

HYDROCHEMICAL AND STABLE-ISOTOPE SIGNATURES OF GROUNDWATER IN THE VIETNAMESE MEKONG DELTA: AQUIFER-SCALE DIFFERENTIATION, UNCERTAINTY AND MANAGEMENT ORIENTATIONS

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Abstract: Groundwater is a strategic water source in the Vietnamese Mekong Delta (VMD), especially during dry-season drought and salinity intrusion. The delta, however, is a multilayered aquifer system rather than a homogeneous groundwater reservoir. The working dataset was compiled from the national project DTDL.CN-54/22 and related hydrogeological records; it includes precipitation, surface-water and groundwater samples collected during 2023-2025 and earlier monitoring records where explicitly stated. After quality screening, the groundwater dataset used for isotope-hydrochemical interpretation comprises 132 stable-isotope records, 132 hydrochemical records, 65 ³H records and 44 paired ¹⁴C/¹³C records, classified by aquifer and checked against well metadata. Stable isotopes were reported relative to VSMOW; repeated laser analyses were accepted only when the standard deviation of the final injections was below 0.05‰ for δ¹⁸O and 0.5‰ for δ²H. The local meteoric water line is δ²H = 6.80δ¹⁸O + 2.23, whereas the optimal regional groundwater line is δ²H = 4.92δ¹⁸O - 13.46 (R² = 0.85; RMSE = 0.34; AICc = -299.69). The lower groundwater slope is interpreted cautiously as the combined result of pre-recharge evaporation, mixed recharge histories, paleo-brackish/saline components, diffusion and water-sediment interaction, rather than as a single diagnostic mechanism. Hydrochemical facies, Cl⁻, EC/TDS, Na⁺/Cl⁻, Cl⁻/Br⁻ and HCO₃⁻ were used as independent checks on the isotope interpretation. The results demonstrate aquifer-scale differentiation: the Holocene aquifer (qh) is surface-sensitive and affected by modern recharge; the Upper Pleistocene (qp₃), Middle-Upper Pleistocene (qp₂₋₃) and Lower Pleistocene (qp₁) aquifers form a transitional domain; the Upper/Middle Pliocene (n₂²) and Lower Pliocene (n₂¹) aquifers preserve stronger paleo-salinity and older-water signals; and the Upper Miocene aquifer (n₁³) behaves as a deeper strategic reserve. These findings support aquifer-specific monitoring, controlled deep pumping and adaptive groundwater management under climate-change stress.

Keywords: Groundwater, stable isotopes, hydrochemistry, Vietnamese Mekong Delta, uncertainty, salinization.

1. Introduction

The Vietnamese Mekong Delta is a young, low-lying deltaic plain influenced simultaneously by the monsoon regime, upstream flooding, tides, salinity intrusion, sea-level rise and land-use change. During the dry season, when surface water may become saline, acidic or locally scarce, groundwater remains a crucial

source for domestic supply, industry, services and part of agricultural production. This role is particularly important in coastal provinces, the Ca Mau Peninsula and dispersed rural settlements, where surface-water supply is not always stable in terms of either quantity or quality. Regional planning and strategic environmental assessments have emphasized that water security under drought, salinity intrusion and climate change is becoming increasingly urgent [1], [2].

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Hydrogeologically, groundwater in the VMD forms a multi-aquifer system rather than a uniform groundwater body. The system comprises the Holocene aquifer (qh), the Upper Pleistocene aquifer (qp₃), the Middle-Upper Pleistocene aquifer (qp₂₋₃), the Lower Pleistocene aquifer (qp₁), the Upper/Middle Pliocene aquifer (n₂²), the Lower Pliocene aquifer (n₂¹) and the Upper Miocene aquifer (n₁³), which are separated by aquitards of relatively low permeability. Each aquifer has a specific depositional history, recharge mechanism, degree of hydraulic connection and fresh-saline water relationship. Consequently, the same hydrochemical expression may originate from different processes: young surface recharge, inter-aquifer leakage, salinity upconing or lateral salinization induced by pumping, residual paleo-seawater trapped in sediments, or long-term water-rock interaction [3-6].

Previous VMD studies provide an essential starting point but also reveal why a more stratified isotope-hydrochemical analysis is needed. Early IAEA-related investigations in Southern Viet Nam and the Mekong Delta identified the value of $\delta^{18}\text{O}$, $\delta^2\text{H}$, ^3H , $\delta^{13}\text{C}$ and ^{14}C for distinguishing meteoric water, river-related recharge and old groundwater. Ho Hua and colleagues reported isotope-hydrochemical evidence from 134 surface-water and groundwater samples in the 1980s, including rainfall-like water in dune or local recharge areas and a separate depleted Mekong-river signal [8]. Hoang and Bäumle later showed, from dry- and wet-season sampling in Soc Trang, that Pleistocene and Pliocene groundwater may have apparent ^{14}C ages of approximately 10.7-22.5 ka and 15.3-40 ka, respectively [9]. Doan, Dang and Nguyen (2018) further examined the origin and salinization of five key aquifers along two regional transects and highlighted weak modern recharge, old groundwater and inter-aquifer connectivity in parts of the delta [10].

