

Research Article

Assessment of groundwater facies in Wates Coastal Area, Kulon Progo, Yogyakarta, Indonesia

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Abstract : The groundwater quality in Wates coastal area is generally a good category but there are high salinity values at some locations. The chemical quality of groundwater from place to place is different. The difference of water quality is a major problem in the study area. A total of 27 groundwater samples were collected in August, 2017. Geochemical signatures of groundwater were used to analyze the major ionic concentrations in the groundwater, to identify the dominant hydrogeochemical processes, and to determine the relationship between groundwater flow and spatial distribution of water types. Hierarchical Cluster analysis and Schoeller diagram, Gibbs plots, Scatter diagrams, and Piper Trilinear diagram were employed to evaluate the hydrogeochemical evolution of groundwater. In Schoeller diagrams, the relative tendency of ions in meq/L shows $\text{Na}^+ > \text{Mg}^{2+} > \text{Ca}^{2+} > \text{K}^+$ and $\text{HCO}_3^- > \text{Cl}^- > \text{SO}_4^{2-}$ trends, typically in saline water. Gibbs diagram reveals that the groundwater chemistry is mainly controlled by rock weathering with secondary contribution from evaporation source. Based on the results of Hierarchical Cluster analysis and Piper diagram, dominant hydrogeochemical facies in the study area are Ca-HCO₃, Na-Cl, and Ca-Na-HCO₃ types. Ca-HCO₃ facies are almost throughout the study area and the evolution of groundwater was mainly controlled by the silicate weathering process. Na-Cl water types are grouping in the study area influenced by cation exchange and evaporation processes, while Ca-Na-HCO₃ types are locally grouping with silicate weathering and cation exchange processes. The geology implies that common silicate minerals are found everywhere in the study area. In fact, the distributions of groundwater facies are related to the local geology, which may result in different hydrochemical processes. In addition, lithology is very influential on the existence of groundwater in the study area.

Keywords: *Gibbs plots, Hierarchical Cluster analysis, hydrochemical facies, Piper Trilinear diagram, Schoeller diagram*

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Introduction

Groundwater salinization is one of the most difficult problems threatening the sustainable groundwater resources particularly in coastal region. Any coastal area often exhibits a complex distribution of fresh water and salt water, or, in general, of different water types (Custodio, 2010). Salt water intrusion to the aquifers can also

involve a range of complex hydrogeochemical processes. In natural hydrological cycling, the groundwater interacts with the surrounding rocks causing a variety of hydrogeochemical processes that alter groundwater chemical components on local or regional scale. The hydrogeochemical processes that are responsible for altering the chemical composition of groundwater vary with respect to space and time. Therefore,

hydrogeochemical study is a vital tool for assessing its quality (Odukoya et al., 2013).

The current study area, Wates, is located in a coastal area. Therefore it can also be affected by the intrusion of salt water. Based on the results of physical measurements, the water quality in the study area is generally a good category. But high salinity values at some locations are likely caused by the high salt composition contained in groundwater. Chemistry of groundwater varies significantly within small local parts through the study area. Other locations show remarkable similarity in chemical composition. Summarizing, the chemical quality of groundwater from place to place is different. Probably the more important factors are the properties of material through which the water moves. So the difference of water quality in the study area may be a major problem in the distribution of hydrochemical facies.

A detailed comprehensive study on hydrogeochemistry of Wates coastal area is lacking till date. Therefore, in response to this problem, the study area was targeted to determine the groundwater facies in the study area based on its chemical compositions. The objectives of the present study are to investigate the spatial distribution of major ions in the groundwater, to identify the dominant hydrogeochemical processes and factors that controlling the chemical characteristics of the groundwater, and to determine the relationship between groundwater flow direction and spatial distribution of the water types. In this case, chemical nature of groundwater and variation in hydrochemical facies can be understood by plotting major cation and anion concentrations on different graphical representations; Hierarchical Cluster analysis and Schoeller diagram, Gibbs plot, scatter diagrams of ionic ratios with simple linear regression, and Piper Trilinear method. On the basis of above analysis results, an attempt was made to highlight the hydrochemical facies of groundwater and their relationships with the local hydro-environmental factor such as flow pattern. Thus, knowledge of hydrogeochemical processes can help to better understand the chemical characteristics of groundwater, which can lead to a reasonable allocation of groundwater resources for many different purposes such as in agriculture, industry, and environmental protection.

Description of the Study Area

The present study was conducted in Wates coastal area, Kulon Progo District, Yogyakarta Special Province, Indonesia. Wates coastal area covers an area of almost 32.00239 km² and it lies between approximately the longitudes 110° 05' 00" and

110° 07' 00" E, the latitudes 7° 50' 00" and 7° 56' 00" S. The study area is bounded to the east by Panjatan Sub-district, to the north by Pengasih Sub-district, to the west by Temon Sub-district and to the south by Indian Ocean. The topography of the study area is generally flat having no high density drainage network with general slope towards the south. The maximum elevation is approximately 50 m above mean sea level as shown in Figure 1.

Geological and geomorphological setting

Wates coastal area is included in the Quaternary age and can be divided into two main geologic units, a southern part comprising Holocene formation known as Sand Dunes and a northern part consisting of Holocene formation known as Wates (Bemmelen, 1970). Based on the sequence of lithostratigraphy in the study area, Wates Formation is divided into two units, namely: (a) Wates Formation (W₁) derived from upper fluvial sediments, composed of clay material, silt, with a small amount of fine sand; and silt lithoral loam deposits at the bottom; (b) Wates Formation (W₂) derived from marine deposits, composed of clays with lenses containing fossils of marine *mollusks*.

Wates Formation that occupies the Alluvial Planes (Fluviomarin Planes) around the Serang River flow, at the bottom is composed by littoral deposits of clay and silt from the weathering of Sentolo Formation and the western Kulon Progo Mountains. In some locations, there are sand and gravel beneath the argillaceous deposits (sediments composed of clay minerals or having a significant amount of clay in their composition). Alluvial Planes were formed by the ancient lagoons and natural levee due to fluvial sedimentation. Wates Formation that occupies the Sand Dunes is composed of fine grained to coarse grained sand materials. This formation occupies along the coast in the study area and it is located above the Wates Formation (W₁ and W₂). The sand materials in this formation consist of many iron minerals and a few other metals. Sand Dunes are the sediments formed by eolian-marine process. Besides, the geomorphological condition greatly affects the geology and formations of aquifer in the study area and it can be divided into several geomorphological units, namely (a) M₁ - beach (Sand Dunes), (b) M₂ - beach ridges (W₂), (c) E - sand dunes and swale (Sand Dunes), and (d) F_m - Fluviomarin Plains (W₁).

