of the measurements have to be improved. Different departments and NGOs must practice a standard data collection, analysis, and presentation pattern. The mere presentation of statistics of the measurements with GIS-based maps on not-easily accessible websites discourages the citizens from using the information. The data is compiled and reported more for fulfilling the official obligation rather than providing the necessary information to the people with whose money the exercise is carried out. Suneel Kumar and others opinioned – ‘Groundwater managers and policymakers in India require such information to monitor groundwater development and make strategic decisions for sustainable groundwater management' [14].

The review paper is thought of with hypotheses put forth elaborately in the above paragraphs. The prime objective of the work is to draw the attention of the various agencies involved in groundwater monitoring towards the shortcomings in the monitoring process which need to be addressed. Rapidly growing groundwater utilization demands a relook at the resource monitoring models, including design, in light of emerging technological advancements in data acquisition, processing, interpretation, and dissemination. Emerging challenges and prospects in the groundwater monitoring domain are presented for value addition to the output. It is also a call to scientists, academicians, and technocrats to develop innovative and path-breaking technologies to turn the GWM robust decision-making tool. Rau et al. also advocated revising groundwater monitoring practices They emphasized, 'New methods and advances in computational science could lead to a much-improved understanding of groundwater processes and subsurface properties. A closer look at current groundwater monitoring practice reveals the need for updates focusing on the benefits of high-frequency and high-resolution datasets' [15].

2. Material and Method

An extensive literature survey was conducted to evaluate the field's current research and development status. GWM database, reports, notes, and publications of various organizations are studied to ascertain the procedures adopted in various monitoring activities. Discussions were held with experts in the domain and persons involved in the monitoring to understand the shortcomings and possibilities in process improvement. Deficiencies in the existing monitoring program and challenges in improving the GWM to meet the futuristic demands are listed based on inputs from published literature and the author's experience.

3. Literature Review

Research publications on GWM are minimal and non-innovative, devoid of novel thoughts of experiments. For decades scientists have regarded water levels as primary data and ignored its application in research for developing new ideas, indices, and plots that would help in understating the resource potential appropriately. Instead, water quality received undue importance from a diverse scientific community, and quite a few publications can be found in this domain. The monitoring methodology is elaborately discussed in a few Hydrology, Hydrogeology related books as a separate chapter. Many research papers focused on the depletion of water levels relying on the monitoring database but should have paid more attention to improving the information collection procedures and data processing. Some papers focused on sensors and simulation techniques to measure, estimate and forecast changes in groundwater storage, but they are still in embryonic state. These experiments have to gain concurrence with ground truths and cannot be generalized due to diversity in hydrogeology and environment-governed fluid dynamics.

3.1 Literature on Indirect Monitoring Methods

Some publications emphasized the need for indirect measurement (estimation) of water levels using geophysical applications like Gravity Recovery and Climate Experiment (GRACE). NASA launched GRACE in 2002 to obtain high-resolution, global measurements of Earth's gravity field from space. Data from GRACE help scientists monitor changes in water storage over large areas. Gravity changes correspond to redistribution in Earth's mass, and scientists can isolate the part caused by water movement. Hydrologists go a step further and combine information from GRACE with soil moisture and other data to isolate changes in groundwater storage (https://photojournal.jpl.nasa.gov/catalog/PIA13243). GRACE is successfully used in India as a pilot project to estimate the change in storage in a large aquifer in north India. A study by Rodell et al. in northwest India used terrestrial water storage-change observations from GRACE and simulated soil-water variations from a data-integrating hydrological modelling system to show that groundwater is being depleted at a mean rate of 4.0 +/- 1.0 cm yr-1 equivalent height of water (17.7 +/- 4.5 km3 yr-1) over the Indian states of Rajasthan, Punjab and Haryana (including Delhi) [16]. During the study period of August 2002 to October 2008, groundwater depletion was equivalent to a net loss of 109 km3 of water, double the capacity of India's largest surface-water reservoir (https://grace.jpl.nasa.gov/applications/groundwater/).

