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Original Article

Groundwater Geochemistry in Aquifers in An Giang, Vietnam

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Abstract: Groundwater plays a vital role in the lives of people and ecosystem. In An Giang province located in the Mekong Delta, groundwater contributes significantly to the domestic water supply and economic development. This study surveyed 142 groundwater samples in An Giang to understand the groundwater geochemical characteristics. The results showed that TDS values of groundwater ranging from 80 to 4,540 mg/L. About 46% of the total 142 samples have TDS > 1,000 mg/L and were not suitable for drinking purpose. Hydrogeochemical facies evolution diagram was applied to investigate salinization and 43% of groundwater samples were impacted by salinization processes. The salinization of groundwater was mainly observed in the upper and upper middle Pleistocene aquifers. In both Holocene aquifer in shallow depth (~ 20 m below land surface) and Pliocene aquifers in very deep depth (>150 m below land surface), groundwater geochemistry indicated freshening condition. The freshening in shallow aquifers was due to recent recharges by rainwater or river system. In the deep aquifers, the freshening process was caused by fossil groundwater in the area. These results highlight the vulnerability of deep fresh aquifers to vertical salinization and underscore the need for improved groundwater protection strategies in the area.

Keywords: Groundwater, freshening/salinization, HFE-diagram, Mekong Delta, *Fossil fresh* groundwater.

1. Introduction

Groundwater salinization is a globally recognized threat in coastal and deltaic aquifers, where increasing salinity reduces freshwater availability and creates long-term pressures on human health, agriculture, and ecosystem resilience [1-3]. Salinization processes can arise

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from multiple drivers, including excessive groundwater abstraction, sea-level rise, irrigation return flow, and surface evaporation, all of which alter natural hydrochemical equilibria [4-7] In large deltas, additional complexities emerge from aquifer heterogeneity, sedimentary layering, legacy salinity sources, and non-marine mechanisms such as evaporative concentration, and paleo-saline groundwater retained in low-permeability lenses [6, 7]. These interacting processes complicate the interpretation of saline groundwater distribution and make depth-resolved hydrochemical investigations necessary for understanding salinity evolution.

In the Mekong Delta (MD), groundwater plays a critical role in domestic supply, irrigation, and economic development. However, the region faces increasing stress due to land subsidence, sea-level rise, and widespread groundwater extraction. The phenomenon of saltwater intrusion is recognized as a matter of national concern, imposing limitations on the extraction of groundwater from aquifers [8-11]. Consequently, it becomes imperative to gain a comprehensive understanding of the intricate hydrogeochemical processes and variables governing the transformation of groundwater into brackish water within MD aquifers, along with a discernment of the sources of this salinization. Nevertheless, the inherent complexity of MD aquifers, marked by aquifer heterogeneity, spatial and temporal fluctuations in the flow patterns, and the intricate interplay between surface water and groundwater, adds a layer of intricacy to the elucidation of the determinants influencing the distribution of fresh and saline groundwater [10, 12].

An Giang Province in the Mekong Delta is indeed recognized for its arsenic-rich groundwater [9, 13], which poses significant health risks. Despite its inland location, high total dissolved solids (TDS) levels exceeding 1000 mg/L are also observed in some monitoring sites [14] (Giao et al., 2019), and private wells [15, 16]. This combination of arsenic and high salinity can lead to serious health issues for the local population [17].

The primary objective of this study was to evaluate the extent of saltwater intrusion and pollutant dispersion by employing well water sampling as a dependable means of assessing water quality impacted by saltwater intrusion, with a specific focus on the overall depth of the collected samples. Hydrogeochemical method such as hydrogeochemical analysis employing ionic deviations of major ions, along with the utilization of hydrochemical facies evolution diagrams (HFE-D) to enhance our understanding of these complex phenomena [18]. The obtained results could provide additional data on the progress of groundwater quality and saline intrusion process which support decision makers to propose sustainable exploitation solutions.

