Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

p-ISSN: 0972-6268
(Print copies up to 2016)
e-ISSN: 2395-3454

Vol. 23 | No. 3 | pp. 1559-1568 | 2024

Original Research Paper

https://doi.org/10.46488/NEPT.2024.v23i03.025

Open Access Journal

Estimation of Surface and Groundwater Interaction by Stable Isotopic Techniques – A Case Study of Chengalpattu District, OMR Region

Surendar Natarajan
Sri Sivasubramaniya Nadar College of Engineering (SSN CE), Department of Civil Engineering, Kalavakkam-603110, Tamil Nadu India
†Corresponding author: Surendar Natarajan; surendarn@ssn.edu.in, surendarnatarajan86@gmail.com

Nat. Env. & Poll. Tech.
Website: www.neptjournal.com

Received: 10-01-2024
Revised: 13-02-2024
Accepted: 14-02-2024

Key Words:
Stable isotopes
OMR region
GMWL
LMWL
Surface-groundwater interaction

ABSTRACT

Isotopes are atoms of an element having the same atomic number but different mass numbers. Isotopes in hydrology and water resources are used for identifying its occurrence, movement, residence times, recharge, and discharge process. Stable isotopes of hydrogen(δ^2H) and oxygen(δ^2O) are used for identifying the surface and groundwater interactions as they constitute hydrogen and oxygen. In this study oxygen and hydrogen stable isotopes are used to identify surface and groundwater interaction in Old Mahabalipuram Road (OMR) regions of Chengalpattu district. The precipitation, lake, surface, and groundwater were collected during pre-monsoon, monsoon, and post-monsoon seasons. The collected sample is analyzed for stable isotopic compositions of oxygen and hydrogen seasonal-wise. The measured stable isotopic compositions during pre-monsoon season of stable oxygen are -4.29 to -2.00 and stable hydrogen are -29.39 to -24.67. The isotopic compositions during monsoon season range from -4.72 to -4.00 and for hydrogen ranges from -29.39 to -23.50. During monsoon season the depletion of isotopic composition is seen and the enrichment of isotopic composition is observed during pre-monsoon season. The variation in stable isotopic composition of oxygen and hydrogen are observed. A Groundwater Water Meteoric Water Line (GMWL) is developed for the study area, and it is compared with a Local Meteoric Water Line (LMWL) for better interpretation of the results. A slight deviation is observed from that of GMWL to LMWL mostly due to isotopic depletion and evaporation effects. From the analysis, a good correlation exists between precipitation and surface water in the study area indicating about recharge mechanism existing in the study area. The groundwater recharge is observed during monsoon seasons and discharge is more towards the pre-monsoon seasons.

INTRODUCTION

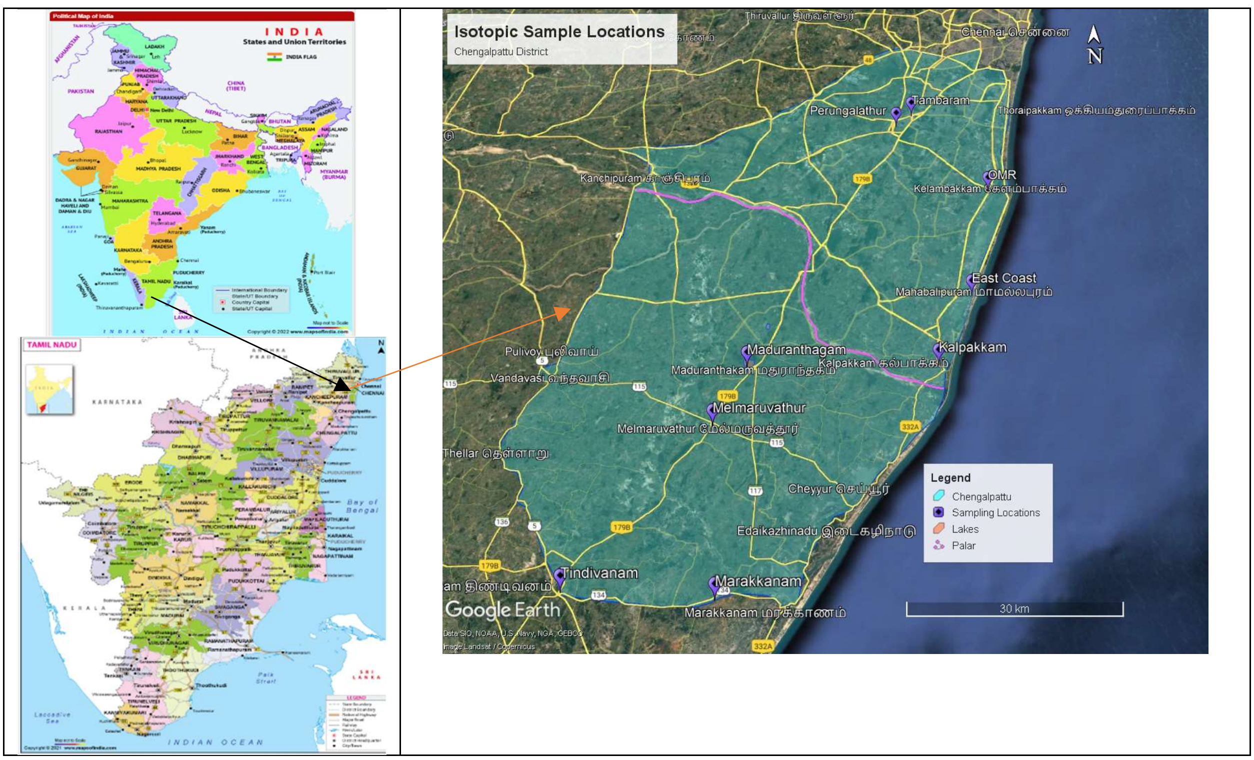
The most crucial problem these days in the world is water scarcity due to population and economic growth. So, it necessitates identifying the water resources, their origin movement, and recharge processes (Greve et al. 2018, Herrera-Franco et al. 2020). The surface and groundwater resources interactions are necessary to study the hydrological cycle and water budget in a watershed (Sophocleous 2002). Knowledge of finding water path, movement, origin, distribution, surface, and groundwater interaction will give a clear knowledge of existing water resources (Esam Ismail et al. 2022). The utilization of excess surface water and groundwater pumping will influence the surface and groundwater interaction in the form of recharge and discharge. The excessive utilization of these water resources leads to a decline in water quality (Chen et al. 2007). The extensive irrigation and industrial activities also decrease the surface and groundwater in arid and semi-arid regions spatially. This extensive use in turn affects the water resources and its effects are seen in the ecological systems. The surface and groundwater interaction not only affects the quantity but also the quality (Zhang et al. 2016).