Alexander developed artificial neural network (ANN) models to directly predict groundwater level changes using a gridded

GRACE product and other publicly available hydrometeorological data sets [17]. Liesch and Ohmer checked the reliability of the data with ground truths [18]. The GRACE-derived groundwater storage (GWS) data were compared with in-situ groundwater levels from five groundwater basins in Jordan using newly gridded GRACE GRCTellus land data. It is shown that the time series for GRACE-derived G.W.S. data and in-situ groundwater-level measurements can be correlated with R2 from 0.55 to 0.74. Samurembi et al. concluded that a good agreement between DTWS-GRACE and DTWS-in-situ exists except where sea-water intrusion occurs [19]. Shukla et al. opinioned GRACE mission, widely used for monitoring groundwater storage change, could be utilized to get information on the exact amount of water above or below the surface of the Earth that may be used to counteract such situations of the water crisis [20]. Claire Pasca et al. suggested advanced methods to improve the data quality close to the measured values [21]. The downscaling performance is evaluated by comparing the downscaled versus in situ GWS data over 38 pixels at 0.50 resolution. The spatial mean of the temporal Pearson correlation coefficient (R) and root mean square error (RMSE) are 0.79 and 7.9 cm, respectively (classic validation). Confronting the downscaled results with the non-downscaling case indicates that the method allows a general improvement in temporal agreement with in situ measurements (R = 0.76 and RMSE = 8.2 cm for the non-downscaling case).

3.2 Literature on Modelling to Predict Water Levels

Some publications suggested modelling to forecast the water levels using hydrometeorology, monitoring data, and aquifer hydraulics. However, these studies are limited to a few watersheds or sub-basins. Modelling requires different data sets, which can be obtained through authentic primary sources and field experiments. This technique may not be feasible for regional-level groundwater monitoring. However, extensive research applying the latest algorithms and artificial intelligence (AI) technology can be tried to develop technology to predict the water levels using GWM historical database. Experiments in this direction are all the more necessary because the scope for GWM would be ever-increasing, and so also the input cost. Groundwater modelling supports traditional monitoring to improve conceptual geological understanding and to assess the quantitative status and the interaction between groundwater and surface water [12]. Many research papers utilizing in situ measurement data of GWM carried by government agencies mostly focused on discussing the water level trends with special emphasis on depleting water levels. Omvir and Amrita undertook to investigate the groundwater level fluctuations in the Haryana state using geographical information system (GIS), universal kriging (geostatistics) interpolation method, and the groundwater level data of 893 observation wells obtained from Groundwater Cell, Department of Agriculture, Government of Haryana, for the period 2004-12 [22]. The average annual decline in groundwater level was above 32 cm/year, with the strongest decline (108.9 cm/year) in the Kurukshetra district. Chandan and Yashwant's study describes Geostatistics methods in GIS to predict the groundwater level and upgrade GWM networks from the randomly distributed observation wells considering multiple parameters such as GWLF and LiRDLH [23]. Jagtap et al. used statistical tools to analyze the large database and draw certain conclusions or assumptions [24]. An automated system is created that monitors the area's water level and water usage. The threshold value for water usage is calculated through prediction algorithms with an accuracy of 89% based on the features of the particular area. Implementing this system in the severely affected areas will stop uncontrolled groundwater usage and bring transparency to groundwater management. Chakraborty et al. utilized Visual-MODFLOW 2000 for analyzing the groundwater-level simulation in Purba (East) Midnapur, West Bengal, India [25]. Shashank et al. using a regional-scale calibrated and validated three-dimensional groundwater flow model, provided the first forecasts of water levels in the study area up to 2028 [26]. Future water levels without any mitigation efforts are anticipated to decline by up to 2.8 m/year in some areas. The study by Kishore et al. is based on secondary data extracted from various sources, namely the Ministry of Agriculture and Farmers Welfare (MoAF&W), Central Ground Water Board (CGWB.), Indian Metrological Department (IMD), Economic and Political Weekly Research Foundation (EPWR) found depletion of groundwater level in 41 districts where water level depleted more than 4 meters between the years 2002 and 2016 [27]. The analysis is based on the panel regression method, and the Hausman test selected fixed effect over the random effect model. Rohde et al. used satellite-based remote sensing to predict groundwater levels under groundwater-dependent ecosystems across California, USA [28]. Depth to groundwater was modelled for 35 years (1985–2019) within all groundwater-dependent ecosystems across the State (n = 95,135). The model was developed within Google Earth Engine using Landsat satellite imagery, climate data, and field-based groundwater data [n = 627 shallow (< 30 m) monitoring wells] as predictors in a Random Forest model. The findings show that 44% of groundwater-dependent ecosystems have experienced a significant long-term (1985–2019) decline in groundwater levels compared to 28% with a significant increase. Pragnaditya et al. developed feed-forward neural network (FNN), recurrent neural network (RNN), and deep learning-based long short-term memory network (LSTM) models using multi-depth in situ observations from a dense network of monitoring wells (n = 5367, 1996–2018), to simulate and forecast groundwater levels (GWL) in India [29]. Higher declining trends will potentially be observed in parts of north-central and south India in the forecasting period of 5 years (2019–2023). Biswajit et al. used point data and statistical tools to predict water levels [30]. For 21 consecutive years (1996–2017), groundwater monitoring well data (pre-and post-monsoon) has been collected from CGWB. The nonparametric Mann–Kendall trend analysis and standardized precipitation index (SPI) have been applied to detect the trend of groundwater level and rainfall variability, respectively. Masood et al. concluded - that GRACE and numerical groundwater modelling are suggested to be used conjunctively to assess the groundwater resources more efficiently [31]. Sreekanth et al. used remote sensing data, field observations, and numerical groundwater modelling to investigate long-term groundwater storage losses in the regional aquifer of the Ganga