2. Study Area

Geographical and climate settings

An Giang province encompasses an area of about 3,536 km^2 with a total population of about 1.904 million people in 2020 [19]. Situated in the upper reaches of the Mekong Delta, this province boasts an intricate river network system, as visually represented in Figure 1. The climatic pattern in the area follows a distinct wet and dry season, with the former extending from May to November, and the latter prevailing during December through April. The region receives an annual average rainfall of approximately 1,551 millimetres, with a substantial 88.5% of this precipitation occurring during the wet season [19]. An Giang province is a typical example of the agricultural intensification endeavours within the Mekong Delta. The management of water resources in this province is predominantly under human control, facilitated through the utilization of sluice gates, canals, and dike systems, as highlighted by previous studies [20].

Hydrogeology

The hydrogeological condition is characterized by seven porous aquifers (Fig. 2; Table 1), namely: Holocene aquifer (qh), Upper

Pleistocene aquifer (qp_3), Middle-Upper Pleistocene aquifer (qp_2^3), Lower Pleistocene aquifer (qp_1), Middle Pliocene aquifer (n_2^2), Lower Pliocene aquifer (n_2^1), Upper Miocene aquifer (n_1^3) and one fractured aquifer (ps-ms) [15].

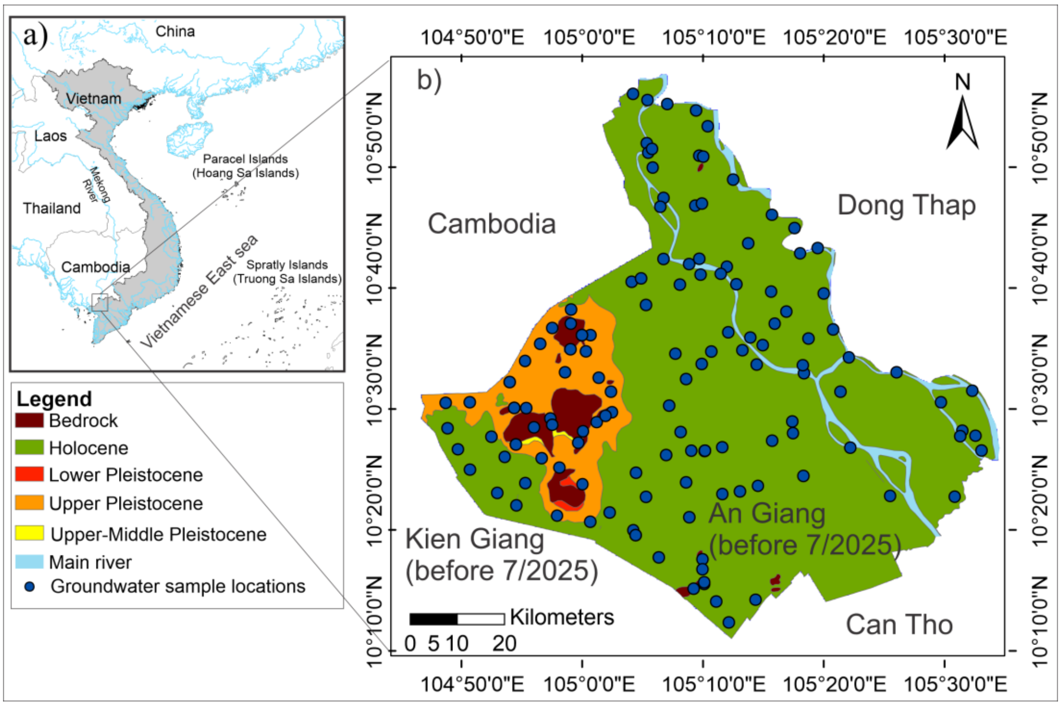

Figure 1. Groundwater sampling location and geological map.

