Bulletin of the Geological Society of Malaysia, Volume 81, May 2026, pp. 71 - 83
DOI: https://doi.org/10.7186/bgsm81202607

Baseline study of surface and groundwater quality in response to groundwater recharge potential

Lakam anak Mejus[1,*], Ismail bin Tawnie[2], Azrul Normi bin Idris[2], Mohd Muzamil bin Mohd Hashim[1], Mohamad Syahiran bin Mustaffa[1], Engku Fahmi bin Engku Chik[1]

[1] Malaysian Nuclear Agency, Waste Technology and Environment Division, Environmental Tracer Application Group, Bangi, 43000 Kajang, Selangor, Malaysia
[2] National Water Research Institute of Malaysia (NAHRIM), Lot 5377, Jalan Putra Permai, 43300 Seri Kembangan, Selangor, Malaysia
* Corresponding author email address: lakam@nm.gov.my

Abstract: The growing demand for water in some parts of Malaysia has resulted in the use of groundwater resources as an alternative water supply. Moreover, the expenses for water supply treatment have recently increased, and water management authorities must increase their water tariffs. To address these challenges, flood mitigation ponds are being upgraded to dual-function ponds to store water resources. However, the impact of dual-function ponds on naturally stabilizing or improving water quality remains largely unexplored in the existing literature. This study aims to address this gap by presenting baseline data on water resource quality during the construction of a dual-function pond, with the goal of establishing a long-term database to support the successful implementation of such ponds. The selection of a suitable dual-function pond site was based on preferable geological conditions. A 3D hydrogeological block model was constructed to characterize a heterogeneous alluvial aquifer system within a portion of the Melaka River Basin. Water samples, including surface water, groundwater, and precipitation, were collected and analysed for their isotopic signatures and chemical properties. The baseline results indicated that a high volume of precipitation within short time frames leads to increased runoff and reduced groundwater recharge. Isotopic analysis revealed a depletion of ^{18}O and ^{2}H at the proposed pond location, with enrichment observed in the southern part of the Melaka River, suggesting a preferential sourcing of river water from isotopically heavier wet season precipitation or water enriched by evaporation from storage in landscapes. Chemical analysis indicated that most heavy metal concentrations were below the maximum allowable limits. Overall, the baseline data suggest that the proposed dual-function pond is suitable for the studied 664 km^2 region, with respect to water quality concerns.

Keywords: Melaka river basin, hydrogeological block model, isotopic signature, chemistry analysis, hydrogeology, Melaka

INTRODUCTION

Malaysia has reliable sources of raw water to accommodate the needs of domestic water supplies and agricultural and industrial use. A 2023 report by the National Water Services Commission (SPAN) reveals that over a three-year period, the number of water treatment plants in Peninsular Malaysia increased from 326 to 342, while water demand rose significantly from 14,944 million liters per day (MLD) to 15,869 MLD (SPAN, 2023). In the future, this figure is likely to increase, and groundwater will become an important water source to meet the increasing requirements of domestic, industrial, and agricultural needs. Some regions in Malaysia are expected to experience water deficits due to changes in land-use patterns and increased urbanization and development, causing the demand for water to exceed available sources. The exponential growth of the human population and the development of agricultural and industrial sectors in recent decades have also caused a sharp increase in nitrogen, sulfur, and carbon loadings to surface water bodies and associated groundwater resources in the region. Water resources, especially groundwater, both in terms of quality and quantity, are deteriorating owing to several factors, such as contributions of untreated chemical effluents from industry, agriculture (pesticides and fertilizers), and domestic sewage. In addition to the direct input of contaminants to water, climate change has also added to water problems. The expected damage will be reflected in water sources, especially groundwater, which is considered an important clean water source in the future. According to a review of groundwater quality in some parts of Malaysia, most borehole monitoring data show an increasing trend in nitrate concentration (Narany *et al*., 2017; Shamsuddin *et al*., 2018; Garba *et al*., 2021).

Underground water storage is commonly used to store excess surface water during periods of high rainfall or river flow. This is for extraction at a later time, during

0126-6187; 2637-109X / Published by the Geological Society of Malaysia.

dry periods, or during times of increased water demand. Numerous studies have documented the success of this approach in improving water quality, mitigating overdrafts, and increasing groundwater levels (Barnett *et al*., 2000; Konikow & Kendy, 2005; Kendy & Bredehoeft, 2006; Reese & Alvarez-Zarikian, 2007; Brown & Misut, 2010; Banerjee & Singh, 2011; Chen *et al*., 2022; Simbo, 2023). Nevertheless, few studies have investigated the impacts of underground water on regional-scale groundwater quality, especially deep aquifers, and at time scales of decades to centuries (Guo *et al*., 2023; Cao *et al*., 2025). Thus, our goal is to draw attention to isotope research to evaluate the sequence of the hydrological cycle model and look for associated repercussions.

Water isotope data can be used for the development, calibration, and validation of atmospheric circulation models. Analysis of water and environmental isotope variability provides fundamental information for hydrological and environmental investigations. A vast amount of research has been documented in the literature (e.g., Vengosh *et al*., 2002; Visser *et al*., 2016; Peters *et al*., 2018; Mejus *et al*., 2021), but a quantification of isotope application to assess the pollution vulnerability of groundwater (for example, Klump *et al*., 2006; Klump *et al*., 2008; Edirisinghe *et al*., 2020; He *et al*., 2022) is not fully and quantitatively considered in Malaysia due to the limitation of isotopic analytic facilities. As a useful indicator of the groundwater renewal rate and residence time, groundwater age is important for understanding the occurrence of contaminants and contaminant trends in aquifers. Organic and inorganic contaminant sources are commonly associated with groundwater recharge (Jankovec *et al*., 2017; Castaldo *et al*., 2021; Carrión-Mero *et al*., 2022). Thus, to gain a better understanding of the possible affected hydrological processes, the integrated use of water, gaseous, and dissolved isotopes has been proposed to provide additional valuable scientific information and contribute to the development, calibration, and application of numerical models for more accurate groundwater pollution risk mapping (e.g., Eberts *et al*., 2012; Jurgens *et al*., 2016).

Numerous experimental, numerical, and analytical studies have been conducted to better understand and predict the concentration of contamination in groundwater. Suitable models have been developed to describe complex phenomena (i.e., the lump parameter model, transport modelling and 3D-hydrological modelling). However, a full understanding of the many processes and mechanisms that influence the hydrological system is still far from satisfactory, as these processes and mechanisms are interrelated. Therefore, the characteristics of groundwater systems related to shallow aquifer vulnerability will be studied through a modelling assessment based on an additional scientific dataset of tritium, noble gases, and other isotopic analyses. The focus of this study is to evaluate the capacity of the Melaka River Basin (e.g., boundaries, storage, contaminant, and seawater intrusion) over multiple seasons and years and to characterize the mixing mechanism of surface and groundwater.

SITE DESCRIPTION

The state of Melaka was selected as the location for a national research initiative to conduct groundwater recharge potential studies (Figure 1a). This study focused on the Melaka River Basin, which provides most of the water supply in the state. The Melaka River Basin, situated in the central part of the state, is serviced by three main tributaries: Tampin, Batang Melaka, and Durian Tunggal rivers. The Melaka River Basin, with a catchment area of approximately 615 km², originates from the northern border of Negeri Sembilan at Batang Melaka. It flows through Alor Gajah, entering a relatively flat terrain before passing through the Durian Tunggal floodplain. The river then meanders through Melaka City before discharging into the Straits of Malacca. Improvements are planned for the current Krubong-Durian Tunggal flood mitigation pond, which will serve as both an operational storage facility for water resources and a flood mitigation pond (NAHRIM, 2022).

The Melaka Basin represents a complex hydrological system heavily shaped by its surface water reservoirs, particularly the Durian Tunggal and Jus reservoirs. These reservoirs are essential for regulating surface water flow through the basin's drainage network and for contributing to groundwater recharge. The Durian Tunggal Reservoir, located in central Melaka, is a key source of potable water that supports agricultural irrigation. Managing surface water flow ensures consistent water supply during dry periods and reduces flood risks during heavy rainfall. Similarly, the Jus Reservoir, situated in the northern part of the basin, plays a pivotal role in water resource management by controlling the flow of water to rivers and streams within the network (Aqvaspace Sdn Bhd., 2018; Hua, 2019).

