Research article

Sustainable Water Use from a Freshwater Lens in the Yumi-Hama Peninsula, Japan – Effects of Precipitation on Groundwater Levels

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Received 29 December 2024   Accepted 7 May 2025   (*Corresponding Author)

Abstract The formation of a freshwater lens, a distinctive lens-shaped body of underground freshwater, is a marvel in areas surrounded by saltwater, such as islands and peninsulas. Despite saltwater infiltration beneath underground freshwater, the density difference ensures that the freshwater floats on the saltwater and remains separate. This freshwater lens, replenished by rainwater infiltration and temporarily storing freshwater, is a precious water resource of immense significance. A freshwater lens has been used for agriculture in the Yumi-Hama Peninsula in Tottori, Japan. However, the limited number of studies on the availability of freshwater resources and their fluctuations in this area is a cause for concern for future sustainability. Moreover, droughts have occurred frequently. Therefore, unstable surface water, such as rivers, reinforces the importance of sustainable groundwater usage. This study investigated the effects of precipitation on groundwater levels using a cross-correlation analysis of the Antecedent Precipitation Index (API) and groundwater levels. The API is an indicator of precipitation involved in groundwater level fluctuations, which is calculated using an exponential function to describe underground infiltration and storage processes. We found positive correlations between the API and groundwater levels at some sites. However, the correlation coefficients were relatively low at sites close to canals, large-scale farms, and shorelines. Possible factors contributing to the low correlation coefficients were the effects of infiltration from canals, pumping for agricultural purposes, and tides. In addition, the time lags for rainwater to reach the groundwater table from the land surface were within 1 day at most sites. These can be explained by the high hydraulic conductivity of sandy soil in the study area.

Keywords freshwater resources, groundwater recharge, antecedent precipitation index, cross-correlation analysis, correlation coefficients, time lags

INTRODUCTION

A freshwater lens is a lens-shaped body of freshwater located underground (Fig. 1). This formation is a global phenomenon that occurs in land areas surrounded by saltwater, such as islands and peninsulas. Despite underground saltwater intrusion from the surrounding land, the water density difference ensures that recharged freshwater floats on saltwater and remains separate. The freshwater lens can temporarily store freshwater and serve as a valuable water resource.

Freshwater lenses are an important water resource internationally, and at the same time, are vulnerable to climate change (IPCC, 2022). Drought and rising sea levels lead to a reduction in water resources and salinization, threatening livelihoods. Therefore, this study is valuable for identifying the factors contributing to freshwater lens fluctuations.

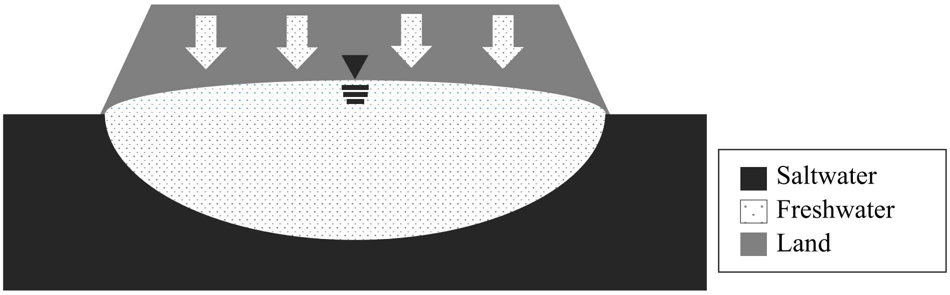
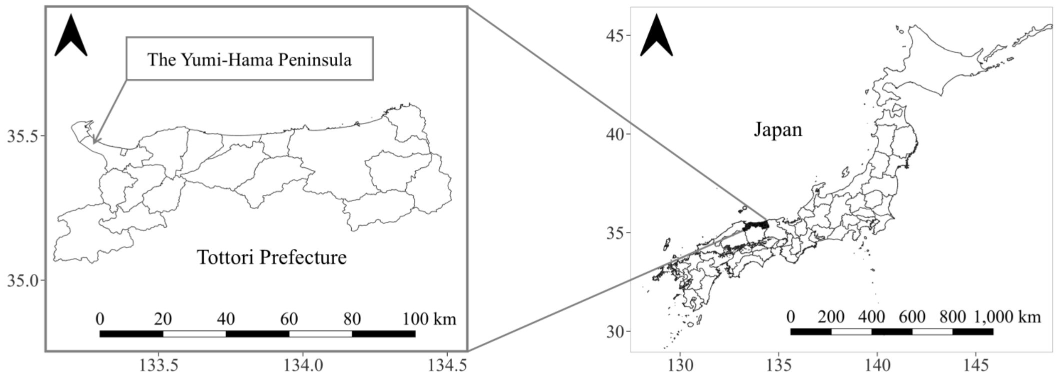


