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Shallow Groundwater Level Monitoring in the Kathmandu Valley: Investigating Citizen Scientist Performance and Groundwater Level Data Fluctuation

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Abstract

Shallow groundwater level monitoring is crucial for the sustainable management of water, particularly in rapidly growing cities like the Kathmandu Valley (Valley). Engaging local communities as citizen scientists (CS) offers cost-effective data collection and creates awareness about groundwater status and management practices. This study investigates the performance of citizen scientists (regularity and data submission error) in groundwater level monitoring and evaluating the groundwater fluctuation trend in the Valley. During 2020, 68% of the groundwater CS was categorized as regular. In 2021 and 2022, regularity increased to 91% compared to the previous years, and regularity decreased in 2023 and increased in 2024. Meanwhile, a rise in the percentage of CS sending incorrect data was observed. Despite these fluctuations, the overall error percentage was very low (<8%), highlighting the reliability of the CS-collected data. The monthly groundwater level was recorded from 2020 to 2024 by citizen scientists mobilized across the Valley. Groundwater levels were shallower during the monsoon and post-monsoon months, while in pre-monsoon and winter, the levels were observed to be deeper. The study demonstrates the reliability of CS-collected data and highlights the seasonal trends in the shallow groundwater wells in the Valley, while also demonstrating the power of citizen science in improving the monitoring and sustainable management of groundwater.

Keywords: Groundwater, Citizen Scientists, Kathmandu Valley

1. Introduction

Groundwater in the Kathmandu Valley (Valley) has been a vital source of water supply since prehistoric times. Globally, almost two billion people use water from the ground to meet their drinking needs (Morris et al., 2003). Groundwater systems are dynamic and mostly impacted by land use, groundwater extraction, and climate change (Taylor & Alley, 2001; Thapa et al., 2019). Since groundwater is deeply percolated through soil pores, it is a dependable substitute for sporadically tapped water delivery systems and is frequently pollutant-free. People in the Valley, since ancient times, have relied on the two groundwater aquifers-shallow (unconfined) and deep (confined)- primarily extracting shallow groundwater through conventional methods such as stone spouts, springs, and wells (Pandey et al., 2023). However, excessive extraction has led to declining groundwater levels in the Valley (Thapa et al., 2019). A rapid increase in population and urbanization has led to deterioration of both water quality and water shortage (Thapa et al., 2017). Due to a lack of institutional responsibility for monitoring and controlling the groundwater setting, several wells have been haphazardly sunk in the Valley's aquifers (Pandey et al., 2010). About half of the Kathmandu Valley's overall water supply is obtained from groundwater, which includes both shallow and deep aquifers (KUKL, 2021). The public organization Kathmandu Upatyaka Khanepani Limited (KUKL) is in the position of maintaining and operating the Valley's water supply and sanitary system. Dug wells, stone spouts, and tube wells are used by the majority of people without access to water through KUKL to draw groundwater from

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shallow aquifers (Thapa et al., 2016). The main source of data regarding groundwater systems is groundwater level readings obtained from observation wells (Taylor & Alley, 2001), and regular monitoring of groundwater is one of the most effective strategies to promote sustainable management of groundwater (Grieef & Hayashi, 2007).

A number of studies have indicated that the Valley's groundwater system is divided into three layers: shallow aquifer, aquitard, and deep aquifer (Cresswell et al., 2001; Metcalf & Addy, 2000; Pandey et al., 2010). Currently, groundwater in the Valley is extracted from shallow and deep aquifers (Metcalf, 2000), whereas before the 1970s, only shallow aquifers were the source of groundwater production (Prajapati et al., 2021). Groundwater levels have been declining since the 1980s (Metcalf 2000; Pandey et al. 2010; Shrestha et al. 2012), since groundwater withdrawal rates are thought to exceed discharge that can be sustainably retrieved (Davids and Mehl 2015). The groundwater pumping rate in the Valley is six times higher than the recharge rate, and it is causing the groundwater table to drop by about 2.5 meters per year (Shrestha, 2009). This situation is expected to become more significant in the future. Hence, the overexploitation of groundwater resources has degraded the quality and quantity of water in the wells. Previous studies have addressed groundwater quantity (Cresswell et al., 2001; JICA, 1990; Dahal et al., 2019) and groundwater quality (Khadka, 1993; Chettri & Smith, 1995; Gurung et al., 2006; Chapagain et al., 2010; Pant, 2011; Ganesh et al., 2018) of the aquifer system of the Kathmandu Valley. These studies mainly focused on deep aquifers, and only a limited amount of research has been carried out on shallow aquifers. However, the main aim of this project is to manage shallow groundwater levels sustainably by using CS to generate data in data-scarce regions like Nepal.

