Hydrogeological Conceptual Model of Guyana's Coastal Aquifer System for Assessing Saltwater Intrusion Vulnerability Due to Groundwater Extraction

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Abstract

Seawater intrusion is a common problem in coastal aquifers that can be exacerbated by extensive groundwater withdrawals and climate change. A complete understanding of the aquifer system along with its natural hydrogeology is necessary for its management. The creation of a conceptual model is important for comprehending and managing the coastal aquifer system and for future evaluations of groundwater contamination. In this paper a hydrogeological conceptual model was constructed using data from geophysical surveys, geological maps, and borehole information. The conceptual hydrogeological model makes it possible to evaluate how susceptible the aquifer is to saline intrusion from groundwater extraction.

Keywords: Conceptual Model, Coastal Aquifer, Groundwater Extraction, Seawater Intrusion

1. Introduction

Fresh water makes up a very small portion of Earth's total water reserves — roughly 75% of which is frozen in the cryosphere — the fresh water that is available for human consumption is either underground or surface water bodies like rivers and lakes (De Filippis et al., 2016). Actually, because groundwater is less vulnerable to pollution and less affected by drought and climate change than surface water, it is typically chosen over surface water when it is available (Howard 2015 as cited in De Filippis et al., 2016). Groundwater management is important for the overall management of water resources since about 90% of freshwater resources are found in hydrogeological systems,. The increasing salinity of groundwater is a frequent and pervasive adverse environmental effect associated with the qualitative degradation of aquifer freshwater supplies (Kallioras et al., 2006). Groundwater salinization may result from the presence of the following, according to Kallergis (2000 as cited in Kallioras et al., 2006): anhydrite or mineral salts; brines (particularly in petroleum areas); gypsum; intense irrigation that raises evapotranspiration; and the existence of connate water at low aquifer depths. However, seawater intrusion, usually brought on by human activity, is one of the most frequent causes of salinization of fresh groundwater. According to Essink (2001, cited in Kallioras et al., 2006), approximately 50% of the world's population resides within 60 kilometers of a coastline. Given that seawater intrusion poses major social and economic risks to the local communities in coastal zones, the aforementioned fact emphasizes the need for integrated groundwater resource management in coastal aquifers. Due to excessive groundwater pumping, seawater intrusion occurs at typical coastal aquifers (Kallioras et al., 2006; see also Kallioras 2002; Kallioras and Pliakas 2005). Essink (2001) mentioned that the primary antropogenic cause of seawater intrusion worldwide is the excessive overpumping of aquifers, particularly those near coasts. According to him, both natural and artificial processes generate significant saltwater intrusion into many of the world's coastal aquifers, particularly the shallow ones. He conducted a thorough investigation of the distribution of fresh and saline groundwater in coastal aquifers, and concluded that variables, including density variations between the liquids and hydrogeological characteristics, influence this distribution.

In their respective conceptualizations of the intrusion of seawater in coastal aquifers, Badon-Ghijben (1889) and Herzberg (1901) assumed hydrostatic equilibrium, immiscible fluids, and the presence of a sharp interface between fresh and saltwater in a homogeneous, unconfined aquifer (Barazzuoli et al., 2008). They discovered that, below sea level (z), the freshwater-saltwater interface's depth is calculated by:

$$z = \frac{\rho_{fw}}{\rho_{sw} - \rho_{fw}} h_w \qquad (1)$$

z = depth of fresh-saline interface below sea level (m)

h_w = head of the freshwater above sea level (m)

ρ_{fw} = freshwater density kg/m^3

ρ_{sw} = saltwater density kg/m^3

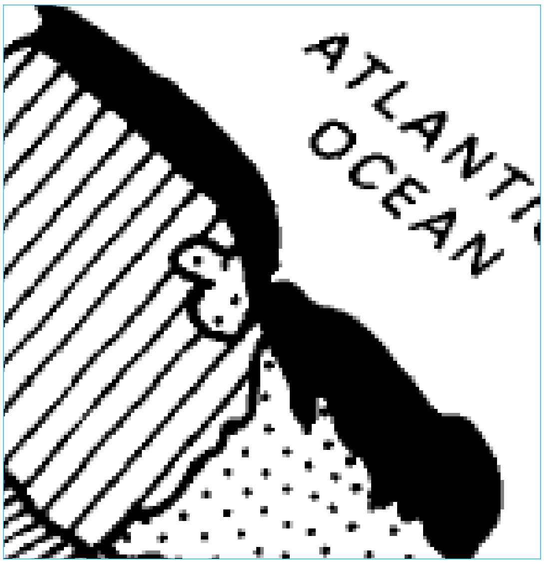
When the equation is applied correctly, the estimated depth closely approximates the real one (Cheng and Ouazar 1999 as cited in Barazzuoli et al., 2008); it is still widely used to simulate saltwater intrusion (Essaid 1990; Cheng and Chen 2001 as cited in Barazzuoli et al., 2008) and, especially for educational purposes, to gain clear insight into the behaviour of fresh and saline groundwater in coastal aquifer systems (Oude Essink 2003 as cited in Barazzuoli et al., 2008). Due to molecular diffusion and hydrodynamic dispersion, fresh and salt water are actually miscible liquids: the contact between the two fluids is therefore a transition zone rather than a sharp interface (Barazzuoli et al., 2008; see also Gambolati et al., 1999; Cheng and Chen, 2001). The situation is further complicated by the fact that the saltwater intrusion itself changes the fluid density, so that this parameter varies in space and time as a function of changes in concentration, temperature, and pressure in the fluid. Furthermore, the porous medium itself is usually stochastically heterogeneous.

