International Journal of Science and Technology (IJST)
Vol. 9:000010 (2025) 2507-9638 https://ijst.clsu.edu.ph

OPEN ACCESS

Application of GIS-Integrated Water Fluctuation Method for Groundwater Fluctuation Estimation

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Keywords: *Hydrology, Groundwater Recharge, Geographic Information System (GIS), Water Table Fluctuation (WTF) Method, Water Resource Management*

Type: Research Article

Submitted: June 2, 2025
Accepted: December 15, 2025
Published: December 31, 2025

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Citation
Flores & Sacdalan (2025). Application of GIS-Integrated Water Fluctuation Method for Groundwater Fluctuation Estimation. *CLSU International Journal of Science and Technology, 9*, 000010. https://doi.org/10.22137/IJST.2025.000010

Abstract

Estimating groundwater recharge is crucial for water resource management, groundwater modeling, and protection. Accurate recharge estimation helps determine the sustainable yield of aquifers, especially important in arid regions where recharge is highly variable. However, estimating groundwater recharge is difficult, especially in arid regions where it is highly variable spatially and temporally. The absence of accurate groundwater recharge estimations can lead to significant challenges in water resource management, agriculture, environment, economy, policy making, and climate change adaptation. Therefore, this case study in Brgy. Bannagao, Aurora, Isabela integrates the water-fluctuation method with GIS to estimate groundwater recharge. Historical rainfall and groundwater level data from June 2020 to May 2021 were analyzed to show the relationship between rainfall and groundwater levels. The volume of water fluctuation ranged from -500,733.61 m^3, the lowest drop in water level of the aquifer, which occurred from January to February, a period with lower rainfall, to 218,046.85 m^3, the highest amount of water recharged in October 2020, the month with the highest rainfall. Results indicate a significant correlation between rainfall and groundwater fluctuations, with GIS aiding in visualizing recharge and discharge volumes. The study concludes that GIS-integrated methods offer promising results for groundwater management. Recommendations include applying this method on a larger scale, increasing monitored tube wells, and incorporating water consumption data to improve accuracy.

Introduction

Groundwater is contained in one of the underground layers of water-bearing material called aquifers. An aquifer is a geological formation that consists of permeable material capable of storing significant quantities of water. For many important agricultural production areas, groundwater will remain the ultimate source of freshwater when surface water sources have been depleted. The aquifers that host groundwater are the primary barriers against drought for both human consumption and crop production. In many concentrations of intensive agriculture, groundwater offers reliability and flexibility in access to water that irrigation canals can hardly cover (Siebert et al. 2010).

Groundwater recharge is generally described as the infiltration of water, such as rainfall, surface water, and snow, from the ground surface to the groundwater table in an aquifer system. The recharge mechanism depends on various geological and hydrogeological parameters; therefore, determining groundwater recharge is one of the most vigorous processes in hydrological studies. To determine groundwater potential in an aquifer system, the groundwater recharge ratio serves as an important parameter for the hydrogeological analysis. In general, many recharge estimation methods are used to estimate the recharge ratio, such as the groundwater level fluctuating, the water balance, the groundwater chloride mass balance, the soil moisture, and the tracing methods based on available hydrological and aquifer characteristic data (Lerner et al. 1990; Scanlon et al. 2002; Leaney et al. 2011).

Groundwater recharge estimation is essential for water resources management, groundwater modelling, and groundwater protection, as it is a main component in the water balance. Knowledge of aquifer recharge helps identify the sustainable yield of a catchment and thus protects the groundwater resources. Estimating groundwater recharge is difficult, especially in arid regions where it is highly variable spatially and temporally. Unlike humid regions, recharge in arid climates occurs indirectly through surface runoff into Wadis, Sabkhas, and karst features (Seiler and Gat, 2007; therefore, it is necessary to consider several factors, such as surface geomorphology, land cover, and terrain for groundwater recharge estimation.

In the literature, numerous recharge estimation techniques are presented. Recharge estimations were divided into seven categories by Healy (2010). Based on the available data and the local climate, each strategy is appropriate for a particular study region. According to their distinct benefits and drawbacks, Kinzelbach et al. (2002) reviewed the most commonly used recharge-estimating techniques for dry regions. The recharge estimation methods were categorized into four groups: direct measurements, including using lysimeters, water balance methods, Darcian methods, and tracer methods from their classification. Kinzelbach et al. (2002) recommend using many independent approaches to estimate recharge.