Smartphones For Water-Nepal (S4W-Nepal), a non-profit research organization, aims to gather hydro-meteorological data, improve knowledge of water resources through research, and assist in making informed decisions about water management. S4W-Nepal uses a viable citizen science technique to achieve this goal, which can be extremely important in research, particularly in regions with limited data, like Nepal. Additionally, S4W-Nepal makes use of young researchers and mobile technology. The development of mobile technology (such as GPS, cameras, etc.) has made it possible for citizen scientists to participate more actively in the scientific data collection process, which helps to manage data gaps and proper understanding of groundwater levels in the Valley. The citizen science approach is the involvement and cooperation of citizens, or non-scientists, with professional scientists in scientific research to produce new scientific knowledge (Buytaert et al., 2014). This CS approach serves as a pivotal tool to manage data gaps in the data-scarce regions (Nigussie et al., 2018). Therefore, utilizing citizen science, a participatory and realistic strategy, might dramatically improve groundwater monitoring and address associated difficulties. Thus, sustainable use of groundwater resources is a crucial concern. As such, Smartphones For Water Nepal (S4W-Nepal) has taken the initiative of enlisting citizen scientists (CS) to monitor groundwater in the Valley.

In growing cities like the Valley, where it is difficult to operate new wells to manage the sustainability of water resources, this research suggested that the CS approach for monitoring groundwater levels using existing wells in the Valley would be a crucial option to sustainably generate groundwater level data to manage data gaps and to evaluate the groundwater data fluctuation trends by investigating CS performance. Thus, this study assesses the reliability and consistency of groundwater level monitoring using a citizen science approach. It also intends to investigate spatial and temporal changes in groundwater levels throughout the Valley. The objectives of this study were:

- To analyze the spatiotemporal variation of shallow groundwater levels in the Valley during different phases (pre-monsoon, monsoon, post-monsoon, and winter)
- To evaluate the performance of CS and to monitor groundwater fluctuation trends in the Valley

2. Materials and Methods

2.1. Study area

This study focuses on the Valley, which includes three administrative districts: Kathmandu, Lalitpur, and Bhaktapur. The Valley, Nepal's urban center, is an intermontane basin that lies between latitudes 27°32′13" and 27°49′10" N and longitudes 85°11′31″ to 85°31′38″ E (Dahal et al., 2019). This bowl-shaped valley covers an area of 664 square kilometers (km^2) (Dahal et al., 2019). With an average elevation of 1340 m above mean sea level (Shrestha et al., 2016), the groundwater basin in the Valley occupies an area of 587 km^2 (Davids et al., 2018). The average annual temperature and rainfall of the Valley are 18.1°C and 1407 mm, respectively (Ishtiaque et al., 2017). With a warm, temperate climate and a semi-tropical location, the Valley receives over 80% of its annual rainfall during the monsoon season, which runs from June to September (Karki et al., 2017). Around 60% of people residing in the Kathmandu Valley rely on groundwater to meet their water needs. (Shrestha et al., 2020). The Kathmandu Valley floor is made up of quaternary basin-fill sediments; the surrounding hills are made up of Precambrian to Devonian foundation rocks, which likewise underlie the sediments on the valley floor (Shrestha & Shah, 2014). The weather of the Valley is classified into four seasons: pre-monsoon (March-May), monsoon (June-September), post-monsoon (October-November), and winter (December-February). The Japan International Cooperation Agency (JICA 1990) divided the Valley into three groundwater districts (Northern, Central, and Southern Groundwater Districts) based on the physical and chemical properties of groundwater. A total of 72 wells, locations of which are shown in figure 1, were monitored in the Valley, which involved mobilizing CS to collect data and to practice sustainable management of groundwater.

