

# Research on groundwater mixing between aquifers by isotope technique: A case study in Ca Mau, Nam Bo Plain

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**Abstract:** *Ca Mau is a province in the Mekong Delta with a complex hydrogeological structure, many faults, hydrogeological windows, and non-uniform distribution of aquitards, including many interspersed salt/fresh groundwater lenses, directly or indirectly affecting the recharge and movement of water in aquifers. In addition, the exploitation of groundwater at high density, focusing on only 3 out of 7 existing aquifers, has seriously reduced the groundwater level, strengthening hydraulic relationships and mixing of water sources between aquifers. To clarify the hydraulic relationships as well as the mixing process between aquifers in Ca Mau province, this study investigated and analysed the mixing of water sources between aquifers using isotopic techniques. We analysed 32 groundwater samples for  $^{14}\text{C}$  activity,  $\delta^{18}\text{O}$ , and  $\delta^2\text{H}$ . Results show that Ca Mau's groundwater is exclusively "Old Groundwater" with no modern recharge. The correlation between  $^{14}\text{C}$  activity and sampling depth is weak ( $r^2 = 0.11$  for fresh and  $0.26$  for saline groundwater), indicating complex mixing processes. Two main factors affecting groundwater mixing were identified: the hydrogeological structure and local mixing processes, including mixing with saline water of marine origin and mixing with other freshwater sources due to the strengthening of the hydraulic relationship between aquifers. The spatial distribution map of  $^{14}\text{C}$  activity and  $\delta^{18}\text{O}$  in Ca Mau Province indicates areas of intense mixing. This study provides crucial insights for sustainable groundwater management in Ca Mau Province.*

**Keywords:** *Groundwater mixing; hydraulic relationship; dissolved inorganic carbon; groundwater age; groundwater origin.*

## 1. Introduction

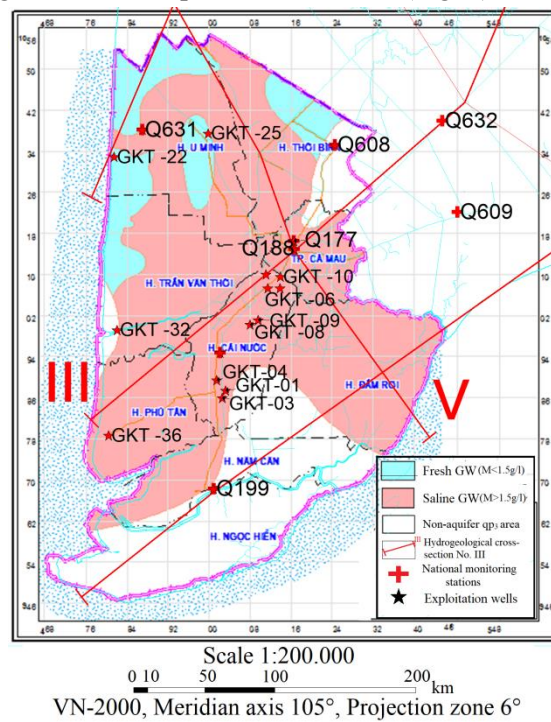
Ca Mau province covers a natural land area of 5,294.9 km<sup>2</sup>, which constitutes most of the Ca Mau peninsula, one of the five hydrogeological areas of the Nam Bo Plain hydrogeologic region [1]. This province is situated in the southernmost part of Viet Nam (Fig. 1).

The terrain of Ca Mau province has a low average altitude, ranging from 1m to 2m above sea level. It is intersected by a dense network of rivers, canals, and creeks, leading to struggles with seawater intrusion. Surface water sources are significantly polluted, with declining quality and quantity due to the impacts of climate change and rising sea levels. As a result, groundwater is the primary water source in the Ca Mau area, accounting for 86.8% of total exploitable reserves [2,3].

The Ca Mau peninsula is part of the Late Cenozoic tectonic sag zone and has a significant sediment thickness of 1,000 meters. It has undergone 7 stages with different geodynamic regimes, resulting in the creation of hydrogeological areas and regions. This indicates that the formation process of groundwater in Ca Mau is very complex. There are 7 aquifers identified: Holocene (qh), Upper Pleistocene (qp3), Middle-Upper Pleistocene (qp2-3), Lower Pleistocene (qp1), Middle Pliocene (n22), Lower Pliocene (n21), and Upper Miocene (n13) [1, 2].

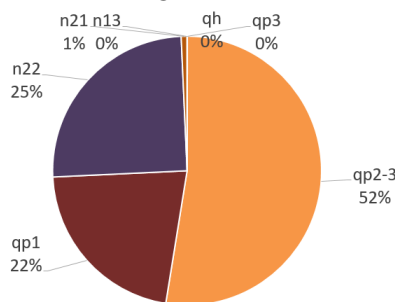
The unconfined aquifer qh is directly impacted by pollution and saltwater intrusion. The next confined aquifer, qp3, is entirely saline groundwater over the Ca Mau area and cannot be utilized (Fig. 1).

Therefore, water exploitation in Ca Mau focuses only on the next 3 aquifers (qp2-3, qp1, and n22), which account for 99% of the total groundwater exploitation reserves (Fig. 2).



**Fig. 1.** Sample collection sites and spatial distribution of total mineralization (TDS) of qp<sub>3</sub> aquifer in Ca Mau province

Furthermore, fractures, faults, and hydrogeological windows are common in this peninsula, affecting integrity and spatial connectivity, and creating conditions that favor the development of preferential flow paths. Along with the increasing water exploitation reserves over time, the degree of hydraulic connectivity between aquifers in the Ca Mau region also changes with time.