Fig. 1 Diagram of freshwater lens

The Yumi-Hama Peninsula, which is the study area, is located in the western part of Tottori Prefecture, Japan (Fig. 2). It is the first location where a freshwater lens was found in Japan, and the water has been used for agricultural purposes. However, a limited number of studies have examined the availability of freshwater resources and fluctuations in this area. This is a cause for concern regarding future sustainability.



(Created by editing the digital national land information (MLIT, 2024))

Fig. 2 Location of the Yumi-Hama Peninsula

The Yumi-Hama Peninsula has no natural rivers, although an artificial concrete canal, the Yone-Gawa River, exists. The water flowing in the canal is obtained from the Hino-Gawa River upstream, a class-A river in the Tottori Prefecture. The intake is regularly 7.77 m^3/s during the irrigation season (April to September). Droughts have frequently occurred in the study area, decreasing river flow and leading to surface water instability. Surface water is the primary source of water for agricultural use. Therefore, unstable surface water reinforces the significance of the availability and sustainability of groundwater use. The Yone-Gawa River canal has a unique feature in that holes in the bottom of the canal are thought to recharge groundwater, and a yet-to-be-defined relationship between the flow rate of the canal and groundwater exists and should be studied.

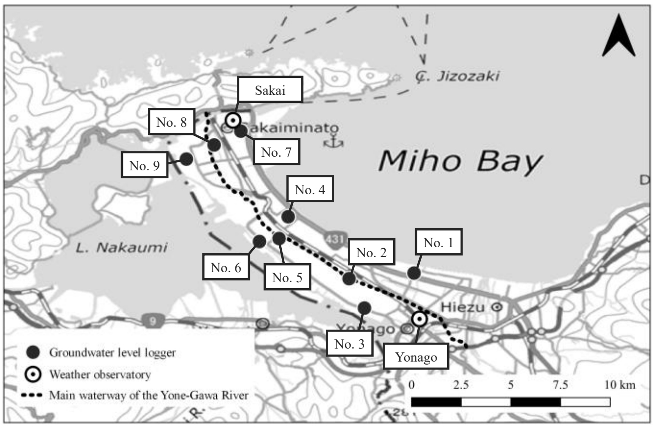
OBJECTIVE

The main objective of this study was to clarify the relationship between the availability of freshwater resources and the factors contributing to groundwater levels. This study focuses on the relationship between groundwater level fluctuations and precipitation.

METHODOLOGY

Data Acquisition

Two data points, groundwater level and precipitation, were collected at the sites, as shown in Figure 3.



(Created by editing the international map (Geospatial Information Authority of Japan, 2013))

Fig. 3 Sites measuring groundwater level and precipitation

Groundwater Levels: At the bottom of the wells, pressure-type water level loggers (HOBO U20-001-02, Onset) were installed to measure the absolute pressure and water temperature. Using the atmospheric pressure measured by another logger, the absolute pressure was converted into water level (the land surface was the standard level = 0.00 m) using Eq. (1). The density of the water used to calculate the water level was calculated using Eq. (2) (Kell, 1975). The measurement intervals were 30 min, and the period was from October 1, 2023, to September 30, 2024. Each site was numbered from 1-9.

$$WL = (P\_abs - P\_atm)/\rho g - h \tag{1}$$

Where, WL is the water level from the land surface (m), P_abs is the absolute pressure at the bottom of the well (kg/m/s^2), P_atm is the atmospheric pressure (kg/m/s^2), ρ is the density of the water (kg/m^3), g is the gravity acceleration (m/s^2), and h is the distance between the land surface and the elevation of the bottom of the well (m).

$$\rho = (999.83952 + 16.945176t - 7.9870401 \times 10\hat{}(-3)\, t\hat{}2 - 46.170461 \times 10\hat{}(-6)\, t\hat{}3 + 105.56302 \times 10\hat{}(-9)\, t\hat{}4 - 280.54253 \times 10\hat{}(-12)\, t\hat{}5)/(1 + 16.879850 \times 10\hat{}(-3)\, t) \tag{2}$$

Where ρ is the density of water (kg/m^3), and t is the water temperature (°C).