It continues to be widely utilized to simulate saltwater intrusion (Essaid 1990; Cheng and Chen 2001 as cited in Barazzuoli et al., 2008); and is particularly beneficial for educational purposes as it provides a clear understanding of the behavior of fresh and saline groundwater in coastal aquifer systems (Oude Essink 2003 as cited in Barazzuoli et al., 2008). When the equation is utilized properly, the estimated depth closely matches the real one (Cheng and Ouazar 1999 as cited in Barazzuoli et al., 2008). The contact between fresh and salt water is consequently a transition zone as opposed to a sharp barrier because both are miscible liquids due to molecular diffusion and hydrodynamic dispersion (Barazzuoli et al., 2008; see also Gambolati et al., 1999; Cheng and Chen, 2001). The fluid density is altered by the saltwater intrusion itself, which further complicates the scenario by causing this parameter to fluctuate over time and space in response to variations in the fluid's concentration, temperature, and pressure. Additionally, the porous medium is typically stochastically heterogeneous in nature.

Research conducted by Worts (1956), Arad (1983), and the US Army Corps of Engineers (1998) shows that Guyana's coastal aquifer groundwater level has been steadily declining as a result of significant water abstraction, mostly for residential use. The A Sand aquifer's piezometric head was 4.5 meters above ground when it was initially exploited. Today, abstractions have led to the head falling to 20 meters below the surface. This can lead to depletion, subsidence, abstraction well deepening, and loss of water quality if it continues. Since the majority of groundwater abstraction wells are situated near the sea and may be vulnerable to salt intrusion, the deterioration of the water quality should be taken into consideration. The purpose of this study is to create a conceptual model of the coastal aquifer system in Guyana, evaluate the system's susceptibility to saline intrusion as a result of groundwater extraction, and offer recommendations for proper management of groundwater resources, including the rate of abstraction and saline intrusion control.

1.1 Study Area

Guyana has a surface area of about 214,970 square kilometers and is situated between 1 and 9 degrees north latitude and 56 and 62 degrees west longitude. The Interior Highlands, the White Sand Belt, and the Coastal Plain make up its three primary geographic zones. Please see Figure 1.1. It stretches from the Courantyne River in the east to the Venezuelan border in the northwest and is 434 kilometers long with a width ranging from around 80 km along the Berbice River to 8 km west of Georgetown. Ninety percent of the nation's population lives in the Coastal Plain, which makes up around 15% of the total area of the country. The region under investigation for the conceptual model's development lies between the Mahaica and Demerara rivers, spanning into the White Sand region and terminating in the vicinity of Linden. Clays from the Demerara and Coropina Formations lie beneath the Coastal Plain. (Refer to Figure 1.2).



Coastal Plain of Guyana

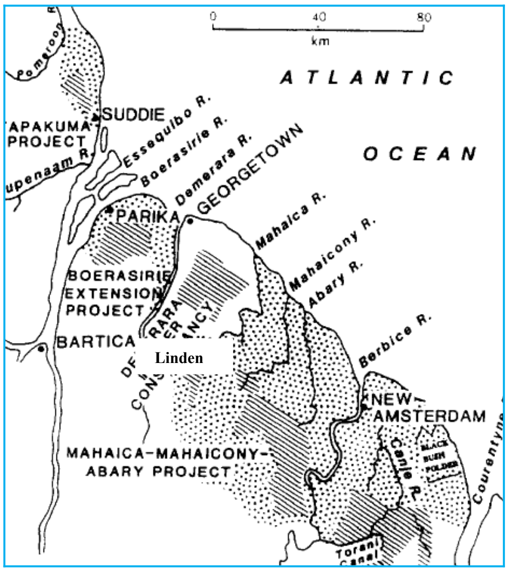


Figure 1.2: Map of Coastal Plain Showing the Study Area

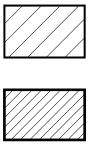


Figure 1.1: Map Depicting the Coastal Plain and White Sand Formation in the Study Area

The coastal region is primarily composed of rich alluvial deposits from the Amazon River which overlie the White Sands. It is home to extensive farming activities. The majority of the White Sand region in the study area consist of exposed fine to medium sand. See Figure 1.4. Huge sand pits can be found in this area that are occasionally mined and utilized for construction. This area contains a network of creeks that serve as the source of the Mahaica and Demerara Rivers. There are numerous laterite-capped hills present in certain places the White Sand region.

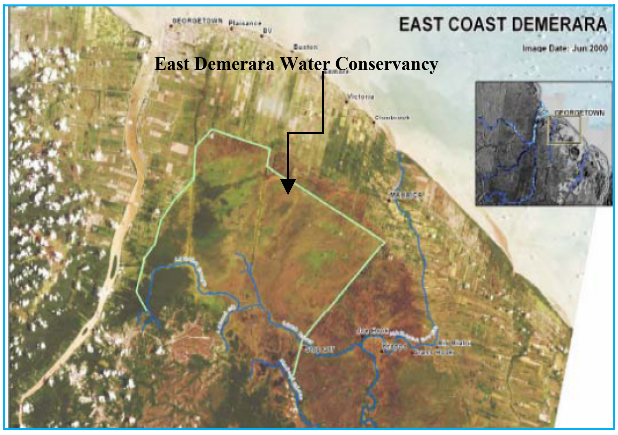


Figure 1.3: Map Depicting the East Demerara Water Conservancy Canal in the Coastal Part of the Study Area (Adopted from Guysuco, 2009)

Figure 1.4: The Dense Vegetation in the White Sand Region

2. Guyana's Coastal Aquifer System

Worts (1958) conducted an evaluation of the state of seawater intrusion into Guyana's coastal aquifer system. He stated that the first wells drilled encountered brackish water that existed in the aquifer, that likely what triggered the existence of saline water in the Upper Sand rather than intrusion brought on by the draft on groundwater. He confirmed that the brackish water in the Upper Sand is seawater that has been retained in the deposits since when the water level was sufficiently high to flood the area and has been partially flushed.