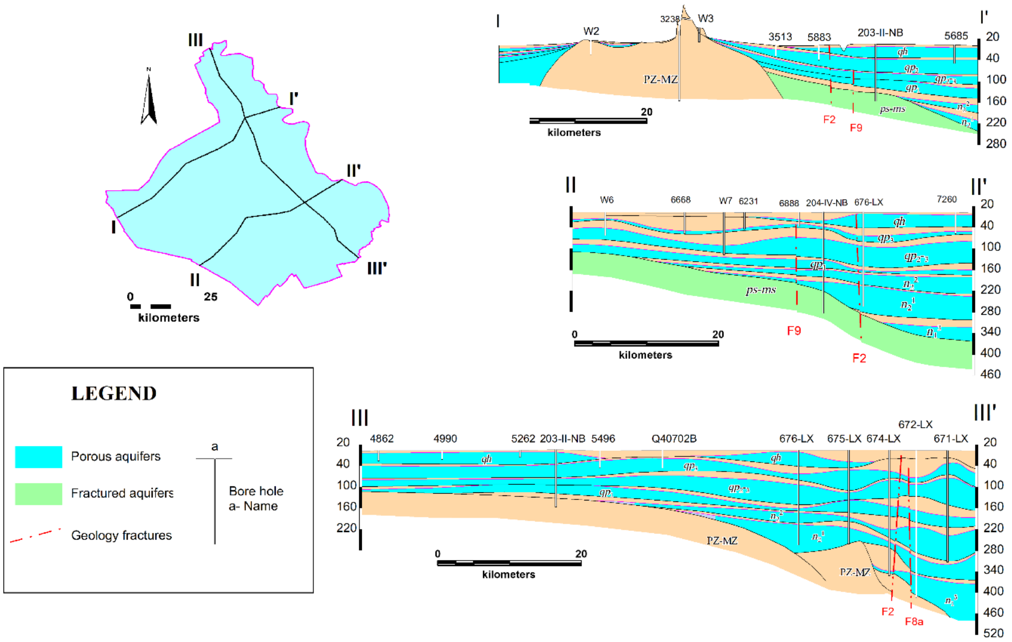

Figure 2. Hydrogeological cross-sections.

Table 1. Summary of depth to aquifer systems

Aquifer	Top (m b.l.s)			Bottom (m b.l.s)			Thickness (m)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
qh	0.0	58.7	15.9	2.3	67.0	27.7	0.9	33.0	11.8
qp_3	0.0	95.0	40.8	3.2	136.0	67.8	3.2	79.0	27.0
qp_2^3	9.7	165.0	77.3	24.5	176.0	109.7	5.1	76.5	32.4
qp_1	52.0	183.4	142.3	57.0	219.6	166.2	5.0	50.0	23.9
n_2^2	130.4	238.5	205.7	144.0	308.5	245.8	4.6	79.0	40.1
n_2^1	196.0	299.9	251.0	222.0	346.5	291.5	8.6	77.5	40.5
n_1^3	315.5	349.0	332.3	406.0	427.0	416.5	57.0	111.5	84.3

Groundwater extraction in this region has predominantly taken place in the Holocene, Upper Pleistocene, Upper-Middle Pleistocene and Middle Pliocene aquifers, as these layers are readily accessible due to surface outcrops, and their waters are utilized for both domestic and irrigation purposes [15, 16]. As of the year 2020, the province has a total of 7,071 groundwater wells with the extracted rate of about 30.988 m^3/day. There are 156 wards, communes and towns of An Giang province have used groundwater to serve the daily life needs, of which Chau Doc city has the least number of groundwater exploitation wells (10 wells) as surface water is the main source of water supply system.