The present study advances beyond these earlier works in four ways. First, it integrates a more recent project database with precipitation, surface-water and groundwater isotope records collected during 2023-2025 and standardized

by aquifer. Second, it establishes both a local meteoric-water reference and a regional groundwater line, then compares aquifer-specific isotope equations for seven aquifers rather than focusing only on selected transects. Third, the isotope interpretation is explicitly checked against hydrochemical facies and ion ratios, including EC/TDS, Cl^- , Na^+/Cl^- , Cl^-/Br^- and HCO_3^- . Fourth, the revised analysis separates observational results, process interpretation, uncertainty and management orientations to avoid over-interpreting isotope slopes as unique evidence for a single mechanism.

This study aims to: (i) Establish the characteristic isotope line of groundwater in comparison with the local meteoric water line; (ii) Examine the vertical differentiation of groundwater origin in qh, qp₃, qp₂₋₃, qp₁, n₂², n₂¹ and n₁³; (iii) Evaluate isotope evidence together with hydrochemical facies and ion ratios; (iv) explicitly discuss uncertainty, seasonality and spatial representativeness; and (v) Derive aquifer-specific management orientations for sustainable groundwater exploitation under changing climate and water-resource conditions.

2. Data and methods

2.1. Study area and aquifer system

The study area covers the Vietnamese part of the Mekong River delta and related hydrogeological areas of Southern Viet Nam. The analysis focuses on seven major porous aquifers: qh, qp₃, qp₂₋₃, qp₁, n₂², n₂¹ and n₁³. These units are widely used in groundwater-resource stratification in Southern Viet Nam and are appropriate for interpreting groundwater origin using environmental isotopes [3]-[6].

The shallow qh aquifer and parts of qp₃ are more closely connected to rainfall, rivers, canals, floodplains and surface conditions. The deeper Pleistocene aquifers represent a transition between modern water and older paleo-meteoric water. The Pliocene-Miocene aquifers generally have longer residence times, lower renewability under the present climate and greater sensitivity to prolonged pressure decline caused by pumping. Well depth and screened-interval information were taken from

monitoring-well metadata and hydrogeological logs where available. Samples with unclear aquifer attribution were not used to define

aquifer-specific isotope equations, although they may be discussed qualitatively when supported by independent hydrogeological evidence.

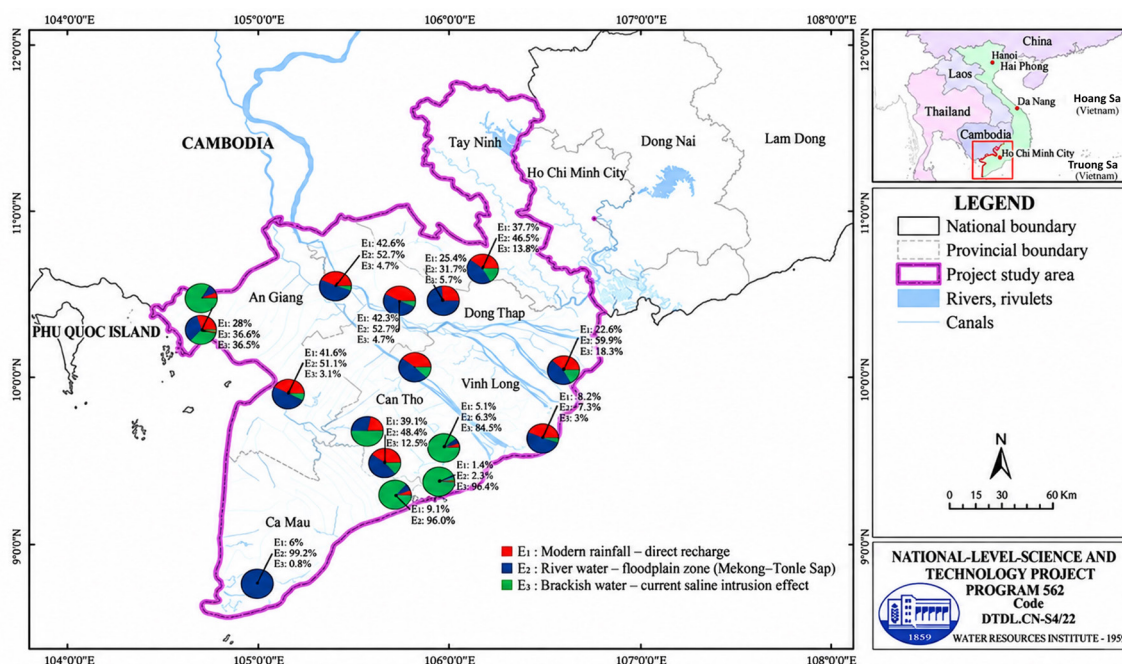


Figure 1. Spatial distribution of source contributions to the qh aquifer in the Vietnamese Mekong Delta: modern rainfall, river-floodwater and brackish/saline water

2.2. Dataset, sampling and laboratory procedures

The dataset was compiled from the national project DTDL.CN-54/22, the doctoral research database and related hydrogeological records. It consists of three water groups: precipitation, surface water and groundwater. Precipitation samples were collected at representative monitoring stations in the Southern Viet Nam/VMD region during May 2023–July 2025; surface-water samples include project sampling and time-series records for the main Mekong branches; groundwater samples were classified by aquifer using well logs, screened intervals and available coordinates. The initial groundwater isotope database contained 140 records; after removing duplicate, incomplete or metadata-inconsistent records, 132 records were retained for the isotope-hydrochemical interpretation reported in this paper.