Studies done by Worts have not revealed any signs of saline intrusion or worsening of the water quality in the A Sands. He clarified that there could be a number of reasons why sea water hasn't occurred: (i) The seawater in the aquifer's offshore portion is diluted; (ii) Because of upward leakage, the initial heads may have been lower than the true heads; (iii) Because of lateral facies changes or faulting, there may be barely any hydraulic continuity between the aquifer and the ocean; and (iv) Because of warping or folding of the deposits beneath the continental shelf, which may have brought the bending or warping of the deposits under the continental shelf, which may have caused the aquifer to drop in depth and prevented saltwater from seeping in. According to his explanation, (i), (iii), and (iv) appear more likely than (ii). Worts further conjectured that if assumption (iii) is shown to be false, insufficient recharge from the landward side may lead to well contamination if there is insufficient groundwater separation between the wells and the ocean. There is no other literature that offers explanations for why saltwater isn't present in the lower aquifers. Arad (1982) noted that the quality of coastal groundwater improves with depth, which is the most notable phenomenon. According to research by Harrison (quoted by Arad, 1982), the upper aquifer's chloride level can reach as high as 1800 mg/l, and in the A and B sand aquifers, chloride concentrations are less than 9 mg/l, which suggests good flushing in the coastal basin's deeper artesian aquifer in the past.

2.1 Geology

Geological Formations of the Coastal Plain

The young and old Coastal Plains are the two divisions of the Coastal Plain. The Coropina Formation covers the latter, and the Demerara Formation covers the former. The Holocene epoch saw the deposition of the Demerara Formation. The majority of the alluvial sediments in this formation were deposited by the sea and come from the Amazon River. Between the White Sand Series and the Demerara Clay, the Coropina Formation is exposed in a narrow band. Overlying the two formations are clays and white sands. A zone of low hills exists around 15 to 25 km inland, where the White Sand Formation is exposed. The lowest parts of the white sand series are tentatively assigned to the Pliocene, whereas the Demerara Formation, Coropina Formation, and upper White Sand Series are thought to be Plio-Pleistocene to recent in age. The most thorough investigation of the stratigraphy of the coastal plain was conducted by Bleackley (as cited by Arad, 1983). (See Figures 2.1 and 2.2)

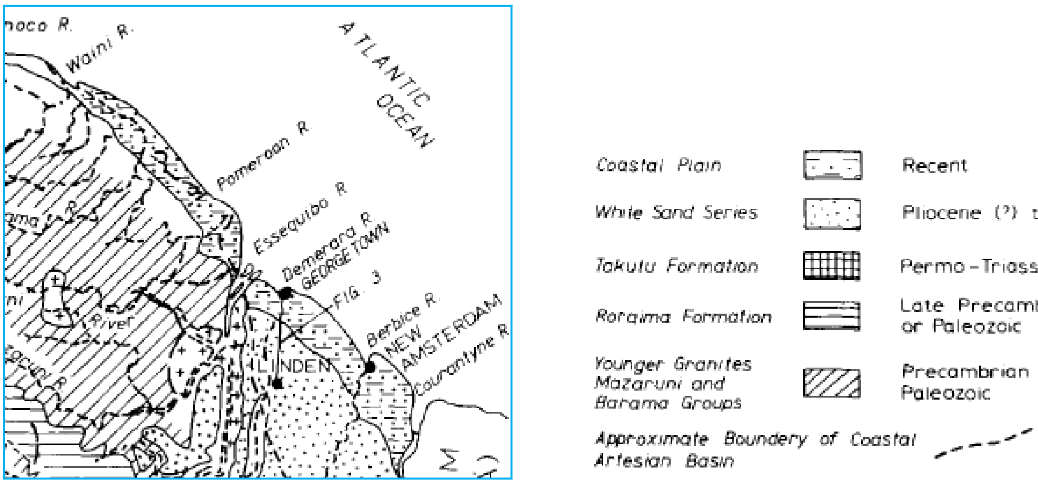


Figure 2.1: Map Showing the Approximate Extent of the Major Geological Groups (Adopted from Arad, 1982)

(1) Basement Complex

The Basement Complex of the Guyana Shield is formed from metamorphic, magmatic and volcanic rocks of Precambrian age.

(2) The Continental Shelf

The continental shelf stretches for about 120 kilometers offshore, where the sea bed is roughly 100 meters below mean sea level (msl). After that, it steepens even more offshore, reaching a depth of 180 m at 136 km and 900 m at 144 km from the coast (Worts, 1958). For a graphical depiction of the continental shelf, see Figure 2.2. Regarding the extension of the geology into the sea, only limited information is available. Exploration oil drilling around 100 km offshore has revealed a considerable facies transition, primarily to marine clay and limestone, according to Abraham Mercador Consultant (1997). This makes it difficult to pinpoint the precise distance at which the geological changes occur. Furthermore, the location of the exploratory wells was not specified, nor was the precise depth at which changes occurred disclosed.