In some places, sewage water and artificial recharge pollute the surface and groundwater. Excess water utilization, pollution, and continuous irrigation will have an impact on surface and groundwater. This excess water usage necessitates identifying new water resources for better water management. The surface and groundwater interaction can be estimated by various methods like numerical modeling (Ala-aho et al. 2015), seepage meters (Ala-aho et al. 2013), environmental tracers (Wright & Novakowski 2019) or by integrating any of these methods.

In recent times environmentally stable isotopic techniques have been used for identifying water origin, movement, climate change, surface, and groundwater interaction (Jassas & Merkel 2015, Dar et al. 2021, Krishan et al. 2022, Boosalik et al. 2022). Stable oxygen and hydrogen are water-containing stable isotopes($\delta^{18}O$, $\delta^{2}H$) that show spatial and temporal variations due to the isotope fractionation which makes changes in the water cycle and its diffusion stages (Gibson et al. 2005). Stable isotopes use the tracing principle, which transforms the relationship between surface and groundwater. Various isotopic studies were done by researchers globally and nationally to identify the water resources. In Tianshan Mountain, the relationship between climatic conditions and water resources is studied on a large scale by stable isotopes (Fan et al. 2022). In North-Central Chile, Grande River basin the isotopic composition in surface and groundwater interactions are studied by Ricardo Oyarzún et al. 2016. The unique gradient is developed for each parameter if there exists a surface and groundwater interaction (Gardner 1999). In Northern Finland, in glaciofluvial aquifers large data sets of stable isotopes are used for determining contamination due to land use. They also found that shallow groundwaters are also susceptible to contamination (Yapiyev et al. 2023). The changes in surface and groundwater interaction by using stable isotopes of oxygen $\delta^{18}O$ and $\delta^{2}H$ hydrogen were studied in Xiong a new area by Zhu et al. 2019. The factors affecting the stable isotopes in precipitation with respect to surface and groundwater recharge process in the Shwan sub-basin northeast, Iraq were studied by adopting stable oxygen and hydrogen (Al-Gburi et al. 2022). At the Indian level, the limited isotopic studies were studied as discussed. In Yamuna River, the surface and groundwater interactions were identified by stable isotopic techniques and developed an LMWL (Krishan et al. 2017). For identifying the water resources and aquifer dynamics in Gangetic basins stable isotopes of ($\delta^{2}H$, $\delta^{18}O$) and $\delta^{13}C_{TIC}$ were the tools used (Manoj Kumar et al. 2019).

Motivation of the Study

The excess utilization of surface and groundwater in OMR regions in Chengalpattu district threatens the existing water resources in this region. So, it necessitates to study of the surface and groundwater interaction by stable isotopic techniques. Urbanization and IT industries, cause more settlements in the OMR region making more surface and groundwater utilization. This enhances to identification of the surface and groundwater resources and their interactions in the study area for better management of existing water resources. Based upon the existing condition in the study area the objectives of the study are framed accordingly.



(Source -Map of India)

Fig. 1: Study area - OMR and its selected areas, India and Tamil Nadu Map.

This publication is licensed under a Creative Commons Attribution 4.0 International License

Objectives of the Study

- To study isotopic compositions in precipitations for various seasons in the study area.
- To identify the surface and groundwater interaction, recharge resources in the OMR region.
- To recommend suitable water harvesting structures in the study area.

MATERIALS AND METHODS

Study Area

Chengalpattu district is known as the lake district bounded by north to Chennai city, to the west by Kanchipuram district as shown in Fig.1

The southern part of the district is surrounded by Villupuram and Tiruvannamalai district. The northeast part of the district is surrounded by the east coast and the coastal line of the district extends up to 57 km. The study area experiences tropical wet and dry climates. The average annual rainfall of the district is 1400 mm and most of the rainfall is received during the Northeast monsoon season. In this study, the east coast part of Chengalpattu district is concentrated as most of the developmental activities are happening around the Old Mahabalipuram Road (OMR) region. The major river that flows through the district is Palar. The few residual hills like St. Thomas Mount, Thirukalukundram, and Vandalur are found in the district. The granite, gneiss, sandstone, and marine deposits are found throughout the district.

Methodology

The methodology adopted for the present study is shown in Fig. 2. The methodology involves data collection, analysis, and discussions as explained in.