**Fig. 2.** The rate of groundwater exploitation from the aquifers in Ca Mau in 2019 [2]

The groundwater extraction rate in the Ca Mau peninsula is 633,522m<sup>3</sup>/day [2], which is within the allowable limit. However, saline intrusion still occurs in some areas. Specifically, the qp<sub>2-3</sub> aquifer is being exploited above the allowable level. The annual groundwater level reduction is significant, ranging from 0m to -14m on average and up to -28m in some areas. The sustainable values have been exceeded multiple times. The assessment using the GALDIT index indicates that the qp<sub>2-3</sub> aquifer is at risk of medium to high levels of salinity intrusion [4].

Therefore, in light of the rapidly increasing demand for water extraction, one of the important tasks of regional hydrogeological research is to study and evaluate the factors and origins contributing to the groundwater mixing process. This process has a direct and substantial impact on the quality and quantity of groundwater in the extraction area

## 2. Methodology and sampling analyses

Research results using isotope hydrological techniques in the Nam Bo Plain [5-8] indicate that groundwater in the Nam Bo Plain and Ca Mau province originated from meteoric water. There are steady-state conditions for the aquifers, with recharging in the southeast and movement and escape in the discharge

area towards the East Sea. The recharge rate is balanced with the discharge rate during this process. The dissolved inorganic carbon content in the groundwater decreases (the groundwater age or transit time increases) in the direction of the flow of groundwater. Meanwhile, isotopes entering the aquifer are no longer exchanged with the outside environment. The isotope ratios  $^{18}\text{O}/^{16}\text{O}$  and  $^2\text{H}/^1\text{H}$  are stable and characterize the conditions of groundwater formation. Such a recharge condition is also known as the “Piston flow Model” [9-11]. Age determined from dissolved inorganic carbon (DIC) content in groundwater represents the transit time of groundwater. Determining the spatial age distribution of groundwater in the Piston flow Model reflects the actual flow direction and velocity of groundwater in the aquifer.

Although groundwater mixing processes directly affect the DIC content in collected groundwater samples, research results using isotopic techniques to evaluate the dynamic characteristics of the groundwater in the Nam Bo Plain often ignore the saline water lenses that are very common here. Furthermore, there are various types of water from various sources that recharge the aquifer in different ways. One of them is the process of hydraulic relationship between aquifers through hydrogeological windows or weak permeable layers. At the regional scale, the hydraulic relationship between aquifers leads to a substantial amount of recharge to the aquifer from other aquifers, but not from the recharge area of that aquifer. Meanwhile, dating methods only provide an absolute age value or a single “mean age” that represents the “transit time” at the sampling locations. Furthermore, on a local scale, where favorable conditions exist to promote hydraulic interaction between aquifers, the DIC content in the sample is the average value of the mixing process from different formation sources, distinct from DIC content in the initial water formed from the recharge area. Therefore, the anomaly in the spatial distribution (according to surface and depth) of DIC content is a clear sign for identifying the mixing process on a regional scale.

To identify anomalies in the spatial distribution of dissolved inorganic carbon content with sampling depth, a scatter plot is used to show the relationship between dependent variables such as isotopic concentrations ( $^{14}\text{C}$ ,  $^{18}\text{O}/^{16}\text{O}$ , and  $^2\text{H}/^1\text{H}$ ) and independent variables like sampling depth ( $z$ ). The scatter plot is a graphical representation that helps us identify cause-and-effect relationships between these variables and easily detect any outliers. Outliers are data points that appear very far from the general distribution and can be identified on the plot. By examining these outlier values, we can evaluate and find out the cause of the noise and its impact on the cause-and-effect relationships within the system.

To identify anomalies in space ( $x,y$ ), the  $^{14}\text{C}$  activity and stable isotope distribution map is constructed using the multivariate geostatistical method called Co-Kriging. Co-Kriging is an extension of Kriging for multivariate data, where there is a spatial correlation between the variables. This method estimates the primary variable based on its measurements and data from other variables.

In this study, the sampling wells network is established based on the national monitoring groundwater station system and groundwater exploitation wells (Fig. 1). A total of 32 samples were collected and analyzed for radioactive carbon content using the sampling procedure of the International Atomic Energy Agency (IAEA) [12] and TCVN 6663-11:2011 [13]. Of these, 13 samples were collected from exploitation wells in the qp<sub>2-3</sub> aquifer and 19 from national monitoring wells in Ca Mau province.

The Dissolved Inorganic Carbon content was determined by analyzing the  $^{14}\text{C}$  activity in water. Carbon-14 obtained from 60 liters of groundwater was initially captured in  $\text{BaCO}_3$  in the field and then transformed into  $\text{C}_6\text{H}_6$  (1-2g) through laboratory synthesis. The  $^{14}\text{C}$  activities were determined by scintillation counting on  $\text{C}_6\text{H}_6$  [14, 15] using the TRI-CARB 3170TR/SL Liquid Scintillation Analyzer (Packard, USA). The  $^{14}\text{C}$  activity in the analyzed sample is expressed as a percentage of modern carbon (PMC). This percentage represents the ratio of the  $^{14}\text{C}$  activity in the analyzed sample (measured in Bq per gram of carbon) to the activity of the oxalic acid standard (NBS, USA) [20]. The measurement error for  $^{14}\text{C}$  activity is derived from various factors that can influence the results. These include weighing the benzene sample, diluting the sample with  $^{14}\text{C}$ -free benzene, calculating the mass correction parameter, measuring activity with a liquid scintillation spectrometer, determining the enrichment factor. The final error  $u(\text{PMC})$

in the measurement of  $^{14}\text{C}$  activity is computed according to the principles of error propagation [20] The analysis results are presented in Table 1.