Beyond their role in water regulation, these reservoirs also promote aquifer recharge. The controlled release of water facilitates gradual infiltration into the ground, replenishing groundwater reserves essential for the sustainability of the Melaka Basin. This integrated water management approach meets the diverse needs of both urban and rural areas while maintaining an ecological balance. In addition to their functional roles, reservoirs provide recreational amenities and support local biodiversity, highlighting their broader environmental and social value. Ensuring their effective operation through continuous monitoring and proactive management is vital for maintaining the hydrological and ecological integrity of the basin (Hua, 2019).

The geology of Melaka is characterized by five primary lithological units, each of which reveals distinct insights into the geological evolution of the region. Acid intrusive, predominantly granite and other silica-rich igneous rocks, dominate the landscape. These formations are indicative of significant magmatic activity during the Mesozoic era, aligning with granitoid occurrences observed elsewhere in

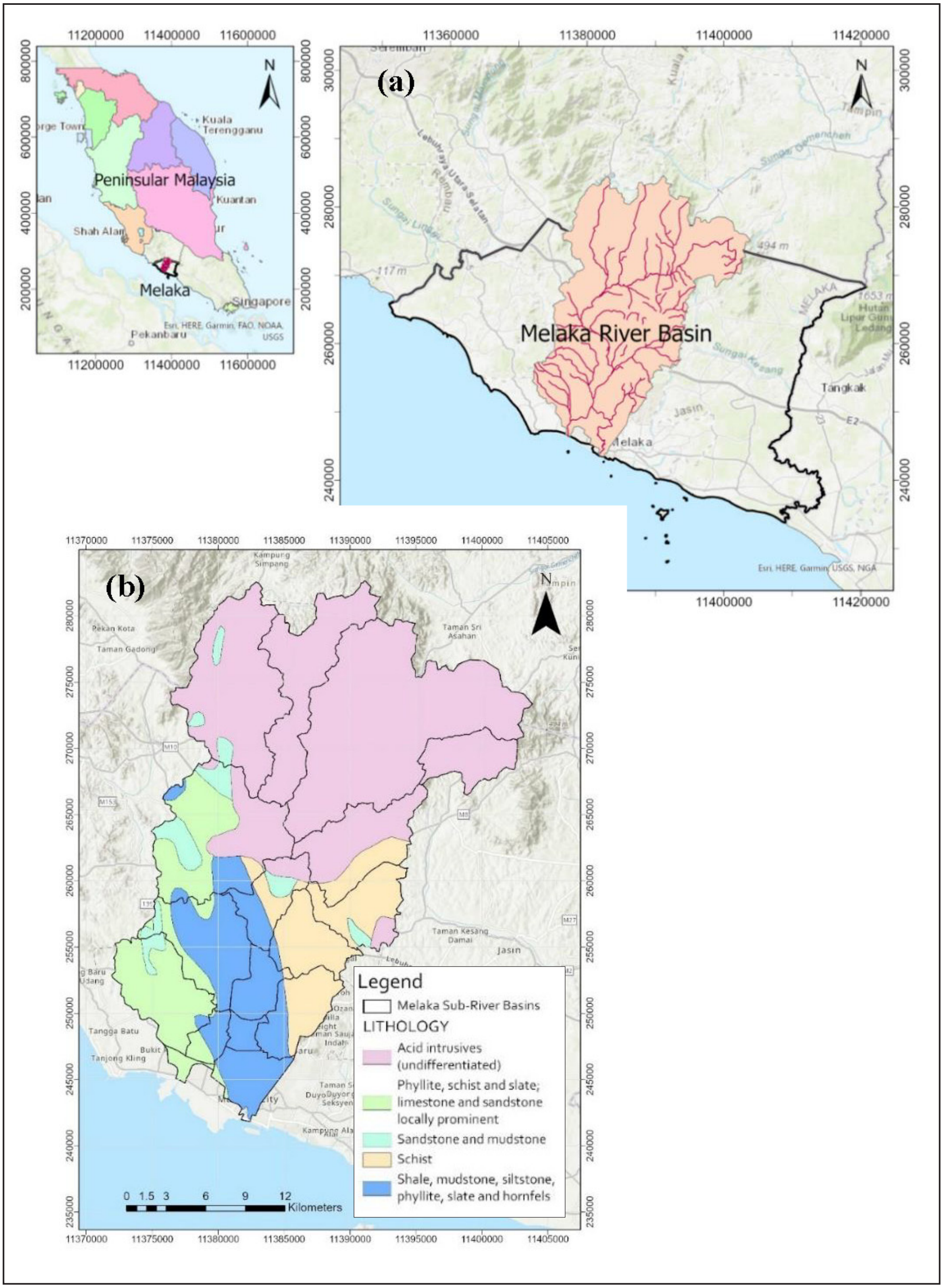

Figure 1: Map showing (a) the State of Melaka and Melaka River Basin and (b) the geology within the Melaka River Basin (JMG, 2014).

Peninsular Malaysia (Ng *et al*., 2015). The phyllite, schist, and slate units, interspersed with limestone and sandstone, point to Paleozoic sedimentary environments that ranged from shallow marine to fluvial systems. Subsequent tectonic activity subjected these deposits to low- to medium-grade metamorphism, reshaping their characteristics (Surjono *et al*., 2020). Sandstone and mudstone deposits reflect sedimentary processes in fluvial and lacustrine settings during the Late Mesozoic to Early Cenozoic periods. The interplay between high- and low-energy depositional conditions is evident in the contrasting lithologies within this unit (Kasim *et al*., 2020). Schist formations derived from sedimentary precursors such as shale bear evidence of medium-grade metamorphism caused by tectonic compression during Paleozoic subduction and collision events (Ahmad Aminuddin *et al*., 2021). Finally, a diverse lithological unit consisting of shale, mudstone, siltstone, phyllite, slate, and hornfels reflects a complex geological history. These rocks were initially deposited in deep marine environments and later underwent varying degrees of metamorphism. In particular, the presence of hornfels suggests contact metamorphism associated with the intrusion of nearby igneous bodies (Kasim *et al*., 2020). Collectively, these lithological units illustrate a dynamic geological history marked by transitions from marine to terrestrial environments, episodes of magmatism and regional metamorphism. These characteristics not only shed light on the geological complexities of Melaka but also contribute to a broader understanding of tectonic events that have shaped Southeast Asia. The stratigraphy and tectonic evolution of the region provide critical insights into the broader context of the geological processes across Peninsular Malaysia.

Melaka state's rapid urbanization and development have indirectly led to significant changes in land usage. Agriculture continues to influence the state economy. Palm oil and rubber are the main crops that are grown. Although some paddy fields are still being cultivated, the state has no plans to implement large-scale irrigation. Moreover, most of the paddy land has either been abandoned or repurposed for other uses (Department of Agriculture Malaysia, 2022). Recently, the agriculture industry in Melaka has lost interest, contributing only 5.5% of the total employment in the state. Agricultural land is now being used for other purposes, particularly residential and commercial, because of the ongoing labor shortage and other problems associated with the agriculture industry. Even if the agricultural sector may not require as much water as before, the quality of the water resources may be affected by these changes in land use pattern.

METHODOLOGY

Subsurface investigation

The geological investigation of the Melaka River Basin involves analyzing the physical characteristics of the site, focusing on rock type and structure. This study aims to identify dense and non-porous bedrock, preferably crystalline rocks, overlain by coarse sand that typically yields higher groundwater. To facilitate this analysis, information from various sources, such as geological data (Department of Mineral and Geoscience Malaysia (JMG)), topographic maps and digital elevation models (Department of Survey and Mapping Malaysia (JUPEM)), aerial photographs and satellite images (Malaysian Space Agency (MYSA)), and geophysical data were compiled. This comprehensive geological investigation approach enables a detailed understanding of the subsurface geology and hydrogeological characteristics of the Melaka River Basin, which is essential for water resource management and development planning.