Data Collection

The data involved in the study are a collection of spatial and temporal data. The spatial data includes the satellite images collected from the USGS website. The temporal data used are precipitation, surface water, and well water samples that are collected seasonally like pre-monsoon, monsoon, and post-

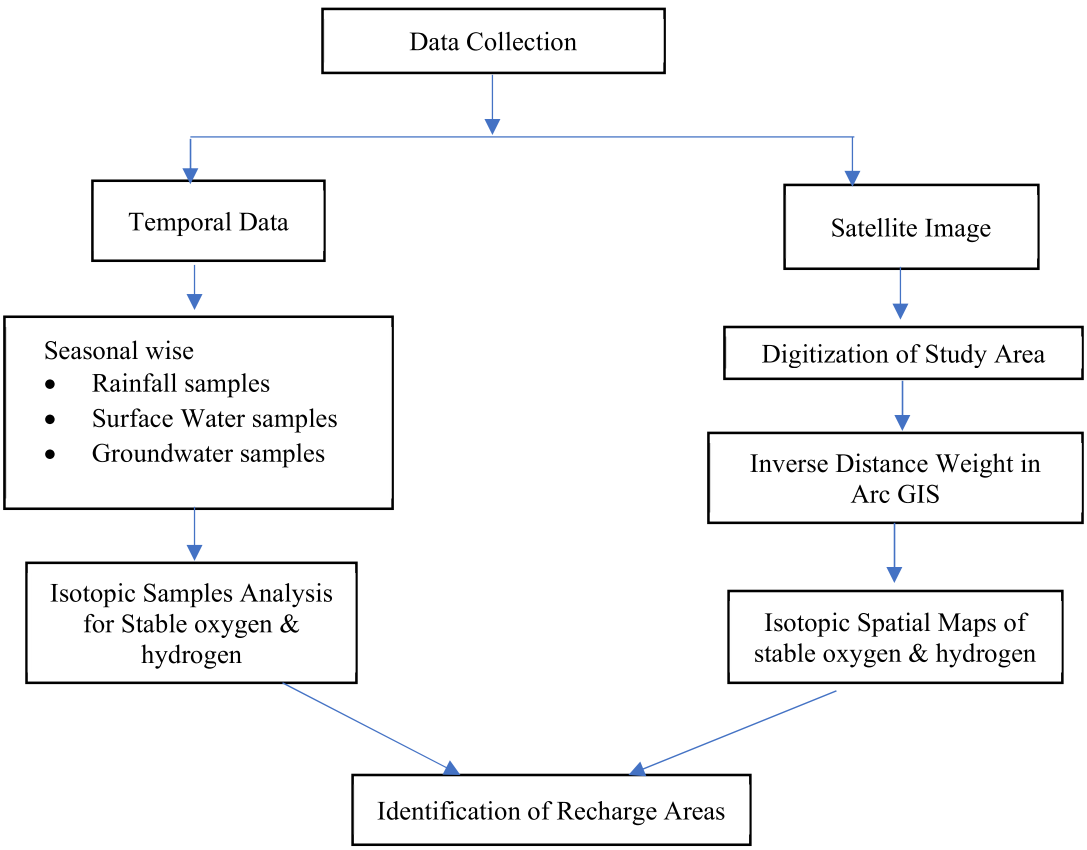


Fig. 2: Proposed methodology of the study.

This publication is licensed under a Creative Commons Attribution 4.0 International License

Fig. 3: Collecting water samples-Thiruporur lake.

monsoon seasons. The collected water samples were analyzed in a continuous stable isotopic mass spectrometer and dual spectrometer at the Centre for Water Resources Development Management (CWRDM) Kozhikode. The limited number of precipitation and surface water samples are collected during the pre-monsoon season due to its availability.

Stable Oxygen and Hydrogen Isotopic Analysis

The precipitation, lake water, and well water samples were collected at selected locations in the OMR region namely Kelambakkam, Thaiyur, and Illalore during the pre-monsoon, monsoon, and post-monsoon seasons as shown in Fig. 3. The water samples were collected in 60 mL High-Density Polyethylene (HDPE) bottles for identifying stable oxygen and hydrogen isotopes as shown in Fig. 3. For δ^2H analysis 1 mL of water sample was kept in equilibrium condition and mixed with hydrogen gas at 50°C with P_t catalyst for 1 h. The mixed hydrogen gas was introduced into the mass spectrometer for stable hydrogen analysis. Similarly, for measuring stable oxygen 1 mL of water is kept at equilibrium condition along with carbon-di-oxide gas at 50°C for 8 hours. Then the gas kept at equilibrium condition was introduced into the mass spectrometer for stable oxygen analysis. The result analysis is reported in δ notation as the deviations are related to standard, V-SMOW (Vienna-Standard Mean Ocean Water) in units of parts per thousand (denoted as %). The δ values are calculated by Equation (1) given below.

$$\delta\% = \left(\frac{Rx}{Rs} - 1\right) \times 1000 \qquad \ldots(1)$$

Here R denotes the ratio of heavy to light isotope. R_x and R_s are the ratios in the sample and standards respectively. The precision of measurement for δ^2H is ± 0.5 % and δ^{18}O is ± 0.1%.

RESULTS AND DISCUSSION

Stable Isotopes in Water Samples

The obtained isotopic analysis for the OMR region is shown in Table 1 which projects the latitude and longitude details as well as the volume of samples used for analyzing isotopic signatures. Limited surface and rainwater samples are collected due to lack of rainfall. The Local Meteoric Water Line (LMWL) is compared with the existing LMWL of the nearby region. The deviation of LMWL with nearby regions gives the isotopic pattern distributions. There is also a seasonal variation of isotopic compositions observed during the study period. Throughout the pre-monsoon season analysis, the average spatial isotopic signatures of oxygen and hydrogen in the lake water are from -2.9 to -21.7, and for the well water, it ranges between -2.57 to -25.8. A depletion of stable isotopes was also seen in the samples collected during the monsoon season. The oxygen and hydrogen isotopes in the well water samples during the monsoon season range from -3.5 to -25.2. Similarly, in the wells, the stable isotopic compositions of oxygen and hydrogen are between -2.6 to -22.7.