Basin in India [32]. Three analyses based on different methods consistently informed that groundwater storage in the aquifer is declining significantly.

3.3 Review of Reports and Data Sets

A scan of the data sets, and reports of some of the monitoring agencies of India (which broadly reflect the situation in developing countries) reveals that many State Ground Water Departments are uploading the data on their websites without any observations or remarks [e.g., Tamil Nadu, District Average-Ground Water Level Status - as on April 2023 (up-to-date GWL data is available at https://www.tn.gov.in/groundwatertnpwd.org.in); Talukwise average static water level of 227 Taluks for the years 2012-2021 is provided for Karnataka State (https://antharjala.karnataka.gov.in/info); Ground Water Quality and Level Data Since 2006 is available in Irrigation Department website, Punjab State as Depth to water table (ft)data (reproduced as written in the report) at the selected field locations (https://irrigation.punjab.gov.pk/page/1071)]. The Directorate of Ground Water Development, Government of Odisha, conducts water table monitoring four times a year at 1216 locations. However, the data and reports could not be located on the website - https://dowr.odisha.gov.in/. Few States provided GWM reports for the monitored month or year, mostly as routine reports without note-worthy inferences. [e.g., GW Level Scenario in Rajasthan – 2020 (https://phedwater.rajasthan.gov.in/); the water levels Report for June 2022 for the Kerala State (contains many typographical and grammatical errors), includes groundwater draught index and rainfall data (https://groundwater.kerala.gov.in/); Status of Ground Water Level Scenario, during May-2022, Telangana State (https://www.gwd.telangana.gov.in/); The Minor Water Resources Department (MWRD) in Bihar released a report on the status of the groundwater table in the state between August 2019 and February 2020. This report noted that the groundwater in the state, which was earlier available at a range from 40 feet to 200 feet, is now down to between 60 and 250 feet (https://www.isas.nus.edu.sg/)]. Ironically, many monitoring agencies provide the data in PDF or other formats, which users cannot readily process or analyze. The nation's apex organization, the CGWB, releases a report 'Ground Water Year Book- India, every year (e.g., 2021-2022), containing monitoring data, rainfall, and some observations. Groundwater levels are measured four times yearly during January, March/April/ May, August, and November. A network of 23209 observation wells, as of 31.03.2022, located all over the country is being monitored. Apart from releasing GWM information annually for the entire country, the Organization provides similar reports for each State at http://cgwb.gov.in/. The reports contain a brief analysis of the data. Each set of measurements is compared with the previous year and the last decade to understand the variations in the groundwater storage and quality parameters. Govt. of India provides GWM data of all monitoring agencies of India at India-WRIS (indiawris.gov.in). However, it is too complex and beyond the ordinary person's comprehension. Above all, the portal is very slow and non-responsive. South Asia Network on Dams, Rivers and People (SANDRP) also hosts the GWL data collected by about 40 highly credible organizations across India since 2020 by the Foundation for Ecological Security (FES) at https://sandrp.in/.