Hydrogeological setting

The study area is mainly composed of two aquifer systems, namely Wates Aquifer System and complex Beach Ridges and Sand Dunes Aquifer System (McDonald and Partners, 1984). The

Wates Aquifer System is constituted by the Alluvial deposits. The general groundwater flow from the Sentolo Hills enters the Wates Aquifer System, and stops to the north of the complex Beach Ridges and Sand Dunes Unit, which is locally separated aquifer system. At the border of Alluvial Plains Unit with the Beach Ridges, the groundwater moves in a curve below the complex

Beach Ridges and Sand Dunes Aquifer System, which is seasonally dependent. The complex Beach Ridges and Sand Dunes Aquifer System is composed of fine to coarse grained sand materials. This type is generally a non-pressured aquifer that resembles the groundwater pockets, which can be grouped into minor aquifers, with fresh groundwater content.

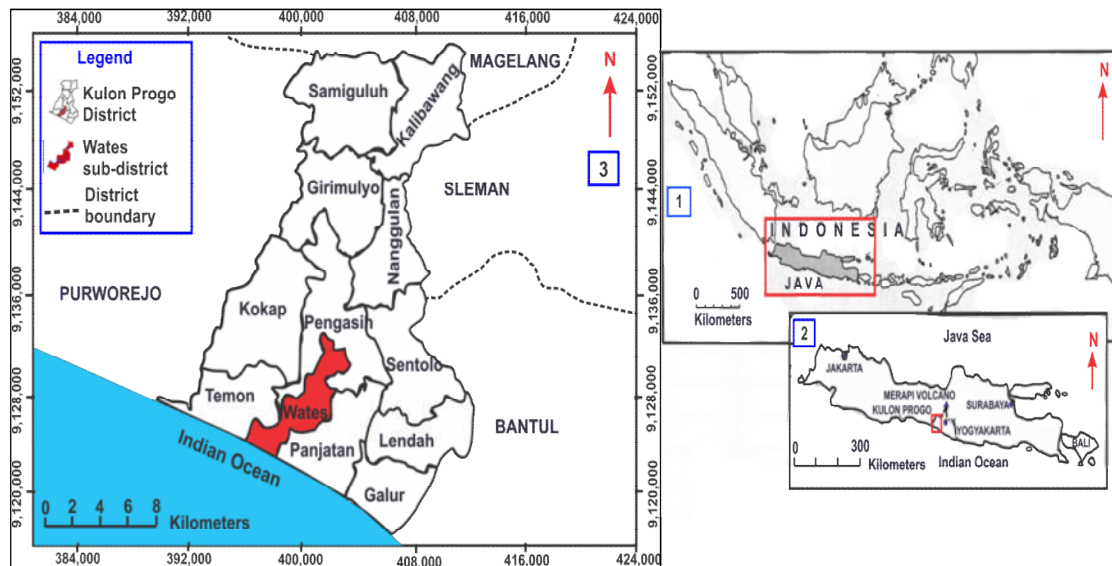


Figure 1. Location map of the study area

The base of complex Beach Ridges and Sand Dunes is the layer of marine clay that is aquitard at a depth of \pm 40-60 m (Hendrayana and Ramadhika, 2016). Therefore, the shape resembles a groundwater pocket that is local, so groundwater input only comes from rain water, which has the local movement with short cycles. Although the existence of complex Beach Ridges and Sand Dunes, the interface has no direct effect on groundwater conditions in this aquifer system, which means that it has not been detected any intrusion of sea water into the aquifer system.

Research Methodology

Water sampling and laboratory analysis

In order to evaluate the mechanism of hydrochemical facies in the study area, groundwater samples were collected from 27 locations during August 2017. A total of sampling locations are shown in Figure 2. To avoid cross contamination, bottles filled up the samples systematically for analyses. The pH, temperature (T), electrical conductivity (EC), and total dissolved solids (TDS) were measured using

water test kit in the field immediately after sampling. Water test kit needs to calibrate before use. The depths to water table were measured in these wells. The preservation of samples in the field, and their transportation to laboratory has been carried out using the standard recommended analytical methods (APHA, 2005). Water samples collected in the field were analyzed for major cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+) and anions (CO_3^{2-} , HCO_3^- , SO_4^{2-} , Cl^- , NO_3^- , PO_4^{3-}) in Laboratory of Biaya Pengujian, Yogyakarta, Indonesia.

Hierarchical Cluster analysis and Schoeller diagram

Hierarchical Cluster analysis, which successively joins the most similar observations, is widely used in hydrochemical analyses to identify different chemical characteristics (Li et al., 2018). In this study, Hierarchical Cluster analysis was applied where clusters were formed sequentially, by starting from the most similar pair of objects and forming higher clusters. The software Cluster 3.0 was used to carry out the analysis. Schoeller diagram can also be used to present average chemical composition of groundwater (Schoeller, 1960). To further evaluate the geochemistry of

groundwater, major constituents were plotted in Shoeller diagram. In this case, major cations ($\text{Na}^+ + \text{K}^+$, Ca^{2+} and Mg^{2+}) were plotted on the left side of the diagram with major anions (SO_4^{2-} , $\text{HCO}_3^- + \text{CO}_3^{2-}$, and Cl^-) plotted on the right side.

Hydrogeochemical processes

Several factors control the groundwater chemistry, which can be related to the physical situation of the aquifer, bedrock mineralogy and weather condition. Hence, Gibbs plot is employed in this study to understand the natural mechanism controlling groundwater chemistry, including the rainfall dominance, rock weathering dominance, and evaporation dominance (Gibbs, 1970). And the results from groundwater analysis were used in order to better understand the hydrochemical processes that take place in the study area. The ratios of Total cation (TZ^+) versus ($\text{Na}+\text{K}$), TZ^+

versus ($\text{Ca}+\text{Mg}$) for the silicate weathering, ($\text{Na} + \text{Cl}$) versus $[(\text{Ca}^{2+} + \text{Mg}^{2+}) - (\text{SO}_4^{2-} + \text{HCO}_3^-)]$ for ion exchange, and Na^+ versus Cl^- , and Na/Cl versus EC for evaporation process were combined with simple linear regression and used to determine the original sources of ions in the groundwater. Simple linear regression is a statistical method that allows to summarize and study relationships between two continuous (quantitative) variables. It can be used to know the strong assumptions about the relationship between the predictor (X_i) and the response (Y), the coefficient of determination (R^2) and the correlation coefficient (R) for the measurements of linear association. If the data points fall in a random pattern, there is no correlation. The higher the correlation, the smaller these errors (Petalas et al., 2006).