In dry parts of Southern Africa, Xu and Beekman (2003) analyzed sixteen techniques of recharge estimation. They evaluated the limitations, data requirements, and applicability of each method. Ultimately, they assigned a score to each approach according to its cost, ease of use, and accuracy. They concluded that six approaches may be used more confidently and simply. These techniques include the Saturated Volume Fluctuation (SVF) method, the Groundwater Modelling (GM), the Chloride Mass Balance (CMB), the Cumulative Rainfall Departure (CRD), and the Extended Model for Aquifer Recharge and soil moisture Transport through unsaturated Hardrock (EARTH) (Beekman et al. 1996). These techniques were used to estimate groundwater recharge in arid locations (Baalousha et al., 2018).

Recent efforts have been initiated to explore integrating GIS into groundwater recharge assessment. Tleane and Ndambuki (2020) conducted a case study in Makotopong Village, South Africa. The study aimed to estimate groundwater recharge using ArcGIS 10.5 to support sustainable water supply in rural areas. Researchers analyzed borehole logs, geological, and hydrogeological data from government sources to assess rainfall variation and recharge rates. The estimated annual recharge ranged from 0 to 51 mm, with a mean of 12.04 mm/year. These results closely matched those from previous methods such as Chlorine Mass Balance and Water-Table Fluctuation, confirming GIS as a reliable tool for groundwater recharge estimation. The study recommends using GIS-based methods for designing sustainable groundwater systems.

Simsek et al. (2020) estimated total groundwater recharge and discharge using a GIS-integrated water level fluctuation method in the Alaşehir alluvial aquifer, Western Anatolia, Turkey. Researchers installed water level data loggers in 16 wells and used spatial analysis to estimate volume changes from monthly groundwater level maps and aquifer storage data. The method accounted for both recharge and discharge mechanisms. The estimated annual recharge was 187 hm^3, attributed to precipitation, surface water leakage, and irrigation. The study concluded that GIS-based fluctuation analysis is an effective and practical approach for estimating recharge in surficial aquifers.

In the Philippines, the Bureau of Soils and Water Management (BSWM) under the Department of Agriculture (2020) conducted a GIS-based evaluation and mapping of groundwater potential and recharge zone areas for sustainable agriculture. The project aimed to identify and map groundwater recharge zones across the country using Geographic Information Systems (GIS). The methodology integrated spatial datasets such as slope, soil type, land cover, and rainfall to evaluate groundwater potential. The outputs support sustainable agricultural planning and aquifer management, especially in areas vulnerable to water scarcity.

The main objective of this research is to estimate groundwater recharge through the integration of the water-fluctuation method and the use of Geographic Information System (GIS). Specifically, this research aims to:

1. Establish the relationship between rainfall amount (precipitation) and groundwater table fluctuation;
2. Generate groundwater level change maps using GIS software to determine and illustrate the increase and decrease of groundwater levels between successive months.
3. Estimate the total change in groundwater level in the aquifer of the study area in terms of volume.

The outcome of this method is the volumetric groundwater level change within the boundary of the sample area. The quantification of the target result was computed using existing data on the average depth of groundwater change and the area covered by groundwater level fluctuation, based on the generated maps.