Pumping tests

Pumping tests were performed in situ to estimate the hydraulic conductivity of the aquifer. The pumping tests were conducted in two boreholes TW17 and TW18 (Figure 2) comprising three phases: step-drawdown test, constant discharge test, and recovery test. The tests were conducted using a Clazzen SP8-10 submersible pump with a maximum capacity of 8 m^3/h at the head of a piezometer of 10 m. The submersible pump for TW17 was installed at a depth of 8 m, while TW18 was installed at a depth of 12 m below ground level, with 50 mm diameter riser

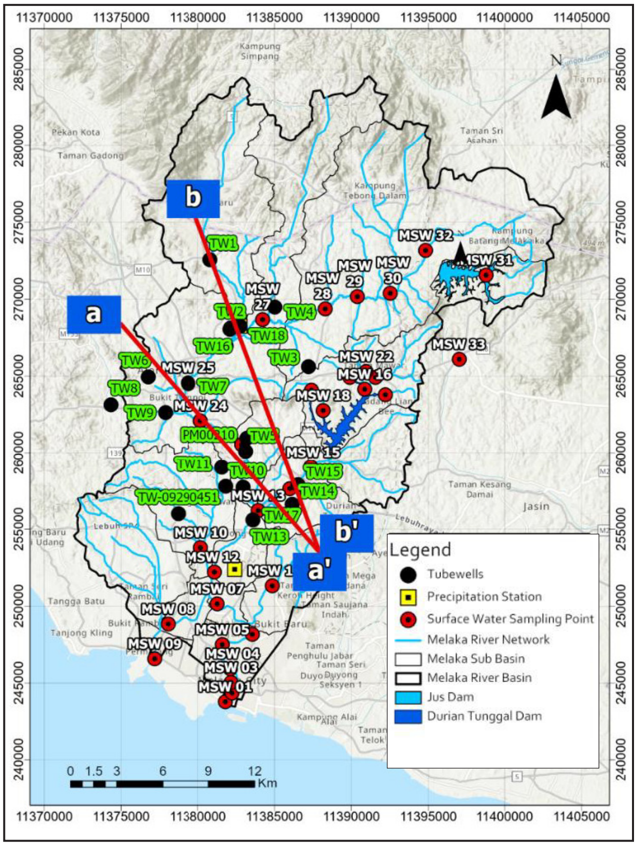

Figure 2: Map showing the surface water sampling and tube well for groundwater sampling locations.

pipes connected to each submersible pump. To regulate the flow rate, a 50 mm diameter gate valve was affixed to the riser pipe. The riser pipes were then directed to a 90° V-notch tank to measure the flow rate accurately. Upon completion of the pump installation and all necessary set-up procedures, a 2-hour calibration test was conducted to determine the capacity of the test well and establish the pumping rate for the Step-Drawdown Test. Table 1 summarizes the borehole information (wherever available), showing the maximum depths of boreholes, piezometers, and the measured hydraulic conductivity obtained from the slug tests.

Water quality sampling

Two river water sampling campaigns were conducted on 32 river tributaries across the Melaka River Basin (Figure 2). The first sampling survey was conducted during the wet season in June 2022, and the second survey was conducted during the dry season in March 2023. A total of 64 river water samples were collected during the survey. Rainwater samples were collected on a monthly basis. Water samples were analyzed for water stable isotope ratios of ^{2}H and ^{18}O using a laser absorption water-vapor isotope spectrometer (LWIA). The elemental concentrations in the water samples were analyzed using inductively coupled plasma mass spectrometry (ICP-MS). The physicochemical parameters were measured in the field using a YSI 556 MPS multiparameter probe.

Table 1: Permeability test result from slug test (falling head) method.

Tubewell ID	Static water level (m)	Depth of test conducted (m)	Hydraulic conductivity, K (m/day)
TW1	0.92	10.00	2.79×10^{-1}
TW2	1.25	10.00	3.68×10^{-1}
TW3	1.90	10.00	2.70×10^{-1}
TW4	0.10	10.00	4.17×10^{-1}
TW5	2.64	10.00	1.64×10^{-1}
TW6	1.82	10.00	2.84×10^{-1}
TW7	1.78	10.00	2.12×10^{-1}
TW8	3.41	10.00	6.03×10^{-1}
TW9	1.52	10.00	5.48×10^{-1}
TW10	4.92	10.00	1.73×10^{-1}
TW11	NA	NA	Artesian well
TW12	1.97	10.00	3.71×10^{-1}
TW13	0.51	10.00	2.10×10^{-1}
TW14	4.15	10.00	3.68×10^{-1}
TW15	2.03	10.00	3.21×10^{-1}

RESULTS AND DISCUSSION

Implications for the characterization of the hydrogeological units

The subsurface and ground-truth investigations suggest a four-layered model structure reflecting lithological variations for model simulation purposes (not discussed in this manuscript). Datasets of solid bedrock and alluvium deposits along with their hydrogeological characteristics were used to construct a 3D hydrogeological block model (Figure 3). This model covers a depth of up to 35 m from the surface. The upper layer was the topsoil with a thickness varies from 0.3 m to 0.5 m. The second layer is an aquitard with a thickness varying from 1 m to 5.3 m and the third layer is an alluvium aquifer with a thickness that varies from 1.0 m to 24.0 m. Two aquifer layers were considered in the model: alluvium and hard rock, which were separated by a thin aquitard layer (0.5 m - 1.0 m). A summary of the boundary conditions and material properties is provided in Table 2.

Figure 4 illustrates the cross-sections along a – a' and b–b' to assess the distribution, thickness, and hydraulic properties of the alluvial aquifer as well as the presence of

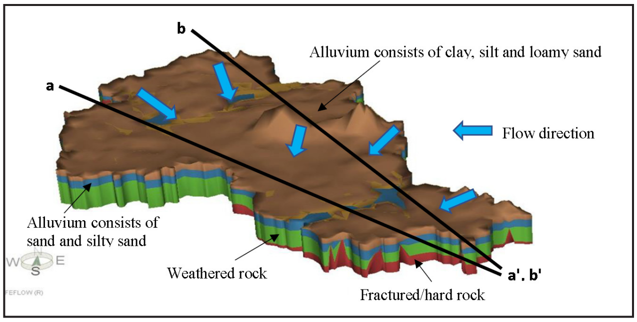

Figure 3: A 3D hydrogeological block model based on regional geological data and existing boring data of the study area.

Table 2: Characteristics of different geological layer of Melaka River Basin.

Formation Parameter	Layer 1	Layer 2	Layer 3	Layer 4
Thickness (m)	0.3 – 0.5	1.0 – 24.0	0.5 – 1.0	1 – 9
Material	Loam Soil	Sand – Sandy Silt	Clay	Fractured / hard rock
Type	Aquitard	Alluvial Shallow Aquifer	Aquitard	Deep Aquifer
Hydraulic Conductivity, $K_{x,y,z}$ (m/s)	1.682×10^{-7} – 4.24×10^{-8}	3.294×10^{-4} – 5.562×10^{-7}	3.194×10^{-8} – 3.976×10^{-10}	5.2×10^{-5} – 8.3×10^{-9}

confining layers or geological structures that may influence groundwater storage and movement. The thickness of the alluvial aquifer varies from 1 to 24 m. The hydraulic conductivity (K) of the aquifer was assumed to be that of sand and gravelly sand. It is further assumed that the basement is an impermeable rock.

Groundwater fluctuations were monitored across 15 wells using data loggers with one-hour intervals (Figure 5). These monitoring wells provided valuable insights into the groundwater level trends throughout the study period. Generally, the groundwater level trends were similar across most monitoring wells, indicating consistent responses to hydrological conditions and groundwater dynamics. However, TW6, located in Kelemak, displayed distinct behavior due to its proximity to a river, which significantly influenced its groundwater fluctuations and attributed to its interaction with surface water dynamics. Proximity to the river introduces additional complexities to its groundwater regime.