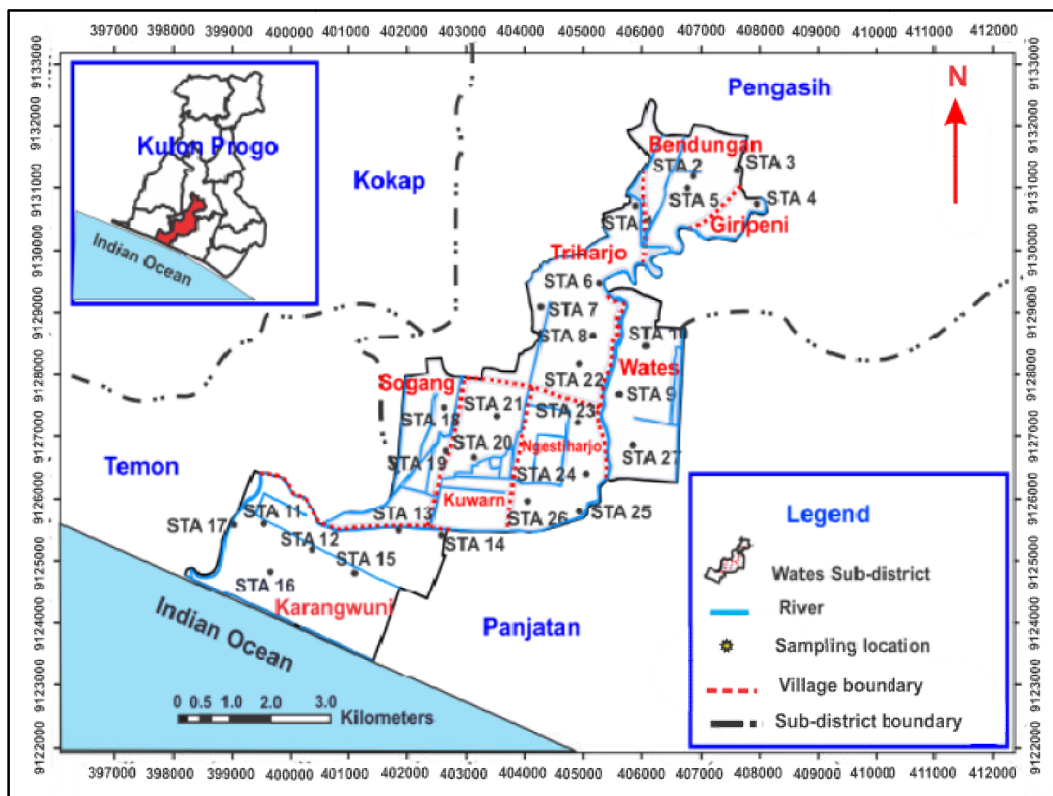


Figure 2. Map showing water sampling sites

Piper Trilinear diagram

Piper Trilinear diagram is a graphical presentation of the major ions which quickly determine the hydrochemical facies of groundwater. Furthermore, this diagram is useful in screening and sorting large numbers of chemical data, which makes interpretation easier and can define the

patterns of spatial change in the water chemistry among geological units (Piper, 1944). In this graph, the major cation and anion concentrations are presented in the bottom triangles on the left and right, respectively. The rhombus in the top center of the diagram presents the composition of both ions and divides the samples into six different facies.

Results and Discussion

General groundwater chemistry

Hierarchical Cluster analysis was identified the groundwater samples into three general classes, namely, Cluster 1 (C_1), Cluster 2 (C_2), and Cluster 3 (C_3) in Figure 3 (a), and based on the similarities among the chemical parameters involved in the groundwater quality of the study area. C_1 contains 26% of all groundwater and has a Na-Cl water type. C_2 is dominated by a mixed Ca-Na- HCO_3 type including 14 groundwater samples, which account for 22% of the total samples and have no distinctive characteristics in regard to the evaluated ions. Groundwater samples in C_3 have a Ca- HCO_3 water type, and account for 52% of the total samples. C_3 samples are located mainly through the study area.

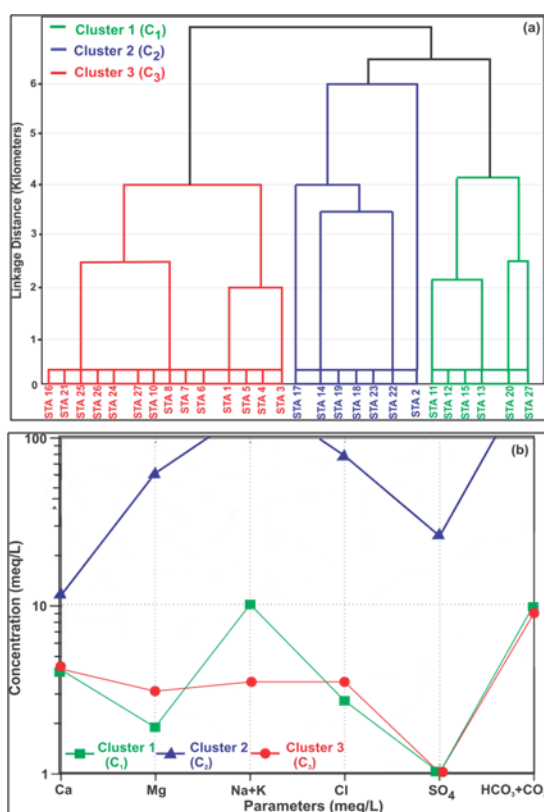


Figure 3. (a) Dendrogram of Hierarchical Cluster analysis; (b) Schoeller diagram of three groundwater clusters

Schoeller diagram gives absolute ionic concentrations in the groundwater. The C_1 water samples tend to brackish water (average TDS = 355.83 mg/L and average EC = 1738.33 $\mu\text{s}/\text{cm}$). The samples in the C_1 show a different ionic composition that is dominated by Na^+ , with abundance orders $\text{Na}^+ > \text{Cl}^-$ in meq/L. The samples

in classes C_2 and C_3 have the similar ionic compositions that are dominated by HCO_3^- . The samples in C_2 represent the mixed water type due to the mean concentrations of TDS = 671.66 mg/L and average EC = 475.33 $\mu\text{s}/\text{cm}$, whilst the C_3 water samples tend to fresh water (average TDS = 315.71 mg/L and average EC = 569.28 $\mu\text{s}/\text{cm}$). The plot shows that the value of (Na+K) exceeds other cations while the value of HCO_3^- ion exceeds that of other anions, clearly and locally indicating a few salt content dominance in the groundwater of the study area in Figure 3 (b). Therefore, Cluster distribution and Schoeller plotting show generally the groundwater characteristics of the study area. To confirm the spatial distributions of dominant ions in three clusters, zoning maps of groundwater quality based on lithology unit intend to know the effect of stratigraphy on groundwater characteristics. Based on the average values chemical parameters, the cations are in the order of abundance as $\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$ while the anions reveal order of abundance as $\text{HCO}_3^- > \text{Cl}^- > \text{SO}_4^{2-}$.