Precipitation: Precipitation was measured by the Japan Meteorological Agency (JMA) at two sites: the Yonago and Sakai observatories. Data were collected from the Internet (JMA, 2024). The collection interval was 1 hr, and the period was from October 1, 2023, to September 30, 2024. Precipitation measured at the Yonago observatory was used to understand the relationship with groundwater levels at sites No. 1 to No. 6, and at the Sakai observatory, it was used from No. 7 to No. 9 because it was the closest observatory to each site.

Cross-correlation Analysis

This analysis calculated a correlation coefficient that indicated the similarity between the groundwater level and precipitation fluctuations, and the time lags taken for rainwater to reach the groundwater table from the land surface at each site.

Antecedent Precipitation Index

Before cross-correlation analysis, precipitation data were converted into the Antecedent Precipitation Index (API). The API is an indicator of precipitation involved in measuring groundwater level fluctuations, which is calculated using an exponential function to describe how wet or dry the soil is based on previous and current precipitation, expressing the underground infiltration and storage processes. The API was calculated using Eq. (3) based on the concept defined by Kohler and Linsley (1951).

$$API = \sum[i = 0,\ n]\, 0.5^\wedge(i\ /\ H) \times P\_i \quad (3)$$

Where API is the Antecedent Precipitation Index (mm/day), n is the accumulation period (days), H is the half-life period (days), and P_i is precipitation i days ago (mm/day). The accumulation period is how many past days of precipitation are used to calculate API. The half-life period is the time taken for the impact of one precipitation event on soil moisture to reduce by half.

The combination of n, H, and time lags was determined when the correlation coefficient was the highest, using data from October 1, 2023, to September 30, 2024. The parameter ranges were as follows: n and H, and ranged from 0 to 100 days. The time lags ranged from 0 to 10 days. In previous studies, there are limited examples of the application of the API to understand the variability of freshwater lenses, and parameter ranges were determined on a trial basis.

After determining the parameter combination, the data from the first 100 days were removed, and the correlation coefficient was calculated again using data from December 30, 2023, to September 30, 2024. This is because the first API could not express the effects of the previous precipitation.

RESULTS AND DISCUSSION

The parameters and correlation coefficients for each site are listed in Table 1.

Table 1 Parameters and correlation coefficient

Site no.	n (days)	H (days)	Time lags (days)	Correlation coefficient
1	48	15	1	0.60
2	100	100	10	0.37
3	38	5	0	0.70
4	51	10	1	0.85
5	100	19	0	0.84
6	28	11	0	0.26
7	54	26	1	0.87
8	56	20	0	0.45
9	100	100	10	-0.11

At sites No. 4, No. 5, and No. 7, the correlation coefficients were greater than 0.80. At these sites, the API primarily explained groundwater level fluctuations. For example, the graph of the groundwater level and API at No. 4 is presented in Figure 4.