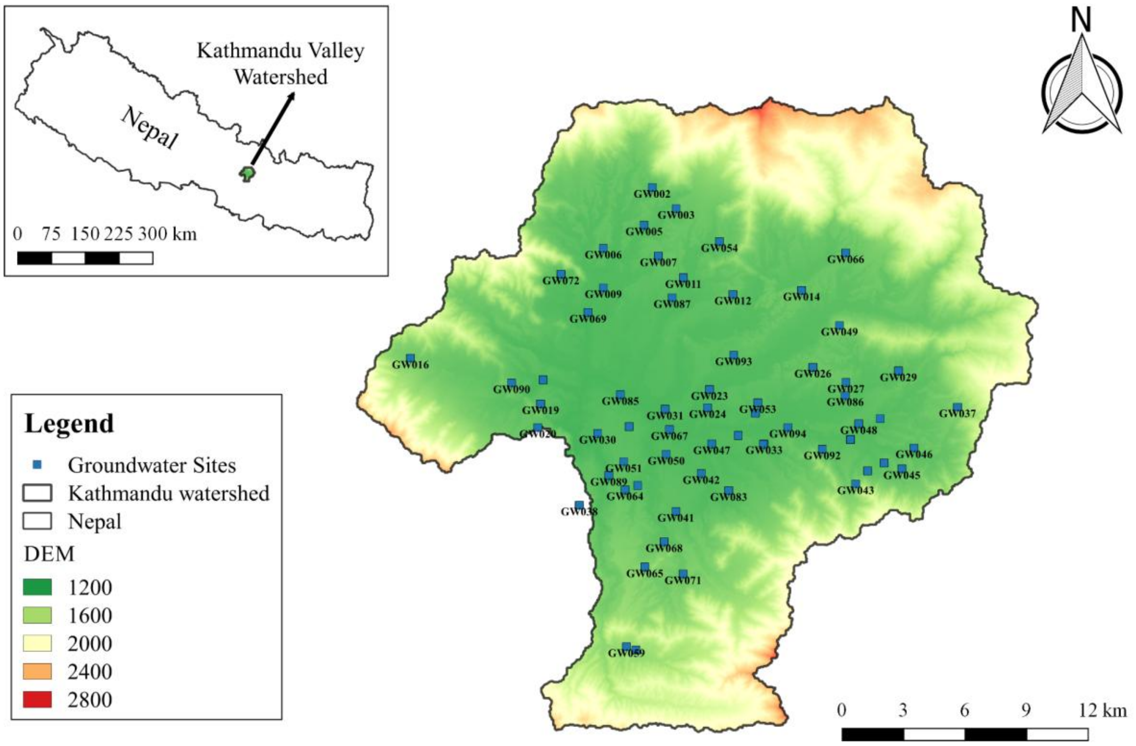

Figure 1. Map showing the locations of monitoring wells

2.2. Data Collection

The monthly groundwater level (depth of the water surface below ground level) was recorded from 2020 to 2024 by CS mobilized across the Valley. CS recruitment involved social media, outreach programs, personal networking, and random site visits. During the recruitment, they were provided with a measuring tape and trained on data collection using forms in an Android mobile application called Open Data Kit (ODK) Collect. CS received monthly text reminders about collecting groundwater level data. Using the measuring tapes and ODK-Collect forms, CS recorded the depth to the water table below the ground surface (bgl) and submitted the data. The bgl values represent the vertical distance between the ground surface and the water table in meters, as illustrated by Figure 2. The higher values denote deeper depths to water tables, and the lower values denote shallower depths to water tables from the ground surface.