The spatial distribution of sodium is classified on the basis of highest desirable level of meq/L in Figure 4 (a). Due to the weathering of plagioclase feldspar, high sodium concentrations occur in the central part and extend towards the extreme south-west of the study area. Figure 4 (b) reveals low chloride distribution over the entire area and the concentrations of chloride over the anions could be attributed to major weathering of rocks and minor evaporation processes. Chloride could not have resulted from sea water intrusion since sea water intrusion may be unlikely in the study area. Figure 4 (c) and (d) show the spatial distribution of EC and TDS which indicates concentrations occurring above permissible limit of 1,000 $\mu\text{s}/\text{cm}$ and 1,000 mg/L (Iyasele, 2015) which suggests that the groundwater in the study area is characterized by high degree of mineralization.

Hydrogeochemical processes

Based on the Gibbs diagram, the 96.2% of plotted entire samples fell into the rock weathering reaction except STA 14 (Karangwuni) and the chemistry of 3.8% of samples has been controlled by the evaporation-precipitation dominance field in Figure 5. However, the hydrochemistry of the study area are mainly influenced by the rock dominance, including the silicate rocks weathering, while one sample plot on the evaporation zone suggests that precipitation-induced chemical weathering with dissolution of rock-forming minerals primarily controls the major ion chemistry of groundwater in the study area.

Effect of silicate weathering on groundwater chemistry

Silicate weathering is one of the keys for the geochemical processes controlling the major ions chemistry of the groundwater. Therefore, the silicate weathering can be understood by estimating the ratio between total cations (TZ^+) versus ($Na+K$) and ($Ca+Mg$) using linear

regression analysis (Kumar et al., 2006). This relationship between total cations (TZ^+) versus ($Na+K$) of the study area in Figure 6 (a) indicates that the majority of groundwater samples fall above 1:1 equiline, indicating less intensive silicate (alkali feldspar) weathering in the geochemical processes, which contributes mainly sodium and potassium ions to the groundwater.

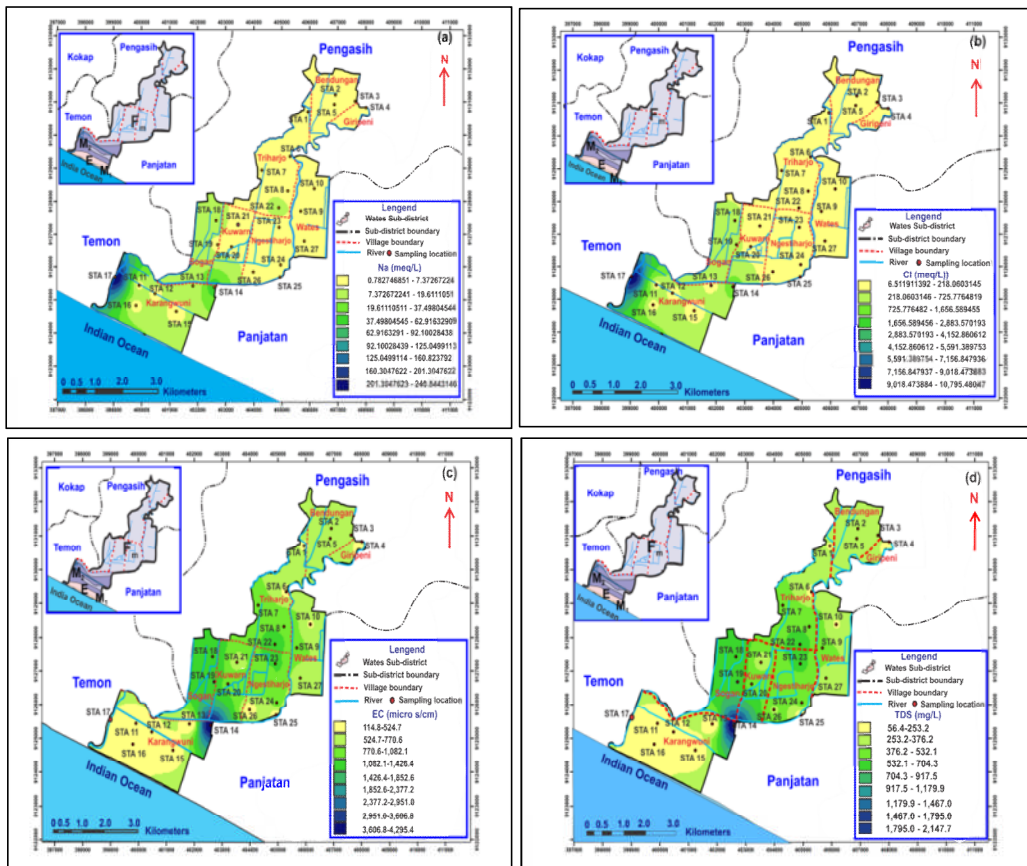


Figure 4. Spatial distributions of (a) Na^+ , (b) Cl^- , (c) EC, and (d) TDS concentrations in the study area