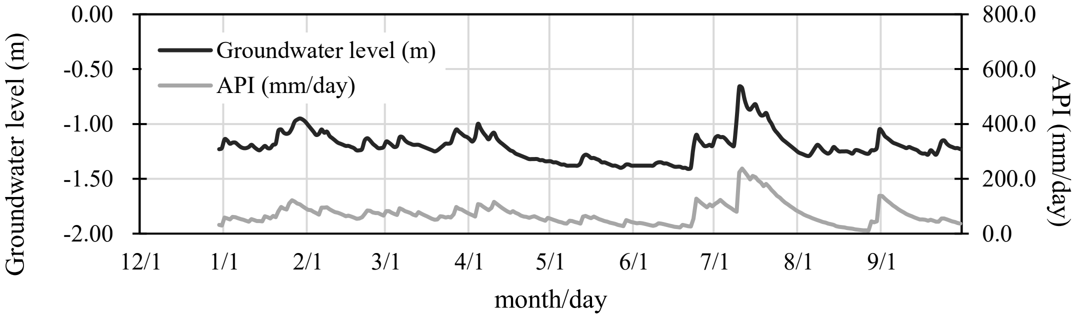


Fig. 4 Groundwater level and API at No. 4

However, at sites No.1, No. 2, No. 3, No. 6, No. 8, and No. 9, the correlation coefficient was less than 0.70. Possible factors for the low correlation coefficients were the low impact of precipitation, the high impact of other factors, and the need to adjust the parameter ranges. Other factors include infiltration from rivers, pumping, and tides. Site No. 2 was the closest to the canal. Therefore, infiltration from the canal could affect groundwater level fluctuations. A graph of the groundwater level and API at site No. 2 is shown in Figure 5. A graph of the water level in the canal, as measured by the local Land Improvement District Office, is shown in Figure 6. The fluctuations in the groundwater level at site No. 2 and the water level in the canal were similar.

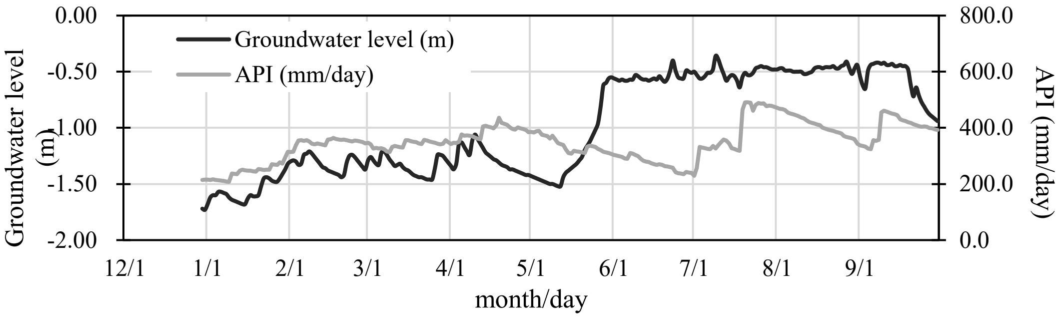


Fig. 5 Groundwater level and API at No. 2

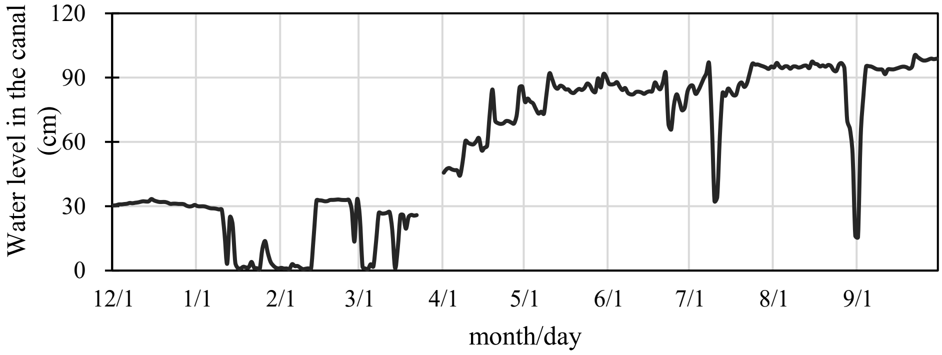


Fig. 6 Water level in the canal (missing from March 23 to 31, 2024)

Site No. 6 was the closest to a large-scale farm and shoreline. Therefore, pumping for agricultural purposes and tides could affect groundwater level fluctuations. A graph of the groundwater level and API at site No. 6 is shown in Fig. 7.