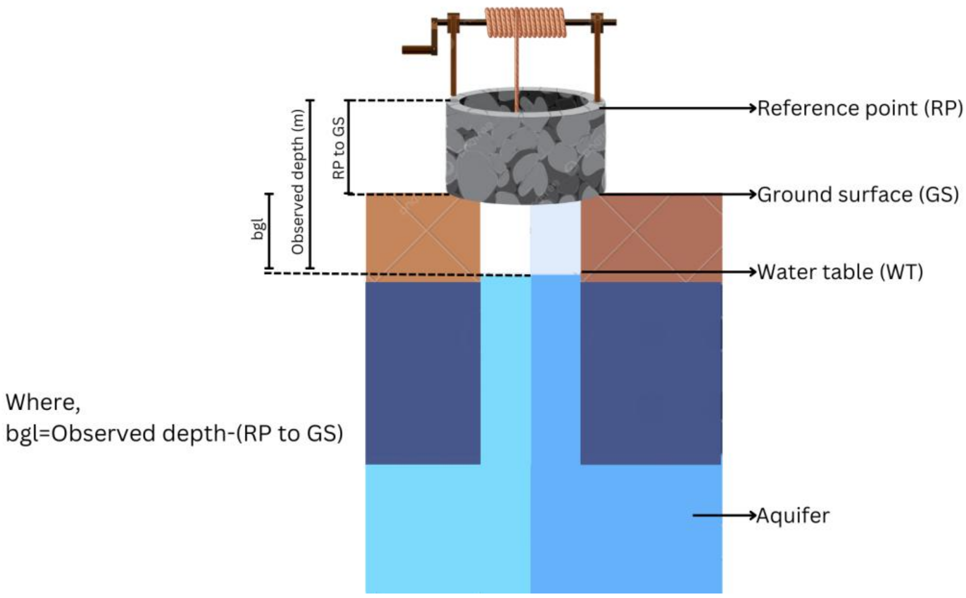

Figure 2. Below ground level (bgl)

Follow-up texts and calls were made to ensure the timely submission of data, resolve any errors, and address challenges faced by the CS during the process. To maintain the reliability of the data submitted by the CS, quality control (QC) was performed by comparing the values with images of the measuring tapes taken during the measurement. Any errors were manually corrected in a Python-based web application, and the forms were labeled with QC flags, “Checked good” and “Checked corrected.”

Every month, CS received acknowledgement texts expressing gratitude for their contributions.

2.3. Data Analysis

2.3.1. Evaluation of the performance of citizen scientists

The performance of CS was evaluated based on their regularity in sending data and the submission errors. The following formula was used to determine regularity:

$$Regularity\ of\ citizen\ scientists = \frac{total\ number\ of\ measurements\ taken}{total\ number\ of\ expected\ measurements} * 100\%$$

$$Error\ Percentage = \frac{No.of\ checked\ corrected\ measurements}{Total\ number\ of\ measurements\ taken} \times 100\ \%$$

Further, the past CS retention rate, i.e., the number of CS continuing the groundwater level monitoring in the upcoming years, was also evaluated and represented in a cohort retention matrix using Python.

2.3.2. Spatial and temporal variation of shallow groundwater level

The temporal variation of groundwater level fluctuations was analyzed using the Python programming language. The monthly fluctuation of groundwater levels was visualized with a heat map. Additionally, the spatial variation of groundwater levels in different seasons, i.e., pre-monsoon (March-May), monsoon (June-September), post-monsoon (October-November), and winter (December-February), was analyzed and visualized in interpolated maps using QuantumGIS.

3. Result and Discussion

3.1. Performance of the citizen scientists

The COVID-19 pandemic significantly affected data regularity among CS in 2020, as shown by Figure 3(a), with only roughly 68% regularity. In 2021 and 2022, motivational approaches such as reminder texts, follow-up calls, and acknowledgment texts led to an increase in regularity (average data regularity > 91%). Additionally, the CS were further encouraged by improved data dissemination and the distribution of water quality reports for the monitoring sites. However, in 2023, there was a slight decrease in regularity (average data regularity = 83.46%), possibly reflecting a period of reduced engagement or shifting priorities among CS. To address such a decline, regular motivational approaches targeting the CS were undertaken. An increase in the regularity was observed in 2024 (average data regularity = 85.57%). Likewise, Figure 3(b) depicts the error percentage of CS that sent incorrect data, which was corrected during quality control by S4W-Nepal young researchers, i.e., 'Checked Corrected' ones. There was an increase in the percentage of CS submission errors from 2020 to 2021, 4.3% to 6.3%, respectively. The increase in submission error percentage could be attributed to newly recruited CS in sites added in those years. To address this, guidance and training were provided through follow-up calls, messages and virtual meetings. As a result, in subsequent years, the error percentage decreased from 2022 to 2023 (3.2% to 2%). In 2024, there was a slight increase in the error percentage (3.2%) compared to 2023 due to the recruitment of new CS. This could be attributed to the inexperience among the newly recruited CS in the data collection process, which improves over time. The main errors made by the CS included measurements with errors ranging from ± 0.1 to 1 m. Blurred and missing images of the measurements in the ODK forms also hindered the quality control of the data, which is also a limitation of this CS based approach.