Materials and Methods

Study Area

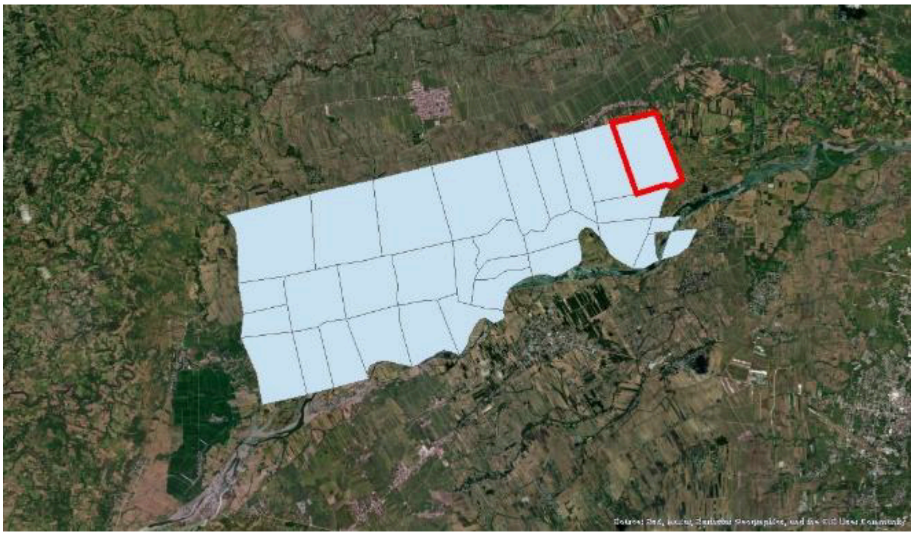


Figure 1. Location of the Study Area at Aurora, Isabela (Source: *World Imagery Basemap*. ArcGIS)

This research will focus on the estimation of groundwater level using the integration of the water fluctuation method and the use of geographical information systems in Brgy. Bannagao, Aurora, Isabela (Figure 1), which is an area of tobacco farms that consumes groundwater for irrigation purposes.

Data to be used

Table 1. Monthly average groundwater level observed from six shallow tubewells.

Observed Shallow Tube Wells	Coordinates		Monthly Groundwater Level (ft)											
			2020							2021				
	Lat	Long	June	July	August	September	October	November	December	January	February	March	April	May
STW 1	16°59′28.68″N	121°41′18.61″E	14.67	14.55	14.47	14.54	14.39	12.87	12.93	13.59	13.86	14.23	14.5	14.72
STW 2	17°0′15.50″N	121°41′42.75″E	10.11	9.83	9.77	9.75	9.48	8.08	8.07	8.35	8.49	8.87	9.13	9.36
STW 3	17°0′3.69″N	121°41′34.46″E	11.78	11.47	11.59	11.65	11.54	9.97	10.03	8.77	11.17	11.51	11.8	12.07
STW 4	17°0′58.18″N	121°41′42.53″E	7.32	7.3	7.09	7.19	6.87	5.52	5.57	8.22	6.88	7.34	7.59	7.79
STW 5	17°0′58.90″N	121°41′46.65″E	10.87	10.64	10.56	10.5	10.35	8.83	8.89	6.4	8.47	8.63	8.98	9.06
STW 6	17°0′32.60″N	121°41′57.28″E	9.92	9.73	9.77	9.79	9.54	8.12	8.09	8.35	8.28	8.87	8.99	9.16
Average			**10.78**	**10.59**	**10.54**	**10.57**	**10.36**	**8.90**	**8.93**	**8.95**	**9.53**	**9.91**	**10.17**	**10.36**

Table 2. Monthly Rainfall Data of the Municipality of Aurora, Isabela.

Monthly Rainfall Data of the Municipality of Aurora, Isabela		
Year	**Month**	**Rainfall (mm)**
2020	June	95.58
2020	July	148.56
2020	August	139.27
2020	September	113.31
2020	October	298.73
2020	November	248.51
2020	December	237.51
2021	January	86.39
2021	February	21.20
2021	March	68.80
2021	April	1.40

2021	May	65.80
2021	June	136.40

Secondary data of the annual groundwater level of Universal Leaf Philippines Inc., which is a tobacco-based company in the Philippines, will be used in this research. Although the researcher personally collected the data during a prior engagement with the company, permission for academic use was obtained to ensure ethical compliance. The data were used solely for research purposes, with no proprietary or confidential information disclosed. All procedures followed ethical standards for data handling, and the company's ownership of the original records is acknowledged.

Water fluctuation is the method used to determine groundwater levels from the observed selected shallow tube wells in the study area. To record these data, a groundwater level-measuring device was inserted into the observed shallow tube well to measure the depth of the water level below the ground surface. In total, there are six (6) observed shallow tube wells that are monitored from June 2020 to May 2021. Only six shallow tube wells were used for monitoring, due to limited resources and small community studies. According to the Philippine Agricultural Engineering Standard (PAES 615:2016), shallow tube wells are commonly used for groundwater irrigation and monitoring in rural areas, and their deployment is often constrained by cost and accessibility. However, the wells were strategically chosen to be in varied locations to represent different areas in the barangay and show how groundwater levels change across locations.