During periods of high river discharge, TW6 likely exhibited rapid fluctuations, reflecting the influence of river water infiltrating the aquifer or causing changes in the hydraulic gradients. Conversely, during low-flow periods, groundwater levels at TW6 might have stabilized or showed less variability. The proximity of the river to TW6 also made it susceptible to fluctuations resulting from storm events

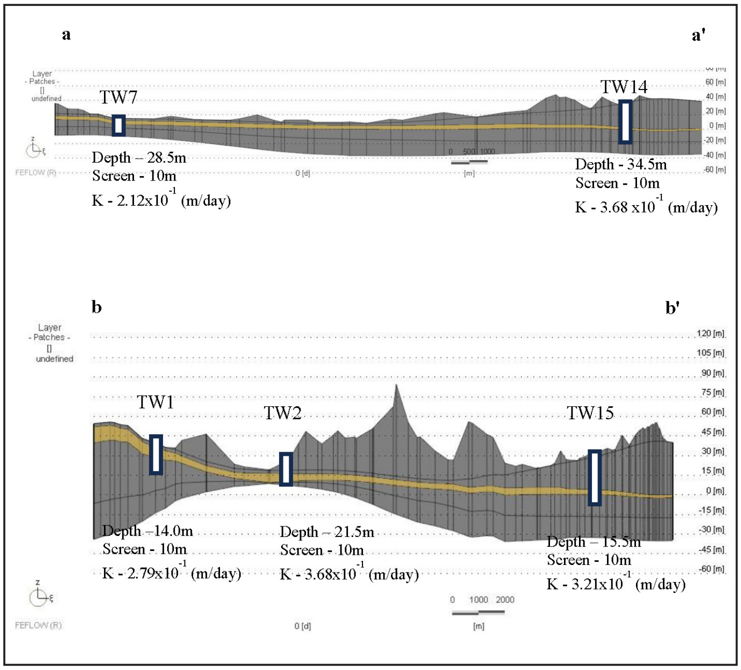

Figure 4: Cross section of a - a' and b - b' illustrating the extension of alluvium aquifer and predicted preferential flow pathways.

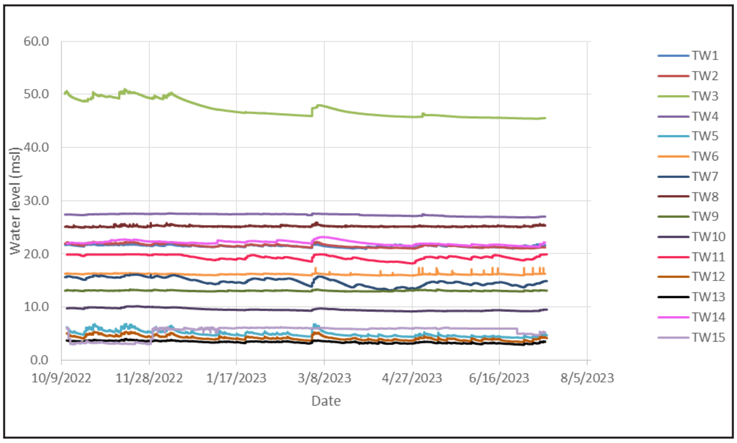

Figure 5: Groundwater level responses monitored from October 2022 to July 2023.

that could elevate groundwater levels through hydraulic connections with the river. The 14 monitoring wells, excluding TW6, likely reflect typical groundwater responses to seasonal variations, recharge events, and anthropogenic influences. During the wet season, groundwater levels tended to rise because of increased recharge from precipitation and runoff. Conversely, in the dry season, groundwater levels gradually decrease as groundwater feeds into surface water bodies, such as streams and rivers (a process known as river gain).

Monitoring wells located close to rivers tend to experience more pronounced fluctuations owing to the direct interaction between the groundwater and surface water bodies. In contrast, monitoring wells located farther away from rivers may exhibit comparatively more stable groundwater levels because they are less influenced by surface water dynamics.

Having successfully constructed a 3D hydrogeological block model of the focus study area along with their hydrogeological characteristics, the following sections describe a series of laboratory experiments to gain a better understanding of the water bodies characteristics in terms of their isotopic and chemistry signatures.

Stable isotope signature

Figure 6 shows the relationship between $\delta^{18}O$ and δ^2H isotopic compositions in different water sources, including groundwater, rainwater, and surface water samples, compared with the Global Meteoric Water Line (GMWL) (Craig, 1961) and the Malaysian Meteoric Water Line (MMWL) (Mostapa *et al*., 2024). River water $\delta^{18}O$ values in the wet season in June 2022 ranged from −9.27‰ to −4.96‰, with an arithmetic mean of −6.75‰, whereas δ^2H values ranged from −70.7‰ to −37.4‰, with an arithmetic mean of −47.6‰. River water $\delta^{18}O$ values during the dry season in March 2023 ranged from −7.95‰ to −1.32‰, with an arithmetic mean of −6.32‰, whereas δ^2H values ranged from −49.1‰ to −9.1‰, with an arithmetic mean of −42.0‰, indicating relatively enriched $\delta^{18}O$ and δ^2H values. Linear regressions between $\delta^{18}O$ and δ^2H for wet season were $\delta^2H = 8.0292\delta^{18}O + 6.6544$, ($R^2 = 0.9472$, n=32, $p<0.001$) and dry season $\delta^2H = 6.1893\delta^{18}O - 2.8771$ ($R^2 = 0.9738$, n=32, $p<0.001$). These trends indicate evaporation effects or mixing processes as the slopes deviate significantly from the GMWL and MMWL.

However, river water $\delta^{18}O$ and δ^2H values in December 2023 can be divided into two clusters: below the GMWL/MMWL and mixing with the groundwater isotope values. This observation suggests variations in evaporation intensity and groundwater recharge. The isotopic ratio differences between December 2023 and March 2023 can be attributed to a combination of factors related to seasonal and local hydrological processes, despite both periods falling within the northeastern monsoon season. In December 2023, the higher rainfall intensity and frequency might have mitigated the evaporative effect, keeping the water isotopically lighter compared to March. In March 2023, evaporation was more pronounced owing to potentially reduced rainfall, leading to greater isotopic enrichment in the surface water.

The groundwater samples plotted above and were closer to the GMWL/MMWL, and generally showed very little variation throughout the year, suggesting minimal evaporation or consistent meteoric origin (Figure 7) and primarily reflecting recharge from precipitation.

Deuterium excess (d-excess), which is typically indicative of evaporation or condensation, is associated with kinetic isotropic fractionation (Dansgaard, 1964; Ala-aho *et al*., 2018). River water d-excess values during the wet season varied from 1.46‰ to 14.5‰, with an arithmetic mean of 6.46‰, whereas during the dry season they

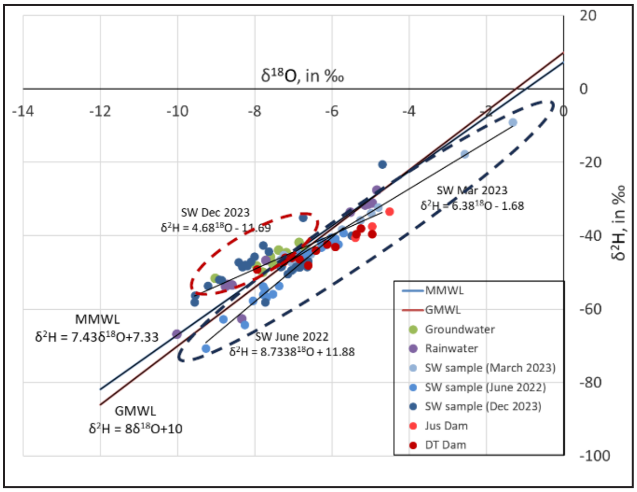

Figure 6: The stable isotope signatures of the water samples are categorized into two distinct clusters, as represented by the red and blue indicators.