3. Methods

3.1. Data Collection

Groundwater geochemical data of 142 samples collected in 142 private wells in An Giang province during 2012 and 2013 is used for this study (Fig. 1). The data is collected from Division for Water Resources Planning and Investigation for the South of Vietnam [15] (Pham et al., 2018). The groundwater samples were analyzed for major cations such as calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K) and major anions: chloride (Cl), bicarbonate (HCO_3), sulphate (SO_4) and nitrate (NO_3), and other ions including nitrite (NO_2), iron (Fe), ammonium (NH_4) and the total dissolved solid (TDS), following the national standards.

3.2. Geochemical Method

The Hydrogeochemical Facies Evolution Diagram (HFED) was introduced by Giménez-Forcada [18] as a framework for analyzing the evolution of groundwater chemistry, particularly in coastal aquifers. The diagram visually represents the distribution of major anions (HCO_3^-, SO_4^{2-}, Cl^-) and cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) in relation to their total concentrations. Four major groundwater geochemical facies are identified: Na-Cl, seawater; Ca-HCO_3, natural freshwater; Ca-Cl, salinized water with reverse exchange; and Na-HCO_3, salinized water with direct exchange.

Using this approach, researchers can identify different hydrogeochemical facies and track changes due to processes like salinization and freshening. The method has gained traction for its effectiveness in assessing seawater intrusion, with a seawater intrusion indicator (SWI) ranging from 1 to 10. Values below 5.5 indicate a freshening stage, while a value of 10 signifies maximum seawater intrusion. This tool has proven instrumental in understanding the complex dynamics of coastal groundwater systems [18, 21]. Detail of the HFE-Diagram is provided in Giménez-Forcada [21].

4. Results and Discussions

4.1. General Groundwater Geochemical Characteristics

Generally, about 46, 46, 42, 15, and 7% of the total (n=142) groundwater samples show Na, Cl, NH_4, Fe and NO_3 concentrations exceeding those values in the drinking water quality standard (DWQ [21]: 200, 250, 0.3, 0.3, 8.9 mg/L for Na, Cl, NH_4, Fe, and NO_3, respectively). Particularly, groundwater pH varies in the range of 6.5-7.8, 5.6-7.7, 2.6-8.1, 7.6-8, and 6.5-8 for samples collected in qh, qp_3, qp_2^3, n_2^2 and rock (ps-ms) aquifer, respectively (Table 2). TDS values vary in the range of 304-2384, 82-4740, 186-3286, 480-1149, and 96 - 939 mg/L for qh, qp_3, qp_2^3, n_2^2 and rock (ps-ms) aquifer, respectively. About 46% of the total 142 samples have TDS > 1000 mg/L and not suitable for drinking. Among of them, 15%, 64%, 53%, and 33% total groundwater samples in the aquifer including qh, qp_3, qp_2^3, and n_2^2 show TDS > 1000 mg/L. Generally, the highest TDS concentration observed in qp_3 aquifer. Groundwater in rock aquifer is generally fresh (TDS <1000). In the same trend 12%, 69%, 47%, and 67% of samples collected in qh, qp_3, qp_2^3 and n_2^2 aquifers show Cl concentrations greater than the limited values (250 mg/L for Cl) for drinking water. However, only 4%, 3%, and 9% of groundwater samples collected in qh, qp_3 and qp_2^3 aquifers show SO_4 concentrations higher than the limited values (SO_4 < 400) for drinking water.

