International Journal of Advances in Applied Sciences (IJAAS)
Vol. 3, No. 2, June 2014, pp. 104~111
ISSN: 2252-8814

The Vulnerability Level of Groundwater Quality Degradation in the Ecosystem of Sand Dune Landscape on the Southern Coast of Central Java and the Yogyakarta Special Region, Indonesia

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Article Info

Article history:

Received March 13, 2014
Revised May 16, 2014
Accepted May 29, 2014

Keyword:

Environment management
Groundwater vulnerability
Sand dune ecosystem

ABSTRACT

The sand dune ecosystem phenomenon in the research area has unique and interesting characters. It is identified that there is an increase in the construction of the environment in the use of sand dune ecosystem which influence the groundwater quality. Such phenomenon is the manifestation of the existence of spatial dynamics influencing the groundwater degradation vulnerability. This research is aimed at 1) predicting the level of groundwater quality degradation vulnerability based on the sand dune ecosystem spatial dynamics; 2) developing an environmental management model to continuously maintain the availability of groundwater. The research employed survey research and inductive mapping. The aspect of the study included an environmental study with hydromorphological and hydrogeological approach. Analysis and evaluation were based on the multiplication of weight and rate, and were done on landscape units resulting from the map overlay. The research result indicates that there are 4 (four) classes of groundwater degradation vulnerability out of the 5 (five) classes of vulnerability determined beforehand. Groundwater degradation vulnerability classes III and IV indicate problems of disturbances in the groundwater supply system and domestic and agricultural waste pollution. In order to overcome the disturbances in the groundwater supply system, water infiltration well should be constructed, communal domestic water processing should be encouraged, and in order to reduce pollution from the use of agricultural fertilizers, the fertilizers should be blended with clay.

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1. INTRODUCTION

The ecosystem of sand dune landscape is located in Java Island, Indonesia, which is in the southern coast of Central Java and the Special Region of Yogyakarta, on the coordinates of 330.912 – 427.820 mT and 9.112.214 – 9.143.318 mU. The ecosystem stretches out from the west to the east at an average length of 106.183 kms and average width of 0.82 kms (Figure 1).

The sand dune ecosystem in the research area has special and interesting landscape characteristics and constituent materials. The uniqueness and attractiveness of the sand dune ecosystem possess significant and important values as follows:

a) Scientific Value, which plays a major role in the studies of geology – geomorphology, geography, oceanography, climatology, and environment.

b) Disaster Rescue Value, as a barrier against tsunami and sea water flooding (Sungkowo, 2007).

c) Economic Value, as a source of minerals for it contains ironsand, pumice, and backfill material. In addition, it could also be used as a place for fish auction, horticulture, and marine tourism site.

d) Social, Cultural, and Community Health Value, as a place where one of the spiritual rituals of the Yogyakarta Sultanate on Parangtritis Beach and Pakualaman on Glagah Beach is held, also a place with healthy air where people work out and where military and earth science education could be conducted.

e) Religious Value, as a place to rehearse the practice of the rituals of Hajj.

Figure 1. The location of the research area

In addition to the aforementioned important, the sand dune area in the research site has attracted investors (of the mega projects) and the communities to establish and develop the environment. There are several mega projects using the sand dune area and the surrounding areas, including:

a) Ironsand mining by PT. Aneka Tambang in Cawang Village, Kutoarjo Subdistrict, Purworejo Regency, Central Java Province since the year of 1987. This activity has changed the mounds of dune into a basin.

b) The construction of a fishing harbor on the creek of Serang River and the surrounding area, in Kulonprogo Regency, The Special Region of Yogyakarta.

c) The plan of the Parangtritis mega tourism project in Yogyakarta, which at the beginning was to develop tourism sector in the 1990s, namely: a natural beach serving as a terrestrial natural laboratory and a center of art, cultural and spiritual activities, but then changed into an artificial "fantasy world" area and golf real estate.

d) The ironsand mining plan in Kulonprogo, the Special Region of Yogyakarta.

e) The plan of constructing Java's southern highway at a distance of 400 – 600 meters from the coastline (on the lane of Diponegoro Street, Kebumen Regency and during the research, land acquisition has been done), at a distance of ± 1 km from the coastline in the south of Purworejo on the lane of Daendles Street.

f) The plan of constructing an (international standard) airport on the southern coast of Kulonprogo Regency.

The aforementioned phenomena of dune demonstrate a spatial dynamics. They illustrate spatial dynamics because there are drives and changes that are able to accommodate various sorts of human activities in fulfilling their needs. Spatial dynamics can take place both naturally and artificially, so that it may influence the occurrence of the vulnerability of groundwater quality degradation.