In the case of post-monsoon season, a difference in isotopic compositions is observed in the well as well as the lake water. The average isotopic composition in the

This publication is licensed under a Creative Commons Attribution 4.0 International License

Table 1: Isotopes in water samples-pre-monsoon season.

Sample	Latitude	Longitude	$\delta^{18}O$	$\delta^{2}H$	Source of sample	Volume/ quantity of sample supplied(mL/mg)
Taiyur Well -1	12.75	80.219	-3.1	-21.7	Well water	60 mL/mg
Tirupur tank Water-1	12.76	80.22	-2.9	-20.9	Lake water	60 mL/mg
Well, no-3	12.77	80.201	-2.7	-18.1	Well water	60 mL/mg
Well, no -9	12.78	80.184	-3.3	-20.3	Well water	60 mL/mg
Well-10	12.79	80.16	-3	-21.1	Well water	60 mL/mg
Well-12	12.80	80.139	-4.3	-25.8	Well water	60 mL/mg
Precipitation	-	-	-	-		

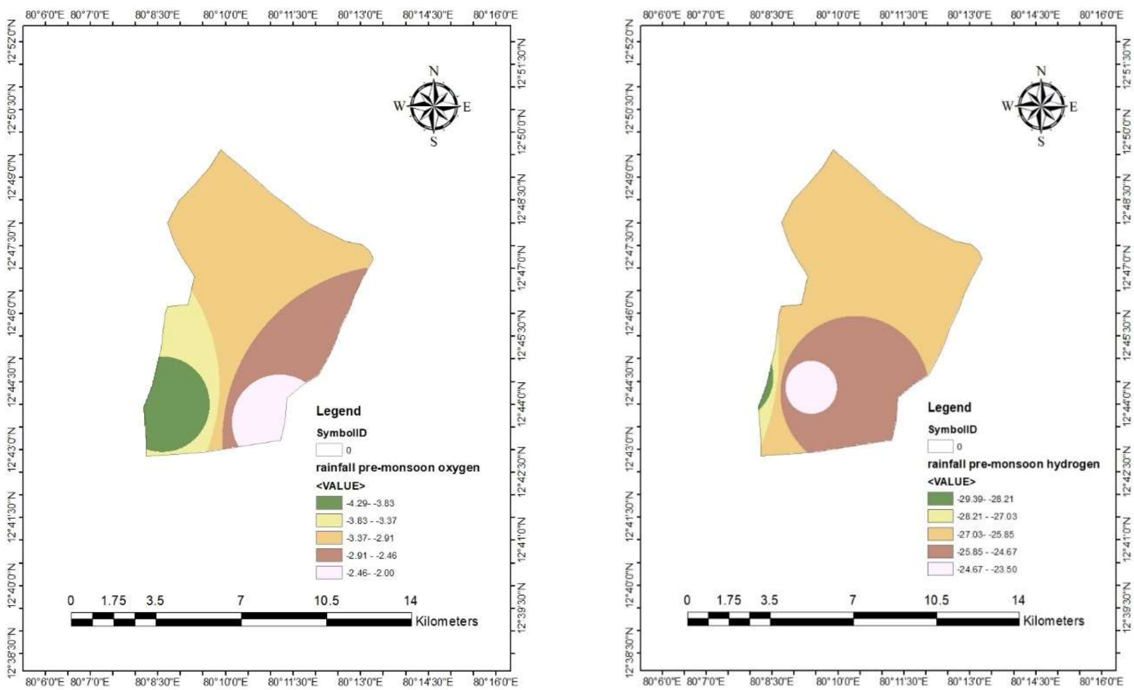


Fig. 4: Stable isotopic composition of rainfall (a) oxygen &(b) hydrogen-post-monsoon season.

well water samples ranges from -3.3 to -21.8. The spatial distribution of stable oxygen and hydrogen isotopic composition in precipitation during monsoon season is created through the Inverse Distance Weight (IDW) method in Arc-GIS as shown in Fig. 4.

The isotopic composition in any region is governed by the water vapor transport process and the moisture air masses present in the precipitation. The observed enrichment and depletion of isotopic composition is due to the coastal influence and evaporation effects that exist in the study area. From the analysis of stable oxygen and hydrogen, the LMWL is developed for the study area. A linear equation of isotopic composition is developed for the study area as given below in equation (2)

$$\delta^2 H = 8\, \delta^{18}O + 35 \qquad \ldots(2)$$

The developed LMWL is compared to the Ground Water Meteoric line and Surface Water Meteoric line. The meteoric water lines show a slighter deviation from the LMWL that indicates a fall in precipitation and has undergone slighter evaporation. The reason for the lower slope of the meteoric water line is due to variations in climatic conditions. The climatic variations can be identified through Deuterium excess which is used for characterizing the origin of water vapor from the precipitation. The developed Deuterium excess is given in equation (3). The d-excess values for the study area range from (+-5%).

$$d - excess\ (\%) = \delta^2 H - 8xd^{18}O \qquad \ldots(3)$$

If there exists a low d-excess in precipitation it reflects the slower evaporation due to high humidity that prevails in the OMR region. If less humidity means, there exists a high

This publication is licensed under a Creative Commons Attribution 4.0 International License