Another data to be used is the historical data of rainfall from June 2020 to May 2021, which was also recorded by the company using the installed rain gauge and weather stations in the study area. This was used to establish the relationship between the amount of rainfall and groundwater level fluctuation.

Methodology Steps

The basic assumption of the water fluctuation method is that the rise in the groundwater table in an unconfined aquifer is due to the recharge water arriving at the water table (Simsek et al., 2020). Therefore, historical data of annual rainfall and annual groundwater level fluctuation per monitored shallow tube well in the area will be used and merged into a single table in Microsoft Excel to generate a graph showing the movement of water level in relation to rainfall. This graph will illustrate how rainfall affects groundwater recharge in the aquifer.

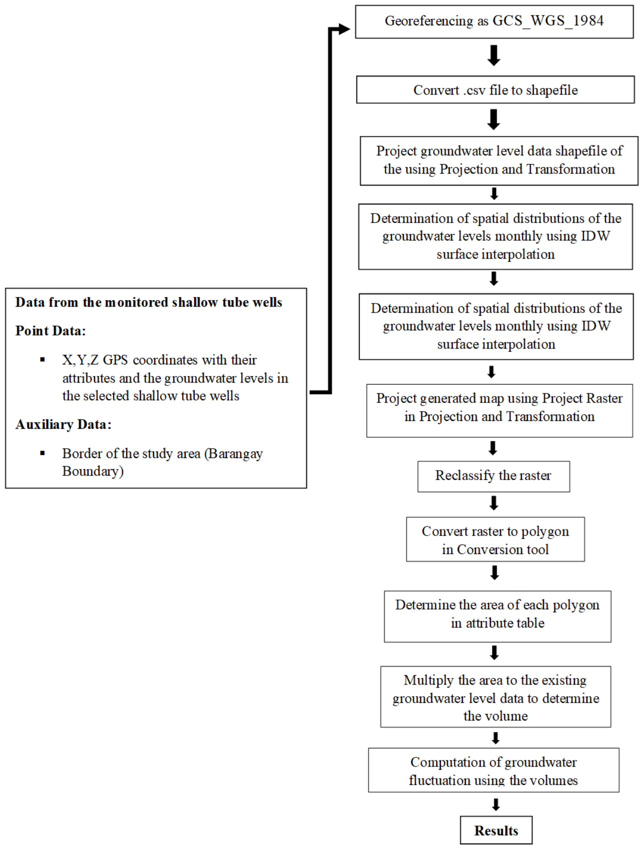


Figure 2. Methodology Steps in the GIS-integrated Assessment Method

For generating maps regarding groundwater changes, the method was adapted from Simsek et al. (2020). Secondary data on groundwater levels obtained from observed wells will be evaluated in ArcGIS. As shown in Figure 2, the locations of wells were determined using a hand-held GPS (X, Y coordinates) during data collection, with an accuracy of ±3 m, and their attributes were recorded. All spatial and attribute data saved as a .csv file will be imported into the GIS platform and geo-referenced in GCS_WGS_1984. The .csv file will then be converted to a shapefile for projection and transformation.

Once projected, the spatial distributions of monthly groundwater levels based on well data and the study area boundary will be determined using surface interpolation. Monthly maps will be generated using inverse distance weighted (IDW) interpolation, showing groundwater levels across the observed tubewells. These maps also display groundwater level differences between successive months. Each map classifies groundwater levels into five ranges based on recorded depth below the ground surface. Positive values indicate a rise in groundwater level from the previous month, while negative values indicate a drop.

The total volume of groundwater level fluctuation will be computed by multiplying the average depth of groundwater change by the area covered. To do this, the area of each polygon generated by the map must be determined. Using the conversion tool, the raster map will be converted into a polygon to calculate the area per groundwater level classification. These maps and raster models will be used to compute the volume of groundwater level fluctuation within the barangay.