3.4 Literature of GWM Review

Publications on the review of monitoring programs are few and are mostly confined to institutional reports. The World Bank, under the global water partnership associate program, published GW•MATE Briefing Note 9 (part of GW•MATE Briefing Note Series), in which a detailed account of GWM is provided to improvise the monitoring. The authors of the Note - Albert Tuinhof et al. provided the concepts and tools for sustainable groundwater management [33]. They also enlisted the GWM requirements for managing aquifer response and quality threats. UN/ECE Task Force on Monitoring and Assessment (2000) issued Guidelines on the Monitoring and Assessment of Transboundary Groundwaters intended to assist ECE governments and joint bodies in developing harmonized rules for the setting up and operating systems for transboundary groundwater monitoring and assessment. Reed et al. suggested a new methodology for sampling plan design to reduce the costs associated with long-term monitoring of sites with groundwater contamination [34]. The method combines a fate-and-transport model, plume interpolation, and a genetic algorithm to identify cost-effective sampling plans that accurately quantify the total mass of dissolved contaminant. International Groundwater Resources Assessment Centre took up worldwide inventory on GWM and published a Report nr. GP 2004-1 [35]. IGRAC's inventory of existing monitoring practices is meant to reveal the state of GWM worldwide and to identify the needs of the international community for support with information and guidelines. This report by Jousma (2004) presents a detailed account of the existing scenario of GWM by responded countries. A holistic picture of the monitoring program is chronicled along with the historical background. Jin-Yong Lee et al. in their review of the National Groundwater Monitoring Network in Korea, made some suggestions and recommendations concerning improvements to the national network, which was started in 1995 [36]. Chen et al. while complimenting the GRACE time-variable gravity data for successful use to quantify long-term groundwater storage changes in different regions over the world, pointed out shortfalls in the in situ measurements [37]. They believe that - It is difficult to rely on in situ groundwater measurements for accurate quantification of significant, regional-scale groundwater storage changes, especially at long timescales due to inadequate spatial and temporal coverage of in situ data and uncertainties in storage coefficients. Jarrod et al. in a review article presented a framework for assessing ecological responses to groundwater regime alteration (FERGRA) [38]. FERGRA is a logical approach to investigating how alterations to groundwater regimes change groundwater connections' timing, variability, duration, frequency, and magnitude to different groundwater-dependent ecosystems (GDEs), affecting their ecological processes and ecosystem service provision. Rau et al. in their article 'Future-proofing hydrogeology by revising groundwater monitoring practice mentioned- "A closer look at current groundwater monitoring practice reveals the need for updates with a special focus on the benefits of high-frequency and high-resolution datasets To futureproof hydrogeology, this technical note raises awareness about the necessity for improvement, provides initial recommendations, and advocates for developing universal guidelines" [15]. Hai Tao et al., in their elaborate review article on Ground Water Level (GWL) prediction using Machine Learning (ML) models, discussed all the types of ML models employed for GWL modelling from 2008 to 2020 (138 articles) and summarized the details of the reviewed papers, including the types of models, data span, time scale, input and output parameters, performance criteria used, and the best models identified [39].