2. THE CONCEPT OF VULNERABILITY

Composed of loose sand deposits, the sand dune is a landscape formed by the process of wind activities shaping a mound or a ridge and other various shapes in various sizes (Flint and Skinner, 1977; Zuidam, 1986; Strahler and Strahler, 1989).

Groundwater in a sand dune ecosystem is vulnerable to quality degradation controlled by the characteristics of landform, lithology as aquifer, and the groundwater itself, as well as the growth and deployment of natural vegetation. In this case, the vulnerability is defined by the existence of potentials or tendencies to degrade, although the degradation has not yet happened. The vulnerability of groundwater quality degradation can only occur if there is a trigger. This trigger is usually in the form of the change of precipitation and human activities that influence the decrease in groundwater quality. Therefore, the concept of the vulnerability of groundwater degradation in this research is influenced by the controlling factors and the trigger factors as follows:

a) Controlling factors, including the landform and the slope, the constituent materials as aquifer that are influenced by the physical traits (hydraulic conductivity aquifer and transmissibility) and the mineral composition, as well as the groundwater's condition.

b) Hydraulic conductivity is the ability of the rocks to transmit water through their holes/pores without changing the water's physical traits. Meanwhile, the coefficient of transmissibility is a measure of flow under similar hydraulic gradient, through a layer on the entire thickness of the aquifer (Tood, 1980).

c) Trigger factors, which are (temporal) tropical climate, namely dry and rainy season, distribution of (natural) vegetations, and human activities in the form of land uses for mining, tourism, agriculture (horticulture), settlement, fish auction, and fish pond.

d) Human activities cause changes in infiltration capacity, groundwater recharge, and water quality index. Infiltration capacity is the maximum rate of soil and/or rock ability to absorb water (fluids), or in the other words, it is the process of fluids flowing into porous soil and/or rock in certain circumstances (Karnawati, 2005; Asdak, 2007; Sianawati, 2009). Groundwater recharge is the amount of precipitation that gets absorbed into the aquifer through infiltration and reaches the groundwater zone of saturation. Meanwhile, groundwater quality index is the relative water quality level of a source of water to the allowed parameter of water quality.

The correlation between the controlling and trigger factors results in groundwater quality degradation, which is also a topic included in the scope of environmental studies. Groundwater quality degradation should be prevented / minimized based on the vulnerability level of the groundwater by applying a management model perceived from the ecological, social, economical and cultural aspects. Proper management is essential in order to continuously maintain the availability of groundwater (Figure 2).

2.1. Aims and Objectives

This research is aimed at responding to the spatial dynamics characteristics of the sand dune landscape ecosystem vulnerable to groundwater quality degradation. In addition, the objectives of this research are:

a) To study the characteristics of the spatial dynamics of the sand dune landscape ecosystem, which influence the vulnerability to groundwater quality degradation.

b) To predict the level of groundwater quality degradation vulnerability based on the units of sand dune landscape ecosystem.

c) To develop an environmental management model for sand dune landscape ecosystems in order to sustainably maintain the availability of groundwater.

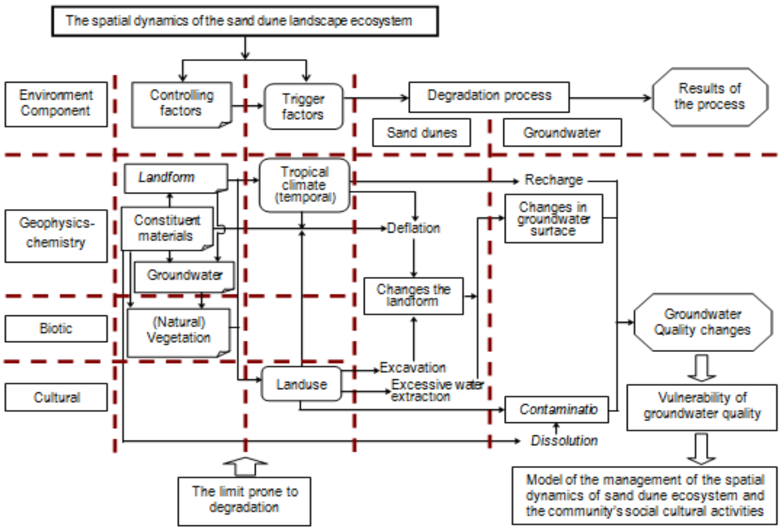

Figure 2. The diagram of the framework of the vulnerability of groundwater quality degradation in the scope of environmental studies

3. METHODOLOGY

This research employed survey research and induced mapping, by using a topographic base map with the scale of 1:25,000. The scope of the study was an environmental study with the hydromorphological and hydrogeologiacl approaches, comprising: 1) geophysical components with the parameter of precipitation, landform, constituent materials and its traits as aquifer (aquifer's conductivity and aquifer's transmissivity), infiltration capacity, aquifer's thickness, groundwater surface elevation, and chemical qualities of water. 2) bio-cultural components including the quality of groundwater bacteriology, land use and the utilization of groundwater.