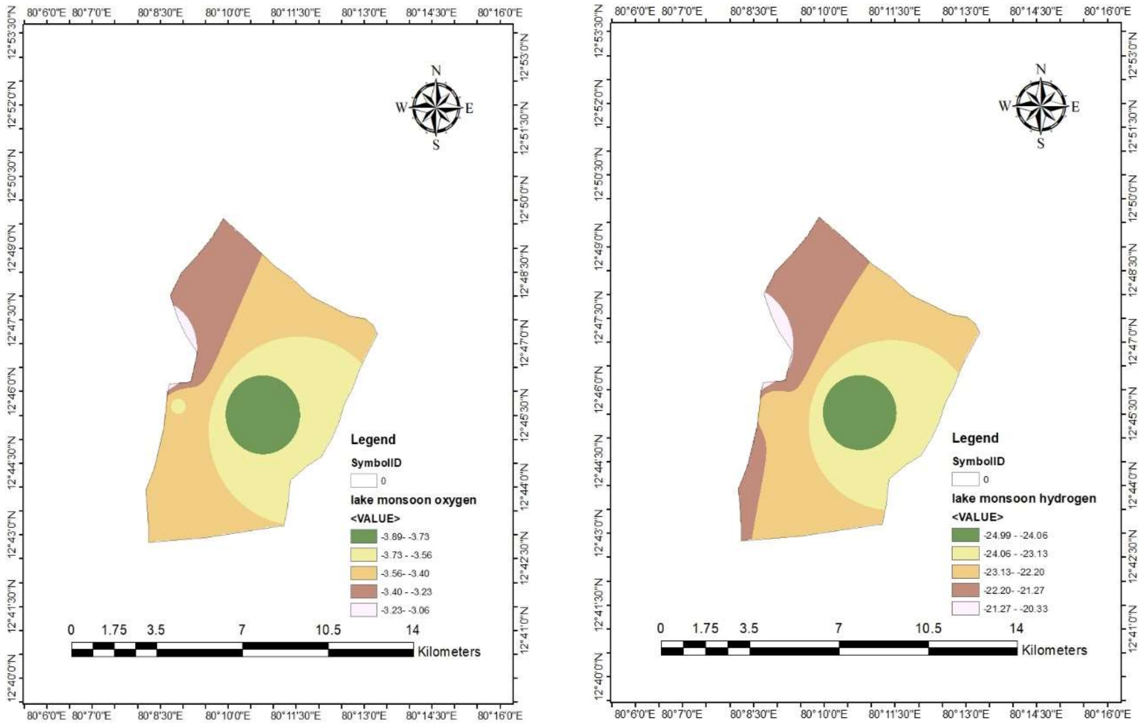


Fig. 5: Stable isotopic composition in Lake water (a) oxygen (b) hydrogen monsoon season.

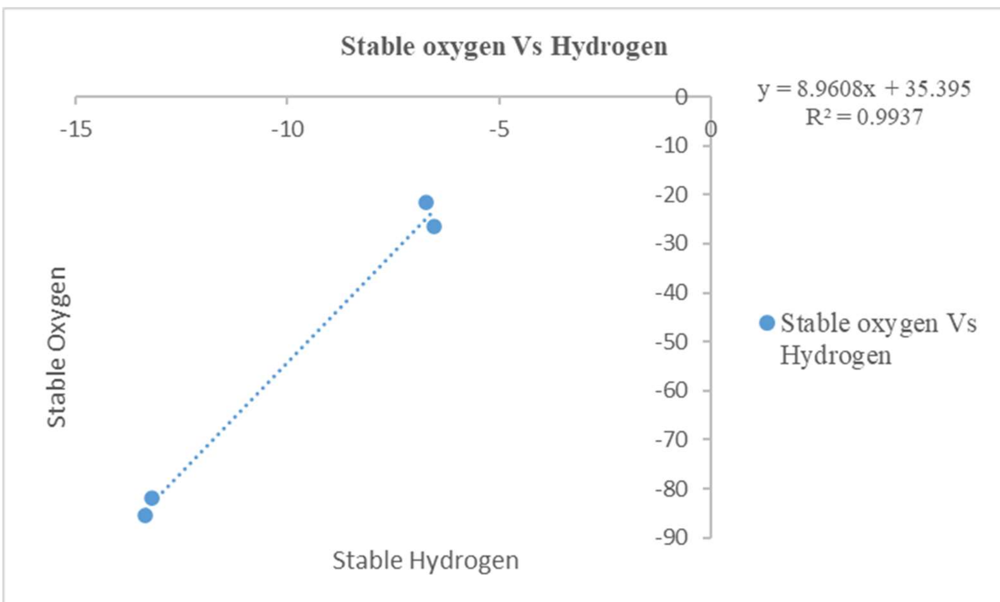


Fig. 6: Derived relation between $\delta^{18}O$ and $\delta^{2}H$ in rainfall.

evaporation. The spatial variation of isotopic composition in lake water during the various seasons is shown in Fig. 5.

The monsoon season for the OMR region usually starts from the Southwest and ends in the Northeast monsoon season. The southwest monsoon season contributes only 10% of the rainfall of annual precipitation. The remaining 90% of rainfall is received during the Northeast monsoon seasons. The source of precipitation during the Northeast Monsoon

This publication is licensed under a Creative Commons Attribution 4.0 International License

season is from the Bay of Bengal due to cyclonic depressions. The weighted stable isotopic compositions during Northeast monsoon ranges from -2.6% to -17.6% with d excess value of 8± to 0.5±. The contribution of rainfall during the southwest monsoon is less and enrichment of isotopic composition is observed in the rainfall. Since the rainfall process of the southwest monsoon is from the Arabian Sea and the Indian Ocean.