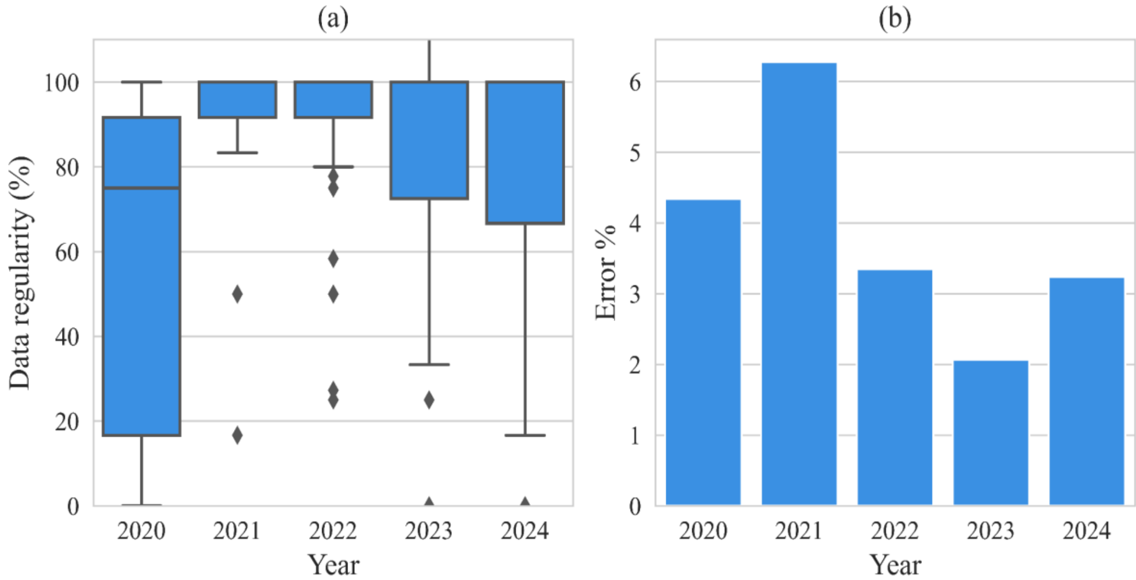

Figure 3. Regularity of CS (a) and error percentage of CS (b) from 2020-2024

Overall, the error percentage is very low (<8%), which closely aligns with the results of the study by Eisma et al. (2023), in which 73 % of CSs submitted rainfall data with errors in fewer than 5 % of their observations, and Wood et al. (2021), in which citizen scientists counting animals from drone imagery, the proportional error was 9% for sea lions and 5% for seals during breeding seasons. The percentage of error was lower (2.9%) in the citizen science-based rainfall monitoring in Western Nepal conducted by Paul et al. (2020). In 63 citizen science-based studies analyzed by Aceves-Bueno et al. (2017), 55% of the studies had error rates exceeding 20%. This shows that the groundwater data collected by the CS (with error percentages ranging from 6.3% in 2021 to 3.2% recently in 2024) is very reliable in comparison to other citizen science-based studies.

Furthermore, the motivational approaches further increased the CS regularity and decreased the error. These approaches facilitate the recruitment, engagement, and motivation of CS, as communication is a crucial element in citizen science (Veeckman et al., 2019).

The cohort retention matrix illustrates the percentage of past CS who continued groundwater level monitoring each subsequent year. From 2020 to 2021, an impressive 97.1% of CS continued groundwater level monitoring. Although the retention rates declined slightly in the following years, a majority of the CS still continued their participation, highlighted by an impressive 71% of CS from 2023 continuing groundwater monitoring in 2024. The willingness to continue groundwater monitoring aligns with the research by Walker et al. (2021), where around 89% of the citizen scientists were enthusiastic to continue their involvement in different citizen science-based water monitoring projects in Nepal.

