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COASTAL AQUIFER GROUNDWATER MODELING IN THE SOUTHERN PART OF YOGYAKARTA AREA, INDONESIA

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Abstract

Parangtritis beach, located in a coastal aquifer at the southern part of Yogyakarta Province, Indonesia is bounded by the Indian Ocean at the South, Opak River at the West, and Tertiary Limestone Rock to the East. Local land-use is predominantly agriculture, rice fields and settlements and the population is estimated to be 9,386 persons as per the 2012 census. The total surface area is estimated at 9.46 km^2. The aims of this research were to understand the system of groundwater and to assess and predict saltwater intrusion by conducting a numerical groundwater model. Hydrological and hydrogeological data were collected directly from the field and from previous work for input into the model.

The model simulates an unconfined aquifer system where the aquifer thickness varies from 30-40 meters. The material of the aquifer consists of sand varying from fine to coarse grain size and fine gravel with hydraulic conductivity values of 8.974 $\times$ 10^{-4}, 1.794 $\times$ 10^{-3}, and 1.337 $\times$ 10^{-3} m/s at the northern, central, and southern part of the research area, respectively. The maximum length of the saltwater interface was estimated at about 205.1 m laterally and 40 m vertically relative to the location of the groundwater table around 1m above sea level. Direction of groundwater flow is from north to south. Groundwater table elevation equals 5 m at the north and 0 m at the south with a hydraulic gradient estimated at about 2.45 $\times$ 10^{-3}.

As a result of a steady-state simulation as well as two cases of prediction for five and ten years in the future, it is determined that that the salinity of the surrounding environment is not potentially adverse to the groundwater quality in the study area. This is in part due to low population in this area and abundant groundwater resources, as well as the results of the groundwater model.

Keywords: *Coastal aquifer, numerical groundwater model, conceptual model, observed heads*

1 Introduction

About 70% of the world's population lives in coastal zones. With economic and population growth, the shortage in freshwater supply is becoming increasingly acute. Due to the progressive depletion and pollution of surface water, coastal communities have turned to groundwater to supplement their fresh water supply. For domestic supply purposes, the percentage of groundwater use has increased to more than 40% on a worldwide basis (Cheng and Ouazar, 2005).

Parangtritis is located in the southern part of the Yogyakarta Area which is known as the city of education, culture and tourism. Parangtritis beach is one of the well-known tourist beaches in Yogyakarta Special Province where the number of tourist increases annually. Guesthouses, hotels, restaurants and so forth have been constructed to accommodate the yearly influx of

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tourists. Along with the infrastructure, the needs of natural resources, particularly fresh water, have also increased.

Generally, coastal aquifers are highly sensitive to anthropogenic disturbances. Groundwater in these areas is vulnerable to deterioration in both quantity and quality due to factors such as saltwater intrusion, land subsidence, and groundwater contamination (Cheng and Ouazar, 2005). Hence, inappropriate management of coastal aquifers can lead to irreversible damages, eventually causing their destruction as freshwater sources. The resultant groundwater degradation can result in many negative impacts on the people, environment and local economy. Without a proper method to manage groundwater in this area, a water crisis will occur and render the area unusable. The continued use of such a contaminated source of water can deteriorate human health and will cause significant damage to the socio-economic value of the area.

Groundwater models are valuable tools for the management of groundwater resources as they are representative of the reality of the natural system. They can be used to complement field monitoring and laboratory bench studies in evaluating and forecasting groundwater flow and transport (Younger, 2007). Furthermore, groundwater modeling is now a major part of projects dealing with groundwater development, protection, and remediation (Kresic, 2007).