4. Status of GWM in India

India, the most populous country and one of the highest groundwater users, must strategically streamline the GWM. Although India started the GWM in 1969, as soon as UNO advised it, the program took a giant leap in the 1990s by launching the National Hydrology Project (NHP). Central and State groundwater departments initiated steps to modernize the GWM by developing piezometers, installing automatic water level recorders (AWLRs), developing a database, analyzing the data by generating graphs, plots, and maps using software, Etc. Including rainfall information and analyzing water level measurements in conjunction with rainfall was another noteworthy development. Nevertheless, after a few years, the tempo of development retarded, and GWM remained a routine task in many organizations. The importance of water levels is felt in severe drought conditions or when water-borne diseases are reported. In a normal situation, the GWM data or reports are hardly looked at by professionals and authorities. This need-based approach left the GWM as non-priority activity.

The ground realities on the state of GWM in India can be gauged from Report No. 9 of 2021 (Performance Audit) of the Comptroller and Auditor General of India on Ground Water Management and Regulation. It states, 'Against the proposed number of 50,000 observation wells (by the end of the XII Plan period, i.e., 2012-17) to measure groundwater level, a network of only 15,851 observation wells were being monitored as of March 31, 2019. CGWB also proposed to undertake Real-time Ground Water Monitoring in various aquifers across the country through purpose-built wells equipped with Digital Water Level Recorders (DWLRs) and Telemetry in convergence with the groundwater component under the National Hydrology Project (NHP) which was still being planned as of March 2020'. (Para 2.4; https://cag.gov.in/).

NHP in India is taken up by World Bank to improve the extent, quality, and accessibility of water resources information and to strengthen the capacity of targeted water resources management institutions in India. It is executed in different phases involving 49 implementing agencies (IAs): the implementing ministry (DoWR, RD & GR, MoJS, Department of Water Resources, RD & GR, Ministry of Jal Shakti); 7 central agencies; 2 river basin organizations; and 39 state/UT agencies (https://nhp.mowr.gov.in/). The web-enabled Water Resources Information Systems (WRISs) strengthen to disseminate real-time data to decision-makers for effective planning, decision-making, and operations (https://jalshakti-dowr.gov.in/national-hydrology-project/). Though the NHP was launched to modernize the monitoring mechanism and provide the agencies' data on one platform, the objectives still needed to be achieved. Validation, integration, and easy access to the data remained a distant dream. Reports on the outcome or achievements of closed phases of NHP are not available on its website.

5. Results and Discussions

5.1 Current Monitoring Model

Groundwater is monitored both for water levels and quality proposes following different methods and instruments by various organizations world over. Frequency and density of sampling too varies widely based on the data requirement and availability of resources. In general water levels are collected more frequently (once in month/quarterly/season-wise) than water sampling for quality tests, which is usually carried out once (before on set of monsoon) or twice in a year (during pre and post-monsoon). Water levels are either collected physically by visiting the site using manual procedures or virtually with the aid of digital recorders and telemetric technology. Few water quality tests are conducted in suite and samples are gathered for major analysis in chemical laboratory. The procedures commonly followed for water levels measurements, water sampling and reporting is elaborated below. This information will help in understanding the deficiencies in the present procedures and strengthen the need for improvement.

5.2 Methods of Measurement

5.2.1 Water Levels

Groundwater is normally monitored periodically from private and public wells, exclusive wells (piezometer wells), piezometer nest (two to five wells drilled down to different depths in an aquifer).

a. Manual

• Graduated Tape and Weight: For open wells where water is visible.
• Chalk and Cut with Graduated Steel Tape: For deep wells (dug wells, bore wells, tube wells).
• Sounders: Graduated tape with air whistle blower.
• Sounders (Electric tape): Graduated tape with light and beep by electric circuit.

b. Automatic

• Recorders with Float: for continuous monitoring (a hydrograph will be generated).
• Digital Water Level Recorders: Submersible pressure transmitter which measures the pressure difference.
• Piezometer: It is used to measure underground water pressure. It converts water pressure to a frequency signal via a diaphragm and a tensioned steel wire [40].