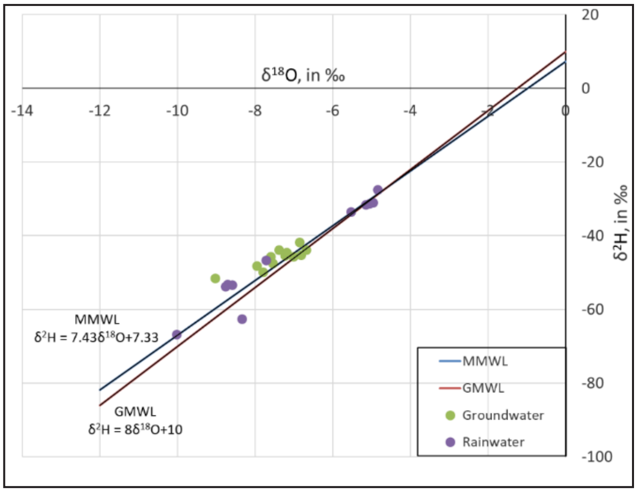

Figure 7: Stable isotope signatures for the groundwater and rainwater samples.

varied from 1.88‰ to 9.54‰, with an arithmetic mean of 8.57‰. Samples with values <10 plot below the GMWL and indicate a deviation from the equilibrium fractionation conditions, that is, the sampled water was subjected to evaporation (Figure 8). Higher d-excess values usually indicate evaporation under low humidity conditions, where kinetic fractionation is more significant. Lower d-excess values can indicate evaporation in environments with higher humidity, where isotopic fractionation is more influenced by equilibrium processes. In both cases, the high evaporation rates are controlled by atmospheric conditions, whereas the low evaporation rates are limited by the hydraulic properties of the drying porous material (Lehmann *et al*., 2008; Assouline *et al*., 2014).

Chemistry analysis

Six elements exhibiting significant variability—calcium (Ca), manganese (Mn), iron (Fe), potassium (K), magnesium (Mg), sodium (Na), and zinc (Zn)—were selected for a comparative analysis across seasons. These elements were chosen to distinguish the sources of elemental presence, including agriculture, saltwater intrusion, wastewater, and geological formations. The concentrations of these six elements in surface water samples collected from the Melaka River, its tributaries, and groundwater are presented in Tables 3 and 4. Generally, the concentrations of Ca, K, Mg, and Na were higher in the estuarine regions compared to the upper sections of the river tributaries. A comparison was conducted for two monsoon seasons, namely the northeast monsoon (November to March) and the southwest monsoon (May to September). Elevated concentrations of these elements were observed during the northeast monsoon season (November to March). Water samples from MSW1 and MSW9 exhibited average Mg concentrations of 436.432 mg/L and 253.613 mg/L, respectively, which exceed the permissible limit of 150 mg/L as recommended by the Department of Environment (DOE) and the Ministry of Health (MOH). In general, the presence of Mg in an aqueous environment is influenced by various factors, such as weather conditions, geochemical structure, atmospheric deposition, vegetation cover, and land use (Grochowska & Tandyrak, 2009). Thus, Mg is a highly available alkali metal found in surface water.

The groundwater samples pose high concentration of Fe and Mn ranged from 6.513 mg/L to 13.342 mg/L and 0.052 mg/L to 1.105 mg/L was found to be above the permissible limits of 1.0 mg/l for raw water recommended by the National Water Quality Standard (NWQS) and MOH. Fe is generally present in water as either a soluble iron ion (Fe2+) or an insoluble ion (Fe3+) (Sarkar & Shekhar, 2018). High iron concentrations in water can lead to an unpleasant metallic taste (Rajjak, 2009). The high concentration of Fe may be due to aquifer sediments containing more reductants, such as pyrite and siderite. A high pyrite content is common in granitic rocks and metamorphic rock formations, such as slate, schist, and phyllite. A detailed summary of surface water and groundwater samples exceeding the permissible limits for iron (Fe), manganese (Mn), sodium (Na), pH, zinc (Zn), and calcium (Ca), as established by the NWQS and MOH, is presented in Table 5.

Most of the groundwater can be categorized as mixed water type, primarily $Ca\text{-}HCO_3$ and $CaSO_4$, suggesting the influence of both carbonate- and sulfate-bearing lithologies (Figure 9). Notably, TW17, located near the downstream section of the Melaka River, exhibits a Na-Cl water type, which is commonly associated with interactions with marine or saline sources and may be attributed to local geological formations comprising schist, phyllite, slate, and limestone.

The isotopic signatures obtained from this study, combined with groundwater level monitoring data, suggest a dynamic interaction between groundwater and surface water. This interaction appears to influence the flow pathways and mixing processes with potential implications for the dilution or attenuation of contaminants. Isotopic signatures are strongly related to seasonal and local hydrological processes, which can be used to predict the effects of climate change on water sustainability. High evaporation would suggest a potentially low water source/input and could be the main cause of water loss in the hydrological cycle. Thus, it appears relevant to account for the continuous availability

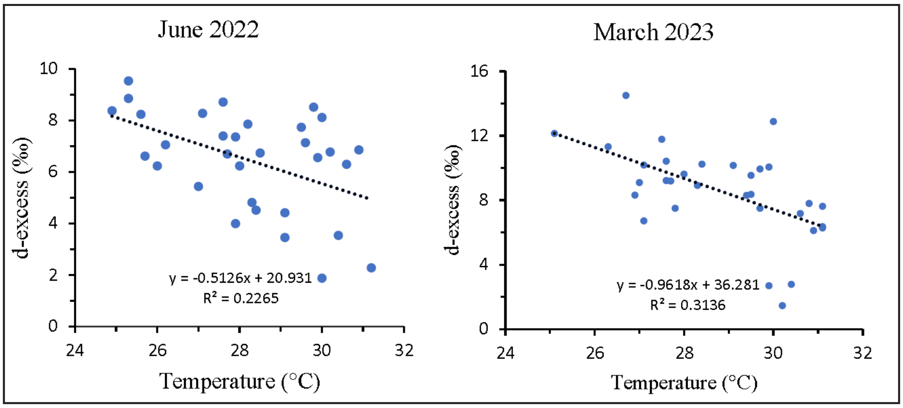

Figure 8: d-excess vs temperature for two different seasonal.

Table 3: Concentrations of selected elements in surface water samples compared with standard limits recommended by the Department of Environment (DOE) and Ministry of Health (MOH) Malaysia. Values exceeding the limits are highlighted in yellow.