Results and Discussion

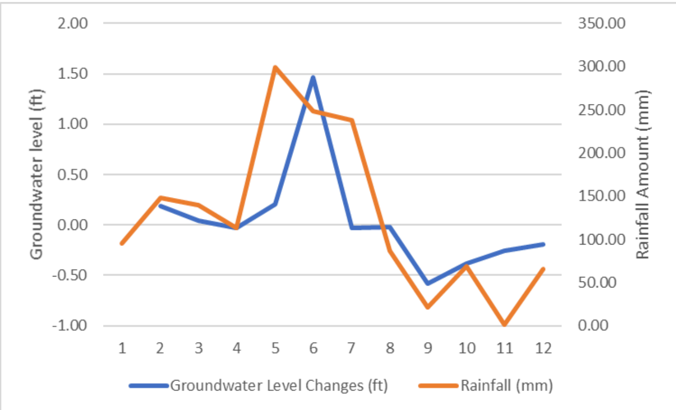


Figure 3. Relationship between Groundwater Level Fluctuation and Rainfall

Based on the recorded data, a graph was generated to show the relationship between rainfall and groundwater level fluctuation, as shown in Figure 3. The graph illustrates the monthly movement of groundwater levels based on the total monthly rainfall from June 2020 to May 2021. The results indicate that the amount of rainfall has a significant effect on the trend of groundwater levels. The higher the amount of rainfall in a certain period, the more the groundwater level rises, indicating a recharge in the groundwater table. Conversely, during months with lower rainfall, such as January to May, the groundwater level drops. This indicates that there is no recharge in the groundwater level; instead, there is a discharge because the amount of rainfall does not replenish the water extracted for consumption purposes.

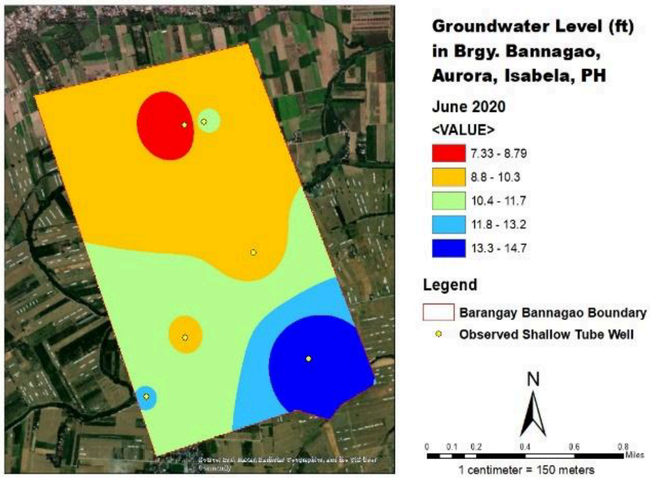
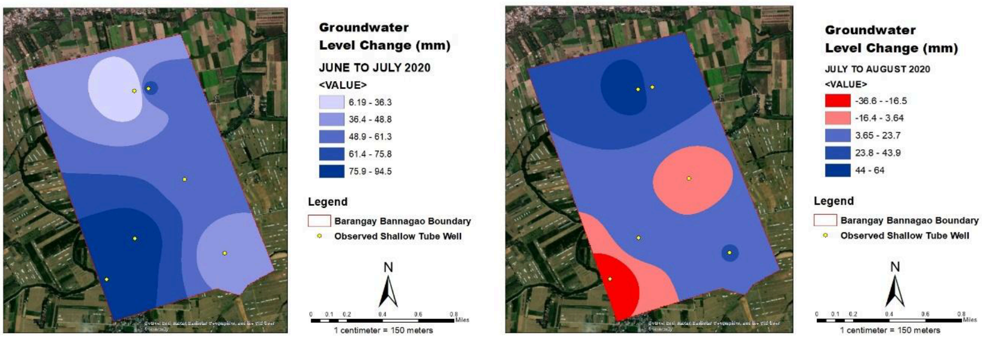


Figure 4. Groundwater level in Brgy. Bannagao, Aurora, Isabela for June 2020

Figure 4 shows the initial groundwater level in Brgy. Bannagao, Aurora, Isabela, for June 2020, which served as the baseline data to determine changes in groundwater levels in the succeeding months. The varied colors within the barangay boundary indicate the value of the groundwater level below the ground surface. Each color corresponds to a specific range of groundwater levels.