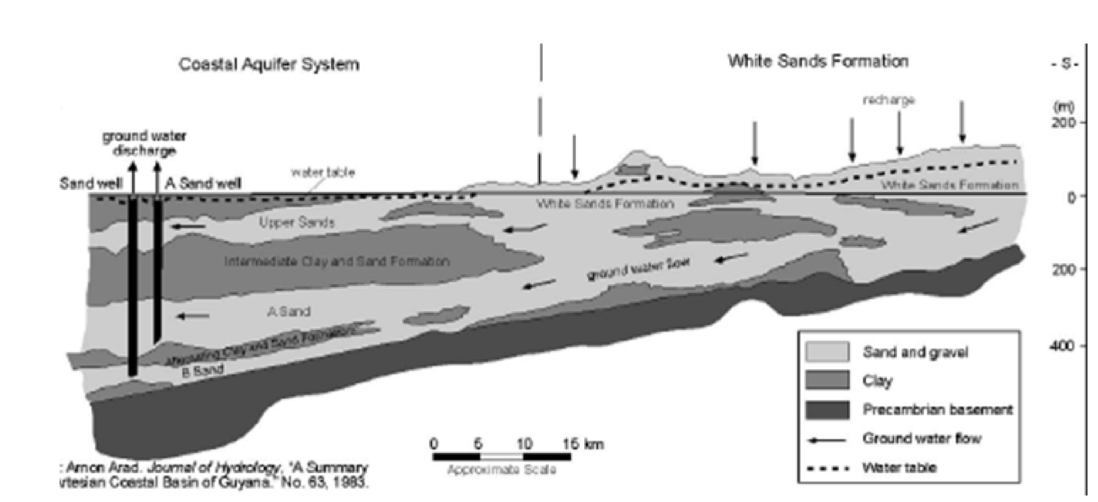


Figure 2.2: Coastal Geology (Adopted from Bleackley (as cited by Arad, 1983))

(3) The Demerara Clay and the Coropina Formation of the Upper Pleistocene

The strata that covers the White Sand Series are referred to as the uppermost clays and have thicknesses of roughly 45 meters. Grey-brown Demerara clay covers the reddish-to-yellow compact clay of the Coropina Formation. These clay-covered areas have poor drainage.

(4) White Sand Series

(a) The Upper Sand Series, which is composed of loose, angular quartz sand with a thickness ranging from 15 to 55 meters, is situated above the Basement Complex and lies beneath the Coropina and Demerara clays. This unit is referred to as dune sand (Harrison as cited by Arad 1982).
(b) The Intermediate Clay and Sand Series is below the Upper Sand Series and is composed of argillaceous and sandy deposits. It is 90 m thick and quite heterogeneous, with kaolinitic lenses that vary greatly in thickness and sand intercalations. It becomes thinner as it moves southward toward the White Sand region.
(c) The Lower Sand Series (A Sands) is made up of quartz sand and gravels and is 12 to 30 meters thick. The series is located between 200 and 250 meters below sea level.
(d) Alternating Clay and Sand Beds: A succession of sand and clay that ranges in thickness from 65 to 130 meters. This series is beneath the Lower Sand Series.
(e) The B Sand Series is made up of hard shale and cemented sand units that alternate. It is less noticeable in the middle of the coastal plain and ranges in thickness from 12 to 22 meters in Georgetown.

2.2. Hydrogeological Maps and Sections

In the Coastal Geological Section adopted from Bleackley (as cited by Arad, 1983), borehole information and geophysical surveys were used to identify the different hydrogeological units and were considered for the construction of hydrogeological maps. The data were also corroborated through field visits. The maps are very important for understanding the groundwater in the coastal aquifer system.

(1) Hydrogeological Cross-section

The geological material beneath the surface is either a potential aquifer or a confining bed. The aquifers are saturated geological formations that yield usable quantities of water. On the other hand, the confining beds are relatively impermeable and do not yield usable amounts of water. Hence, it is important to describe them on a depth scale. In other words, cross-sections have been prepared.

(2) Cross-Section North-South

Information from borehole logs and existing geological sections enabled the construction of hydrogeological sections in the north-south and northwest-east directions. Figure 2.3 depicts the north-south hydrogeological section of the study area. It shows that seven distinct layers of hydrogeological units exist in the coastal part of the study area. However, as the White Sand Series becomes exposed towards the south, the layers become thinner, and it is rather impossible to distinctly differentiate between them. The aquifuge shown in the section represents the basement complex. The depth of the basement is approximately 522 m in Georgetown and 100 m towards the southern boundary of the study area. Approximately 25 km further inland from the southern boundary of the study area, the basement system and White Sand Series form the southern end boundary of the groundwater system. The figure also shows the groundwater flow direction under natural conditions.