Location/ Sampling station/ Limit	**Concentration (mg/L)**														**pH**
	Ca		**Mn**		**Fe**		**K**		**Mg**		**Na**		**Zn**		
	Jun-22	Mar-23	Jun-22	Mar-23	Jun-22	Mar-23	Jun-22	Mar-23	Jun-22	Mar-23	Jun-22	Mar-23	Jun-22	Mar-23	
MSW1	90.72	254.79	< 0.001	0.01	2.84	0.33	93.95	204.32	315.29	557.58	2818.50	5042.41	0.01	< 0.001	8.30
MSW2	26.65	103.05	< 0.001	0.05	2.69	0.24	18.85	75.97	55.83	203.07	490.87	1816.27	0.01	< 0.001	8.40
MSW3	26.12	118.45	< 0.001	0.06	2.86	0.41	18.29	85.39	52.56	223.18	459.58	1980.53	0.04	< 0.001	8.50
MSW4	10.47	77.31	0.08	0.06	2.94	0.46	4.69	54.65	2.54	143.13	23.86	1269.26	0.04	< 0.001	9.30
MSW5	9.02	65.97	0.07	0.09	3.11	0.75	3.69	45.47	1.21	110.67	10.28	963.72	0.04	< 0.001	9.00
MSW6	13.08	30.35	0.04	0.06	2.13	0.59	5.93	18.65	1.44	38.38	36.12	359.86	0.08	0.02	7.90
MSW7	13.57	22.85	0.05	0.07	2.21	1.72	6.07	10.68	1.48	10.38	37.18	107.01	0.09	0.04	7.30
MSW8	11.41	18.65	0.05	0.07	2.95	1.59	4.04	9.98	1.23	2.39	18.56	26.81	0.06	0.03	6.70
MSW9	9.82	231.13	0.05	0.02	4.06	0.38	5.94	185.10	1.23	506.00	13.42	4542.56	0.05	0.05	8.10
MSW10	10.42	57.24	0.06	0.06	4.59	3.40	5.86	41.25	2.95	2.25	34.11	91.72	0.07	0.06	6.00
MSW11	18.94	25.32	0.10	0.12	4.65	7.33	7.21	12.49	1.60	1.90	27.87	34.86	0.15	0.13	7.00
MSW12	6.64	7.30	0.06	0.08	3.48	2.18	4.75	5.06	1.01	1.39	5.59	7.28	0.03	0.02	5.50
MSW13	6.84	8.00	0.12	0.15	3.12	2.91	4.34	3.92	1.32	1.44	7.99	6.37	0.03	0.03	5.60
MSW14	5.77	8.00	0.08	0.15	3.27	2.91	3.95	3.92	1.18	1.44	5.70	6.37	0.01	0.03	5.80
MSW15	5.62	6.46	0.08	0.11	3.40	2.27	4.24	3.29	1.28	1.49	5.68	5.96	0.02	0.02	7.50
MSW16	9.63	3.71	0.07	0.02	2.18	1.34	12.81	2.80	2.99	0.83	8.54	6.07	0.03	0.02	6.70
MSW17	9.70	8.40	0.07	0.08	2.16	5.62	12.80	8.16	3.01	1.87	8.56	6.49	0.03	0.01	6.60
MSW18	6.67	10.06	0.07	0.05	3.89	0.63	6.67	13.40	1.38	3.00	3.77	8.30	0.02	0.02	6.50
MSW19	5.49	5.15	0.04	0.03	2.03	2.14	5.59	5.09	1.35	1.16	6.28	6.17	0.02	0.01	6.20
MSW20	4.53	5.46	0.01	0.04	2.28	0.64	5.38	5.41	1.23	1.31	5.81	5.53	0.03	0.02	6.70
MSW21	5.86	5.30	0.03	0.03	1.31	1.43	6.12	5.47	1.83	1.51	5.19	5.65	0.02	0.02	6.70
MSW22	10.52	9.37	0.05	0.05	1.86	1.99	4.98	5.16	1.68	1.66	12.06	13.35	0.02	0.01	6.70
MSW23	6.46	8.02	0.07	0.07	3.45	2.94	4.85	5.77	1.19	1.36	6.45	8.27	0.03	0.02	7.20
MSW24	6.72	7.79	0.06	0.07	3.27	2.85	4.97	5.85	1.22	1.36	6.85	8.38	0.03	0.02	7.10
MSW25	6.13	7.21	0.06	0.07	2.88	2.84	5.19	5.86	1.23	1.41	6.55	7.18	0.03	0.02	7.00
MSW26	6.99	6.45	0.04	0.07	2.25	3.54	4.37	4.53	1.13	1.06	7.36	7.46	0.02	0.03	6.80
MSW27	6.07	6.39	0.08	0.08	2.42	1.93	6.31	6.57	1.41	1.44	6.57	6.79	0.03	0.02	6.90
MSW28	6.63	7.30	0.06	0.08	1.71	1.64	7.18	7.55	1.57	1.70	6.92	6.72	0.02	0.02	6.90
MSW29	7.53	8.63	0.08	0.10	1.50	1.55	6.75	8.00	1.60	1.80	7.05	7.45	0.02	0.02	6.90
MSW30	6.63	7.44	0.10	0.13	1.43	1.67	6.83	7.25	1.82	1.95	6.63	5.90	0.02	0.02	7.10
MSW31	3.52	3.57	0.03	0.04	0.20	0.88	15.54	14.58	1.80	1.69	3.44	3.56	0.02	0.01	7.00
MSW32	12.05	9.43	0.12	0.22	0.02	2.09	14.07	8.69	4.55	2.56	7.43	7.14	0.03	0.02	7.10
EQA 1974 (Sewage) 2009			0.2		1		-		-		-		2.0		
NWQS (Class 1-V)			0.1-0.2		1		-		-		-		2.0 -5.0		
MOH Recommended Raw Water Quality)			0.2		1		-		150		200		3.0		

Table 4: Concentrations of selected elements in groundwater samples compared with standard limits recommended by the Department of Environment (DOE) and Ministry of Health (MOH) Malaysia. Values exceeding the limits are highlighted in yellow.

Location/ Sampling station/ Limit	Concentration (mg/L)								
	Ca	Mn	Fe	K	Mg	Na	Zn	pH	Lithology
TW1	12.313	0.298	10.566	3.369	1.832	1.819	0.03	6.41	Granite
TW5	17.754	1.105	13.342	0.373	3.162	3.703	0.037	7.08	Schist
TW11	0.566	0.052	6.513	0.455	1.109	1.462	0.053	7.93	Shale
EQA 1974 (Sewage) 2009		0.2	1.0	-	-		2		
NWQS (Class 1-V)		0.1-0.2	1.0	-	-		2 - 5		
MOH (Recommended Raw Water Quality)		0.2	1.0	-	150	200	3		

Table 5: Summary of the chemistry analysis results.

Parameter	Stations Exceeding Guidelines	Remarks
Iron (Fe)	MSW11–14, TW1, TW5, TW11	Up to 13.34 mg/L; exceeds all standard limits
Manganese (Mn)	MSW30, MSW32, TW1, TW5	TW5 highest at 1.105 mg/L
Sodium (Na)	MSW1, MSW2–4	Up to 5042.41 mg/L; may impact health and crops
pH	MSW4, MSW11–13, TW1	Outside 6.5–8.5 range
Zinc (Zn)	None	All within standard limits
Calcium (Ca)	No formal limit breached, but MSW1 high	Potential hardness/scaling concern

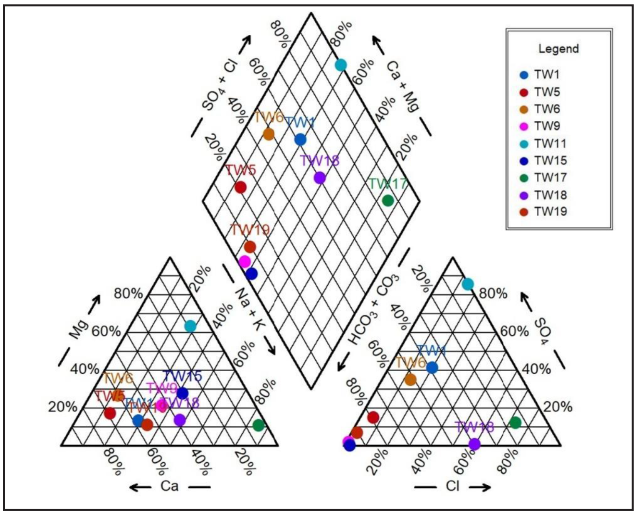

Figure 9: Piper plot of the groundwater samples.

of groundwater sources for water storage. Importantly, these results suggest that strategic, high-intensity recharge operations on geologically favorable sub-basins can improve the long-term benefits for regional groundwater quality. The data presented on isotopic signatures and chemistry analysis across the Melaka River Basin could further be used to quantitatively assess the mixing between surface water and groundwater, which will be the focus of future work.

CONCLUSION

A flood mitigation pond is under consideration by the Department of Irrigation and Drainage (DID) to be upgraded into a dual-function pond for water storage in the unconsolidated deposit aquifer beneath the Melaka River Basin. Located in the center of Melaka State, it is deemed appropriate as it encompasses a large area that experiences water shortages during dry periods. The study found that the Melaka River Basin, covering an area of 664 km², has two potential underground storage areas: The Gadek and Krubong subbasins. The Gadek sub-basin covers 139 km², with an underground water storage capacity of 21.5 MCM. The Krubong Flood Mitigation Plan (RTB) area of 6.1 km² with an underground water storage capacity of 4.57 MCM. Therefore, the total underground water storage for both sub-basins in the Melaka River Basin was 26.07 MCM. The findings also showed that aquifers can significantly increase water availability, with groundwater serving as a supplementary source of water supply, thereby alleviating water shortages.