2 Location of Study Area

The study area is located in the coastal zone of the southern part of Yogyakarta Special Province, Indonesia. The total population is estimated around 9, 386 persons as per the 2012 census with a total surface equaled to 9.46 km2. The research area is bounded by the hydrogeological conditions of the Indian Ocean at the south, the Opak River at the west, and tertiary limestone rock at the east (Figure 1). The lithology in the research area consists of sand and gravel of the Wates Formation and sand dunes (MacDonald and Partners, 1984). The clean water supply in the sand dunes area poses a problem because in this area, wells and springs are rare and water quality is poor due to high salinity (Putra, 2003). Based on the land-use map (Bakosurtanal, 1999), the research area is occupied mostly by rice field.

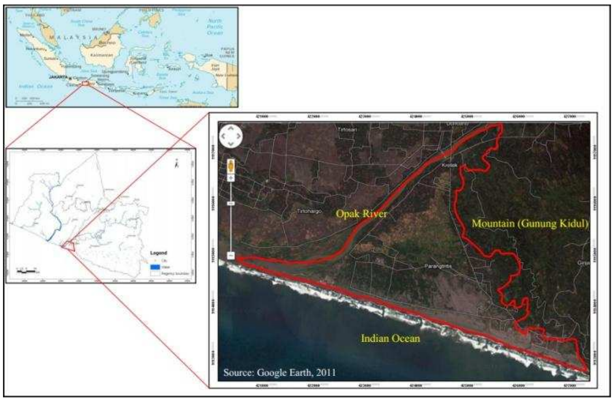

Figure 1: Location of the research area .

3 Research Methodology

All available secondary data was collected which included a topographical map, land-use map, geological map, rainfall data, temperature data, and population data. The primary data was measured directly in the field and included the groundwater head, river parameters, and TDS values. Together, these data were input to the numerical model. A systematic research flow chart can be seen in the Figure 2.

4 Data Evaluation

4.1 Hydrology

Rainfall Based on annual rainfall data obtained from the Department of Meteorology and Geophysics of Bantul Regency which was measured in the station of meteorology Pundong from the year 2000 to 2011, monthly rainfall intensity in study area varied from month to month depending on the rainy season (Table 1). From these data, the average annual rainfall was esimated to be 1855.2 mm/years.

Evapotranspiration Evapotranspiration was estimated as the function of annual precipitation and mean temperature by using an empir-

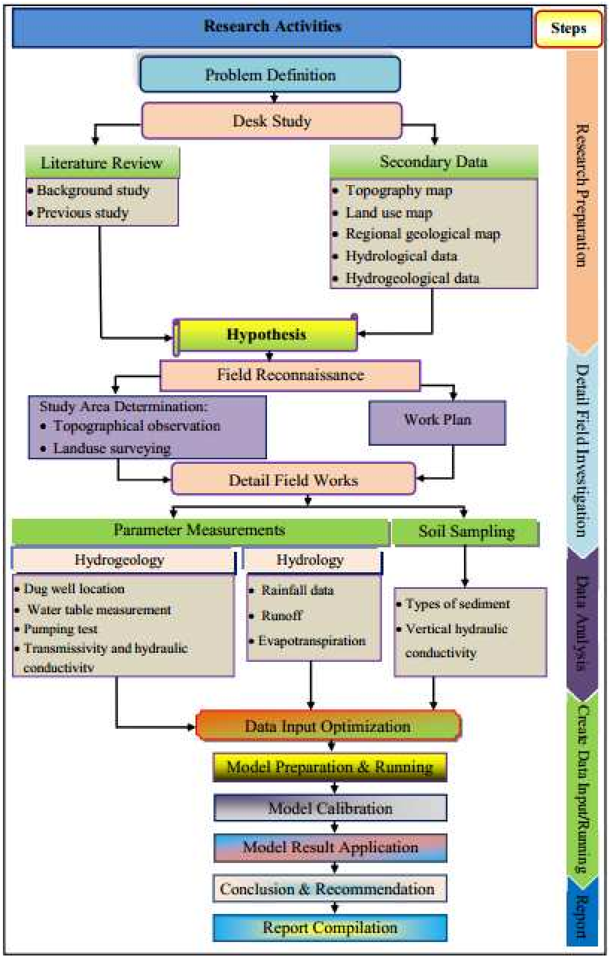

Figure 2: Flow chart of research methodology.