Various efforts, such as acknowledgement texts, experience-sharing opportunities, capacity-building training, and the “Citizen Scientist of the Year” award, were impactful in sustaining the engagement of the CS. Additionally, with the discontinuation of some CS at some groundwater sites, the monitoring efforts were either undertaken by S4W-Nepal young researchers or new CS were recruited. In some cases, the former CS facilitated the handover by recruiting the new CS themselves.

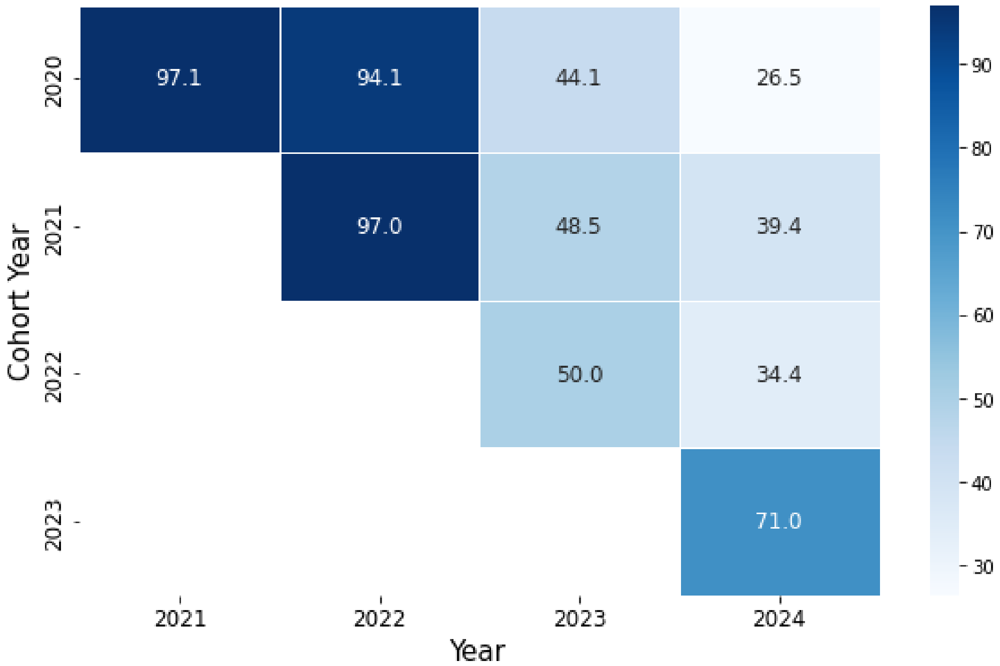

Figure 4. Past citizen scientists cohort retention matrix (Each box shows the percentage of citizen scientists (CS) from a given cohort year (Y-axis) who continued participating in measurement campaigns in the following years (X-axis). Higher percentages indicate stronger retention within a cohort over time)

3.2. Spatial and temporal variation of groundwater level

3.2.1. Spatial variations

Figure 5 exhibits pronounced spatial and seasonal variations in the groundwater level over the five-year period (2020-2024). The annual trend shows groundwater table depth gradually increasing, with a significant decline in spatial coverage of groundwater table shallower than 1.5 m bgl from the year 2020 to 2024. The areas with groundwater tables of depth shallower than 1.5 m bgl have reduced. There is a noticeable sprawl of zones with deep groundwater levels towards the edges of the valley, and there is a shift in the number of groundwater sites whose depth increased from < 3 m bgl to 3-4.5 m bgl.

The groundwater table on the outskirts of the valley; to the South, South-East and North-West consistently remained shallow, even during the periods of lower precipitation (winter and pre-monsoon). It could possibly be due to natural land use practices in the areas, facilitating groundwater recharge (Prajapati et al., 2021). The central areas of the valley predominantly show deeper groundwater levels, even during monsoon season. It is possibly because of low recharge through built-up surfaces, combined with extensive groundwater extraction (Gautam and Prajapati, 2014).