Masood et. al. suggested - 'These methods and instruments include steel tape, electronic measuring tapes, pressure transducers, sounding devices, test drilling, geophysical investigation techniques, piezometers, digital water level recorders, exploratory well drilling, and isotopes, etc.' [31].

5.2.2 U S Environmental Protection Agency Operating Procedure

SESDPROC-105-R2, Groundwater Level and Well Depth Measurement, January 29, 2013, describes the following methods.

a. Electronic Water Level Indicators

These types of instruments consist of a spool of dual conductor wire, a probe attached to the end and an indicator. When the probe comes in contact with the water, the circuit is closed and a meter light and/or audible buzzer attached to the spool will signal contact. Penlight or 9-volt batteries are normally used as a power source.

b. Other Methods

There are other types of water level indicators and recorders available on the market, such as weighted steel tape, chalked tape, sliding float method, airline pressure method and automatic recording methods. These methods are primarily used for closed systems or permanent monitoring wells.

Acoustic water level indicators are also available which measure water levels based on the measured return of an emitted acoustical impulse.

Methods	Type/nature
1. Gravimetric method	Direct, destructive
2. Electrical resistivity method	Indirect, non-destructive
3. Capacitance method	Indirect, non-destructive
4. Gamma radiation method	Indirect, non-destructive
5. Neutron method	Indirect, non-destructive
6. Remote sensing method	Indirect, non-destructive

Table 1: Various Methods of Groundwater Level Measurements Mentioned by Oyedele et. al. [45].

5.2.3 Water Sampling

Water samples can be collected by manual withdrawal, pumping, specific depth sampling using bailers. Commonly used water sampling methods are:-

• Direct sampling from monitoring well.
• Direct sampling from general (group of) wells.
• Passive Samplers: Contaminants are collected by diffusion and/or sorption over extended periods of time. After sampling using these devices, contaminants are removed from the receiving phases or whole samplers by solvent extraction or thermodesorption and analyzed chemically [41].
• Integral Pumping Tests: The issue of heterogeneity of the contaminant distribution in the subsurface is addressed by using the integral pumping test method. During pumping, concentrations of target contaminants are measured in the pumped groundwater. From the concentration time series, the concentration distribution along the control plane and thus the presence of contaminant plumes can be determined [42].
• The contaminant concentration can simply be determined by analyzing water samples from discrete grab or bottle samples. Automated sampling systems can facilitate sample collection for long-term monitoring [42].

Sampling protocols vary based on the parameters to be tested. Basic parameters such as Temperature, pH, EC/TDS, TH, Ca, Mg, Na, K, CO3, HCO3, Cl, SO4, NO3, F are analyzed in standard laboratories following APHA procedures periodically for general mentoring purposes.

6. Data Processing and Reports

Water level and water quality data is validated and processed using certain exclusive or general software to produce tables and figures which helps in analyzing and understanding the data. Reports are prepared providing the summarized data and outcome of the mentoring to help in the follow up action wherever necessary. Data and reports are submitted to the concerned officials and some are kept in the public domain.

7. Shortfalls in the Present Monitoring Mechanism

Some shortfalls in ongoing monitoring procedures are listed based on a detailed appraisal of the literature, reports, and visits to the websites of the many GWM agencies, added with authors' own experience in the domains. The identified deficiencies can be found in organizations of many countries though some are continuing the monitoring program since the initial stage (1970). These issues require the immediate attention of the authorities to improve, revitalize and modernize the entire monitoring program to meet the people's aspirations.

• Monitoring points (density of observation wells) are inconsistent with groundwater development.
• The spatial distribution of wells is uneven regarding geographical and hydrogeological aspects.
• Multiple aquifers are not monitored. Monitoring is limited primarily to phreatic or single aquifers.
• Piezometers or exclusive wells are not developed to replace open/dug (observation) wells.
• Non-automation of water level measuring methods.
• Lack of real-time data presentation facilities.