Table 1: Hydrological parameters of research area

Hydrological Parameters	Average Value (mm/year)
Rainfall	1855.2
Evapotranspiration	1330.8
Runoff	310.50

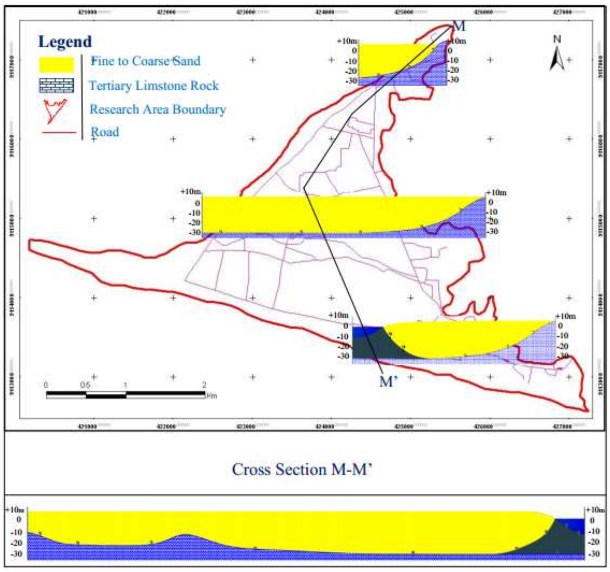

Figure 3:

ical equation. The value of evapotranspiration within the study area was calculated to be equal to 1330.8 mm/year.

Runoff Runoff was assumed to be a function of annual rainfall, average temperature and area of watershed. The amount of surface runoff calculated in this way was estimated at 310.5 mm/year.

4.2 Hydrogeology

Aquifer System Since there are no existing borehole data and no new boreholes drilled for this study, the groundwater system and subsurface condition had to be developed based on the geological map of the Yogyakarta Province (scale 1:100 000), prepared by the Geological Research and Development Center of Indonesia in 1995 (Djaeni & Soekardi, 1974) and review of relevant research. The result of this estimation is that the thickness of the aquifer within the study area varies from 30m at the north and 40m at the south (Figure 3).

Aquifer Properties In order to estimate hydraulic conductivity, slug tests were carried out in three different locations in the study area. The first test was located in the southern part of study area, near to the boundary of the In-

Table 2: Hydraulic conductivity of the research area.

Hydraulic Conductivity	Value (m/s)
K1	$1.337\ 10^{-3}$
K2	$1.794\ 10^{-3}$
K3	$8.974\ 10^{-4}$

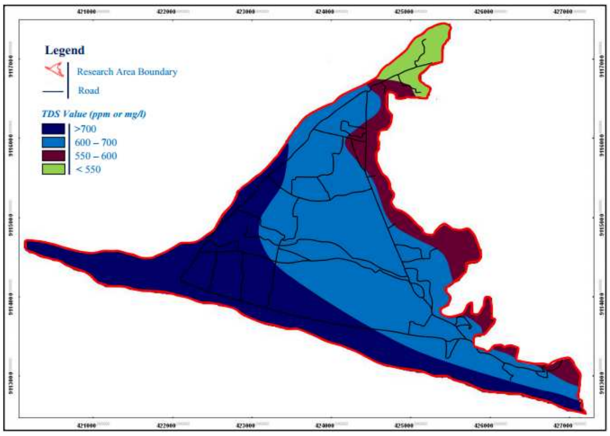

Figure 4: Distribution of TDS value of research area.

dian Ocean. The second test was located in the central area and the last test was located along the northern boundary. The value of hydraulic conductivities are represented as K_1, K_2, and K_3, respectively (Table 2).