Field and laboratory handling followed a conservative QA/QC procedure. Water samples

used for inorganic chemistry were stored in the dark at approximately 4 °C and transported to the laboratory. Filtration was conducted using 0.45 µm membranes; for inorganic analyses, sample containers and filtration systems were rinsed with acid-cleaned water, ultrapure water and sample water before final collection. Stable-isotope samples were analyzed at the Hydrological Isotope Laboratory, Ho Chi Minh City Nuclear Center, using a Los Gatos DLT-100 laser isotope analyzer with a high-precision vaporization module. The isotope results are expressed as $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in per mil relative to VSMOW. Each sample was injected at least six times; the run was accepted when the standard deviation of the final four injections was below 0.05‰ for $\delta^{18}\text{O}$ and below 0.5‰ for $\delta^2\text{H}$.

Representativeness was assessed at three levels. Seasonally, rainfall and surface-water records cover both wet and dry periods, whereas groundwater represents a multi-aquifer spatial

survey and is less suitable for detecting short-term seasonal fluctuations in deeper aquifers. Spatially, the dataset covers upstream, central, coastal and Ca Mau Peninsula domains, but sample density is not uniform among aquifers

and provinces. Stratigraphically, interpretations were made by aquifer rather than by administrative boundary, thereby reducing the risk of mixing samples from hydrologically different units.

Table 1. Revised dataset description, data origin and QA/QC role

Data group	Working sample size	Period/source	Analytical role and QA/QC note
Precipitation $\delta^{18}\text{O}$, $\delta^2\text{H}$	144	Project monitoring and related records, 2023-2025	Establishing the local meteoric water line; rainfall seasonality and recharge baseline.
Surface water $\delta^{18}\text{O}$, $\delta^2\text{H}$	224	Project sampling and main-river records	Comparing river, floodwater and rainfall signals; supporting rainfall-river recharge interpretation.
Groundwater $\delta^{18}\text{O}$, $\delta^2\text{H}$	132 after screening	Project/doctoral database, classified by aquifer	Establishing regional and aquifer-specific groundwater lines; samples with uncertain aquifer metadata excluded from regression.
Groundwater ^3H , ^{14}C , ^{13}C	65; 44; 44	Selected groundwater samples	Identifying modern/sub-modern/old groundwater and supporting residence-time interpretation.
Groundwater physicochemistry	132	Same groundwater set where available	Checking EC/TDS, Cl^- , HCO_3^- , Na^+/Cl^- , Cl^-/Br^- and hydrochemical facies; identifying salinity and water-sediment interaction.

2.3. Statistical, isotope and hydrochemical analyses

The isotope regression was implemented at two scales: (i) Pooled regional data to define a VMD groundwater reference line and (ii) Aquifer-specific subsets to identify vertical differentiation. Ordinary least squares (OLS) was used as a baseline. Precipitation-weighted least-squares regression (PWLSR) was used for meteoric-water lines where event magnitude is relevant, whereas depth-weighted and Cl^- -weighted PWLSR variants were tested for groundwater because depth and salinity are physically meaningful controls in a stratified coastal delta. Robust Huber and Theil-Sen regressions were used as sensitivity checks against outliers. The final equations were selected using hydrogeological plausibility and statistical indicators, including R^2 , RMSE, AICc and residual patterns. Therefore, the regional line and the aquifer-specific lines should be understood as representative empirical relations, not as universal or deterministic laws.

Outlier treatment followed a conservative rule. A sample was flagged when isotope values, salinity indicators or well metadata were inconsistent with the aquifer assignment, or when a single point exerted disproportionate influence on the slope without hydrogeological support. Flagged samples were reviewed against metadata; only records with defensible aquifer and laboratory information were retained in the regression. The regional groundwater equation was obtained from the best-performing depth-weighted PWLSR model, with $R^2 = 0.85$, RMSE = 0.34 and AICc = -299.69. For the qh, qp₃, qp₂₋₃ and n₁³ aquifers, the available model diagnostics are reported with the equations to show regression uncertainty.

Hydrochemical interpretation was expanded. Piper facies and major-ion ratios were used to test, rather than replace, isotope evidence. Cl^- was used as a salinity indicator; EC and TDS as mineralization indicators; Na^+/Cl^- and Cl^-/Br^- as indicators of seawater mixing, paleo-salinity and cation exchange; and HCO_3^- as a marker of

recharge, silicate weathering and long residence time in reducing sediments. A mechanism was accepted only when isotope evidence and hydrochemical evidence were consistent. Low $\delta^2\text{H}$ - $\delta^{18}\text{O}$ slopes were therefore interpreted cautiously and in combination with Cl^- , EC/TDS, Na^+/Cl^- , Cl^-/Br^- , ^3H and ^{14}C .