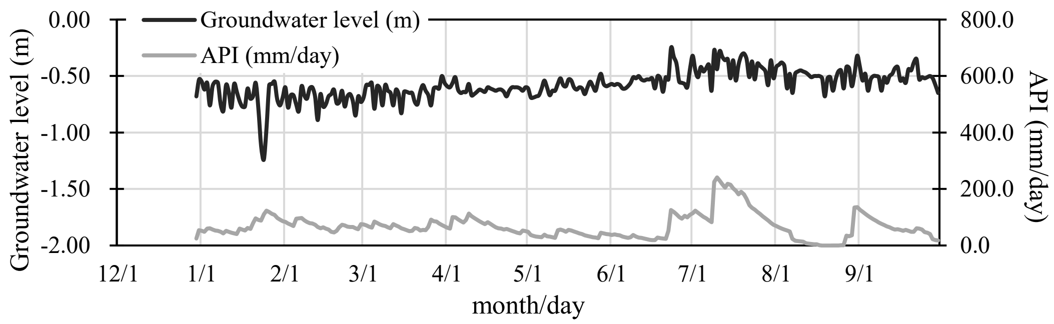


Fig. 7 Groundwater level and API at No. 6

In addition, the time lags were within one day at most sites. This can be explained by the high hydraulic conductivity of sandy soil. The Yumi-Hama Peninsula is largely composed of sand layers (Nakamura et al., 2001).

CONCLUSION

This study investigated the relationship between the groundwater level and API. As a result, some sites had high positive correlations with each other. However, the correlation coefficients were relatively low at the other sites. Possible factors contributing to this were the effects of infiltration from canals, pumping for agricultural purposes, and tides. In addition, the time lags were within one day at most sites. These can be explained by the high hydraulic conductivity of sandy soil in the study area.

Two improvements were made to the model. The first is to prove correctness. In this study, we conducted only learning steps regarding groundwater levels, which are thought to have annual fluctuations and have not been validated. Second, the number of weather observatories should be increased. Only two observatories could cause a spatial bias. The solution is to interpolate or install new rain gauges in these areas.

As a future enhancement, to estimate the amount of water in the freshwater lens, the saltwater-freshwater boundary needs to be determined by methods including electrical conductivity and electromagnetic measurements. There is also a lack of data on the factors affecting fluctuations in the freshwater lens, which need to be collected. For example, in this study, pumping could influence groundwater levels, but there was a lack of quantitative pumping data. After these are clarified, predictions of freshwater lens fluctuations can be realized. The simulation allows for more efficient water use, making it easier and timelier to plan countermeasures against water shortages caused by climate change.

ACKNOWLEDGEMENTS

This study was conducted with residents and water-use management staff in the Yone-Gawa Land Improvement District and was financially supported by the Community-based Research Project 2023, funded by Tottori University, Tottori, Japan.

REFERENCES

Geospatial Information Authority of Japan. 2013. GSI tiles, Japan. Retrieved from URL https://maps.gsi.go.jp/development/ichiran.html

IPCC. 2022. IPCC sixth assessment report, impacts, adaptation and vulnerability. Chapter 4, Water, Box 4.2. Intergovernmental Panel on Climate Change (IPCC), Retrieved from URL https://www.ipcc.ch/report/ar6/wg2/chapter/chapter-4/

JMA. 2024. Search on weather history archive. Meteorological Agency Japan, Retrieved from URL https://www.data.jma.go.jp/stats/etrn/index.php

Kell, S.G. 1975. Density, thermal expansivity, and compressibility of liquid water from 0. deg. to 150. deg. correlations and tables for atmospheric pressure and saturation reviewed and expressed on 1968 temperature scale. Journal of Chemical and Engineering Data, 20, 1, 97-105, Retrieved from DOI https://doi.org/10.1021/je60064a005

Kohler, A.M. and Linsley, K.R. 1951. Predicting the runoff from storm rainfall. Research Paper 34, Weather Bureau, Department of Commerce, Washington D.C., USA, Retrieved from URL https://www.nrc.gov/docs/ML0819/ML081900279.pdf

MLIT. 2024. Digital national land information (Administrative division data). Ministry of Land, Infrastructure, Transport and Tourism Japan, Retrieved from URL https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-N03-2024.html

Nakamura, T., Shigematsu, S. and Tokuoka, T. 2001. Late quaternary sediments of the Yumigahama sandbar, Tottori Prefecture, southwest Japan. Geoscience Rept. Shimane University, 20, 189-194, Retrieved from DOI https://doi.org/10.24568/6101