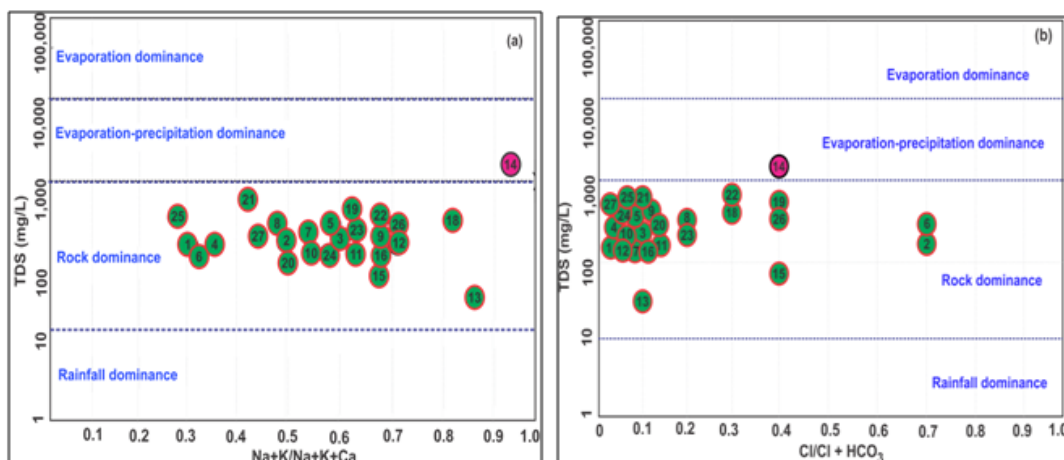


Figure 5. Gibbs plots indicating the mechanism of groundwater in the study area

Only a few groundwater samples are close to the line, pointing out that the process of silicate degradation can occur the Ca/Na exchange reaction. A plot of total cations (TZ⁺) versus (Ca + Mg) in Figure 6 (b) shows majority of the values below the 1:1 equiline, reflecting an increasing contribution of Na⁺ and K⁺ with increasing dissolved solids. However, some of the values also fall above 1:1 line equiline, indicating that some of these ions (Ca + Mg) result from the weathering of silicate minerals (Ghrefat, 2014).

Additionally, the geology also implies that the alkali earth silicates occur everywhere in the area. Therefore, it indicates that pagioclase (albite), K-feldspar, and mica are the common sodium and potassium bearing minerals, and pyroxene and amphibole are calcium and magnesium bearing minerals in silicate rocks. Felsic rocks contribute to Na⁺ and K⁺, Ca²⁺ and Mg²⁺, and HCO₃⁻ ions to the groundwater, which could be described in the following equations. Feldspars are more susceptible to weathering and alteration than quartz in the silicate rocks. In the

groundwater of the study area. K⁺ is, however, not as abundant as that of Na⁺, due to its fixation in the formation of clay minerals.

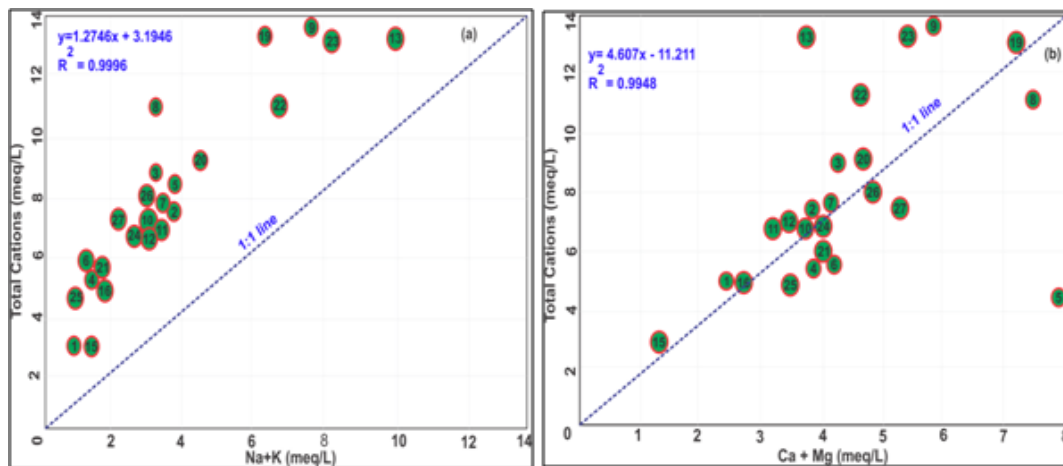
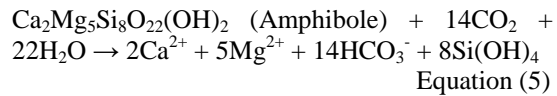
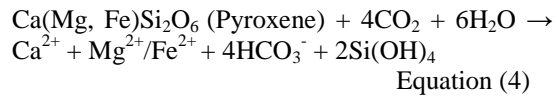
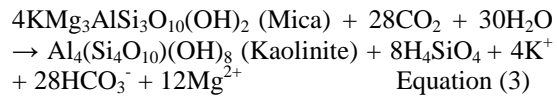
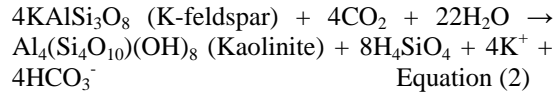
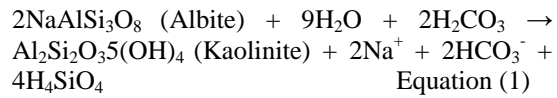
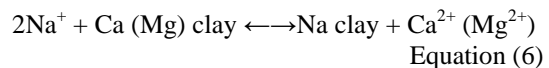


Figure 6. Scatter diagrams of (a) total cations (TZ⁺) versus (Na+K), and (b) total cations (TZ⁺) versus (Ca+Mg)

Ion exchange process

Ion exchange is an important hydrochemical process that has significant influence on the evolution of hydrochemical characteristics of groundwater. To investigate the importance of ion exchange processes in groundwater chemistry, the relationship between the concentration of (Na + Cl) and [(Ca²⁺ + Mg²⁺) - (SO₄²⁻ - HCO₃⁻)] is usually applied to evaluate the role of cation exchange taking place in the aquifer. Calcium and magnesium in aquifer material exchange with sodium in the water as explained by the equation below.



The ratios of (Na + Cl) / [(Ca²⁺ + Mg²⁺) - (SO₄²⁻ - HCO₃⁻)] for most groundwater samples are close to 1:1 in Figure 7 (a), which indicates that cation exchange is a significant factor affecting the hydrochemical composition of the groundwater (Yuan et al., 2017).

It is essential to know the changes in chemical composition of groundwater during its travel in the subsurface. The Chloro Alkaline Indices (CAI) 1 and 2 indicate the ion exchange

between the groundwater and its host environment. The Chloro Alkaline Indices used in the evaluation of base exchange are calculated using the following equations:

$$CAI\ 1 = [Cl - (Na + K) / Cl] \quad \text{Equation (7)}$$

$$CAI\ 2 = [Cl - (Na + K)] / (SO_4 + HCO_3 + CO_3 + NO_3) \quad \text{Equation (8)}$$

All values are expressed in meq/L. An exchange between Na^+ and K^+ in the groundwater with Ca^{2+} and Mg^{2+} in the aquifer material will result in a positive index indicating reverse ion exchange.