The general reasons for stable isotope enrichment and depletion are due to the seasonal reversal of temperature and pressure gradients and its associated wind circulation patterns. If a negative correlation exists between $\delta^{18}O$ it will result in heavy rainfall, and it is termed an amount effect. The derived relationship between $\delta^{18}O$ and $\delta^{2}H$ in the rainfall is shown in Fig. 6. From the analysis it is observed that some samples show a good correlation of isotopic composition of rainfall collected during the northeast monsoon season. The best-fit line equation generated between the stable oxygen and hydrogen is given below. The average rate of depletion of stable isotopes is found to be –6 % to -80%.

Isotopic Compositions in Surface and Groundwater

The lake water samples collected during post-monsoon seasons show maximum enrichment of stable oxygen and hydrogen isotopes with an average of -3.5% to -22.5%. The rainfall samples of the post-monsoon season were not collected because of non-occurrence of rainfall. The mean stable oxygen and hydrogen isotopes of groundwater samples analyzed for post-monsoon season range from -3.48 % and -22.57%. The variations of stable isotopes are observed in surface and groundwater samples during the post-monsoon seasonal analysis. This shows that there is a contribution of surface water to groundwater in the post-monsoon season. The derived distribution of stable oxygen and hydrogen isotopes in the water samples is shown in Fig. 7. The best-fit line of post-monsoon seasons of isotopic samples for surface water samples is given by equation (4). From the analysis, it is observed that the meteoric water line deviates from LMWL and has a lower slope indicating an existence of evaporation in the surface water during pre-monsoon season. There is not much deviation observed in the best-fit line during the monsoon season which indicates groundwater recharge that is happening from the surface water. This shows that the lake water, groundwater, and rainfall have the same meteoric origin and isotopic composition despite the evaporation. The deviation of the slope is lesser when there occurs a mixing of surface and groundwater, and a difficult process to differentiate between these two mixing processes. For a better understanding of the recharge process between surface and groundwater, it is necessary to assess the enrichment and depletion of stable isotopes.

$$\delta^2 H = 3\, \delta^{18}O - 4 \quad \ldots(4)$$

Identification of Surface and Groundwater Interaction

The mixing model is used to estimate the recharge between precipitation, surface, and groundwater. The assumptions

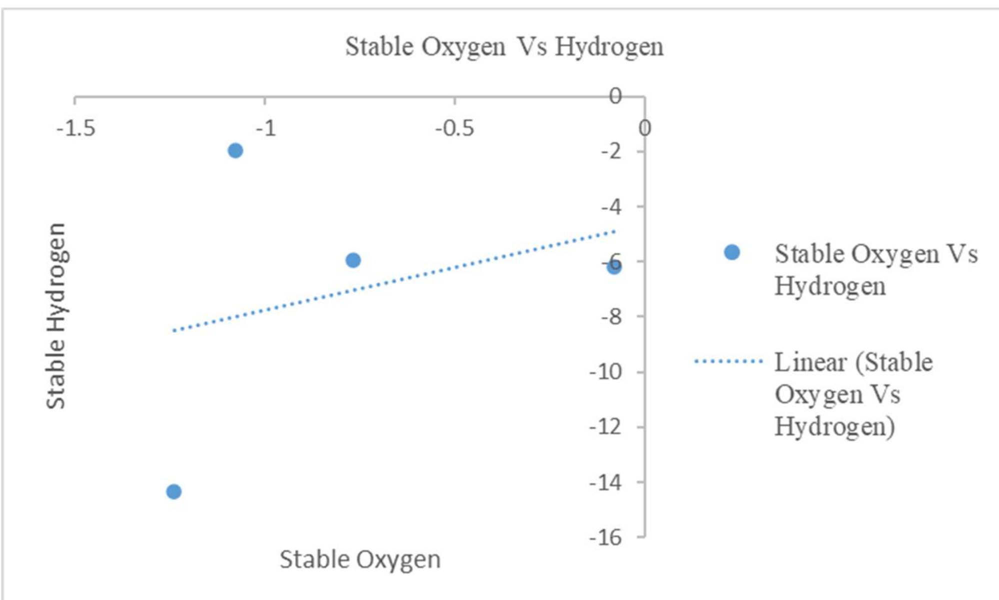


Fig. 7: Distribution of stable $\delta^{18}O$ and $\delta^{2}H$ in Lake water.

This publication is licensed under a Creative Commons Attribution 4.0 International License

made in this model are that both surface and groundwater should have the same isotopic composition and mix conservatively. The percentage of recharge from surface to groundwater is estimated from the equation (5) and (6).

$$X\% = \frac{(\delta^{18}O_g - \delta^{18}O_p)}{(\delta^{18}O_{sl} - \delta^{18}O_p)} 100 \quad \ldots(5)$$

$$\delta^2 H = 1.6\, \delta^{18}O - 13.4 \quad \ldots(6)$$

Where $\delta^{18}O_g$, $\delta_{18}O_p$, and $\delta_{18}O_{st}$ represent $\delta_{18}O$ of groundwater, precipitation, recharged groundwater, and surface water from lake recharge water respectively. The average of $\delta_{18}O_{sl}$ for surface water and $\delta_{18}O_p$ is taken for the mixing model calculation to identify the influences of surface water on the groundwater. Slight evaporation is seen during the recharge process since more humidity is seen in the study area. The surface and groundwater relation in the form of a best-fit line is shown in Fig. 8. The surface and groundwater mixing happens in the study area as a process of recharge which is inferred through stable oxygen and hydrogen isotope variations. In some places there is less contribution from surface water to groundwater is also observed because of the higher electrical conductivity. If the groundwater is brackish then exists a higher electrical conductivity. The less electrical conductivity indicates a process of recharging.