Stable isotope ratio ( $^{18}\text{O}/^{16}\text{O}$ ,  $^2\text{H}/^1\text{H}$ ) analyses were performed using the Laser Absorption Spectrometry measurements LGR DLT 100 [9]. Each sample is injected and analyzed six times. The software automatically discards the results of the first two measurements to avoid instability and the "memory" effect from the previous sample. The recorded result is the average of the final four measurements. The measurement error, defined as the standard deviation of these four measurements, is rigorously controlled and must be less than 2‰ for  $^2\text{H}$  and 0.3‰ for  $^{18}\text{O}$ . If these values are exceeded, the software will prompt a re-measurement of the sample. The concentrations of these isotopes are expressed in parts per thousand and are denoted by the symbol delta ( $\delta$ ). This is defined as follows:

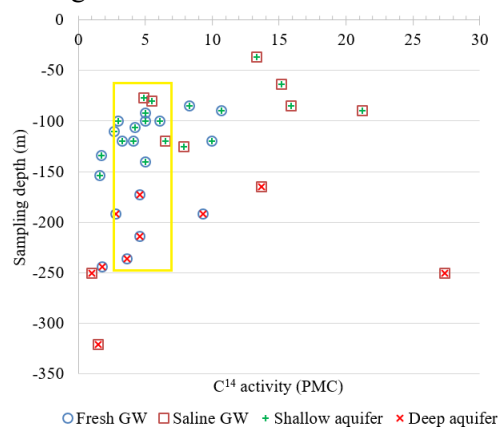
$$\delta = (R_S - R_{Std}) / R_{Std} \times 1000$$

In this equation,  $R_S$  and  $R_{Std}$  refer to the isotope ratios ( $^2\text{H}/^1\text{H}$  or  $^{18}\text{O}/^{16}\text{O}$ ) of the sample and the standard, respectively. The standard used is a secondary standard that has been calibrated against the international standard VSMOW (Vienna Standard Mean Ocean Water).

### 3. Results and discussion

#### 3.1 The relationship between dependent variables ( $^{14}\text{C}$ ) and independent variables (sampling depth):

All  $^{14}\text{C}$  activities in groundwater samples of confined aquifers in Ca Mau province are less than 27.4PMC and the sampling depth ranges from 37 - 321m.

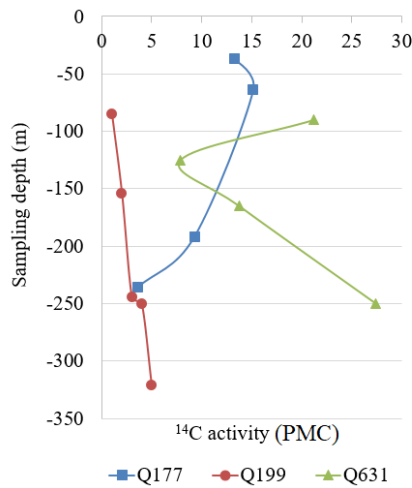


**Fig. 3.** Chart of change in  $^{14}\text{C}$  activity of groundwater of Ca Mau region aquifers according to sampling depth.

The 32 groundwater samples were categorized into two groups. Group 1 comprised 20 fresh groundwater samples, showing a Pearson correlation coefficient 0.11. Group 2 included 12 saline groundwater samples, with a Pearson correlation coefficient of 0.26..

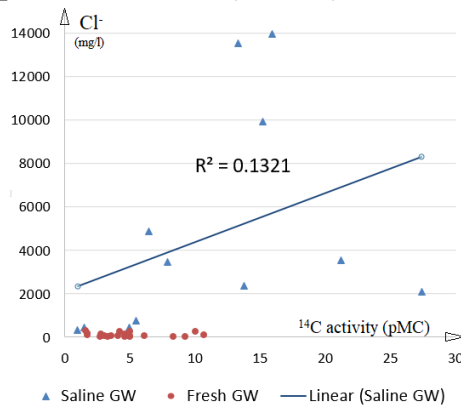
When considering the Pearson correlation coefficient of the group of shallow aquifers (22 samples), which includes 3 samples from qp<sub>3</sub> and 19 samples from qp<sub>2-3</sub>, the correlation is weak, at 0.40. In comparison, the correlation for the group of deep aquifers (10 samples), consisting of 5 samples from qp<sub>1</sub>, 3 samples from n<sub>2</sub><sup>2</sup>, and 2 samples from n<sub>2</sub><sup>1</sup>, is moderate, with a coefficient of 0.58. .

There are three national monitoring stations (Q177, Q199, Q631) with sampling wells for different aquifers at the same location. Analysis results here indicate that the  $^{14}\text{C}$  activity in samples from the lower aquifer is higher than that in the upper aquifer (Fig. 4).