On the other hand, an exchange between Na^+ and K^+ in the aquifer with Ca^{2+} and Mg^{2+} in the groundwater will result in a negative index indication of cation exchange (Schoeller, 1977). The CAI 1 and 2 are calculated for the waters of the study area in Figure 7 (b). From Equation (7) and (8), 89% of groundwater samples has negative and 11 % of groundwater samples has positive Chloro Alkaline Indices. The results of the Chloro Alkaline Indices also support the fact that cation exchange is the main hydrochemical process controlling the groundwater chemistry in the study area whereas reverse ion exchange is also noticed in a very few locations.

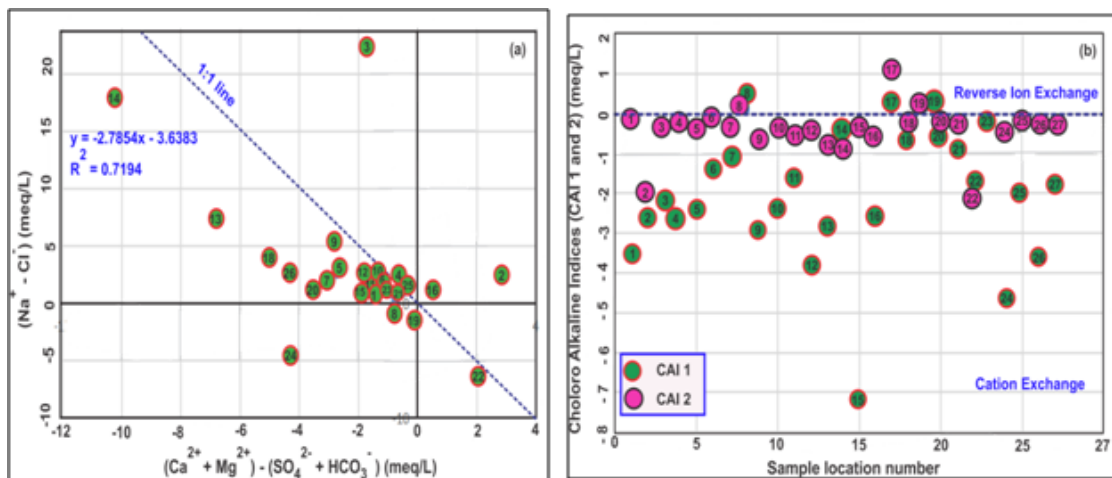
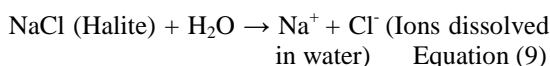


Figure 7. (a) Relationship between $(Na + Cl)$ and $[(Ca^{2+} + Mg^{2+}) - (SO_4^{2-} + HCO_3^-)]$ in the groundwater samples, (b) Chloro Alkaline Indices (CAI) 1 and 2 indicating ion exchange processes

Evaporation

Evaporation is a natural process that increases the concentration of ions in the groundwater. Na/Cl ratio can be used to identify the evaporation process in the groundwater. Evaporation will increase the concentration of total dissolved solids in the groundwater, and the Na/Cl ratio remains the same, and it is one of the good indicative factors of evaporation (Subramani et al., 2010). Halite ($NaCl$) is extremely soluble. When sodium and chlorine become the dissolution process, the water develops a salty taste. It can be described in the following equation:



The linear relationship between Na^+ and Cl^- suggests that the dissolution of halite is one of important sources of Na^+ and Cl^- in the groundwater. If Na/Cl ratio is greater than 1, it is

an indication of silicate weathering (Mayback, 1987). But the samples are along the 1:1 line with increasing ion concentration, while some ions deviate from equiline in Figure 8 (a). Most of the samples have around or above Na/Cl ratio. This indicates that an ion exchange process is prevalent in the study area (Kumar et al., 2006). The evidence for ion exchange in the development of salinization can lead to release of Na^+ from clay products, replacing Ca^{2+} that is present in the groundwater.

In the scatter diagram for Na/Cl versus EC in Figure 8 (b), Na/Cl shows a decreasing trend with increasing EC along with higher Na/Cl ratio, indicating release of Na^+ from silicate weathering process. This is also supported by higher HCO_3^- values in groundwater due to the reaction of feldspar minerals with carbonic acid that might be one of the reasons for increase in high salinity value. If evaporation is the dominant process, Na/Cl ratio should be constant when rising EC (Jankowski and Acworth, 1997). This observation

indicates that evaporation may not be the major geochemical process controlling the chemistry of groundwater in the study area, or ion exchange

reaction dominating over evaporation. However, Gibbs diagrams in Figure 5 justify that evaporation is not a dominant process in the study area.

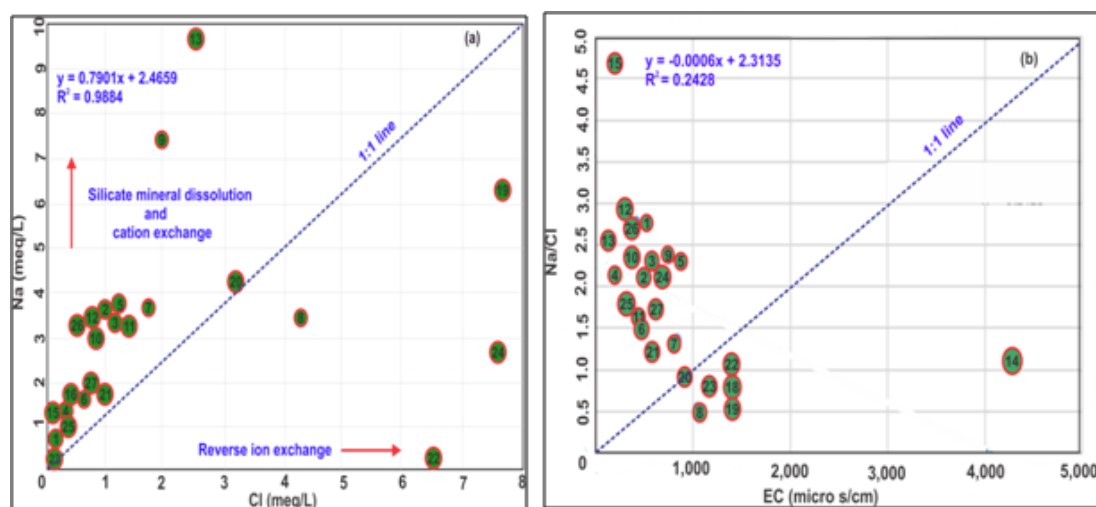


Figure 8. (a) Scatter diagram showing Na^+ versus Cl^- (b) Na^+/Cl^- versus EC in the groundwater samples of the study area

Groundwater flow pattern and spatial distribution of water chemical facies

The groundwater flow system in the study area is suspended on the former Alluvial Plains (Fluviomarine Plains). This is due to the obstruction of the flow system by local structure of complex aquifer system of Beach Ridges and Sand Dunes in the south, which is the result of marine processes. The complex Beach Ridges and Sand Dunes are locally distributed the specification units in the coastal area, as a local aquifer system. Because the complex form of Beach Ridges and Sand Dunes is composed of sand material that is very easily permeable through aquifer.