3. Results and discussion

3.1. Groundwater source characteristics

Source-apportionment results for the qh aquifer show that it is the aquifer that responds most rapidly to surface hydrological processes. The qh aquifer simultaneously records the effects of modern rainfall, river-floodwater and brackish/saline water. Source contributions vary markedly in space: upstream areas and corridors along the river network show higher rainfall-river contributions, whereas some coastal and Ca Mau Peninsula locations exhibit a clearer

brackish/saline influence. This differentiation demonstrates that the shallow aquifer is not homogeneous in terms of recharge; rather, it functions as a transitional system linking meteorological input, river-canal hydrology and marine influence.

From a management perspective, the qh results indicate that groundwater assessment must be placed in a spatial context. A single aquifer may receive multiple source inputs, and source proportions may vary with season, location and hydraulic conditions. When the spatial distribution is combined with aquifer-specific isotope lines, three principal signals can be separated: modern rainfall-river recharge, paleo-meteoric water stored in Pleistocene aquifers, and paleo-brackish/saline water retained in deep sediments or coastal zones.

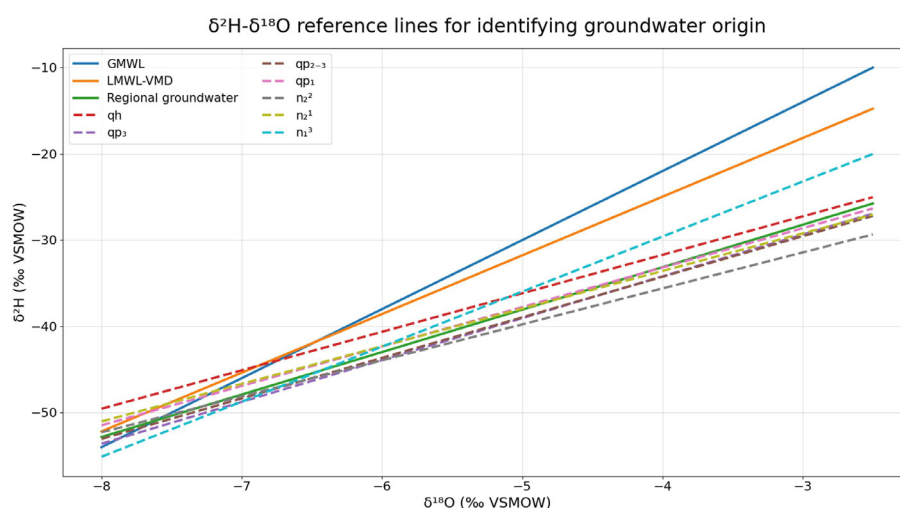


Figure 2. Comparison of $\delta^2\text{H}$ - $\delta^{18}\text{O}$ reference lines for precipitation, regional groundwater and the main aquifers in the Vietnamese Mekong Delta

3.2. Comparison with previous VMD isotope-hydrochemical studies

Here we explicitly compare the present findings with previous isotope-hydrochemical studies in the VMD. The older investigations established that groundwater in the delta includes meteoric components, depleted Mekong-related signals and old water with low modern recharge. The present dataset confirms this general picture but improves

the interpretation by combining a 2023-2025 local meteoric-water baseline, aquifer-specific isotope equations and hydrochemical screening across seven aquifers. This comparison is important because the lower regional groundwater slope found here should not be interpreted as an entirely new phenomenon; rather, the novelty lies in quantifying and organizing that phenomenon by aquifer and by management-relevant mechanism.

Table 2. Comparison with previous VMD isotope-hydrochemical and groundwater studies

Study or data source	Main focus	Aquifer/data coverage	How the present study advances the interpretation
Early IAEA-related studies and Ho/Hua et al. [8]	First isotope-hydrochemical evidence for groundwater origin in the VMD.	Surface water and groundwater; 134 samples reported in early investigations.	Provides historical baseline; the present study adds a recent LMWL and aquifer-specific equations for seven aquifers.
Hoang and Bäumle [9]	Dry/wet-season isotope-hydrochemistry in Soc Trang; ^{14}C age constraints.	Local coastal domain; Pleistocene and Pliocene groundwater age ranges.	The present study extends from a local coastal setting to delta-scale aquifer comparison.
Doan, Dang and Nguyen [10]	Origin and salinization in key aquifers along two regional transects.	Five aquifers: qp ₂₋₃ , qp ₁ , n ₂ ² , n ₂ ¹ and n ₁ ³ .	The present study incorporates qh and qp ₃ , updates data, and combines isotope equations with ion-ratio and uncertainty screening.
Recent salinity, dynamics and subsidence studies [12]-[17]	Groundwater quality, salinity prediction, water-level decline, land subsidence and salt intrusion.	Hydrochemical, modelling or remote-sensing datasets.	The present study adds source-origin and residence-time information that helps separate modern salinity from paleo-salinity and inter-aquifer leakage.