Salinity Since the study area is located adjacent to the ocean, it is necessary to identify salinity from natural saltwater by using a TDS (Total Dissolve Solid) meter. The maximum measured TDS was found to be equal to 926 mg/l at southern boundary while the minimum was 500 mg/l at the northern boundary (Figure 4). Since the TDS value was less than 100mg/l, the groundwater in this area is still consider as fresh (Hemker, 1994).

Initial Position of Saltwater Interface The possibility of a saltwater interface was accounted for by using the theory of lateral encroachment and vertical upconing of Ghijben-Herzberg principle (Figure 5).

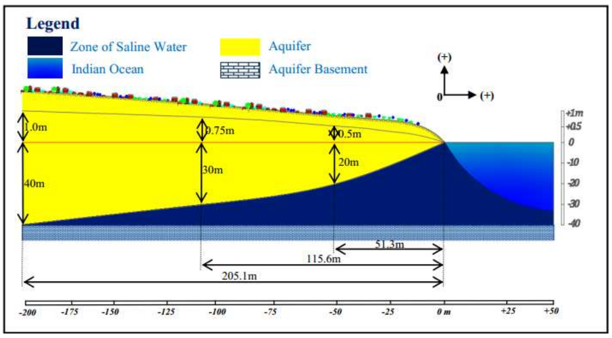

Figure 5: Position of the saltwater interface.

5 Results and Discussion

5.1 Conceptual Model

The type of aquifer in the model area is an unconfined aquifer consisting of fine to coarse sand, gravel, sandy-clay, silt, undifferentiated tuff, ash, and breccias with a basement rock consisting of Tertiary limestone (Figure 6). The geometry of the aquifer is assumed as shallowest at the eastern part and gradually deeper to the south with a thickness ranging from 30 to 40 meters, respectively.

The study area is bordered by a major river located in the western boundary of the study area known as the Opak River. This river is assigned as a river boundary of the study area for modeling purposes. The Indian Ocean is assumed as a constant-head or zero-flow boundary of the research area. In the north-east, the study area is connected to a hilly mountain with a lithology dominated by Tertiary limestone rock which was assigned as a no-flow boundary for modeling purposes. Groundwater flow direction in the study area runs from north to south.

The recharge rate in the aquifer is assumed to come entirely from rainfall. Therefore, the rate of groundwater recharge used for modeling purposes is equal to the average rainfall rate of 213.9 mm/year.

5.2 Groundwater Model Results

In order to generate a reliable groundwater flow pattern, the model has been calibrated and ran several times. Comparing all the results of groundwater equipotential lines obtained

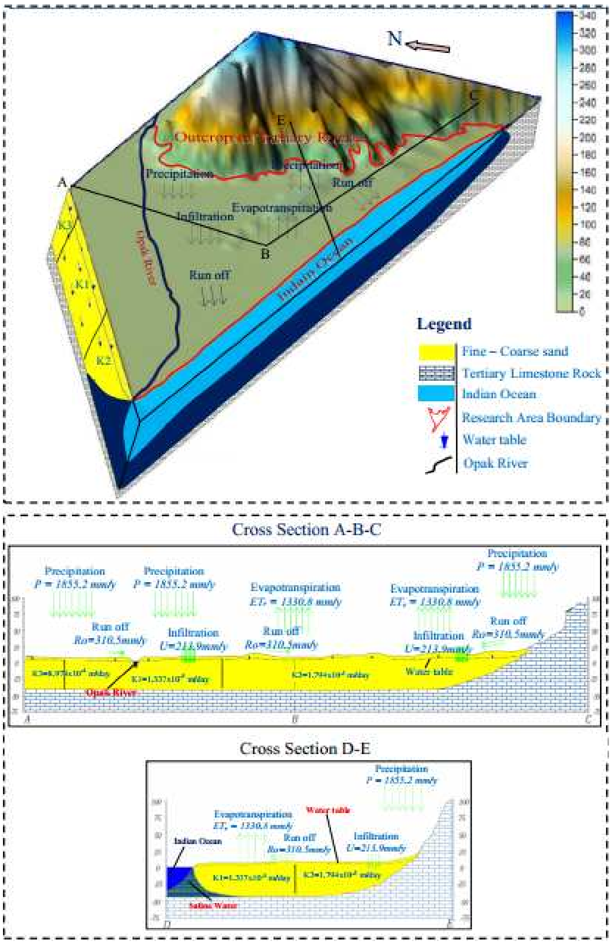

Figure 6: Conceptual model of research area.