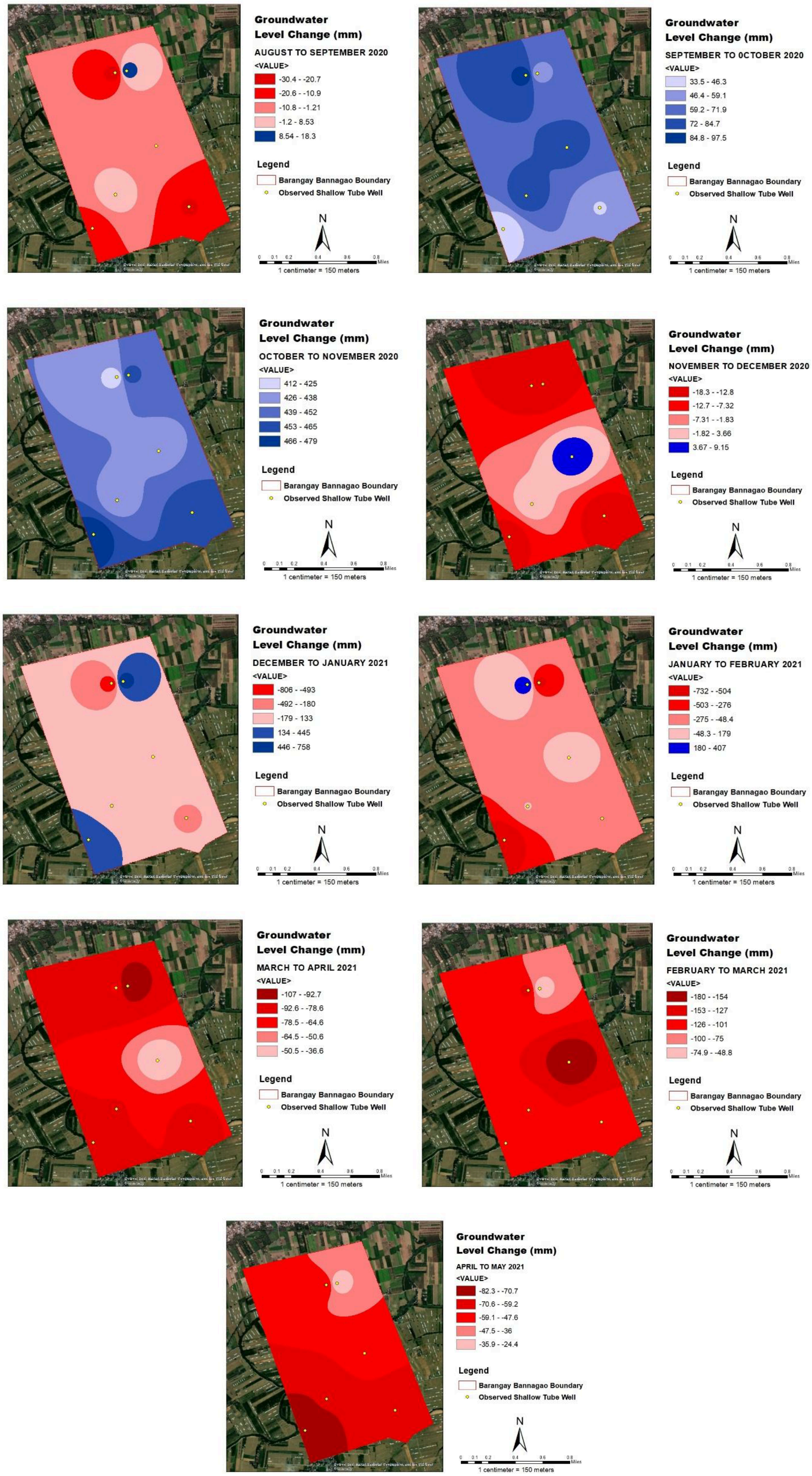


Figure 5. Generated Maps showing the Groundwater Level Changes between Successive Months

The maps shown in Figure 5 were generated to illustrate groundwater level changes and to determine the increase and decrease in groundwater levels between successive months. The groundwater level change was calculated by subtracting the current groundwater level from the groundwater level of the previous month. The colors within the barangay boundary indicate changes in groundwater level, measured in millimeters. Blue, ranging from light to dark, represents a positive groundwater level, indicating groundwater recharge in that specific month. Red, ranging from light to dark, shows a negative value of groundwater level, indicating a drop in groundwater level from the previous month. Lighter colors indicate lower groundwater fluctuation, while darker colors indicate greater groundwater level fluctuation.