3.3. Local meteoric water line and regional groundwater line

The local meteoric water line of the VMD, derived from 144 precipitation samples, is $\delta^2\text{H} = 6.80\delta^{18}\text{O} + 2.23$. Compared with the global meteoric water line ($\delta^2\text{H} = 8\delta^{18}\text{O} + 10$), both the slope and intercept are lower, consistent with a tropical monsoon setting in which precipitation is affected by moisture recycling, secondary evaporation below the cloud base and seasonal variability in humidity and temperature. This line provides the reference needed to distinguish direct meteoric recharge from water that experienced evaporation or mixing prior to infiltration. Establishing a local isotope baseline is therefore essential for identifying recharge sources in the aquifer system [18]-[22].

For groundwater, the optimal regional representative line is $\delta^2\text{H} = 4.92\delta^{18}\text{O} - 13.46$, with $R^2 = 0.85$, RMSE = 0.34 and AICc = -299.69. The lower slope and negative intercept indicate that VMD groundwater does not behave as a simple product of direct modern rainfall infiltration. The displacement from the LMWL is consistent with

several non-exclusive processes: (i) evaporation before recharge in paddy fields, ponds, floodplains and canals; (ii) mixing of modern water with brackish/saline water retained in Holocene and late Quaternary sediments; (iii) mixed recharge histories involving rainfall, river and floodwater; (iv) diffusion through aquitards; and (v) long residence time and water-sediment interaction in reducing environments.

The regional isotope line therefore acts as a screening tool, not a stand-alone proof of origin. Two groundwater samples with similar TDS may have different management meanings if one represents qh water affected by modern salinity intrusion, whereas another represents n₂² groundwater carrying a paleo-salinity signature. For this reason, the revised analysis uses isotope lines together with hydrochemical facies, ion ratios and radioactive isotopes before deriving process interpretations.

3.4. Aquifer-scale isotope-hydrochemical differentiation

Vertical differentiation is expressed by slope, intercept, data dispersion and the relationship

with salinity indicators. The qh aquifer has a low slope and more scattered data because it is directly affected by surface evaporation, seasonal variability, rivers, tides and surface pollution sources. It is the aquifer that responds most quickly to drought-salinity events and land-use change. The qp₃, qp₂₋₃ and qp₁ aquifers show

more coherent isotope relationships, reflecting a transition from modern recharge toward mixed paleo-meteoric water. The n₂² and n₂¹ aquifers show stronger paleo-salinity signatures, whereas n₁³ plots closer to the meteoric line but still represents old groundwater with limited renewability.

Table 3. Characteristic isotope lines by aquifer with additional model-diagnostic information

Aquifer	Representative $\delta^2\text{H}$ - $\delta^{18}\text{O}$ equation	Model diagnostics reported in project analysis	Source and hydrochemical interpretation
qh	$\delta^2\text{H} = 4.46\delta^{18}\text{O} - 13.87$; $R^2 = 0.74$	RMSE = 1.41; AICc = 15.96	Modern recharge; affected by evaporation, surface water, tides and surface pollution sources.
qp ₃	$\delta^2\text{H} = 4.85\delta^{18}\text{O} - 14.80$; $R^2 = 0.92$	RMSE $\approx$ 0.82; AICc $\approx$ -4.8	Mixed paleo-meteoric water; leakage from qh and pumping influence are possible.
qp ₂₋₃	$\delta^2\text{H} = 4.70\delta^{18}\text{O} - 15.45$; $R^2 = 0.78$	RMSE = 0.85; AICc = -3.64	Transitional aquifer; Cl^- and Na^+/Cl^- become important for salinity interpretation.
qp ₁	$\delta^2\text{H} = 4.57\delta^{18}\text{O} - 14.91$; $R^2 = 0.90$	R^2 high; residual screening used	Older groundwater; relatively stable salinity but sensitive to hydraulic-head decline.
n ₂ ²	$\delta^2\text{H} = 4.17\delta^{18}\text{O} - 18.92$; $R^2 = 0.92$	R^2 high; Cl^- /depth weighting used	Strong paleo-salinity signature; slow recovery and limited modern renewability.
n ₂ ¹	$\delta^2\text{H} = 4.36\delta^{18}\text{O} - 16.14$; $R^2 = 0.82$	R^2 moderate-high; Cl^- weighting relevant	Paleo-meteoric water mixed with saline components; slow seasonal response.
n ₁ ³	$\delta^2\text{H} = 6.38\delta^{18}\text{O} - 4.07$; $R^2 = 0.88$	RMSE = 1.07; AICc = 6.91	Deep old groundwater; closer to the meteoric line, requiring strategic-reserve management.