The analysis of isotopic enrichment and depletion in the mixing model indicates there exists an interaction between rainfall, surface water, and groundwater. The percentage of recharge from surface water to groundwater is around 30%. The recharge percentage from lake to well water depends upon the distance from the lake and the existing geological conditions in OMR regions. Further enhancing the water recharging process, it is also recommended to rehabilitate the existing lakes in the study area.

CONCLUSIONS

In this study, the environmentally stable isotopes are applied to identify the surface and groundwater recharge in OMR regions of Chengalpattu district. Initially, the isotopic characteristics in rainfall, lake water, and well water samples were analyzed season-wise. The variations of isotopic signatures were observed in collected water samples. The enrichment of stable oxygen and hydrogen isotopes is observed during the pre-monsoon season and the depletion of isotopic composition is observed during the post-monsoon season. The average enrichment of isotopic composition in surface water ranges from -3.48 to -21.92. The isotopic composition in the rainfall during the post-monsoon season shows an enrichment of isotopic composition. This is due to the southwest monsoon season as its moisture originates from the Arabian Sea and Indian Ocean. The southwest monsoon rainfall contribution from surface to groundwater recharge is less when compared to the Northeast monsoon season. The depletion of isotopic composition is observed during the monsoon season. During the Northeast monsoon season, the moisture for rainfall originates from the Bay of Bengal which brings more rainfall and depletes isotopic composition in the study area. There exists a strong correlation between stable isotopic composition of the precipitation during

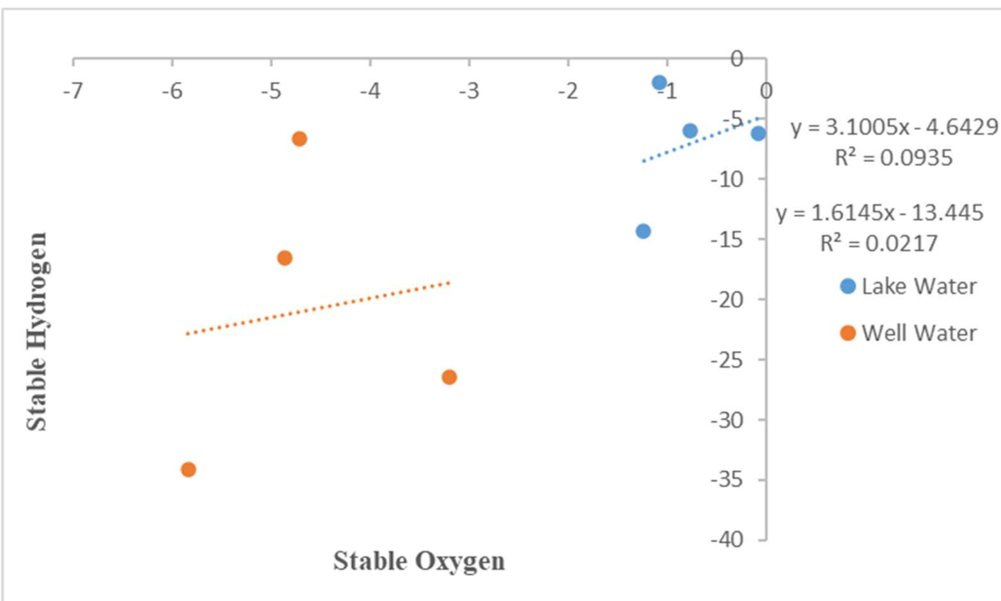


Fig. 8: Surface and groundwater interaction (a) pre-monsoon season.

This publication is licensed under a Creative Commons Attribution 4.0 International License

Northeast monsoon season which indicates the recharge is from rainfall to groundwater. The inferences observed from the study are discussed below.

Inferences from the Study

- The analyzed isotopic data indicates two sources of groundwater recharge, one is directly from precipitation and the other one is from the nearby lakes.
- The observed isotopic compositions show that groundwater recharge mostly occurs during North-East monsoon season.
- The lower slope of the GWML line indicates the existence of evaporation in the study area.

Future Scope of the Study

- The climatic conditions during enrichment and depletions of isotopic studies should be studied.
- The origination of precipitation and its moisture content should be studied through stable isotopic composition.
- The more precipitation, surface and groundwater samples should be collected spatially for more years.
- The irrigation return flow of the study area should also be considered.
- For better estimation of surface and groundwater interaction, an integrated approach like an electrical resistivity survey should be done for identifying groundwater potential zones.

ACKNOWLEDGMENTS

This work was done through the Internal Faculty Funded Project (IFFP-2021) sponsored by SSN Trust. The author extends thanks to CWRDM Calicut for isotopes analysis and the USGS website for providing satellite data free of cost. The author also extends thanks to the reviewers for reviewing the manuscript.

REFERENCES

Ala-aho, P., Rossi, P. M. and Kløve, B. 2015. Estimation of temporal and spatial variations in groundwater recharge in unconfined sand aquifers using Scots pine inventories. Hydrol. Earth Syst. Sci., 19(4): 1961-1976. https://doi.org/10.5194/hess-19-1961-2015

Ala-aho, P., Rossi, P. M. and Kløve, B. 2013. Interaction of esker groundwater with headwater lakes and streams. J. Hydrol., 500: 144-156. https://doi.org/10.1016/J.JHYDROL.2013.07.014

Boosalik, Z., Jafari, H., Clark, I. D. and Bagheri, R. 2022. Chemo-isotopic tracing of the groundwater salinity in arid regions: An example of Shahrood aquifer (Iran). J. Geochem. Explor., 239: 107029.