Figure 5 shows that the groundwater level across the entire barangay is not constant from month to month. Some areas have higher groundwater recharge, while others have lower recharge. Similarly, some parts of the barangay experience a smaller drop in groundwater levels, while others experience an extreme drop. Maps for June to November 2020 show that the barangay has higher groundwater recharge during months with higher rainfall, while the majority of the area experiences a drop in groundwater levels from December 2020 to May 2021, during periods with lower rainfall.

Table 3. Estimated Volume of Groundwater Level Change from June 2020 to May 2021.

Year	Months	Estimated Recharge/Discharge within the Barangay (m^3)
2020	June to July	183889.06
	July to August	54816.69
	August to September	-25110.35
	September to October	218046.85
	October to November	1458864.18
	November to December	-28308.12
2021	December to January	-391212.92
	January to February	-500733.61
	February to March	-387966.92
	March to April	-254354.92
	April to May	-197337.70

Based on the calculations integrating the water fluctuation method with GIS, the results presented in Table 3 show that from June 2020 to May 2021, the volume of water fluctuation ranged from –500,733.61 m^3, representing the lowest drop in aquifer water level observed between January and February, to 218,046.85 m^3, indicating the highest recharge recorded in October 2020. This study did not include a cross-validation on the generated area in the maps, which aligns with the methodology of Simsek et al. (2020). However, existing research shows that IDW is an acceptable GIS tool for Spatial Interpolation for the estimation and distribution of groundwater level (Antonakos and Lambrakis, 2021). Model accuracy of IDW was assessed using the Root Mean Square Error (RMSE) and Mean Absolute Error (MAE). Results indicated that the IDW interpolation method is more accurate for groundwater analysis (Susatio et al, 2025; Vallesteros et al, 2014).

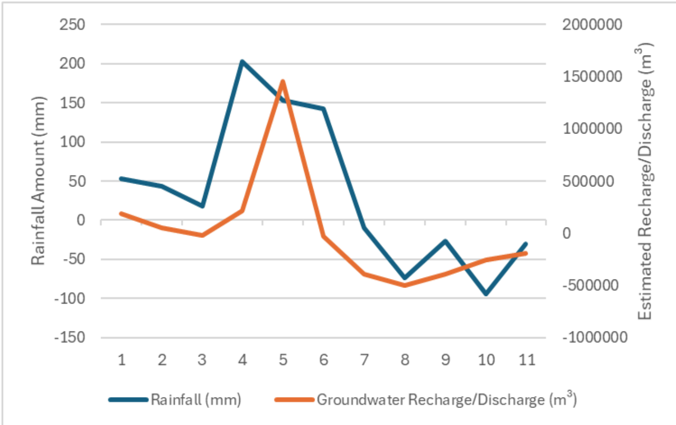


Figure 6. Relationship between Rainfall and Volume of Groundwater Recharge/Discharge

The relationship between recharge and discharge volumes (Figure 6) indicates that aquifer water levels fluctuate in response to rainfall. Higher rainfall increases recharge, while lower rainfall reduces water volume, confirming the accuracy of the generated results. However, other factors not considered in this study, such as the volume of water extracted from shallow tube wells for irrigation and human consumption, can be included in future studies on groundwater recharge estimation. Another factor to consider for improving the accuracy of the results is the number of observed tube wells. Increasing the number of observed tube wells may enhance the accuracy of groundwater level measurements, which can be applied in future studies. Overall, the GIS-integrated groundwater level fluctuation estimation shows promising results in estimating the volume of fluctuation rather than depth alone, making it easier to visualize how much water is added to or removed from our groundwater table.