The groundwater in the study area flows from north to south following the pattern of topographic slope. Fluvial Plains are the unit formed by the marine process, which is further enclosed by the fluvial sediment materials with topographic slope towards the south. Therefore, groundwater flow also depends on the morphological pattern and structure of the Fluviomarin Plains. These plains in the study area are the Alluvial Plains of former lithoral zones and lagoons, so there are traps of marine clay with a coating system that alternates between marine clay and fluvial sediment. At the boundary between the oldest beach (located in northernmost of the study area) with the Fluviomarin Plains, there is a marine clay layer as the boundary plane.

This condition is the base of a long aquifer bowl. This phenomenon is thought to be the cause of the groundwater flow system from the direction of the hill unit on the Fluviomarin Plains, obstructed by the old beach. Thus, it can be said that the groundwater flow system in the study area is separated between the Fluviomarin Foothills System and the complex system of Beach Ridges and Sand Dunes.

The results of the chemical analysis of the water samples in the study area based on the Piper diagram method are presented in Figure 9, demonstrating that the water samples occupy a wide area of the Piper diagram ranging from fresh to saline waters. An examination of Figure 9 shows that three major hydrogeochemical facies are dominant in the study area, as presented in Table 1. These are Ca-HCO_3 facies (bicarbonate water - type 1), Na-Cl facies (saline water - type 2) and Ca-Na-HCO_3 facies (semi-bicarbonate water - type 3).

Type 1 (Ca-HCO_3) facies

In the study area, the groundwater belonging to the hydrogeochemistry of type 1 is commonly found almost through the study area. This may indicate that the hydrochemical properties as well as the factors affecting the hydrochemistry of these landforms are similar. Type 1 is characterized by low electrical conductivity values (EC) ($<1,000 \mu\text{s}/\text{cm}$). This condition provides that the hydrogeochemical type 1 is the

bicarbonate groundwater with the content of calcium (Ca^{2+}) and magnesium (Mg^{2+}) and high bicarbonate (HCO_3^-), low to moderate sodium (Na^+) and potassium (K^+), while the values of

total dissolved solids (TDS) and groundwater (pH) are low. Groundwater is good quality, and is usually formed in Quaternary landscapes, as the units of Holocene in the study area.

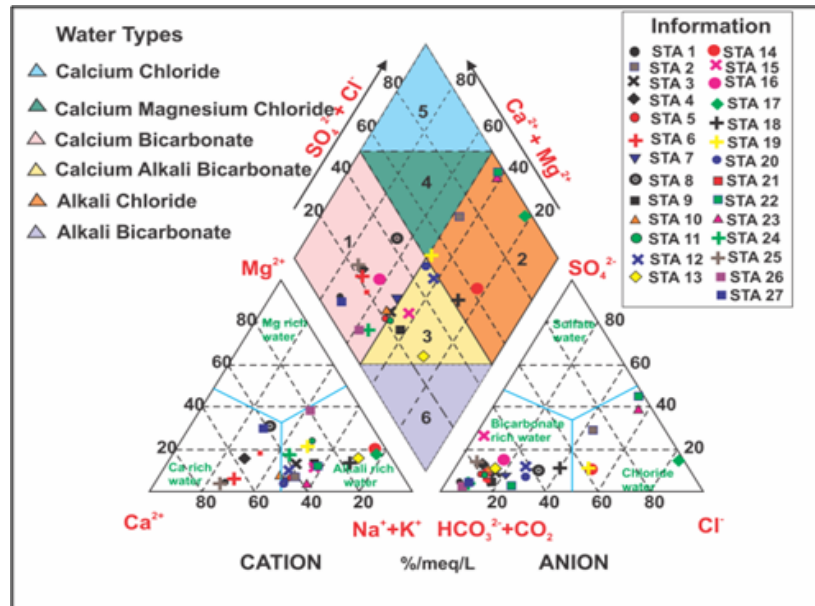


Figure 9. Piper diagram showing the water types

Table 1. Hydrogeochemical zoning of groundwater in the study area

Water Type	Geomorphological Unit and Lithology	Mineral	Hydrogeochemical Processes	Distribution
Ca-HCO ₃	F _m -Fluvial sediment with clay, silt and sand	Albite (NaAlSi ₃ O ₈)	Silicate weathering	Almost throughout the study area (52%)
	M ₂ - Marine deposit with clay lenses	K-Feldspar (KAlSi ₃ O ₈)		
	E - Fine grained sand with iron ore	Mica (KMg ₃ AlSi ₃ O ₁₀)		
	M ₁ - Fine grained sand with iron ore	Pyroxene [Ca(Mg,Fe)Si ₂ O ₆] Amphibole [Ca ₂ Mg ₅ Si ₈ O ₂₂ (OH) ₂]		
Na-Cl	F _m -Fluvial sediment with clay, silt and sand	Albite (NaAlSi ₃ O ₈) Halite (NaCl)	Cation exchange and evaporation	Bendungan, Triharjo, Ngestiharjo, Sogan, and Karangwuni (26%)
Ca-Mg-HCO ₃	F _m -Fluvial sediment with clay, silt and sand	Albite (NaAlSi ₃ O ₈) Pyroxene [Ca(Mg,Fe)Si ₂ O ₆]	Silicate weathering and cation exchange	Wates, Kuwarn, and Karangwuni (22%)
	M ₂ - Marine deposit with clay lenses	Amphibole [Ca ₂ Mg ₅ Si ₈ O ₂₂ (OH) ₂]		

Type 2 (Na-Cl) facies

The hydrogeochemical condition of type 2 dominates on unit of Alluvial Plains in the study area. Type 2 is the saline water derived from shallow groundwater, with high chloride (Cl⁻) and sulphate (SO₄²⁻), high calcium (Ca²⁺) and magnesium (Mg²⁺), while sodium (Na⁺) and potassium (K⁺), bicarbonate (HCO₃⁻) and carbonate (CO₃²⁻) contents are low. In general, the groundwater is salty and usually derived from swampy plains of older lagoon or delta. This concept is consistent with the existing conditions in the study area that type 2 is found in Alluvial Plains. Because Alluvial Plains are genetically the marine processes in the form of former shallow marine zones and lagoons, and develop into a back swamp to finally form the Fluviomarin Plains due to the dynamics of the process in the Quaternary era dominated by fluvial process. It can be analyzed that the high content of chloride (Cl⁻) ion in type 2 water is caused by salt crystal

washing process trapped in marine sediments of shallow sea zone due to high evaporation process during Pliocene-Pleistocene, while high calcium (Ca²⁺) and magnesium (Mg²⁺) contents are caused by the cation exchange process with minerals contained in the marine clay deposits found at the bottom of the shallow sea zone and the lagoon at that time. Consequently, the groundwater to be salty is indicated by the high content of chloride (Cl⁻) ions and electrical conductivity ranging (>1,000 µs/cm).