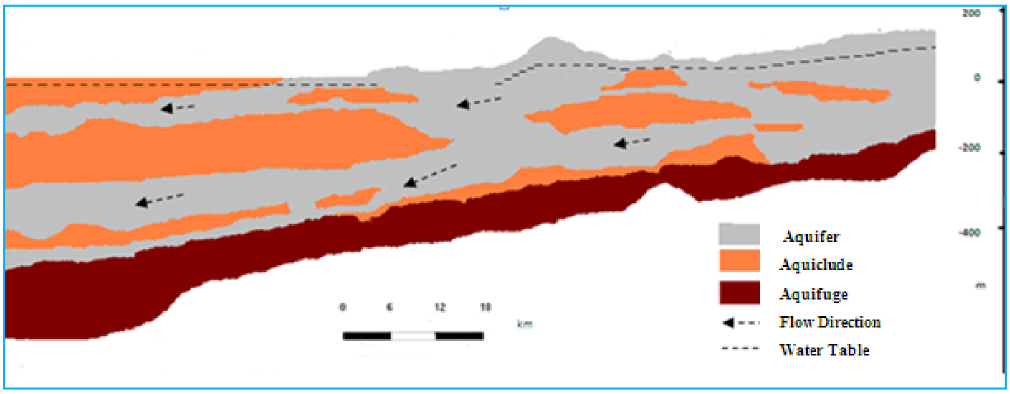


Figure 2.3: North-South Hydrogeological Section of the Study Area

(3) Cross-Section Northwest-East

Figure 2.4 depicts the northwest-east hydrogeological section of the study area. The section shows that, again, seven distinct layers of hydrogeological units exist. It shows that over the entire width, the aquifer is confined by impermeable Coropina and Demerara Clay Formations. Even though several boreholes are present along Guyana's Coastal Plain, very few penetrate the B Sand aquifer. Hence, it is likely that the bottom units are not accurately represented in Figure 3.17. The hydrogeological section shows that the depth of the basement increases from Georgetown to Mahaica. In Georgetown, the depth of the basement is approximately 522 m, and in Mahaica, it increases to about 760 m. The depth of the basement in the coastal part of the study area was gathered from seismic surveys carried out by the Trinidad Leaseholds Company and provided by Bleackley (1956). The possible eastern component of the groundwater flow direction is shown. The effect of groundwater abstraction is not considered.

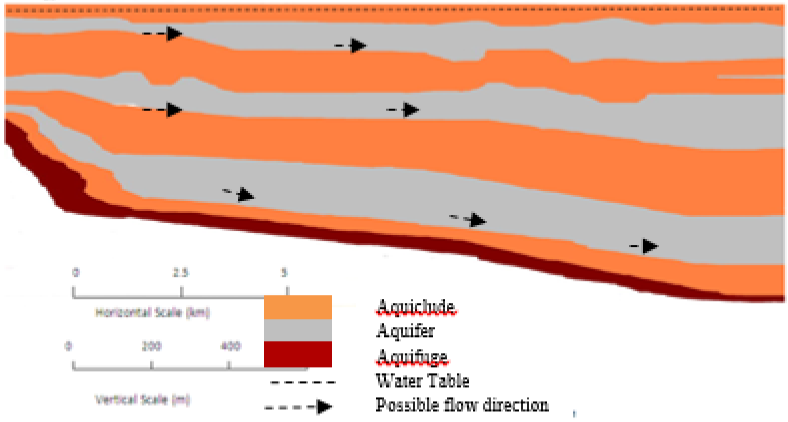


Figure 2.4: Northwest-East Hydrogeological Section of the Study Area

(4) Continental Shelf

It is likely that the outlet of the aquifer system of the White Sand Series is to the Atlantic Ocean. If there is some amount of hydraulic continuity between the aquifer units and the waters of the Atlantic Ocean, then the theoretical location of the aquifer outlets in terms of their distance from the coast can be determined from Figure 2.5. Table 3.1 has been prepared to present the approximate theoretical outlet distance of each formation from the coast based on the assumption that there is a direct hydraulic connection with the ocean. This information is useful for determining any model boundary conditions. Alternatively, it might be assumed that the Upper Sand aquifer has a direct outlet to the ocean, possibly at an estimated 60 km from the coast, whereas the A and B Sands are connected indirectly to the ocean through leakage to the Upper Sand Formation. Assuming that the aquifer units are hydraulically isolated from the ocean might lead to erroneous management decisions in terms of the possibility of saline intrusion.

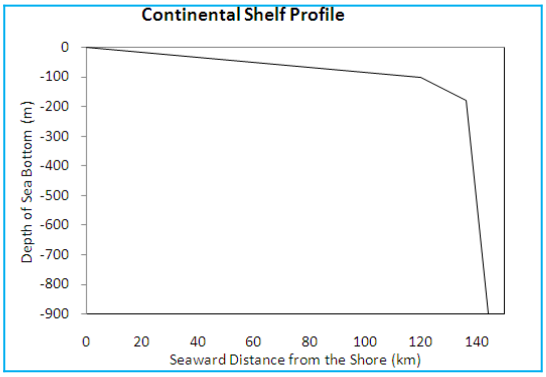


Figure 2.5: Graphical Representation of the Continental Shelf

Additionally, if there was no hydraulic connection to the sea, the historical water levels of the coastal wells could have been equal to the historical heads in the White Sand region. Even another alternative could be that the Upper Sand aquifer leaks water to the ocean through the Coropina and Demerara Formations before the estimated outlet point at 60 km from the coast.

Table 2.1: Approximate Theoretical Outlet Distance of Each Formation from the Coast

Formation	Average Upper Layer Depth below Ground-Surface (m)	Theoretical Outlet Distance from the Coast (km)
Upper Sands	50	60
Á Sands	200	137
B Sands	380	140

Figure 2.6 has been prepared to show the apparent groundwater levels for different parts of the study area after the pumps have been switched off for 8 hours. These measurements were taken with reference to the mean sea level. It shows that in all instances, the groundwater levels are below mean sea level along the coast. However, the huge differences in groundwater levels in some neighboring wells along the coast can be explained by inaccuracies associated with the measurements. For instance, measurements might have been taken in one well while neighbouring wells were switched on, or measurements might have been taken before full recovery of groundwater levels occurred. This, of course, leads to inaccuracies in the measurement. Further inland, towards the White Sand outcrop area, the water levels are above mean sea level. It is logical that the groundwater flows from this region towards the sea, as shown by the contour lines and flow lines.