The boundary of the surface saltwater intrusion can be determined from chemical analysis and extended near the proposed underground water storage facility. Furthermore, it is believed that the Melaka River Basin formation waters tend to be more saline toward the southeast. The high concentration of Fe in groundwater could result in granitic rock formation.

This study provides a detailed summary of the baseline water quality and evaluates the suitability of aquifers for recharge potential. Additionally, it identifies potential risks, such as increased salinity or contamination, and offers recommendations for monitoring and managing water quality during and after recharge. The study also predicts the impact of recharge on water quality, supported by numerical modeling, and outlines the precautions or further studies needed to ensure safe implementation. Isotope signatures highlight the distinct hydrological processes that affect different water sources. Surface waters show evidence of evaporation and seasonal changes, whereas groundwater and rainwater maintain isotopic signatures consistent with local meteoric input. Another reason for these observations is likely regional effects, such as local climatic conditions (e.g., temperature and humidity) or geographic factors. Understanding these dynamics is essential for water resource management and hydrological cycle studies.

This study is of considerable significance in the context of Malaysia's escalating water demand and the rising costs associated with water treatment. By investigating the potential of dual-function ponds as sustainable water sources, this research proposes an innovative strategy that repurposes existing flood mitigation ponds to fulfil dual roles in flood control and water storage. This study addresses a critical knowledge gap by establishing baseline water quality data during the construction phase, thereby providing essential insights into the inherent capacity of these systems to maintain or enhance water quality. The development of a three-dimensional hydrogeological block model facilitates a comprehensive characterization of the complex and heterogeneous alluvial aquifer system within the Melaka River Basin, which is crucial for effective groundwater management. Isotopic and chemical analyses further enhance the study by elucidating water sources and seasonal dynamics, while also confirming that heavy metal concentrations remain within permissible limits. Collectively, these findings offer a valuable framework for long-term environmental monitoring, inform resource management decisions, and guide the strategic placement of future dual-function ponds, thereby advancing integrated water resource management practices in the region.

Currently, progress work includes carrying out a numerical model based on the hydrogeological conditions in the two potential underground storage areas using the FEFLOW software. The FEFLOW software will be used to construct a groundwater flow numerical model of the area, including the underground reservoir, and the impacts of various site selections and water storage factors on the groundwater system.

ACKNOWLEDGEMENT

The authors express their gratitude to the International Atomic Energy Agency (IAEA) for its technical support and training provided through the implementation of the IAEA RAS7040 project. Special appreciation is extended to the National Water Research Institute of Malaysia (NAHRIM) for their invaluable support and collaboration in this project. We also acknowledge the Department of Mineral and Geoscience Malaysia (JMG), the Department of Survey and Mapping Malaysia (JUPEM), and the Malaysian Space Agency (MYSA) for supplying additional information essential for this study. Lastly, we thank the anonymous reviewers for their constructive comments and feedback.

AUTHORS CONTRIBUTION

Conceptualization: LAM, IT, ANI and MMMH; methodology: LAM, IT, ANI, MMMH and MSM; data collection: LAM, IT, ANI, MMMH and MSM; software analysis: ANI, MMMH and MSM; laboratory analysis: LAM, MMMH, MSM and EFEC; writing: LAM; reviewed and improved final manuscript: IT, MMMH, MSM and EFEC. All authors have read and agreed to the published version of the manuscript.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest to the contents of this manuscript.

REFERENCES

Ahmad Aminuddin, M., Imam Setiawan, N., Warmada, I., Ariffin, K., & Yonezu, K., 2021. Petrography and Geochemistry of Metasedimentary Rocks from the Taku Schist in Kelantan, North-East Peninsular Malaysia. Journal of Applied Geology, 5(2), 124-140. https://doi.org/10.22146/jag.61183.

Ala-aho, P., Soulsby, C., Pokrovsky, O.S., Kirpotin, S.N., Karlsson, J., Serikova, S., Vorobyev, S.N., Manasypov, R.M., Loiko, S. & Tetzlaff, D., 2018. Using stable isotopes to assess surface water source dynamics and hydrological connectivity in a high-latitude wetland and permafrost influenced landscape. Journal of Hydrology, 556, 279–293.

Aqvaspace Sdn Bhd., 2018. Coastal Hydraulic Study for nProjek Penambakan Laut Seluas 120 Ekar Di Mukim Klebang Besar, Central District of Malacca, Malacca (Extended Report) AQSP/RPT/01-2018/ AWANPLASMA/MDL/10103. https://www.collegesidekick.com/study-docs/4377552. Accessed 20 March 2025.

Assouline, S., Narkis, K., Gherabli, R., Lefort, P. & Prat, M., 2014. Analysis of the impact of surface layer properties on evaporation from porous systems using column experiments and a modified definition of the characteristic length. Water Resources Research, 50, 3933–3955. https://doi.org/10.1002/2013WR014489.

Banerjee, P., & Singh, V. S., 2011. Optimization of pumping rate and recharge through numerical modeling with special reference to small coral island aquifer. Physics and Chemistry of the Earth, Parts A/B/C, 36(16), 1363–1372.

Barnett, S.R., Howles, S.R., Martin, R.R., & Gerges, N.Z., 2000. Aquifer storage and recharge: Innovation in water resources management. Australian Journal of Earth Sciences, 47(1), 13–19.

Brown, C.J. & Misut, P.E., 2010. Aquifer geochemistry at potential aquifer storage and recovery sites in coastal plain aquifers in the New York City area, USA. Applied Geochemistry, 25(9), 1431–1452.

Cao, H., Qian, J., Chen, H., Liu, C., Lyu, M., Gao, S., Dong, W., & Hu, C., 2025. Managed aquifer recharge and exploitation impacts on dynamics of groundwater level and quality in northern China karst area: Quantitative research by multi-methods. Preprint EGUsphere-2025-281. https://doi.org/10.5194/egusphere-2025-281.

Carrión-Mero, P., Montalván-Burbano, N., Herrera-Franco, G., Domínguez-Granda, L., Bravo-Montero, L. & Morante-Carballo, F., 2022. Research trends in groundwater and stable isotopes. Water, 14(3173), 1–26. https://doi.org/10.3390/w14193173.

Castaldo, G., Visser, A., Fogg, G.E., & Harter, T., 2021. Effect of groundwater age and recharge source on nitrate concentrations in domestic wells in the San Joaquin Valley. Environmental Science & Technology, 55(4), 2265–2275. https://doi.org/10.1021/acs.est.0c03071.

Chen, Y., Zhang, Y., Xia, F., Xing, Z., & Wang, L., 2022. Impacts of Underground Reservoir Site Selection and Water Storage on the Groundwater Flow System in a Mining Area-A Case Study of Daliuta Mine. Water, 14(20), 3282.

Craig, H., 1961. Isotopic variations in meteoric waters. Science, 133(3465), 1702–1703.

Dansgaard, W., 1964. Stable Isotopes in Precipitation. Tellus, 16(4), 436–443.

Department of Agriculture Malaysia, 2022. Status of paddy cultivation in Malaysia: Annual report. Ministry of Agriculture and Food Security, Kuala Lumpur.

Eberts, S.M., Böhlke, J.K., Kauffman, L.J., & Jurgens, B.C., 2012. Comparison of particle-tracking and lumped-parameter age-distribution models for evaluating vulnerability of production wells to contamination. Hydrogeology Journal, 20(2), 263–282. https://doi.org/10.1007/s1004001108106.

Edirisinghe, E.A.N.V., Karunarathne, G.R.R., Tilakarathna, I.A.N.D.P., Gunasekara, J.D.C., & Priyadarshanee, K.S.G.S., 2020. Isotope and chemical assessment of natural water in the Jaffna Peninsula in northern Sri Lanka for groundwater development aspects. Isotopes in Environmental and Health Studies, 56(3), 205–219. https://doi.org/10.1080/10256016.2020.1766457.