3.5. Hydrochemical facies and ion-ratio evidence

Piper classification was used to separate Ca-Na-HCO₃, Na-HCO₃, mixed HCO₃-Cl and Na-Cl/Cl-Na facies. These facies are not interpreted alone; they are evaluated together with $\delta^{18}\text{O}$, $\delta^2\text{H}$, ^3H and ^{14}C . In general, young recharge and river-floodwater components tend toward low Cl^- , low EC, measurable ^3H and HCO₃-rich facies. Modern brackish or saline influence is characterized by higher EC/TDS and Cl^- , Na^+/Cl^- close to seawater values, and enriched $\delta^{18}\text{O}$. Paleo-saline components are identified where high Cl^- or Cl^-/Br^- is accompanied by low or absent ^3H , low ^{14}C activity and aquifer positions

consistent with marine or fluvial-marine sediments.

This hydrochemical evidence constrains the isotope interpretation. A low isotope slope in qh is interpreted primarily through the lens of evaporation, modern recharge variability and surface-water mixing. A low slope in n₂² or n₂¹ is interpreted more cautiously as a combination of paleo-salinity, diffusion, long residence time and possible mixing, because these aquifers have different geological and hydrodynamic settings. Thus, the same isotope pattern can have different mechanisms in different aquifers, and the revised manuscript avoids treating slope and intercept as uniquely diagnostic indicators.

Table 4. Revised hydrochemical facies and ion-ratio screening used to support isotope interpretation

Hydrochemical / isotope domain	Indicative hydrochemical features	Isotope/radioisotope support	Interpretive use in this study
Modern rainfall recharge	Low EC; low Cl^- concentrations, from below 10 mg/L to about 50 mg/L; Na^+/Cl^- commonly >1; HCO_3^- -rich facies.	$\delta^{18}\text{O}$ about -7.5 to -6.5‰; $\delta^2\text{H}$ about -50 to -45‰; ^3H commonly 3-7 TU; ^{14}C about 90-110 pMC.	Identifies recent recharge windows and surface-sensitive zones, mainly in qh and locally in qp ₃ .
River-floodwater contribution	Cl^- commonly 10-150 mg/L; EC about 150-600 $\mu\text{S}/\text{cm}$; Na-Ca- HCO_3 to mixed facies.	$\delta^{18}\text{O}$ about -7.0 to -6.2‰; $\delta^2\text{H}$ about -48 to -42‰; measurable ^3H and high ^{14}C .	Supports rainfall-river recharge and hydraulic connection near river/floodplain corridors.
Modern brackish/saline influence	Cl^- commonly 1,000-10,000 mg/L; EC about 3,000-20,000 $\mu\text{S}/\text{cm}$; Na^+/Cl^- about 0.85-0.95; Na-Cl facies.	Relatively enriched $\delta^{18}\text{O}$ and $\delta^2\text{H}$; often low ^3H and lower ^{14}C where mixing includes older saline water.	Separates modern salinity intrusion from fresh recharge in shallow and coastal domains.
Paleo-meteoric / old fresh water	Na- HCO_3 or Ca- HCO_3 facies; low to moderate Cl^- ; HCO_3^- elevated by water-sediment interaction.	Depleted $\delta^{18}\text{O}/\delta^2\text{H}$; low ^3H ; older ^{14}C signatures.	Identifies older, slowly renewable groundwater in Pleistocene-Pliocene aquifers.
Paleo-seawater / relic salinity	High Cl^- ; EC often >3,000 $\mu\text{S}/\text{cm}$; Na^+/Cl^- around 0.85-0.90; Cl^-/Br^- close to the seawater ratio with clay-related deviations.	Low or absent ^3H ; low ^{14}C ; isotope enrichment or mixed signals depending on aquifer history.	Tests whether salinity is inherited from marine sediments rather than solely caused by modern intrusion.

3.6. Mechanisms of groundwater formation and evolution

The isotope-hydrochemical evidence identifies four dominant mechanisms. The first is pre-recharge evaporation. In the VMD, rainfall and river water commonly reside in paddy fields, ponds, canals, depressions or floodplains before infiltrating. Evaporation enriches $\delta^{18}\text{O}$ and $\delta^2\text{H}$ but lowers the slope of the $\delta^2\text{H}$ - $\delta^{18}\text{O}$ relationship, especially in qh and other shallow zones with strong surface exchange. This mechanism explains why qh samples are more scattered and more seasonally sensitive than groundwater in deeper aquifers. It is consistent with the low topography, dense canal network and seasonal wet-dry regime of the delta [1], [23].

The second mechanism is mixing between paleo-meteoric water and paleo-brackish/saline components. Delta evolution through marine transgressions and regressions, fluvial-

marine sedimentation and clay-rich pore-water reservoirs has produced relic saline or brackish water bodies. Under natural conditions, these components may evolve slowly. Prolonged pumping, however, modifies hydraulic gradients and may promote ion diffusion, inter-aquifer leakage and migration of the freshwater-saltwater interface. Diagnostic evidence includes increases in Cl^- , EC or TDS together with isotope displacement and low modern-age indicators. Paleo-salinity is therefore linked to both sedimentary history and current hydraulic stress, not to isotope slope alone [3]-[6].