• Lack of dedicated software for data processing and development of the database.
• Limited water quality parameters are analyzed irrespective of regional or local needs/ demands.
• The frequency of water level measurements is minimal and not to local needs.
• Data validation is not carried out, and outliers (extreme values) are not eliminated in the data processing.
• Database development is poor and historical data is not available.
• Some agencies are just presenting the data without reports.
• Reports are in standard official format sans executable guidelines.
• Data or reports are not user-friendly and hard to access, even on websites.
• Monitoring activities are often not carried out on schedule and are done as sundry or routine jobs without a dedicated team or facilities.

8. Challenges to Groundwater Regime Monitoring

Apart from improving the monitoring methods addressing the system lacunae, there is an urgent need to adopt out-of-box strategies and innovative ideas using the latest technology. The need of the hour is to convert the numerical data into workable information for the benefit of the authorities and end users, including the commoner. Measurement is no longer a science; forecasting and predicting is the demand of the day to prepare for unforeseen weather vagaries. Some opportunities, mainly in the R&D stage, are identified, which can be implemented in phases. Financial resources should be balanced in accomplishing the futuristic needs of GWM. Implementing some of the suggestions may be challenging, especially for developing countries. However, it is time to take a relook at the present GWM program and make it robust for sustainable development and management of groundwater.

• Initiating the indirect methods of monitoring using satellite-based geophysical sensors, e.g., GRACE.
• Predicting the water levels using modelling, GIS, statistical tools, IA, and related software.
• Developing the concept of Long Term Average (LTA) water level (akin to Normal or LTA rainfall) for each monitoring station. This helps in assessing the extent of variation from average values.
• Developing the national level standard protocols considering the country's seasons and hydrological cycle for following uniform monitoring models by all agencies.
• Inbuilt provision for periodic (maybe every ten years) review of the ongoing monitoring program to offer concrete suggestions and scope to implement.
• Considering the principle input (rainfall) and output (extraction) components of the hydrological cycle in an analysis of GWM data.
• Development of stand-alone wells (piezometers) piercing different aquifers for GWM (phase-out open well monitoring).
• Achieving complete automation of WL measurements with online real-time data display in the public domain.
• All activities of GWM should be taken up in project mode to accomplish all tasks as per the schedule.
• Creation of a nodal agency at the ministerial level to facilitate coordination among all water resource monitoring agencies and bring synergy to GWM.

9. Conclusions

A survey of the literature indicates that the GWM domain has yet to gain the attention of the researchers, particularly the change in the storage component. The GWM methodology is not reviewed periodically either by academicians or professionals. Many countries follow the traditional monitoring methods without inventing or investing in modernization. A few flaws in the current monitoring procedures are visible in the reports and data of the GWM agencies, which need to be addressed to maintain the precision and authenticity of the information. The output of GWM is a decision-making tool; delayed, inaccurate, or red herring data has a cascading effect on groundwater management; hence, it must be carried out in project mode with all precautions confined to the schedule. Data analysis and presentation in the form of reports had to be improvised to meet the demands of authorities and end users' expectations. Reports should include site-specific groundwater management plans to address the issues evident in GWM. The database has to be strengthened to include complete point data since the beginning and should be placed in the public domain. Regular press releases have to be issued; press conferences can be conducted to develop an awareness of water levels and water quality situation among the general public. While improving the in situ monitoring model, GWM has to make a breakthrough by adopting the latest technology in indirect measurements, estimation, and forecasting of the parameters. Monitoring has to be strengthened by regular review and input from R&D studies by academicians and the scientific community. Symposia/seminars need to be held involving all stakeholders and inter-discipline professionals for upgrading GWM designs. It is all the more necessary to resilience to the climate change impact and rapidly growing groundwater extraction by initiating proactive measures based on genuine monitoring information.

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No data is used in the Paper.

Conflict of Interest Statement

No conflict of interest is involved.

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