Garba, T.E., Richard, R.L., Thani, N.E.A., Majid, M.A.A., & Lawal, M., 2021. Geological effects on water quality: A review of issues and challenges in Malaysia. Sains Malaysiana, 50(7), 1857–1870. https://doi.org/10.17576/jsm-2021-5007-03.

Grochowska, J. & Tandyrak, R., 2009. The influence of the use of land on the content of calcium, magnesium, iron, and manganese in water exemplified in three lakes in the Olsztyn vicinity. Limnological Review, 9(1), 9–16.

Guo, Z., Fogg, G.E., Chen, K., Pauloo, R., & Zheng, C., 2023. Sustainability of regional groundwater quality in response to managed aquifer recharge. Water Resources Research, 59(1), e2021WR031459. https://doi.org/10.1029/2021WR031459.

He, S., Li, P., Su, F., Wang, D., & Ren, X., 2022. Identification and apportionment of shallow groundwater nitrate pollution in Weining Plain, northwest China, using hydrochemical indices, nitrate stable isotopes, and the new Bayesian stable isotope mixing model (MixSIAR). Environmental Pollution, 298, 118852. https://doi.org/10.1016/j.envpol.2022.118852.

Hua A.K., 2019. Applied structural equation model in sustainable development of water resources management. Journal of Water and Land Development, 42(VII–IX), 83–90. https://doi.org/10.2478/jwld-2019-0048.

Jabatan Mineral dan Geosains (JMG), 2014. Geological Map of Peninsular Malaysia. 9th edition, Scale 1:750,000.

Jankovec, J., Vitvar, T., Sanda, M., Matsumoto, T., & Han, L.F., 2017. Groundwater recharge and residence times evaluated by isotopes of hydrogen and oxygen, noble gases, and CFCs in a mountain catchment in the Jizera Mts., northern Czech Republic. Geochemical Journal, 51, 423–437. https://doi.org/10.2343/geochemj.2.0469.

Jurgens, B.C., Böhlke, J.K., Kauffman, L.J., Belitz, K., & Esser, B.K., 2016. A partial exponential lumped parameter model to evaluate groundwater age distributions and nitrate trends in long-screened wells. Journal of Hydrology, 543, 109–126. https://doi.org/10.1016/j.jhydrol.2016.05.011.

Kasim, S.A., Ismail, M.S., & Salim, A.M., 2020. Cenozoic Stratigraphy, Sedimentation and Tectonic Setting, Onshore Peninsular Malaysia: A Review. In: Proceedings of the International Conference on Science and Technology 2020, Kuala Lumpur, Malaysia, 29 Dec 2020. Atlantis Press.

Kendy, E., & Bredehoeft, J.D., 2006. Transient effects of groundwater pumping and surface-water-irrigation returns on streamflow. Water Resources Research, 42(8), 1–12.

Klump, S., Grundl, T., Purtschert, R., & Kipfer, R., 2008. Groundwater and climate dynamics derived from noble gas, 14C, and stable isotope data. Geology, 36(5), 395–400. https://doi.org/10.1130/G24604A.1.

Klump, S., Kipfer, R., Cirpka, O.A., Harvey, C.F., Brennwald, M.S., Ashfaque, K.N., Badruzzaman, A.B.M., Hug, S.J., & Imboden, D.M., 2006. Groundwater dynamics and arsenic mobilization in Bangladesh assessed using noble gases and tritium. Environmental Science & Technology, 40(1), 243–254. https://doi.org/10.1021/es051284w.

Konikow, L.F., & Kendy, E., 2005. Groundwater depletion: A global problem. Hydrogeology Journal, 13(1), 317–320.

Lehmann, P., Assouline, S., & Or, D., 2008. Characteristic lengths affecting evaporative drying of porous media. Physical Review E, 77(5), 56309. https://doi.org/10.1103/PhysRevE.77.056309.

Mejus, L., Asfahani, J., Hashim, M.M.M., Yaccup, R., Mustaffa, M.S., & Gerusu, G.J., 2021. Dam seepage assessment based on combined electrical resistivity tomography and environmental isotope techniques at Machap Reservoir, Malaysia. Pollution Research, 40(3), 1–12. ISSN 0257–8050.

Mostapa, R., Samuding, K., Shah, Z.A., & Ali Khan, M.M., 2024. Stable isotope characteristics of precipitation in Malaysia: Establishment of local meteoric water line. Theoretical and Applied Climatology, 155, 7017–7034. https://doi.org/10.1007/s00704-024-05054-x.

Narany, T.S., Aris, A.Z., Sefie, A., & Keesstra, S., 2017. Detecting and predicting the impact of land use changes on groundwater quality: A case study in Northern Kelantan, Malaysia. Science of the Total Environment, 599–600, 844–853. https://doi.org/10.1016/j.scitotenv.2017.04.171.

National Water Research Institute of Malaysia (NAHRIM), 2022. Assessment of Managed Aquifer Recharge (MAR) to increase water supply reserve in Melaka River Sub-Basin, Melaka. Progress Report 1 (Unpublished).

National Water Services Commission (SPAN), 2023. Water and Sewerage Fact Book: Peninsular Malaysia and F.T. Labuan. https://www.span.gov.my/. Accessed 20 March 2025.

Ng, S.W.-P., Chung, S., Robb, L., Searle, M.P., Ghani, A.A., Whitehouse, M.J., Oliver, G.J.H., Sone, M., Gardiner, N.J., & Roselee, M.H., 2015. Petrogenesis of Malaysian granitoids in the Southeast Asian tin belt: Part 1. Geochemical and Sr-Nd isotopic characteristics. Geological Society of America Bulletin, 127, 1209. https://doi.org/10.1130/b31213.1.

Peters, E., Visser, A., Esser, B.K., & Moran, J.E., 2018. Tracers reveal recharge elevations, groundwater flow paths, and travel times on Mount Shasta, California. Water, 10(2), 97. https://doi.org/10.3390/w10020097.

Rajjak, S.P., 2009. Iron and manganese contents in Godavari River water at Nanded, Maharashtra. Nature Environment and Pollution Technology, 8(3), 575–581.

Reese, R.S., & Alvarez-Zarikian, C.A., 2007. Hydrogeology and aquifer storage and recovery performance in the Upper Floridan Aquifer, Southern Florida. U.S. Geological Survey Scientific Investigations Report, 2006-5239. 117 p.

Sarkar, A., & Shekhar, S., 2018. Iron contamination in the waters of Upper Yamuna Basin. Groundwater for Sustainable Development, 7, 421–429.

Shamsuddin, A.S., Ismail, S.N.S., Abidin, E.Z., & Bin, H.Y., 2018. Classifying sources of nitrate contamination in an alluvial deposit aquifer system using hydrogeochemical properties and multivariate statistical techniques. Malaysian Journal of Medical and Health Sciences, 14, 30–39.

Simbo, C.W., 2023. Hydrogeochemical evaluation of aquifer storage and recovery in Edwards Aquifer, New Braunfels, Texas. Groundwater, 62, 560–577.

Surjono, S.S., Leman, M.S., Mohamed, K.R., & Ali, C.A., 2020. A Combined Petrographic-Geochemical Provenance and Tectonic Setting Study of Palaeozoic Rocks, in East Johor Basin, Peninsular Malaysia. Indonesian Journal on Geoscience, 8(1), 11–24. https://doi.org/10.17014/ijog.8.1.11-24.

Vengosh, A., Gill, J., Davisson, M.L., & Hudson, G.B., 2002. A multi-isotope (B, Sr, O, H, and C) and age dating (3H - 3He and 14C) study of groundwater from Salinas Valley, California: Hydrochemistry, dynamics, and contamination processes. Water Resources Research, 38(1), 9-1–9-17. https://doi.org/10.1029/2001WR000517.

Visser, A., Moran, J.E., Hillegonds, D., Singleton, M.J., Kulongoski, J.T., Belitz, K., & Esser, B.K., 2016. Geostatistical analysis of tritium, groundwater age, and other noble gas derived parameters in California. Water Research, 91, 314–330.

Manuscript received 12 June 2025;
Received in revised form 4 July 2025;
Accepted 17 July 2025
Available online 29 May 2026