Figure 2.6: Apparent Groundwater Level in the A Sand wells and a Few B Sand Wells

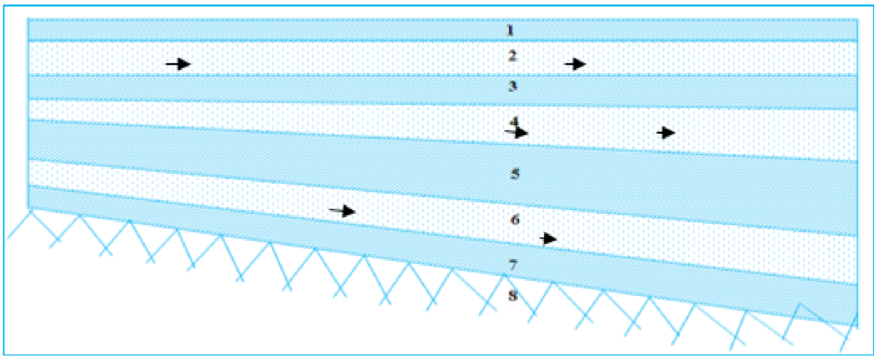
3. Conceptual Model

One of the most important and initial stages of modeling is model conceptualization. This procedure is what allows for the systematic assembly of complex field data to represent site conditions. The most significant stratigraphic and geologic contact linkages, hydrogeologic boundaries, groundwater balance, external inputs, and stress functions are all identified in this way. System analysis and modeling are made easier by the conceptual model. Model conceptualization makes it possible to choose the appropriate model approach. In order to accurately represent system behavior, the conceptual model is kept as simple as possible while preserving the most significant hydrogeological conditions (Zhou and Herath, 2017).

3.1. Layer Schematization

Model layer schematization was obtained based on a thorough hydrogeological interpretation of the various soil types present in the study area. Based on the hydrogeological interpretations presented in

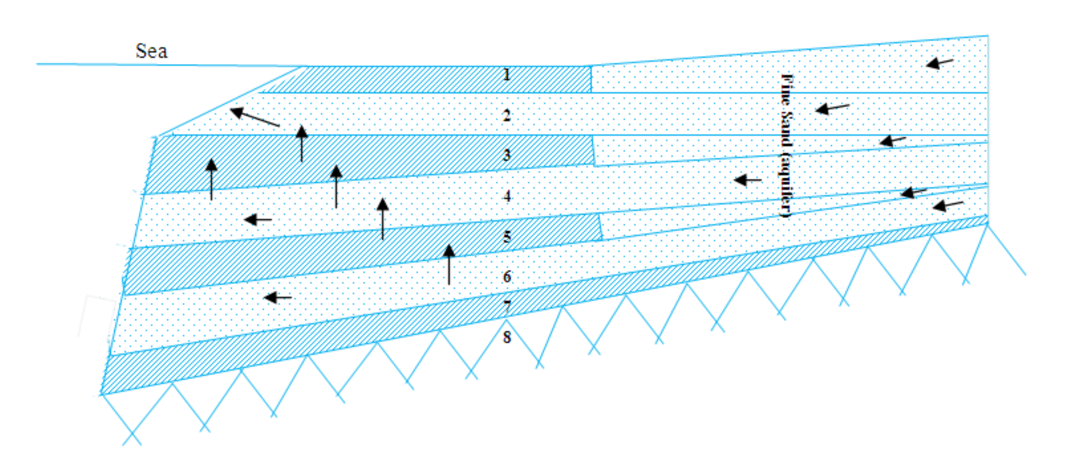
Section 3.3, the layer schematization for the conceptual model was done. Figure 3.1 depicts the model schematization for the coastal part of the study area. The picture shows that the model is schematized into 7 distinct model layers. These are 3 aquifer layers consisting mostly of sand and 4 layers representing aquitards or aquicludes comprising silty clay. Figure 5.2 presents the north-south model layer schematization along the Demerara River. This schematized section starts from the coastal part of the study area and extends into the White Sand outcrop area. Again, based on the hydrogeology, the coastal part was schematized as seven distinct layers. The hydrogeological interpretation in Section 3.3 shows that the top overlying silty clay layer of the Demerara and Coropina Formations disappears in the White Sand outcrop area. The Intermediate Sands and Clays and the Alternating Sands and Clays in the White Sand area appear as patches, and it is impossible to distinctly distinguish them. Based on the occurrence of these two units in the hydrogeological section, it appears reasonable to discontinue them in the schematized section in the White Sand area. Hence, in the White Sand outcrop area of the north-south model layer schematization section, six of the seven layers are fine sand aquifers.



1 - Silty clay (aquitard/ aquiclude)
2 - Well sorted fine sand (Upper Sand aquifer)
3 - Intermediate sands and clay (aquiclude)
4 - Well Sorted Fine Sand (A Sand aquifer)
5 - Alternating sands and clay (aquiclude)
6 - Well Sorted Fine Sand B Sand aquifer
7 - Clay (aquiclude)
8 - Basement Complex (aquifuge)

Figure 3.1: West- East Model Layer Schematization of West-East (Coastal Part of the Study Area)

Refer to Figure 3.2. The model assumption used in the conceptual model is that the Upper Sand aquifer has a direct outlet to the ocean, possibly at an estimated 60 km from the coast, whereas the A and B Sands are connected indirectly to the ocean through leakage exchange with the Upper Sand Formation. Leakage from the upper sand to the ocean through the silty clays of the Demerara and Coropina Formations is also an option. According to Abraham Mercador Consultant (1997), exploration oil drilling approximately 100 km offshore has shown a significant facies change to predominantly marine clay and limestone. However, this is not sufficient to say how the geology exactly extends into the sea for the various model layers.