Table 2. Groundwater geochemical characteristic of multilayer aquifers

Aquifer	Parameters	pH	TDS	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Na^+	K^+	Ca^{2+}	Mg^{2+}	NH_4^+	Fe
qh	Average	7.3	634.7	342.1	137.0	34.2	2.5	101.1	6.2	64.9	25.0	6.8	0.2
	Max	7.8	2384.0	488.2	1109.6	264.2	15.0	700.0	15.3	234.5	70.5	29.8	0.8
	Min	6.5	304.0	183.1	10.6	2.4	0.1	18.2	1.0	8.0	4.9	0.0	0.1
	SD	0.3	445.6	97.5	234.5	66.5	2.9	142.6	3.4	52.6	15.1	8.6	0.1
	N	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0
% exceeded DWQ		0.0	15%		12%	4%	4%	12%				54%	15%
qp_3	Average	7.0	1708.8	336.0	732.6	77.4	3.5	413.7	10.7	70.1	71.5	2.1	0.2
	Max	7.7	4740.0	1037.3	2694.2	399.6	42.6	1297.0	236.8	286.6	248.1	23.7	2.1
	Min	5.6	82.0	24.4	10.6	0.1	0.1	5.8	0.7	4.0	1.0	0.0	0.0
	SD	0.4	1229.4	201.9	678.8	80.0	6.7	336.8	28.3	58.2	59.1	4.4	0.3
	N	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0
% exceeded DWQ		0%	64%		69%	3%	6%	16%				40%	16%
qp_2^3	Average	6.7	1271.3	240.9	441.3	177.6	5.9	275.2	8.7	55.5	58.3	0.8	3.8
	Max	8.1	3286.0	622.4	1375.5	2036.8	93.7	800.0	82.3	198.4	184.6	12.0	60.1
	Min	2.6	186.0	0.1	16.0	0.5	0.2	12.2	0.8	12.2	3.4	0.0	0.0
	SD	1.1	831.0	157.4	414.6	447.9	17.0	177.5	14.0	42.2	53.2	2.4	14.2
	N	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0
% exceeded DWQ		0%	53%		47%	9%	9%	53%				22%	22%
n_2^2	Average	7.8	856.3	343.7	249.3	57.6	1.1	252.7	4.6	26.1	17.0	0.0	0.1
	Max	8.0	1149.0	396.6	395.3	76.9	2.1	311.2	6.3	39.1	27.4	0.0	0.3
	Min	7.6	480.0	299.0	86.9	28.8	0.6	141.8	3.7	16.0	11.6	0.0	0.0
	SD	0.2	279.5	40.3	126.5	20.8	0.7	78.4	1.2	9.6	7.3	0.0	0.1
	N	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
% exceeded DWQ		0%	33%		67%	0%	0%	67%				0%	0%
rock	Average	7.1	425.7	216.4	52.6	35.1	9.6	64.7	10.2	36.8	12.5	0.4	0.2
	Max	8.0	939.0	476.0	163.1	130.2	78.2	165.0	47.3	101.4	40.3	3.0	1.7
	Min	6.5	96.0	42.7	14.2	2.4	0.4	10.0	0.8	7.0	0.6	0.0	0.0
	SD	0.5	206.2	122.0	42.7	41.2	21.5	46.4	12.1	21.8	11.1	0.8	0.4
	N	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
% exceeded DWQ		0%	0%		0%	0%	0%	0%				0%	0%

4.2. Salinization of Groundwater

The results of HFE-D indicated that 43% of total (n=142) groundwater samples show SWI values greater than 5.4 indicating the impact of salinization processes (Fig. 3). Whereas, 38% of the total samples show SWI values is even greater than 8 showing that these groundwater samples are seriously impact by salinization. The remain part (57%) of the total groundwater samples show freshening processes. The groundwater samples show freshening characteristics is generally observed near river and mountain areas associating with low Cl concentration. All groundwater samples in n_2^2 and rock aquifers show freshening characteristics. Only some samples in qh aquifer show salinization. But salinization mainly observed in qp^3 and qp_2^3 aquifers associating with high Cl concentrations.

High saline concentrations is widely observed in the Mekong Delta [9], the saline groundwater may be trapped in aquifer system since Holocene during seawater level high stand or even since 60 kya [8]. Some previous studies in Mekong Delta suggested that the saline groundwater may be horizontally intruded to fresh water zone by over extraction or inter aquifer flow by leaking through broken well casing [10, 23]. This study demonstrates that many groundwater samples (43%) in private wells show signs of salinization, rising concerns for sustainable water management and human health risks [1, 24]. Because most of the private wells were use for drinking purpose [15]. Recent studies suggested that drinking high salt concentration in water may have greater risk of high blood pressure and other adverse health problems [25].