Compared with the findings of Simsek et al. (2020), both studies confirmed a strong correlation between rainfall and groundwater recharge. In both cases, groundwater levels rose during wet months and declined during dry periods, especially when irrigation demand was high. Regarding the spatial variability, both studies revealed that groundwater level changes are not uniform across the study area. In Brgy. Bannagao, recharge and discharge varied spatially within the barangay boundary. In the alluvial aquifer, the Northwestern region showed higher permeability and recharge potential due to favorable lithology. The volume estimation and groundwater budget generated in both studies indicated that groundwater discharge exceeded recharge, largely due to agricultural and domestic use during dry seasons. Both studies demonstrated the value of GIS in visualizing and quantifying groundwater dynamics in volumetric terms, thereby contributing to groundwater management.

Conclusion

Accurate groundwater recharge estimation plays an important role in effective groundwater management. Although overextraction of groundwater is detrimental to our resources, it is inevitable due to the growing demand for water, primarily for irrigation and human consumption. This is why monitoring groundwater levels is important. The water-table fluctuation method is a well-known technique for estimating groundwater fluctuations, but monitoring depth alone makes visualizing these fluctuations difficult. Therefore, GIS was integrated into this existing method to estimate the volume of water dropped or replenished within the Brgy. Bannagao, Aurora, Isabela. From June 2020 to May 2021, the aquifer experienced a range of water volume changes, from a maximum recharge of 218,046.85 m^3 in October 2020, coinciding with peak rainfall, to a significant decline of −500,733.61 m^3 between January and February, a period marked by minimal precipitation. This case study demonstrates that the GIS-integrated water table fluctuation method can estimate the volume of groundwater-level fluctuation, clearly showing its relationship with rainfall.

This study shows how using GIS with the water table fluctuation method can help us see changes in groundwater not just by depth, but by actual volume. Rather than relying solely on depth measurements, the approach enables quantification of groundwater recharge and discharge in volumetric terms (cubic meters), providing a more precise assessment of aquifer fluctuation changes. This makes it easier to understand how rainfall affects groundwater levels. Most importantly, this can help farmers plan irrigation more effectively by knowing how much groundwater is really available, which is very useful for agriculture in areas that rely on it.

To achieve more accurate results in groundwater recharge estimation, this study recommends applying the method on a larger area. Additionally, the number of tube wells monitored should be increased for more accurate results. The greater the number of monitored tube wells, the more groundwater level data can be processed, leading to more accurate results. Finally, future studies should include data collection on water consumption within the observed area, mainly for irrigation and human consumption, to be used as a factor in groundwater discharge. This case study concludes that using GIS-integrated groundwater recharge estimation yields promising results for estimating the volume of groundwater level fluctuations rather than depth alone, making it easier to visualize how much water is added to or removed from our groundwater table, which can be used for planning effective groundwater resource management.

Ethical Statement

The study followed ethical standards during and after its conduct. Permission for academic use of the data was obtained from the company to ensure compliance. Informed consent was respected, and confidentiality was maintained by using the data only for research purposes, with no sensitive or proprietary information disclosed. All procedures were carried out responsibly to minimize any possible harm. The company's ownership of the original records is acknowledged, and the data were handled with integrity throughout the research.

Conflict of Interest Statement

The authors declare no conflict of interest related to the conduct and publication of this research. All procedures followed were in accordance with institutional and ethical standards, and there were no financial or personal relationships that could have influenced the outcomes of this study.

Acknowledgements

The authors would like to thank the DOST-ERDT scholarship for the opportunity to pursue graduate school, which made this research possible. A word of appreciation is also extended to the Department of Agricultural and Biosystems Engineering of Central Luzon State University and its curriculum for the inclusion of the Applied Hydrology subject. The authors would also like to give credit to Universal Leaf Philippines Inc. for their primary data that was instrumental in this study. Finally, the authors would like to thank Chariz N. Raros for sharing her knowledge in technical writing, specifically in content, which made this paper presentable.

Declaration of Generative AI and AI-Assisted Technologies

This work was prepared entirely by the author(s) without the use of generative AI or AI-assisted technologies.

Data Availability

All data supporting the findings of this study are available within the paper.

Author Contributions

RRF: Conceptualization, Formal Analysis, Investigation, Writing - Original Draft and Visualization; **JPCS:** Supervision, Project administration, and Writing - Review and Editing.

Funding

The author(s) declare that no specific grant from public, commercial, or nonprofit organizations was received for this study.

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