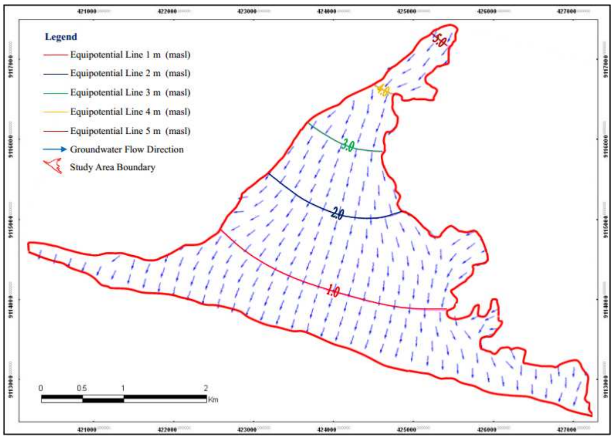

Figure 7: Groundwater flow pattern map of the study area.

Table 3: Groundwater mass balance

Parameters	In (m^3/day)	Out (m^3/day)
Constant Head	0	11, 383.65
River Leakage	5980.73	2087.613
Evapotranspriration	0	148.707
Recharge	7,643.056	0
Total	13,623.79	13,619.97
Discrepancy	0.03 %	

from variables such as hydraulic conductivities, groundwater basement, and groundwater recharge variation, the best result is shown in Figure 7.

Based on Figure 7, the groundwater flow direction is oriented from north to south in the research area with a maximum groundwater flow velocity of about 0.84 m/day. Based on the model calculation, the groundwater mass balance was estimated with the discrepancy of 0.03% (Table 3; Figure 8).

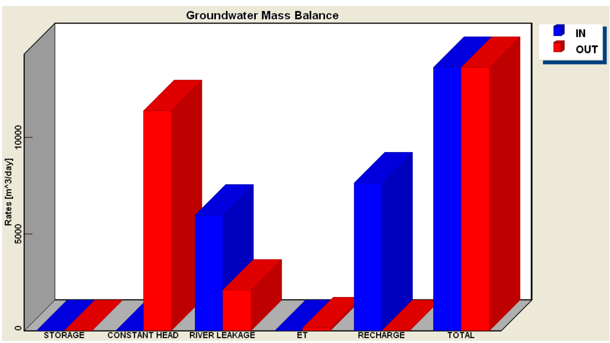

Figure 8: Groundwater mass balance.

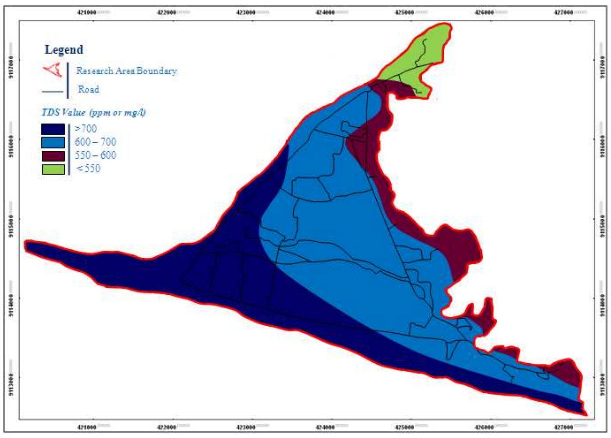

Figure 9: Groundwater equipotential line of case 1 (next 5 years of prediction) and case 2 (next 10 years of prediction) vs. calibrated model result.