The first step was to make cluster sampling areas. The next step was to take stratified proporsionate random samples.

The analysis of the vulnerability of groundwater quality degradation began by determining the rate of the controlling and triggers factors parameter based on the scales of their influence over groundwater vulnerability. Subsequently, an evaluation was performed in order to assess the class of the vulnerability of groundwater quality degradation, based on the result of the multiplication of the weight by the rate. The assessment of the class of the vulnerability of groundwater quality was based on the landscape units, the overlay result of the landform map and the variations of the slope, the constituent materials, and the land use. According to Saaty (1990), the weight value is determined by using an approach based on the method of Analytic Hierarchy Process (AHP).

4. RESULT OF THE RESEARCH AND DISCUSSION

The results of the research were in line with the objectives, as follow:

1. The characteristics of the spatial dynamics of sand dune landscape ecosystem that influence the occurrence of the vulnerability of groundwater quality degradation were manifested in a system in which controlling and trigger factors can be found. Trigger factors influenced controlling factors dynamically.
   a. The controlling factors in the research areas included:
      1) Landform, that comprised of:
         a) Sand dune units whose shapes differed due to the wind process, as well as wind process and human activities were:
            The types of sand dunes formed by the wind process (wind deflation and deposition) were the transverse type with slope gradient of rather steep - steep, the longitudinal type with its slope gradient of slant – rather steep, and the hillocks type with its slope gradient of rather steep – steep, the barchans type with slope gradient of rather steep – very steep.
            The types of sand dunes formed by the wind process and human activities were the transverse type with its slope gradient of oblique – rather steep, and the undulating sloping topography type with slope gradient of oblique – rather steep.
         b) The swale unit in the form of valleys with elongated profiles was framed with mounting sand dunes and formed by the marine process and wind deposition. The swale unit consisted of wet swale with the slope gradient of flat – oblique and dry swale with the slope gradient of oblique – slant.
         c) The alluvial plains and flood plains units, which were the result of the deposition process of a river with the slope gradient of plain – oblique.
         d) Mined valleys, which were valleys with the slope gradient of oblique – slant as the result of human activities mining the sand containing iron ore.
      2) Constituent materials were water carrier materials (aquifer) in loose conditions, instead of solid, which possess different aquifer conductivity and transmissibility ability, namely:
         a) Wind deposition sand units, with rather good – reasonably better conductivity capability in the category of water permeability, while its transmissibility rate was in the category of rather heavy – heavier flow.
         b) Sand gravel of alluvial deposits units, with rather faster conductivity capability in the category of water permeability, while its transmissibility rate was in the category of heavier flow.
         c) Swale clay deposits unit, with slow – rather slow conductivity capability in the category of water permeability, while its transmissibility rate was in the category of rather light flow.
      3) The aquifer in the research area was an unconfined aquifer whose water surface tended to match the topography relief. The higher the topography relief was, the deeper the groundwater would be, and the opposite applied for lower topography reliefs. The patterns

of the groundwater flow also followed the patterns of the steepness of the topography slope pulled by gravity, from the topography relief on a higher ground to that on a lower ground. The shallower the groundwater was, it meant less time was needed for pollutant to contaminate the groundwater, and vice versa.