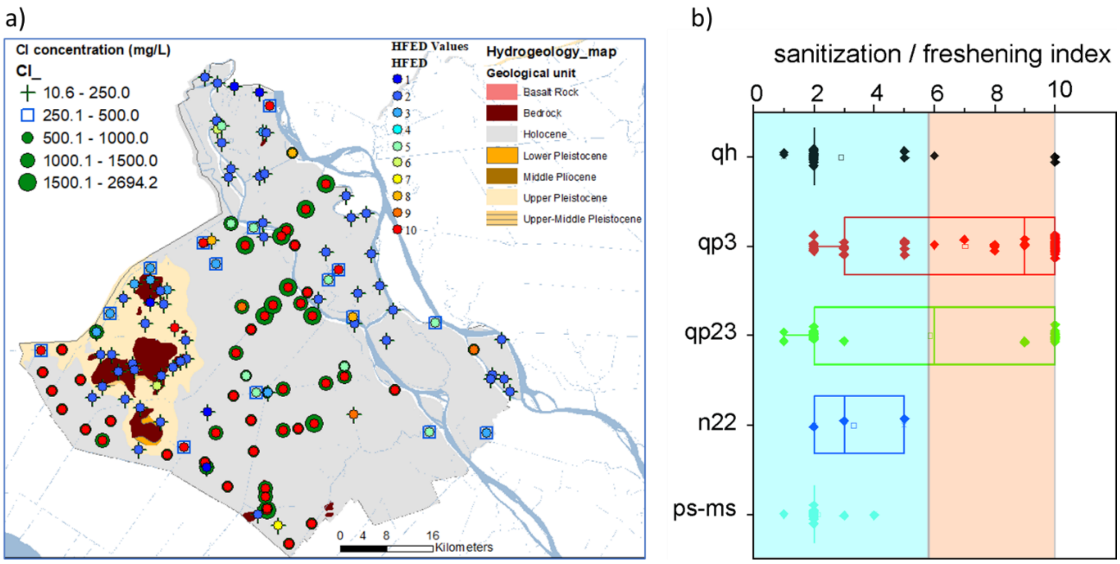

Figure 3. Salinization and freshening index distribution.

5. Conclusion

This study provides a depth-resolved evaluation of groundwater geochemistry in An Giang province using 142 well samples. Nearly half (46%) of the samples exceed the drinking-water TDS limit, and 43% exhibit salinization (SWI > 5.4), especially in the qp^3 and qp_2^3 aquifers. In contrast, groundwater in the shallow Holocene and deep Pliocene aquifers displays freshening characteristics linked to modern recharge and fossil fresh groundwater, respectively. Although these deep aquifers currently provide good-quality water, they are vulnerable to vertical salinization from over-exploitation of groundwater. The findings highlight the need for caution when installing new wells, the identification of sustainable groundwater yields for deep aquifers, and the strengthening of long-term monitoring programs to ensure safe and sustainable groundwater management.

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References

[1] B. Zhou, P. Perel, G. A. Mensah, M. Ezzati, Global Epidemiology, Health Burden and Effective Interventions for Elevated Blood Pressure and Hypertension. Nature Reviews Cardiology, Vol. 18, No. 11, 2021, pp. 785-802, https://doi.org/10.1038/s41569-021-00559-8.

[2] E. R. Herbert, P. Boon, A. J. Burgin, S. C. Neubauer, R. B. Franklin, M. Ardón, K. N. Hopfensperger, L. P. Lamers, P. Gell, A Global Perspective on Wetland Salinization: Ecological Consequences of a Growing Threat to Freshwater Wetlands, *Ecosphere*, Vol. 6, No. 10, 2015, pp. 1-43, https://doi.org/10.1890/ES14-00534.1.