Chen, Y., Li, J., Chen, W.-H., Chen, Y.-I., Liu, J.Z. and He, B. 2007. Ecological effect of synthesized governing in Tarim River valley. China Environ. Sci., 27: 24-28.

Dar, F. A., Jeelani, G., Perrin, J. and Ahmed, S. 2021. Groundwater recharge in semi-arid karst context using chloride and stable water isotopes. Groundw. Sustain. Dev., 14: 100634. doi:10.1016/j.gsd.2021.100634.

Ismail, E., Abdelhalim, A., Ali, A., Ahmed, M. S., Scholger, R. and Khalil, M. M. 2022. Isotopic, geophysical, and hydrogeochemical investigations of groundwater in west middle upper Egypt. ACS Omega. https://doi.org/10.1021/acsomega.2c05387

Fan, Y., Wu, Y., Wang, Y., Jiang, S., Yu, S. and Shang, H. 2022. An analysis of surface water–groundwater interactions based on isotopic data from the Kaidu River Basin, South Tianshan Mountain. Water, 14: 2259. https://doi.org/10.3390/w14142259

Gardner, K. M. 1999. The importance of surface water groundwater interactions. Issue paper; Environmental Protection Agency, Seattle.

Gibson, J. J., Edwards, T. W. D., Birks, S. J., St Amour, N. A., Buhay, W. M., McEachern, P., Wolfe, B. B. and Peters, D. L. 2005. Progress in isotope tracer hydrology in Canada. Hydrol. Process, 19: 303-327.

Krishan, G., Singh, S., Sharma, A., Sandhu, C., Kumar, S., Kumar, C. P. and Gurjar, S. 2017. Assessment of river Yamuna and groundwater interaction using isotopes in Agra and Mathura area of Uttar Pradesh, India. Int. J. Hydro., 1(3): 86-89.

Greve, P., Kahil, T., Mochizuki, J., Schinko, T., Satoh, Y., Burek, P., Fischer, G., Tramberend, S., Burtscher, R. and Langan, S. 2018. Global assessment of water challenges under uncertainty in water scarcity projections. Nat. Sustain., 1: 486-494.

Herrera-Franco, G., Carrión-Mero, P., Aguilar-Aguilar, M., Morante-Carballo, F., Jaya-Montalvo, M. and Morillo-Balsera, M. C. C. 2020. Groundwater resilience assessment in a communal coastal aquifer system. The case of Manglaralto in Santa Elena, Ecuador. Sustainability, 12: 8290.

Al-Gburi, H. F., Al-Tawash, B. S., Al–Tamimi, O. S. and Schüth, C. 2022. Stable isotope composition in precipitation and groundwater of Shwan Sub-Basin, Kirkuk governorate, northeast of Iraq. Water Supply, 22(10): 7442-7459. doi: https://doi.org/10.2166/ws.2022.327

Jassas, H. A. and Merkel, B. J. 2015. Investigating groundwater recharge by means of stable isotopes in the Al-Khazir Gomal Basin, northern Iraq. Environ. Earth Sci., 73: 8533-8546. doi:10.1007/s12665-015-4013-7.

Krishan, G., Rao, M. S., Vashisht, R., Chaudhary, A., Singh, J. and Kumar, A. 2022. Isotopic assessment of groundwater salinity: a case study of the Southwest (SW) Region of Punjab, India. Water, 14(1): 133. doi:10.3390/w14010133

Manoj Kumar, A. L., Ramanathan, A., Mukherjee, A., Sawlani, R. and Ranjan, S. 2019. Delineating sources of groundwater recharge and carbon in Holocene aquifers of the central Gangetic basin using stable isotopic signatures. Isot. Environ. Health Stud., 55(3): 254-271. doi: 10.1080/10256016.2019.1600515

Oyarzún, R., Zambra, S., Maturana, H., Oyarzún, J., Aguirre, E. and Kretschmer, N. 2016. Chemical and isotopic assessment of surface water–shallow groundwater interaction in the arid Grande river basin, North-Central Chile. Hydrol. Sci. J., 61(12): 2193-2204. doi: 10.1080/02626667.2015.1093635

Sophocleous, M. 2002. Interactions between groundwater and surface water: The state of the science. Hydrogeol. J., 10: 52-67.

Wright, S. N. and Novakowski, K. S. 2019. Groundwater recharge, flow, and stable isotope attenuation in sedimentary and crystalline fractured rocks: Spatio-temporal monitoring from multi-level wells. J. Hydrol., 571: 178-192. https://doi.org/10.1016/j.jhydrol.2019.01.028

Yapiyev, V., Rossi, P. M., Ala-Aho, P. and Marttila, H. 2023. Stable water isotopes as an indicator of surface water intrusion in shallow aquifer wells: A cold climate perspective. Water Resour. Res., 59. https://doi.org/10.1029/2022WR033056

Zhang, B., Song, X., Zhang, Y. et al. 2016. The interaction between surface water and groundwater and its effect on water quality in the Second Songhua River basin, northeast China. J. Earth Syst. Sci., 125: 1495-1507. https://doi.org/10.1007/s12040-016-0742-6

This publication is licensed under a Creative Commons Attribution 4.0 International License

Zhu, M., Wang, S., Kong, X., Zheng, W., Feng, W., Zhang, X., Yuan, R., Song, X. and Sprenger, M. 2019. Interaction of surface water and groundwater influenced by groundwater over-extraction, wastewater discharge and water transfer in Xiong'an new area, China. Water, 11(3): 539. https://doi.org/10.3390/w11030539

ORCID DETAILS OF THE AUTHORS

Surendar Natarajan: https://orcid.org/0000-0002-6545-8544

This publication is licensed under a Creative Commons Attribution 4.0 International License