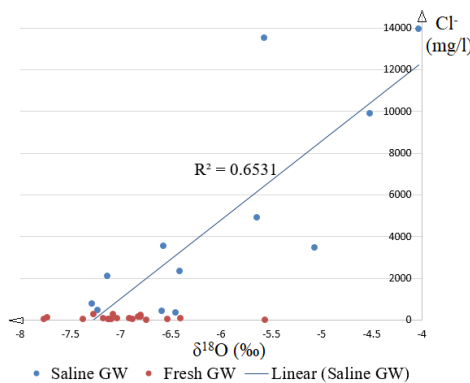
**Fig. 4.** Change of  $^{14}\text{C}$  activity according to sampling depth at a location

**3.2 The relationship between dependent variables ( $^{18}\text{O}$ ,  $^{14}\text{C}$ ) and mediating variable (chlorine anion):**

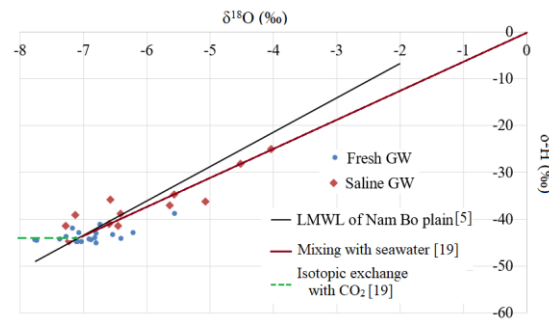


**Fig. 5.** The relationship between  $^{14}\text{C}$  activity and chlorine anion

For 12 saline groundwater samples, the Pearson correlation coefficient between the isotope ratio  $^{18}\text{O}$  and chlorine anion is moderate (0.65). Meanwhile, the correlation coefficient between  $^{14}\text{C}$  activity and chlorine anion is very low (0.13).



**Fig. 6.** The relationship between  $\delta^{18}\text{O}$  and chlorine anion

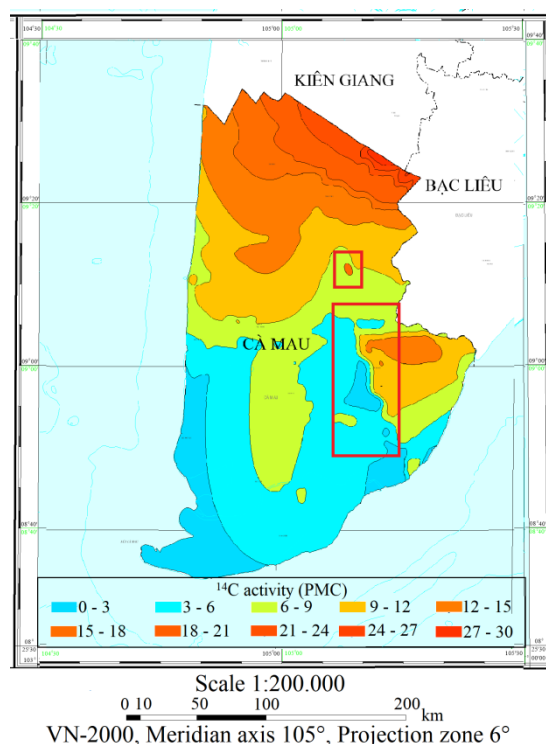


**Fig. 7.** The relationship between  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  in Ca Mau province

The analytical data indicate that the stable isotope composition in fresh groundwater is a bit narrow, with  $\delta^{18}\text{O}$  (‰) varying from -7.76 to -5.56;  $\delta^2\text{H}$  (‰) varying from -45.51 to -38.82. In the chart of the relationship between  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  (Fig. 7), the value points are distributed below the meteorological water line in the Nam Bo Plain ( $(\delta^2\text{H} = 7.33 \delta^{18}\text{O} + 7.9 \text{ (‰)}, r^2 = 0.93 [5])$ ). This shows that the fresh groundwater is meteorological water formed under evaporation or water mass mixing conditions. The negative shift of  $\delta^{18}\text{O}$  along the isotopic exchange with the  $\text{CO}_2$  line, on the left side of the LMWL of Nam Bo Plain, is attributed to the water-rock interaction process in the aquifer system with high ratios of  $\text{CO}_2$  to water.

### 3.3 A spatial distribution map of DIC content and $\delta^{18}\text{O}$

The qp<sub>2-3</sub> aquifer with the largest exploitable reserves in Ca Mau was selected to survey the distribution of  $^{14}\text{C}$  activity according to surface. The groundwater  $^{14}\text{C}$  activity distribution map base on using multivariate geostatistics, which is an advanced and effective interpolation method, helping to make the most of collected research data when the number of collected samples is restricted over a large area. In this case, the primary variable of interest is the  $^{14}\text{C}$  activity in groundwater and the secondary datasets are determined as sampling depth values for the general spatial interpolation model of several Cokriging correlated variables. Furthermore, the qualitative factors (flow direction) of the research object are generalized into quantitative to be included in the process of analyzing and modeling spatial correlation – Variogram. The above process uses the GS+ version 9 program, resulting in a  $^{14}\text{C}$  activity distribution map with Cross-validation  $r^2 = 0.81$ .