The third mechanism is spatially uneven modern recharge. Recharge is stronger along river corridors, in upstream areas and where hydraulic windows or more permeable surface covers exist; it is weaker in coastal zones where clay caps, brackish/saline water and tidal forcing dominate. The qh source distribution indicates

that even within the shallow aquifer, rainfall recharge, river-floodwater recharge and brackish/saline influence vary substantially in space.

The fourth mechanism is water-sediment interaction during long residence time. In deeper aquifers, cation exchange, mineral dissolution, iron-manganese reduction and anoxic conditions

modify hydrochemical composition even when isotopic source signals vary only slightly. Deep groundwater may therefore appear seasonally stable, but this stability does not imply rapid renewability or safe expansion of pumping. Figure 3 conceptualizes these mechanisms along the vertical aquifer sequence.

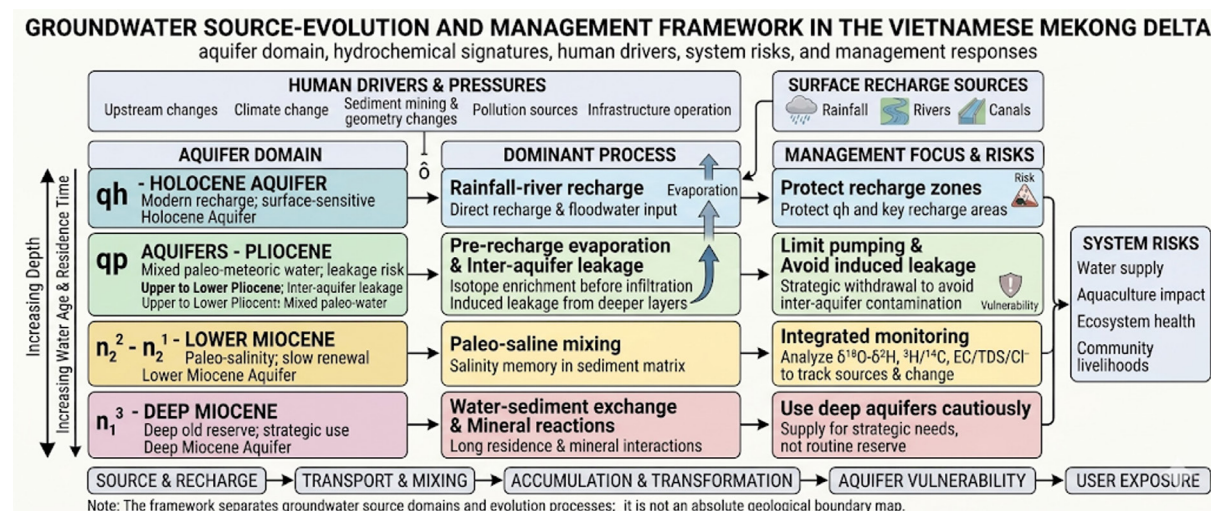


Figure 3. Conceptual model of groundwater source-evolution and management framework in the Vietnamese Mekong Delta aquifer system

3.7. Uncertainty, limitations and representativeness

The interpretation contains several sources of uncertainty. First, the groundwater sampling design is spatially broad but not uniformly dense in every aquifer or province. Therefore, aquifer equations should be considered representative for the working dataset rather than definitive for all wells in the delta. Second, groundwater in deeper aquifers is less seasonally variable than precipitation and surface water, but the current groundwater dataset is not sufficient to quantify seasonal hysteresis for every aquifer. Third, regression uncertainty is controlled by the number of samples, the distribution of depth and salinity, and the presence of mixed groundwater populations. These factors are why robust regression and PWLSR variants were checked against OLS and why results are interpreted with hydrochemical indicators.

For mixing and source-apportionment calculations in the project database, the

reported performance is generally high, with RMSE% below 5% and 95% confidence intervals commonly below 0.10 in fraction units for the seven aquifers. Nevertheless, uncertainty increases where two or more end-members overlap in $\delta^{18}\text{O}$ - $\delta^2\text{H}$ space or where a salinity signal can be produced by both modern intrusion and paleo-saline water. Low isotope slopes, negative intercepts or high Cl^- values are treated as converging evidence only when they are consistent with aquifer position, hydrochemical facies, $^3\text{H}/^{14}\text{C}$ evidence and the regional hydrogeological setting.

Future work should publish well-by-well supplementary tables, add seasonal repeat sampling in qh and qp₃, expand $^3\text{H}/^{14}\text{C}$ coverage in the deeper aquifers, and integrate isotope-hydrochemistry with groundwater-flow and salt-transport models. These limitations do not invalidate the aquifer-scale patterns reported here, but they define the confidence envelope within which management decisions should use the results.