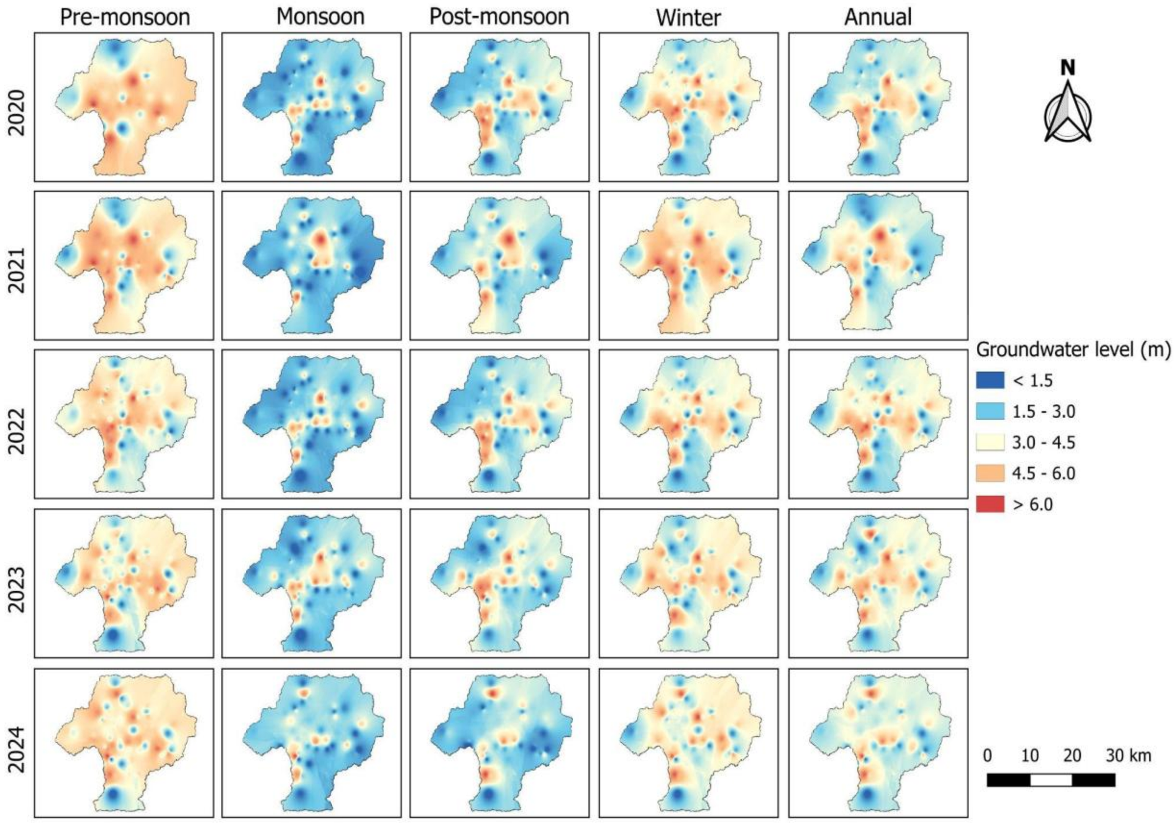

Figure 5. Spatial variation of groundwater level in Kathmandu Valley

3.2.2. Temporal variations

The groundwater table throughout the Valley was shallow in all five years. The below-ground level (bgl) fluctuation ranged from 0.13 m to 16.18 m (Mean = 4.35 m, S.D. = 2.71 m). It was observed that from June to September (monsoon months), the groundwater levels were comparatively shallower. This can be attributed to the recharge of the groundwater sites during the monsoon season, as 80% of the total precipitation occurs during these months (Adhikari et al., 2022). After the withdrawal of the monsoon, the groundwater level became deeper in the months of October and November. Despite some decline in the water levels after the monsoon, the depths remained shallow, indicating effective aquifer replenishment during the rainy months, sustaining abstraction throughout the post-monsoon period (Prajapati et al., 2021). In the winter months of December and January, the groundwater level became noticeably deeper as there was no recharge. The winter rainfall in the months of December to February, which contributes nearly 3% of the total annual rainfall (Sigdel and Ikeda, 2012), had almost no impact on the groundwater level.

Thirty of the groundwater sites were comparatively shallower, with an average groundwater level up to 4 m throughout the year. On the other hand, five groundwater sites (GW002, GW012, GW024, GW039, and GW077) were comparatively deeper, having an average groundwater depth higher than 8 m. The remaining wells had groundwater levels fluctuating between 5 and 8 m.