Type 3 (Ca-Na-HCO₃) facies

In some locations, there is a change of hydrogeochemical type from bicarbonate water (type 1) and saline water (type 2) into semi-bicarbonate water (type 3), especially in Alluvial Plains. The hydrogeochemistry of type 3 is a semi-bicarbonate groundwater, with a balanced composition between (Ca²⁺ + Mg²⁺) and (Na⁺ + K⁺) with (Cl⁻ + SO₄²⁻) and (HCO₃⁻ + CO₃²⁻).

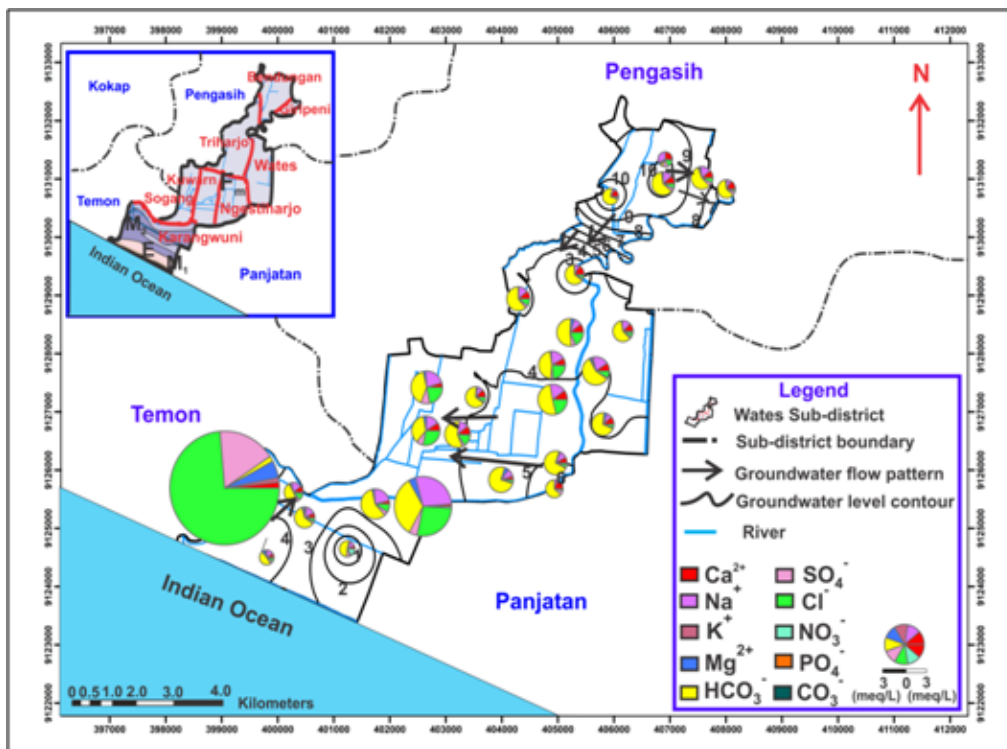


Figure 10. Groundwater flow pattern and spatial distribution of water types

The chemical composition of groundwater is dominated by bicarbonate ions (HCO₃⁻) and still in good quality. There are in the landscape of flood plains or lowlands of the coastal area, which is the precipitate of the fluvial process. This concept is also in accordance with the reality in the study area, that the units of complex form of Beach and Sand Dunes, old beach and flood

plains include in the lowlands of the coastal area. Furthermore, there is a real relationship between the groundwater flow patterns with concentrations of electrical conductivity values in Figure 4 (c). Locations which are concentrations of high electrical conductivity values with salty groundwater are in units of Alluvial Plains. This phenomenon explains or provides evidence that

these sites were once a lagoon, where seawater was inundated and eventually trapped by Alluvial deposits of fluvial activity, with a lower elevation of its surroundings. This condition will also affect the characteristics and evolution of groundwater in the study area, which is shown by the change of hydrogeochemical process in the direction of the groundwater flow pattern from north to south in Figure 10.

Conclusion

In this study, an attempt has been made to evaluate the geochemical processes regulating groundwater quality in the coastal area of Wates. Three clusters with different characteristics were identified using Hierarchical Cluster analysis in the study area, which is in accordance with the different water types. Cluster 1 exhibits Na-Cl facies, while clusters 2 and 3 exhibit hydrochemical facies of mixed Ca-Na-HCO₃ and Ca-HCO₃, respectively. The Schoeller diagram showed that Na⁺, Ca²⁺, HCO₃⁻, and Cl⁻ were the dominant ions in almost all of the groundwater samples. Hydrochemical processes show the predominance of ionic exchange and evaporation in cluster 1, and silicate weathering and ionic exchange in cluster 2 and silicate weathering in cluster 3. Spatial variation maps also depicted completely that groundwater flow direction and rock-water interaction were the processes that had played a major role in the spatial variation of these major ions in the groundwater of the study area.

The prominent hydrochemical facie in Piper diagram is bicarbonate water type almost throughout the study area. The second salt water type is grouping, while semi-bicarbonate water type is locally outcropping in the study area. So salt water intrusion plays a minor role in the distribution of hydrochemical facies. This study revealed the dominant processes governing the hydrogeochemical characteristics of groundwater. In conclusion, the present study describes a range of salinity values which are noticed in the study area. This is due to the wide range of Alluvial Plains that occurs in the coastal plain. Hence, good quality of groundwater is restricted almost throughout the study area. This study indicates the existence of hydrochemical facies and a close relationship between the groundwater and geological conditions (morphology and lithology). Beneficially, the results of this study can be used to improve understanding of hydrogeochemical processes, to conduct for more comprehensive research and for better water resources management.

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