1 - Silty clay (aquitard/aquiclude)
2 - Well sorted fine sand (Upper Sand aquifer)
3 - Intermediate sands and clay (aquiclude)
4 - Well Sorted Fine Sand (A Sand aquifer)
5 - Alternating sands and clay (aquiclude)
6 - Well Sorted Fine Sand B Sand aquifer
7 - Clay (aquiclude)
8 - Basement Complex (aquifuge)
← Flow Direction

Figure 3.2 North - South Model Layer Schematization (from the Coastal Part of the Study Area and Extending into the White Sand Outcrop Area)

4. Guyana's Coastal Aquifer Hydraulic Properties

For the purpose of computing groundwater flow, the hydraulic parameters of the aquifer for each of the hydrogeological units are crucial. Numerous characteristics, including transmissivity, hydraulic conductivity, storativity, and leakance, are used to represent them. "Transmissivity and hydraulic conductivity describe the general ability of the aquifer to transmit water (over the entire saturated thickness for transmissivity and over a unit thickness for hydraulic conductivity)." Data regarding the aquifer's hydraulic characteristics originate from studies conducted by Worts (1958) and Halcrow (as cited by Abraham Mercador Consultant, 1997). Worts used three separate procedures to conduct aquifer testing under controlled conditions: (i) analysis of specific discharge in individual wells; (ii) interference tests, which involved measuring interference at surrounding wells and one pumping (or recovery) well; and (iii) cyclical techniques, in which the interpretation of transmissivity is predicated on the observation of fluctuations in water levels in coastal wells brought on by tidal fluctuations. Worts conducted tests mostly for the A Sand aquifer, while Halcrow Consultants conducted tests for the B Sands. The hydraulic parameters of the aquifer that were discovered during each test are listed below.

4.1 Specific Discharge in individual wells (A Sand)

For the A Sand aquifer, Worts (1958) determined the permeability to be 31 m/d and the transmissivity to be 590 m2/d, utilizing the average aquifer thickness and the specific discharge of 158 wells.

(1) Interference test (A Sand)

An interference test was also carried out in the A Sand Aquifer by Worts (1958). He conducted an interference test by pumping the Shelterbelt 1 well while monitoring the water in the neighboring Shelterbelt 2 and Campbelville wells. He employed automatic water level recorders for the test. The results were interpreted using the Theis type 2 curve approach. The transmissivity values found for an aquifer thickness of 30.5 m in the Shelterbelt Well were 2244 m2/d and 1535 m2/d, resulting in an average value of 1890 m^2/d. It is estimated that the average hydraulic conductivity is 62 m/d. The experiments yielded storativity scores of 1.5×10^{-4} and 2.5×10^{-4}, respectively.

(2) Interference Test (B Sand)

Transmissivity and storativity values of 650 m^2/d and 7.5×10^{-5}, respectively, were obtained from an interference test conducted by Halcrow Consultants between two of the Shelterbelt wells that penetrate the B Sands aquifer. Hydraulic conductivity at the Shelterbelt wells is predicted to be 33 m/d because the aquifer thickness of the B Sand is only around 20 meters.

(3) Cyclic Method

Worts (1958) employed two methods to implement this approach:

- Time-lag technique: this involves measuring, one at a time, the lag between ocean tides and their response in certain monitoring wells.
- The range ratio technique, which is based on the analysis of all monitoring wells taken together, yielded transmissivity estimates of 1600 m2/d for the range ratio approach and 2362 m^2/d to 3190 m^2/d for the time-lag method. The storativity value is 2×10^{-4}, while the hydraulic conductivity values are 91 m/d and 53 m/d, respectively.

It can be concluded that a wide variety of hydraulic conductivity values are obtained from Worts's (1958) thorough experiments on the A sand. All of the results, meanwhile, exceed the approximation made with the Thiem formula-based specific discharge technique. Worts clarified that the additional head loss of 0.3 m for every 4 m of 5.45 m^3/d discharge in the 150 mm diameter casing, which ran from 12 to 60 m below the surface, could be the cause of this. In addition, there are further head losses in the screen and the aquifer next to the well. He suggested that, as a result, the specific discharge was calculated using drawdowns that were larger than the theoretical drawdowns using the Thiem equation. Because of this, transmissivity values calculated using the Thiem equation turned out to be significantly lower than actual transmissivity. For each of the sites where the A Sand aquifer was examined, Worts (1958) proposes an appropriate value for the hydraulic conductivity of 75 m/d, the transmissivity of around 2250 m^2/d, and the storativity of 2×10^{-4}.

It appears that the hydraulic conductivity of the A Sand in the Georgetown region is more than double that of the B Sand, using the representative values supplied by Worts (1958). It must be stressed that the hydraulic parameters derived from the three wells in the Georgetown region might not be indicative of the entire coastal portion of the research area. Nonetheless, they do offer some understanding of the aquifer's hydraulic characteristics. It is also important to take into account that the groundwater in the A Sand had a relatively high temperature (between 29 and 38°C). Worts (1958) states that the values of the field coefficient of permeability must be adjusted to a standard water temperature of 16°C. In order to translate the field measurements to laboratory values, he provides a coefficient of 0.66. When this hydraulic conductivity is translated to a laboratory equivalent, it will be 50 m/d. Worts' proposal is sound because it is well known that kinematic viscosity is a fluid characteristic that affects hydraulic conductivity.