[3] S. S. Kaushal, G. E. Likens, M. L. Pace, J. E. Reimer, C. M. Maas, J. G. Galella, R. M. Utz, S. Duan, J. R. Kryger, A. M. Yaculak, W. L. Boger, Freshwater Salinization Syndrome: from Emerging Global Problem to Managing Risks, *Biogeochemistry*, Vol. 154, No. 2, 2021, pp. 255-292, https://doi.org/10.1007/s10533-021-00784-w.

[4] A. P. Bosch, J. P. R. Sanchez, A. Vallejos, J. M. Andreu, J. C. Cerón, L. M. Sanchez, F. Sola, Impacts Of Agricultural Irrigation on Groundwater Salinity, Environmental Earth Sciences, Vol. 77, No. 5, 2018, pp. 197, https://doi.org/10.1007/s12665-018-7386-6.

[5] M. Mirzavand, H. Ghasemieh, S. J. Sadatinejad, R. Bagheri, An Overview on Source, Mechanism and Investigation Approaches in Groundwater Salinization Studies. International Journal of Environmental Science and Technology, Vol. 17, No. 4, 2020, pp. 2463-2476, https://doi.org/10.1007/s13762-020-02647-7.

[6] F. Larsen, H. V. Hoang, L. V. Tran, N. Q. Pham, Paleo-Climatic Control on Recharge and Fresh-Salt Groundwater Distribution in the Red River Delta Plain, Vietnam, Scientific Reports, Vol. 14, No. 1, 2024, pp. 21280. https://doi.org/10.1038/s41598-024-71899-x.

[7] C. A. J. Appelo, D. Postma, Geochemistry, Groundwater and Pollution, CRC Press, 2004.

[8] V. H. Pham, F. C. Van Geer, V. B. Tran, W. Dubelaar, G. H. O. Essink, Paleo-Hydrogeological Reconstruction of the Fresh-Saline Groundwater Distribution in the Vietnamese Mekong Delta Since the Late Pleistocene. Journal of Hydrology: Regional Studies, Vol. 23, 2019, pp. 100594, https://doi.org/10.1016/j.ejrh.2019.100594.

[9] Q. K. Ha, K. Kim, N. L. Phan, T. H. Phung, J. Lee, V. K. Nguyen, C. N. Phan, A Hydrogeological and Geochemical Review of Groundwater Issues in Southern Vietnam. Geosciences Journal, Vol. 23, 2019, pp.1005-1023, https://doi.org/10.1007/s12303-019-0021-z.

[10] Q. K. Ha, V. T. Dang, L. P. Vo, D. H. Dang, Integrated Approaches to Track Saline Intrusion for Fresh Groundwater Resource Protection in the Mekong Delta. Groundwater for Sustainable Development, Vol. 23, 2023, pp.101046, https://doi.org/10.1016/j.gsd.2023.101046.

[11] H. Xiao, Y. Tang, H. Li, L. Zhang, T. N. Duc, D. Chen, Q. Tang, Saltwater Intrusion into Groundwater Systems in the Mekong Delta and Links to Global Change. Advances in Climate Change Research, Vol. 12, No. 3, 2021, pp. 342-352, https://doi.org/10.1016/j.accre.2021.04.005.

[12] J. L. Gunnink, H. V. Pham, G. H. Oude Essink, and M. F. Bierkens, The Three-Dimensional Groundwater Salinity Distribution and Fresh Groundwater Volumes in the Mekong Delta, Vietnam, Inferred from Geostatistical Analyses. Earth System Science Data, Vol. 13, No. 7, 2021, pp. 3297-3319, https://doi.org/10.5194/essd-13-3297-2021.

[13] T. H. Hoang, S. Bang, K. W. Kim, M. H. Nguyen, D. M. Dang, Arsenic in groundwater and sediment in the Mekong River delta, Vietnam, Environmental Pollution, Vol. 158, No. 8, 2010, pp. 2648-2658, https://doi.org/10.1016/j.envpol.2010.05.001.