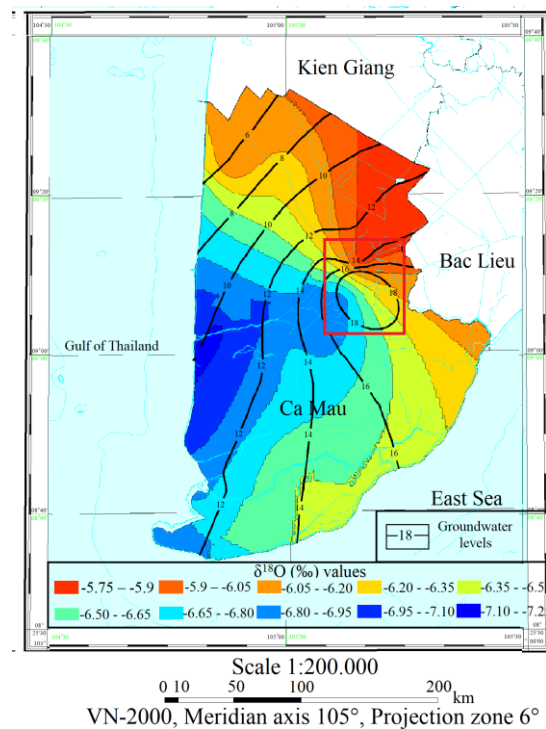


**Fig. 8.**  $^{14}\text{C}$  activity distribution map of the groundwater qp<sub>2-3</sub> aquifer in Ca Mau province

According to the  $^{14}\text{C}$  activity distribution map (Fig. 8), the north end has the highest  $^{14}\text{C}$  activity and it gradually decreases in the north-south direction. The groundwater flow in the aquifer qp<sub>2-3</sub> moves in this

direction. There is a scattered distribution of a few abnormal color points across a large color range (red square area, Fig. 8).

The distribution map of isotope ratio  $\delta^{18}\text{O}$  of groundwater in the qp<sub>2-3</sub> aquifer in Ca Mau (Fig. 9) is also done in a similar way to the  $^{14}\text{C}$  activity distribution map. This map shows that the content of isotope  $^{18}\text{O}$  is distributed with a stable trend, from the content being highest in the north to gradually decreasing towards the south.



**Fig. 9.** The distribution map of isotope ratio  $\delta^{18}\text{O}$  and groundwater level in the qp<sub>2-3</sub> aquifer in Ca Mau:

### 3.4 Discussion

All  $^{14}\text{C}$  activities in groundwater samples are less than 27.4PMC showing that within the study area there is only "Old Groundwater" that is not recharged from modern water. Confined aquifers in Ca Mau province only get recharged water from other areas, there is no on-site recharged water.

Previous research results [5, 6, 7, 17, 18] indicated a strong correlation between DIC content and sampling depth throughout Nam Bo Plain. The greater the sampling depth, the lower the  $^{14}\text{C}$  activity. However, Ca Mau province, one of its five hydrogeological areas, has a weak relationship (Fig. 3). Furthermore, analysis results at stations Q177, Q199, and Q631 indicate that the  $^{14}\text{C}$  activity in samples does not decrease with sampling depth (Fig. 4). Why is there a weakening of the correlation coefficient in this area? Are these confounding factors local in nature? The hypothesis for this phenomenon is that there is no uniformity in the dynamic state between aquifers. Currently, there are not enough studies on the dynamic state of all the aquifers here to conclude whether they are homogeneous or not, however, in terms of structure and regional hydrogeological characteristics for the aquifers, their morphology is almost similar. In this case, if the dynamic groundwater states are similar, it might be due to groundwater mixing through faults, hydrogeological windows, overlapping sediment layers with higher permeability, or thin aquitards (red square on Fig. 10, 11). Alternatively, it could be a combination of these factors.

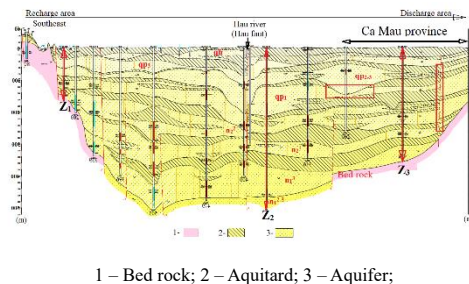
In Figure 3, the area delineated in the yellow square is pointing with the depth that varies greatly from 77 to 236m, but the  $^{14}\text{C}$  activity is almost the same, only fluctuating between 3 and 6PMC. These noisy data include two groups: the saline groundwater group and the fresh groundwater group.

The group of saline groundwater that has a conductivity of over 2120 $\mu\text{S}/\text{cm}$ , low  $^{14}\text{C}$  activity, and a shallow depth. The above outcome was achieved by mixing fresh groundwater with saline water from marine origin. So the  $^{14}\text{C}$  activity in saline groundwater samples is the average value from at least two sources with formation processes differing. Fresh groundwater originates from meteoric water and infiltrates the aquifer from the recharge area. And saline water is seawater that infiltrates the aquifer during periods of sea transgression (distinguished from Fossil seawater). Therefore, although many samples have shallow depths, the  $^{14}\text{C}$  activity is low due to mixing with seawater.