No test was carried out to determine the hydraulic properties of the aquifer system in the White Sand outcrops. Hence, representative values are not available for the White Sand Series. However, empirical relationships exist whereby the hydraulic conductivity is correlated to soil properties such as pore size, particle size (grain size), distribution, and texture. In my effort to determine the hydraulic conductivity of the white sand in the White Sand outcrop area, the Fair and Hatch permeability formula was used. The Fair and Hatch permeability formula is given by:

$$k = \frac{1}{m\left[\frac{(1-\sigma)^2}{(\sigma^3)}\right]\left[\frac{\theta}{100}\sum\left[\frac{P}{dm}\right]\right]^2} \quad (2)$$

where:

σ = porosity
m = packing factor (found experimentally to be 5)
θ = sand shape factor, varying from 6.0 for spherical grains to 7.7 for angular grains
P = percentage of sand held between adjacent sieves
d_m = geometrical mean of the rated sizes of adjacent sieves

For the actual computation of the hydraulic conductivity, a sand shape factor of 7.7 was used since the samples are angular. The equation is dimensionally correct, so that any consistent system of units may be introduced. Using the grain size distribution of the samples taken during the field work and the typical porosity value of fine sand as 0.3, the calculated permeability is 39 m/d. However, based on much of the literature consulted, such as Nonner (2010), the hydraulic conductivity of fine sand is a bit lower, in the range of 10^{-1} to 30 m/d.

4.2. Hydraulic Properties of the Aquicludes

It is reasonable to refer to the Intermediate Sands and Clays and the Alternating Sands and Clays as aquitards or aquicludes. The borehole logs' descriptions suggest that the hydraulic conductivities of these two units are most likely between 10^{-3} and 1 m/d. The higher confining units are essentially silty clays known as the Demerara and Coropina Formations. The proportion of white sand does, nonetheless, progressively rise toward the White Sand outcrop. Kirkham (2005) states that the hydraulic conductivity of silty clay is around 0.02 m/d. Fan et al. (2007) offer values for hydraulic conductivity for different mixes of loam, sand, silt, and clay according to the USDA Textural Class. Table 4.1 displays the associated hydraulic conductivity values for combinations of clay, sand, and silt that exist in the research area, while Figure 4.1 displays textural classifications for various combinations of these materials. For further model studies, the conceptual model can use these numbers to determine which calibration is most appropriate.

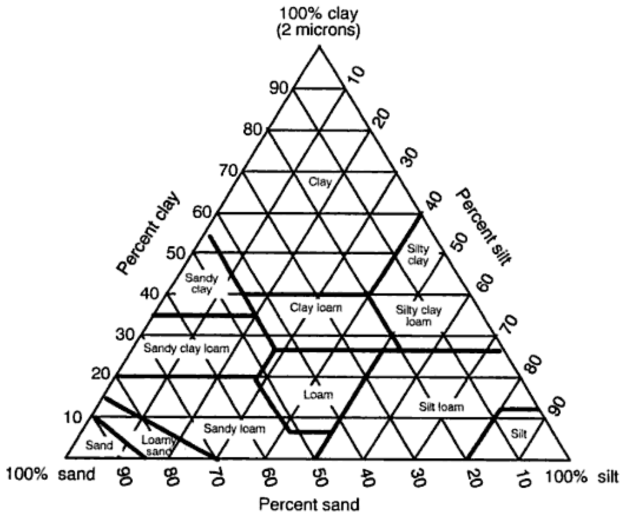


Figure 4.1: USDA Textural Classification Based on the Percentages of Clay Sand and Silt (Adopted from: Moreno-Maroto & Alonso-Azcárate, 2022)

Table 4.1 Hydraulic Conductivity for Various Rock Types (Adopted from: Fan et al, 2007)

Name	Hydraulic Conductivity m/d
sand	15.2064
loamy sand	13.5043
sandy loam	2.9981
silt loam	0.6221
loam	0.6048
sandy clay loam	0.5443
silty clay loam	0.1210
clay loam	0.2160
sandy clay	0.1901
silty clay	0.0864
clay	0.1123

Conclusion

Because of their proximity to the sea and consequent susceptibility to salinization, coastal aquifers are particularly vulnerable sources of groundwater. In addition, their high population density means that freshwater resources are constantly being overexploited to meet human demands. In order to simulate the hydrodynamics of the coastal plain aquifer, a conceptual model was created. The model can be used to detect river, aquifer, and sea linkages, as well as the most crucial elements of the water budget, and to evaluate the system's susceptibility to saltwater intrusion brought on by groundwater extraction from Guyana's coastal aquifer. Since most groundwater abstraction wells are situated near the sea and may be vulnerable to saline intrusion, the decline in water quality caused by the wells' decreased piezometric head in the costal aquifer should be taken into consideration.

The conceptual model assumes that the A and B Sands are indirectly connected to the ocean through leaky exchange with the Upper Sand Formation, while the Upper Sand aquifer has a direct exit to the ocean, probably at a distance of 60 km. Another possibility is for the Upper Sand to leak into the ocean through the silty clays of the Coropina and Demerara Formations. Exploration oil drilling around 100 km offshore has revealed a considerable facies transition, primarily to marine clay and limestone, according to Abraham Mercador Consultant (1997). This alone, however, does not provide enough information to determine how precisely the different model strata' geology reaches the sea. To find out how the geology extends into the water, more offshore drilling needs to be done. These data, together with all previous data, ought to be safely kept and readily accessible in a database made especially for this use.

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