5.3 Model Application

The purpose of applying the groundwater modeling used in this study is to use the results to predict the behavior of hydrogeological condition in the research area for the next 5 and 10 years. Trends have been identified in decreasing groundwater table and saltwater intrusion.

Decreasing of Groundwater Table The decreasing of groundwater table was determined based on population and land-use characterization of research area (Figure 9). In two cases of prediction (for 2017 and 2022), the population in the research area is expected to be around 10,306 and 11,315 persons with a total rate of groundwater abstraction of 1,546 and 1,700 m^3/day, respectively.

Figure 9 illustrates that the mean equipotential line of the groundwater table has moved towards the north of the model area. This is a mechanical response to the increase in rate of groundwater abstraction.

Saltwater Intrusion The results of groundwater modeling for saline water intrusion have been applied to calculate the position of the seawater interface in terms of vertical upconing and lateral encroachment by using theory of Ghijben-Herzherg. The thickness of the aquifer

Table 4: Position of saltwater interface.

Points	Model Result			Next 5 years			Next 10 years		
	WT	VL	HL	WT	VL	HL	WT	VL	HL
P1	0.50	20	51.3	0.39	15.6	51.8	0.35	14	52.0
P2	1.00	40	205.1	0.86	34.4	206.5	0.82	32.8	206.9

Note: WT = *Water Table*
VL = *Vertical Length of Saltwater Interface*
HL = *Horizontal Length of Saltwater Interface*

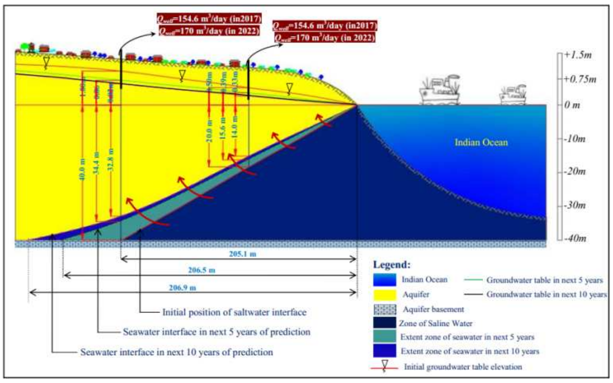

Figure 10: Position of saltwater interface in next 5 and 10 years of prediction vs. initial condition

is approximately 40m maximum, and the position of the saltwater interface is at a minimum of 0 m and a maximum of 1m. Where groundwater elevation is equal to 1m, the position of interface is equal to 40m that reaches to the basement of the aquifer. Consequently, only the area beneath the locations where groundwater elevation is 0m to 1m is there a potential for saltwater intrusion from the ocean (Table 4). The initial saltwater interface in steady-state condition and predictions for future placement are illustrated in Figure 10 below.

6 Conclusion

Based on the field observation and modeling results, the maximum head in the research area is equal to 5m in the north and the minimum head is equal to 0.5m in the south. The hydraulic gradient is estimated to be about 2.45×10^{-3}. Therefore, the groundwater depth within the study area is shallow and oriented from north to south. The results of sensitivity testing of aquifer thickness variation yield thickness values varying from 30 to 40m. We can conclude that the thickness of aquifer in the study area is equal to 30m at the north and equal to 40m at the south. The value of hydraulic conductivity was estimated using the slug test method in three locations within the study area, which yielded values of 1.794×10^{-3}, 1.337×10^{-3}, and 8.974×10^{-4} m/s, representing sand and fine gravel material. Hence, the composition of the aquifer in the study area is surly sand and fine gravel.

As a result of modeling under steady-state conditions, the initial saltwater interface beneath the study area is found with a maximum length of protrusion of 205.1m horizontally and 40m vertically from the land surface. Also from the groundwater modeling for sea water intrusion, it is estimated that in the next 5 and 10 years that the study area is at a low vulnerability to sea water intrusion. The results of modeling and prediction have shown that the water table can be dropped down.

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