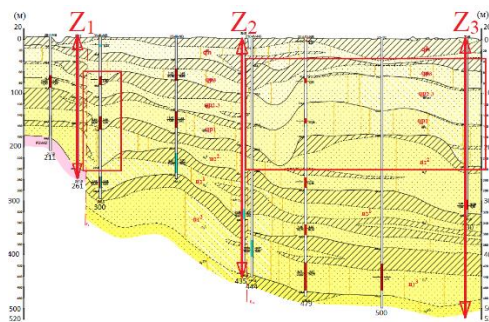
For a clearer understanding of the origin of saline groundwater in this area, take a look at Fig. 5,6,7: The  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  values of the saline groundwater distributed along the Mixing with seawater line show that the salty origin of the groundwater in Ca Mau is due to mixing with seawater. Seawater is both high in chlorine anion and isotope  $^{18}\text{O}$  content. Therefore, when it mixes with groundwater, the  $^{18}\text{O}$  content and the chlorine anion of the samples show a linear relationship (Fig. 6). In reverse, as a result of the process of mixing with seawater, the chlorine anion changes abnormally, without any relationships with the  $^{14}\text{C}$  activity (Fig. 5). This factor shows that the mixing process with seawater directly affects the  $^{14}\text{C}$  content in the sample, leading to the phenomenon of saltwater distributed at shallow depths but with low  $^{14}\text{C}$  activity, interfering with the level of correlation between  $^{14}\text{C}$  activity and sampling depth.

The group of fresh groundwater that has a conductivity of less  $2120\mu\text{S}/\text{cm}$ , low  $^{14}\text{C}$  activity, and a shallow depth. There are two causes for this phenomena:

The first reason is due to the geological structure of the aquifers in this area. According to the direction of movement of groundwater in confined aquifers from the Southeast to the discharge area in Ca Mau, the deepest position of the aquifers is at the Hau River fault area and gradually rises towards Ca Mau (Fig. 10). This means that the decrease in dissolved inorganic Carbon content along the moving direction does not correspond to an increase in sampling depth ( $z_1 < z_2 > z_3$ ) (Fig. 10), but only to with increasing distance from the recharging location to the sampling location. In another section in the Northwest - Southeast direction, it shows a trend that the closer it is to the discharge area, the deeper the aquifer ( $z_1 < z_2 < z_3$ ) (Fig. 11). However, groundwater does not move in this direction towards the discharge area.



**Fig. 10.** Hydrogeological cross-section No. III from the Southeast to Ca Mau [1] with distribution of aquifer depth  $z_1 < z_2 > z_3$



**Fig. 11.** Hydrogeological cross-section No. V [1] in the Northeast - Southwest direction with distribution of aquifer depth  $z_1 < z_2 < z_3$

The second cause is due to the mixing of other freshwater sources. This occurs due to the strengthening of the hydraulic relationship between aquifers through faults, hydrogeological windows, intercalation of higher-permeability sediment layers at locations with large concentrations of exploitation. As a result, the  $^{14}\text{C}$  activity in the collected samples represents the average  $^{14}\text{C}$  content from mixing and does not reflect the water that was recharged from the recharge area. When considering the internal correlation coefficient of the group of shallow aquifers (including  $qp_3$  and  $qp_{2-3}$ ) is weak (0.40), while the correlation of the group of deep aquifers ( $qp_1, n_2^2, n_2^1, n_1^3$ ) is moderate (0.58) (Fig. 3) shows that the mixing process occurs more strongly in the group of shallow aquifers.

Observe the red squares on Figure 8 to analyze the spatial distribution of  $^{14}\text{C}$  activity, and isotope ratio  $\delta^{18}\text{O}$  of the groundwater in  $qp_{2-3}$  aquifer, Ca Mau province. In the red squares likely where mixing occurs. Thus, there is a noticeable increase or decrease in  $^{14}\text{C}$  activity in a local region when compared to its surroundings. Besides that a large fluctuation amplitude of the value of Oxygen isotope ratio ( $\delta^{18}\text{O}$ ) values over a narrow range was also observed. This phenomenon, especially occurs in exploitation areas, where overexploitation leads to a decrease in the groundwater table. This is a consequence of the large

concentrated exploitation process leading to a lowering of the groundwater level, changing the natural dynamic state, and losing the original stable and balanced state of the aquifer.

#### 4. Conclusions

The research findings above indicate that there is a hydraulic relationship and groundwater mixing between aquifers, resulting in a weak spatial correlation between  $^{14}\text{C}$  activity and sampling depth. This weak correlation is attributed to two main reasons. Firstly, it is related to the hydrogeological structure of the aquifer. Secondly, it is attributed to groundwater mixing. In the Ca Mau area, groundwater mixing is influenced by two main factors. Firstly, saline groundwater is caused by mixing with seawater formed during periods of sea transgression. Secondly, fresh groundwater mixes from the strengthening hydraulic relationships between aquifers due to the presence of favorable conditions in the study area including faults, hydrogeological windows, intercalation of sediment layers with higher permeability, and overexploitation.

Observing the distribution map of isotope ratio  $\delta^{18}\text{O}$  and  $^{14}\text{C}$  activity also provides an additional basis for determining the extent of the area where favourable conditions for mixing factors exist. The unusual locations of the spatial distribution indicate these areas have lost the initial stability of the dynamic groundwater state. It is necessary to consider an appropriate model for determining groundwater age in mixing groundwater areas.

In conclusion, in the Ca Mau province, there is no modern water recharge, as this area serves as both the movement and discharge area of aquifers in the Nam Bo Plain. The tectonic characteristics of this area are complex, with some places being raised and others lowered. The aquifers are cut and moved up and down, leading to connections and obstructions in some places. Lenses containing saline and fresh groundwater are interspersed, and the overexploitation of a few aquifers in the area has lowered the groundwater level, changing the dynamic characteristics of the aquifer. On a local scale near water exploitation wells, the movement direction of groundwater in aquifers becomes complex and heterogeneous, leading to increased hydraulic interaction and mixed groundwater. This indicates that to manage regional groundwater resources effectively, a more comprehensive and detailed survey is necessary. This survey should aim to specifically determine the scope of strengthening hydraulic relationships and the mixing of water sources between aquifers, thereby limiting the exploitation of concentrated groundwater at high densities in these areas.