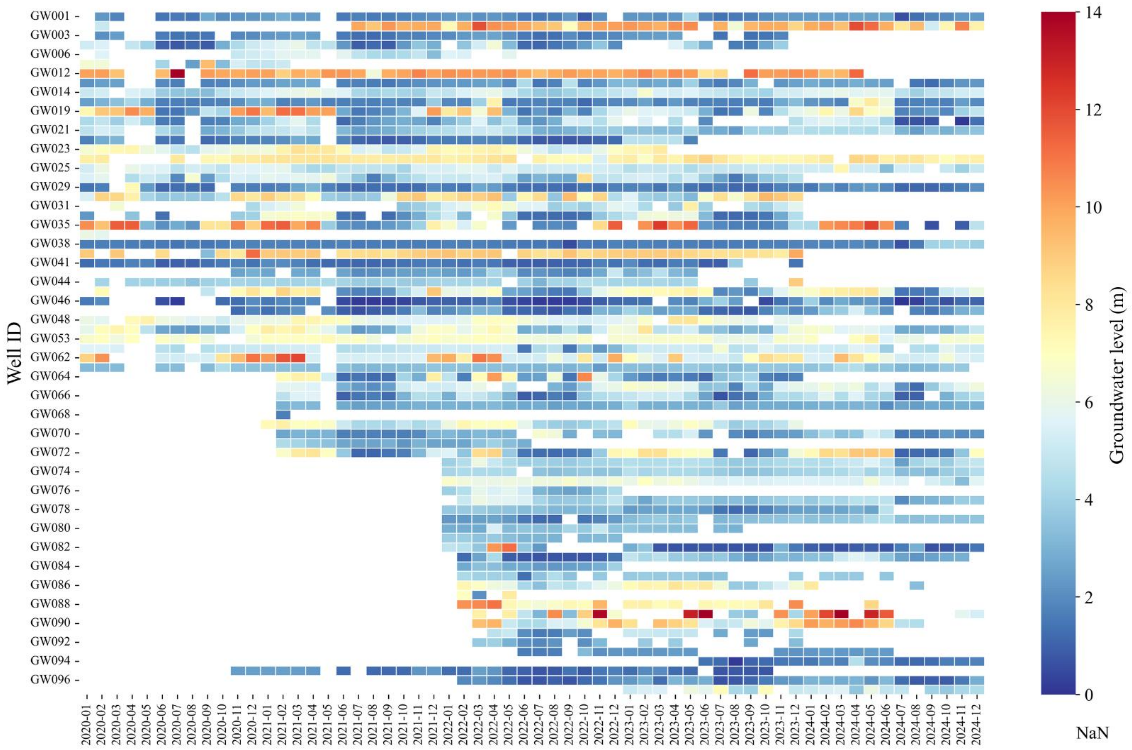

Figure 6. Heat map showing monthly fluctuations of groundwater levels

The study uses an extensive monitoring network with monthly groundwater level observations in the Kathmandu Valley, providing spatial coverage of land uses. The data is shared through S4W-Nepal's public data portal, social media platforms, posters, and research publications. The data offers valuable insights into groundwater management, supporting sustainable planning and policy-making. By leveraging this data for public awareness, research, and stakeholder engagement, more informed decisions regarding water resource management can be made.

4. Conclusion

This study analyzes the application and reliability of the citizen science approach in groundwater level monitoring in the Kathmandu Valley. The findings indicate that the overall performance of the CS is strong, characterized by high regularity and low errors when motivational strategies and follow-ups are implemented. This highlights the importance of follow-ups and motivational approaches in sustaining the retention of CS participation and the quality of groundwater level data.

During the study period, the groundwater levels fluctuated between 0.13 and 16.18 m bgl, with a significant influence from the monsoon season. Additionally, the depth to the water table was observed to be deeper in the core areas of the valley, primarily due to built-up land use and higher extraction rates.

In conclusion, the citizen science approach is a viable approach for sustainable groundwater management. Collaboration of citizens can play a pivotal role in addressing the current and future water needs in the Kathmandu Valley.

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