[14] K. A. Phan, N. T. Giao, Groundwater Quality and Human Health Risk Assessment Related to Groundwater Consumption in an Giang Province. ARCHIVOS DE MEDICINA, Vol. 3, No. 2, 2018, pp. 4, https://doi.org/10.13141/jve.vol10.no2.pp85-91.

[15] DWRPIS, Report on Investigation of Groundwater Resources for the Economic Key Zone of Souththerm of Mekong Delta, Vietnam, Division of Water Resources Planning and Investigation for the South of Vietnam, 2018 (in Vietnamese).

[16] DWRPIS, Report on Project on Building the Map of Prohibited, Limited Zones for Constructing New Groundwater Exploitable Well in an Giang Province. Division of Water Resources Planning and Investigation for the South of Viet Nam, 2020 (in Vietnamese).

[17] Q. K. Ha, V. T. Dang, T. B. Loc, D. T. Vo, L.P. Vo, Arsenic, Trace Metals, and Salinity Co-Contamination in Groundwater of an Giang, Mekong Delta: Health Risks and Geochemical Drivers, Environmental Earth Sciences, Vol. 84, 2025, pp. 596, https://doi.org/10.1007/s12665-025-12631-4.

[18] E. G. Forcada, Dynamic of Sea Water Interface Using Hydrochemical Facies Evolution Diagram, Groundwater, Vol. 48, No. 2, 2010, pp. 212-216, https://doi.org/10.1111/j.1745-6584.2009.00649.x.

[19] An Giang Province Statistical Yearbook (ASY), An Giang Province, Vietnam, 2020.

[20] J. Livsey, C. T. Da, A. Scaini, T. H. P. Lan, T. X. Long, H. Berg, S. Manzoni, Floods, soil and food–Interactions Between Water Management and Rice Production Within an Giang Province, Vietnam, Agriculture, Ecosystems & Environment, Vol. 320, 2021, pp. 107589, https://doi.org/10.1016/j.agee.2021.107589.

[21] E. G. Forcada, Space/Time Development of Seawater Intrusion: A Study Case in Vinaroz Coastal Plain (Eastern Spain) Using HFE-Diagram, and Spatial Distribution of Hydrochemical Facies, Journal of Hydrology, Vol. 517, 2014, pp. 617-627, https://doi.org/10.1016/j.jhydrol.2014.05.056.

[22] QCVN 01-1:2018/BYT, National Technical Regulation on Domestic Water Quality.

[23] Q. K. Ha, S. Choi, N. L. Phan, K. Kim, C. N. Phan, V. K. Nguyen, K. S. Ko, Occurrence of Metal-Rich Acidic Groundwaters Around the Mekong Delta (Vietnam): A Phenomenon Linked to Well Installation. Science of the Total Environment, Vol. 654, 2019, pp. 1100-1109, https://doi.org/10.1016/j.scitotenv.2018.11.200.

[24] M. Shammi, M. M. Rahman, S. E. Bondad, M. B. Doza, Impacts of Salinity Intrusion in Community Health: A Review of Experiences on Drinking Water Sodium from Coastal Areas of Bangladesh, in *Healthcare,* Vol. 7, No. 1, 2019, pp. 50, https://doi.org/10.3390/healthcare7010050.

[25] W. Mueller, D. Zamrsky, G. O. Essink, L. E. Fleming, A. Deshpande, K. C. Makris, B. W. Wheeler, J. N. Newton, K. V. Narayan, A. M. Naser, M. O. Gribble, Saltwater Intrusion and Human Health Risks for Coastal Populations Under 2050 Climate Scenarios. Scientific Reports, Vol. 14, No. 1, 2024, pp. 15881, https://doi.org/10.1038/s41598-024-66956-4.