The study results show the feasibility of specifically determining strengthening hydraulic relationships and the mixing of water sources between aquifers in space using  $^{14}\text{C}$  and stable isotopes. In further studies, with a more detailed and extensive sampling density, it is possible to fully and accurately assess how strengthening hydraulic relationships and the mixing process occur between aquifers. From which aquifers recharge to which aquifers? And what is the recharge rate for them?

#### 5. Acknowledgements

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**Tab. 1.** Analytical results

No	ID*	Aquifer	Sampling depth	t	pH	EC	<sup>14</sup> C activity	u(PMC)	δ <sup>2</sup> H	δ <sup>18</sup> O	Cl <sup>-</sup>
			m	°C		(μS/cm)	PMC		(‰)	(‰)	mg/l
1	Q177.qp <sub>3</sub>	qp <sub>3</sub>	37.0	29.0	6.74	17,000	13.30	1.18	-34.80	-5.57	13531
2	Q631.qp <sub>3</sub>	qp <sub>3</sub>	90.0	29.2	7.12	10,350	21.20	0.88	-35.8	-6.57	3557
3	Q199.qp <sub>3</sub>	qp <sub>3</sub>	85.0	30.8	6.61	21,200	15.90	1.33	-25.10	-4.03	13941
4	Q177.qp <sub>2-3</sub>	qp <sub>2-3</sub>	64.0	31.0	6.79	26,200	15.15	1.25	-28.16	-4.52	9904
5	Q631.qp <sub>2-3</sub>	qp <sub>2-3</sub>	125.0	30.9	7.15	9,340	7.88	0.95	-36.31	-5.07	3457.2
6	Q608.qp <sub>2-3</sub>	qp <sub>2-3</sub>	140.0	32.5	7.13	584	5.01	1.70	-38.82	-5.56	KPH (LOD=6)
7	Q199.qp <sub>2-3</sub>	qp <sub>2-3</sub>	154.0	34.0	8.24	2,110	1.60	0.58	-42.87	-6.21	278.4
8	Q629.qp <sub>2-3</sub>	qp <sub>2-3</sub>	133.7	32.2	7.89	1,490	1.71	0.41	-44.14	-6.40	78
9	Q188.qp <sub>2-3</sub>	qp <sub>2-3</sub>	120.0	31.9	7.18	13,000	6.46	1.08	-37.04	-5.64	4889.1
10	GKT-01	qp <sub>2-3</sub>	110.0	33.0	8.05	940	2.73	0.86	-44.42	-6.88	26.6
11	GKT-03	qp <sub>2-3</sub>	100.0	32.9	7.56	1,076	3.01	1.09	-44.31	-6.91	69.9
12	GKT-04	qp <sub>2-3</sub>	120.0	33.9	7.97	866	3.27	0.91	-43.32	-6.53	37.6
13	GKT -06	qp <sub>2-3</sub>	100.0	33.7	7.59	920	4.98	1.15	-44.78	-7.11	51.5
14	GKT -08	qp <sub>2-3</sub>	106.0	33.9	7.68	1,344	4.18	1.21	-42.97	-7.07	264.2
15	GKT -09	qp <sub>2-3</sub>	120.0	33.9	7.73	830	4.07	1.18	-44.28	-7.12	54.7
16	GKT -10	qp <sub>2-3</sub>	100.0	33.9	7.54	920	6.12	1.16	-44.86	-7.03	71.2
17	GKT -11	qp <sub>2-3</sub>	92.0	33.8	7.66	1,310	4.97	1.25	-43.78	-7.27	266.2
18	GKT -12	qp <sub>2-3</sub>	80.0	30.7	7.76	2,321	5.47	0.98	-41.40	-7.28	775.6
19	GKT -22	qp <sub>2-3</sub>	90.0	31.1	7.56	806	10.70	1.25	-41.99	-7.17	79.2
20	GKT -25	qp <sub>2-3</sub>	120.0	32.0	7.25	1,175	10.00	1.80	-43.01	-6.80	238.9
21	GKT -32	qp <sub>2-3</sub>	85.0	33.9	7.54	820	8.34	1.12	-44.27	-7.37	19.4
22	GKT -36	qp <sub>2-3</sub>	77.0	35.4	8.09	2,580	4.94	0.79	-44.77	-7.23	446.1
23	Q177.qp <sub>1</sub>	qp <sub>1</sub>	192.0	34.5	8.48	845	9.27	0.94	-44.80	-7.09	32.8
24	Q631.qp <sub>1</sub>	qp <sub>1</sub>	165.0	32.1	7.46	6,760	13.72	1.16	-38.78	-6.41	2349.2
25	Q608.qp <sub>1</sub>	qp <sub>1</sub>	173.0	33.0	7.30	637	4.63	0.94	-41.13	-6.74	KPH (LOD=6)
26	Q199.qp <sub>1</sub>	qp <sub>1</sub>	244.0	36.0	8.24	1,900	1.75	0.60	-44.04	-6.82	165.2
27	Q188.qp <sub>1</sub>	qp <sub>1</sub>	192.1	35.5	7.95	1,540	2.78	0.85	-45.10	-6.80	147.4
28	Q177.n <sub>2</sub> <sup>2</sup>	n <sub>2</sub> <sup>2</sup>	236.0	35.3	8.58	834	3.59	0.81	-44.45	-7.76	54
29	Q631.n <sub>2</sub> <sup>2</sup>	n <sub>2</sub> <sup>2</sup>	250.0	30.1	7.20	5,560	27.36	0.70	-39.06	-7.13	2090.2
30	Q199.n <sub>2</sub> <sup>2</sup>	n <sub>2</sub> <sup>2</sup>	250.0	36.9	7.92	2,550	0.98	0.48	-41.50	-6.45	328.1
31	Q629.n <sub>2</sub> <sup>2</sup>	n <sub>2</sub> <sup>2</sup>	214.0	35.5	8.08	1,400	4.60	0.74	-44.61	-7.73	119.7
32	Q199.n <sub>2</sub> <sup>1</sup>	n <sub>2</sub> <sup>1</sup>	321.0	39.0	8.02	3,330	1.47	0.63	-41.04	-6.59	433