3.8. Management orientations

The main scientific contribution of this study is the identification of groundwater source characteristics through an integrated isotope-hydrochemical framework, rather than a simple description of current water quality. The regional groundwater isotope line has a lower slope than the local meteoric water line, and the equations differ among aquifers, indicating that the VMD contains multiple groundwater domains with distinct evolutionary histories. This finding explains why uniform management measures at the delta scale are often ineffective: qh requires recharge protection and surface-source control; the qp aquifers require abstraction limits and inter-aquifer leakage monitoring; and n_2^2 - n_2^1 - n_1^3 require management based on hydraulic trends, groundwater age and slow renewability.

For groundwater abstraction, licensing criteria should not be based only on water quality at the time of sampling or on average calculated reserves. Source origin, residence time and salinity mechanism should also be incorporated. Old groundwater or groundwater containing paleo-salinity, even if treatable at

present, should not be regarded as an unlimited supplementary source. When pressure declines persist, the system may mobilize brackish/saline water from aquitards or adjacent zones, leading to degradation that is difficult to reverse. This is particularly important as several areas are reducing groundwater extraction and shifting toward alternative water supplies under regional plans [1], [2].

For monitoring, single-parameter observation networks should be upgraded to integrated networks that combine water level, pumping rate, EC/TDS/ Cl^- , stable isotopes and periodic $^3H/^4C$. EC, TDS and Cl^- are useful for rapid warning, whereas $\delta^{18}O$, δ^2H and $^3H/^4C$ help answer where salinity originates, whether recharge is modern and whether an aquifer is experiencing abnormal mixing. When these indicators are integrated into GIS/WebGIS platforms, management agencies can detect trends before salinization becomes a water-supply incident. Such integrated monitoring is necessary to separate modern salinity from paleo-salinity and to identify inter-aquifer leakage risks at an early stage [6].

Table 5. Groundwater source characteristics and priority management orientations by aquifer group

Aquifer group	Groundwater source characteristics	Main risks	Priority management orientation
qh	Modern recharge from rainfall, rivers, floodplains and tides; rapid seasonal response.	Evaporation, microbial and organic contamination, pesticides, acid-saline conditions in shallow zones.	Protect recharge zones; control sanitation and surface pollution sources; monitor seasonal isotopes and EC/ Cl^- .
qp ₃ -qp ₂₋₃	Sub-modern groundwater, leakage from qh and local recharge.	Water-level decline, localized salinity migration, increased EC/TDS/ Cl^- .	Limit abstraction; monitor dynamic/static water levels, seasonal isotopes and Na^+/Cl^- .
qp ₁	Older groundwater with more stable saline mixing than overlying aquifers.	Inter-aquifer leakage and displacement of the fresh-saline interface during pumping.	Control pumping by well clusters and trends in Cl^- /TDS and $^3H/^4C$.
n_2^2 - n_2^1	Paleo-meteoric water mixed with paleo-seawater; long residence time.	Deep salinization, high mineralization and slow recovery.	Do not treat as a rapidly renewable source; restrict expansion of deep abstraction.
n_1^3	Deep old groundwater with limited seasonal variability and water-rock interaction.	Pressure decline and mobilization of deep brackish/saline water.	Manage as a strategic reserve with strictly controlled abstraction.

4. Conclusions

This study established hydrochemical and stable-isotope signatures for identifying groundwater origin and evolution in the VMD by aquifer. The local meteoric water line, $\delta^2\text{H} = 6.80\delta^{18}\text{O} + 2.23$, and the regional groundwater line, $\delta^2\text{H} = 4.92\delta^{18}\text{O} - 13.46$ ($R^2 = 0.85$; $\text{RMSE} = 0.34$; $\text{AICc} = -299.69$), indicate that groundwater is not a simple product of direct modern rainfall infiltration. Instead, it reflects multiple processes, including pre-recharge evaporation, rainfall-river mixing, paleo-salinity, diffusion and water-sediment interaction.

With increasing depth, qh reflects modern recharge and is the most surface-sensitive aquifer; the Pleistocene aquifers represent a transitional domain of mixed paleo-meteoric water under pumping pressure; n_2^2 and n_2^1 retain pronounced paleo-salinity signatures and have slow recoverability; and n_1^3 behaves as a deep, old groundwater reserve with limited seasonal variability. This differentiation provides scientific evidence that groundwater management should be aquifer-specific and mechanism-based rather

than based on regional averages.

The revised hydrochemical analysis shows that isotope relationships must be tested against facies and ion-ratio evidence. Cl^- , EC/TDS , Na^+/Cl^- , Cl^-/Br^- , HCO_3^- , ^3H and ^{14}C together help distinguish modern salinity intrusion, relic paleo-salinity, water-sediment interaction and modern recharge. This combined approach reduces over-interpretation and improves the practical reliability of the results.

The main limitation is the non-uniform spatial and stratigraphic density of groundwater samples and the limited seasonal repeat sampling in deeper aquifers. Future research should expand seasonal isotope monitoring, add $^3\text{H}/^{14}\text{C}$ data for deep aquifers, integrate groundwater-flow and salt-transport modelling, and continuously update abstraction and land-subsidence data. Combining isotopes, hydrochemistry, groundwater dynamics and GIS/WebGIS will help shift VMD groundwater management from post-degradation response to source-, mechanism- and risk-based management.

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