**Literature - References**

1. Nguyen Huu Dung, et al., "The relationship of groundwater and solid minerals with stratigraphic units and geological structures, Report on N-Q Stratigraphic Division and Study of Geological Structure of the Nam Bo Plain," Department of Geology and Mineral Resources of Vietnam, Ho Chi Minh, 2004.

2. Le Van Chung, et al., "Results of implementing the project to protect groundwater in large urban area phase II - Ca Mau province," Division for Water Resources Planning and Investigation for the South of Viet Nam, the Vietnam Ministry of Natural Resources and Environment, Ha Noi, 2021.
3. Center for Water Resources Warning and Forecasting, "Newsletter of announcement, forecast and warning on groundwater resources in Ca Mau province," Division for Water Resources Planning and Investigation for the South of Viet Nam, the Vietnam Ministry of Natural Resources and Environment, Ha Noi, 04/2022.
4. Dao Hong Hai, Nguyen Dinh Tu, "Assessing the middle – upper Pleistocene aquifer vulnerability due to the seawater intrusion in Ca Mau peninsula," Science and Technology Development Journal, Vols. Natural Sciences, Vol 2, no. 4, p. 190, 15-10-2018.
5. Lien, T.T.B., et al., "Study the Upper Pleistocene groundwater dynamic in the Nambo Plain for sustainable management of groundwater resources by isotope techniques," Radioanal Nucl Chem, Vol. 332, no. <https://doi.org/10.1007/s10967-023-09062-5>, p. 3559–3570, 2023.
6. Nguyen Kien Chinh, et al., "Summary report of Project “Study groundwater dynamics by the isotope hydrological techniques for water,” Center for Nuclear technologies, Vietnam Atomic Energy Institute, the Vietnam Ministry of Science and Technology, Ho Chi Minh, 2015-2016.
7. Nguyen Viet Ky, "Mechanism of formation of groundwater salinity zones in the northern Tien River region," Ho Chi Minh City University of Technology, Ho Chi Minh, 2003.
8. Doan Van Canh, et al., "Groundwater resources in the Mekong Delta: Challenges and solutions," Journal of Water Resources Science and Technology, vol. 14, 2013.
9. IAEA Library Cataloguing in Publication, "Isotope methods for dating old groundwater," in Isotope methods for dating old groundwater, Vienna, International Atomic Energy Agency, 2013, pp. 22, 24, 69.
10. F. Cornaton, P. Perrochet, "Groundwater age, life expectancy and transit time distributions in advective{dispersive systems:1. Generalized Reservoir Theory.," F. Cornaton \*, P. Perrochet, pp. 2-4, November 2018.
11. M. A. Geyh, "An Overview Of  $^{14}\text{C}$  Analysis In The Study Of Groundwater," Radiocarbon, vol. 42, pp. 99-114, 2000.
12. IAEA, "Sampling Procedures for Isotope Hydrology," in Water Resource Programme, Vienna, September, 2014..
13. TCVN 6663-11:2011, Water Quality - Sampling - Part 11: Guidelines For Groundwater Sampling, Ministry of Science and Technology, 2011.
14. P. H. Stuiver M, "Reporting of  $^{14}\text{C}$  data.," Radiocarbon, p. 355–363, 1977.
15. G. J. Fontes JCh, "Determination of the initial  $^{14}\text{C}$  activity of the total dissolved carbon: a review of the existing models and a new approach.," Water Resour Res, vol. 15, pp. 399-413, 1979.
16. Penna, et al., "On the reproducibility and repeatability of laser absorption spectroscopy measurements for  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  isotopic analysis," Hydrol Earth Syst Sci Discuss, vol. 7, p. 2975–3014, 2010.
17. Doan Van Canh, et al., "Study on the formation and groundwater age in the Nam Bo Plain using isotopic techniques," Vietnam Science and Technology, vol. 4(2), pp. 40-45, 2016.
18. Chau Tran Vinh, et al., "Study on the formation of groundwater reserves from hydraulic relationships sources in Nam Bo Plain aquifers using isotopic techniques," VNU Journal of Science, vol. 31, no. 3S, pp. 286-294, 2015.
19. Zhonghe Pang, et al., "An Isotopic Geoindicator in the Hydrological Cycle," Procedia Earth and Planetary Science, vol. 17, p. 534 – 537, 2017.
20. K. Rozanski, M. Gröning. Carbon-14 assay in water samples using benzene synthesis and liquid scintillation spectrometry, 219-228, IAEA-TECDOC 1401, 2002.