b. The trigger factor that influenced the controlling factors resulting in the vulnerability of groundwater quality degradation was human activities in land use. The impacts were as follow:
   1) The changes of infiltration capacity on:
      a) Sand dunes, as a result of using land for settlement areas and coastal settlement/tourism areas. they had a slower infiltration capacity (around 0.51 – 1.12 cms/min from the estimated 0.36 – 1.238 cms/min); settlement and mixed garden areas, moors, and coastal resorts had a slow infiltration capacity (around 1.40 – 1.78 cms/min from the estimated 1.238 – 2.116 cms/min); mixed garden and coconut plantation had an average infiltration capacity (around 1.50 – 2.50 cms/min from the estimated 2.116 – 2.994 cms/min).
      b) Wet swale resulting from irrigated rice-growing activities slowed down the infiltration capacity (0.36 cms/min from the estimated 0.36 – 1.238 cms/min); dry swale resulting from activities in moor/rainfed paddy field caused slow infiltration capacity (1.24 cms/min from the estimated 1.238 – 2.116 cms/min), and mixed garden activities caused average infiltration capacity (about 2.57 cms/min from the estimated 2.116 – 2.994 cms/min).
      c) Alluvial plains, which with flat-oblique slopes filled with irrigated paddy fields cause lower infiltration capacity (0.90 cms/min from the estimated 0.36 – 1.238 cms/min).
      d) Valleys that had once been iron sand mines that were used for moors/rainfed paddy fields, which caused a slow infiltration capacity (around 1.40 cms/min from the estimated 1.238 – 2.116 cms/min).
   2) Changes of groundwater recharges on:
      a) Sand dunes with a small amount of groundwater recharge (7,277.23 – 255,273.36 m^3/year from the estimated1,770.98 – 366,853.93 m^3/year) due to the impacts of land use in the forms of: settlement areas, coastal settlement/resort areas, settlements and mixed gardens, moors, and mixed garden; the category with relatively ample groundwater recharge (367,022.98 – 712,710.97 m^3/year from the estimated 366,853.93 – 731,936.88 m^3/year) was resulted as the impact of settlement and mixed garden areas, mixed gardens, and transversed coconut plantation; the category with a considerable amount of groundwater recharge (732,253.53 – 995,340.04 m^3/year from the estimated 731,936.88 – 1,097,019.83 m^3/year) was resulted as the impact of moors and mixed garden plantation.
      b) Wet swale resulting from settlement and mixed garden activities caused a small amount of water recharged (9,686.39 m3/year from the estimated 1,770.98 – 366,853.93 m3/year), and moors/rainfed paddy fields caused more amount of water recharge (1,213,342.31 m3/year from the estimated 1,097,019.83 – 1,462,102.78 m3/year); dry swale resulting from settlements and mixed garden activities, mixed gardens, coconut plantations caused a small amount of groundwater recharge (10,703.25 – 39,261.52 m3/year from the estimated 1,770.98 – 366,853.93 m3/year).
      c) Alluvial plains with flat-oblique slopes, occupied by settlements and mixed garden, moors/rainfed paddy field, and coconut plantations resulted in a small amount of groundwater recharge (432,608.76 m3/year from the estimated 366,853.93 – 731,936.88 m3/year).
      d) Valleys that had once been iron sand mines that were used for moors/rainfed paddy fields resulted in a small amount of groundwater recharge (432,608.76m3/year from the estimated 366,853.93 – 731,936.88 m3/year).
      e) The changes in the groundwater quality index in the research area, which were influenced by the constituent materials of the sand dunes landscape ecosystem and land use, were as follow:
      f) Acceptable groundwater quality index (around 5.31 – 5.72 from the estimated 5.294 – 5.720) occurred on the transverse type sand dunes used as mixed gardens, coconut gardens, and open fields-natural vegetations; and dry swale as mixed gardens.
      g) Acceptable groundwater quality index (about 4.58 – 5.24 from the estimated 4.868 – 5.294) occurred on the trasverse type sand dunes with slant – rather steep slope used as settlements and mixed gardens, and coconut plantations.

h) Poor groundwater quality index (around 4.45 – 4.85 from the estimated 4.442 – 4.868), occurred on the transverse type sand dunes (with slant – steep slopes) used as settlements, settlements and mixed gardens, moors on open fields and natural vegetations; crescentic sand dune with rather steep – very steep slopes, settlements; valleys with rather steep – steep slopes used as duck farms on moors and open fields as well as natural vegetations; dry swale with moors/rainfed paddy fields and alluvial plains as irrigated paddy fiels; and valleys that had been sand mines as moors/rainfed paddy fields.

i) Poorer ground water quality index (around 4.04 – 4.44 from the estimated 4.442 – 4.016), occurred in transverse type sand dune with rather steep – steep slopes, whose open fields and natural vegetations were used as coastal settlements/resorts and fish auction, similarly with the slant – steep slopes used as moors; and the undulating topography type with oblique – slant slopes used as coastal settlements/resorts and moors.

j) A very poor groundwater quality index (about 3.59 – 3.99 from the estimated 3.590 – 4.016), occurred on the transverse type sand dune with rather steep – steep slopes as coastal settlements/resorts; wet swale used as moors/rainfed paddy fields; and dry swale used as moors/rainfed paddy fields.

2. The level of vulnerability of groundwater quality degradation in the sand dune landscape ecosystem in the research area was determined based on the characteristics and spatial dynamics.

It was important to determine the level of vulnerability of groundwater quality degradation for the formulation of environment management model in correlation with groundwater preservation.

These characteristics include the parameters of precipitation, infiltration capacity, groundwater recharge, and aquifer hydraulic conductivity, transmissivity, and fresh groundwater supply, depth of the groundwater, groundwater quality index, groundwater utilization, population density, and land use. The results of the study showed that there were 4 (four) levels of vulnerability of groundwater quality degradation out of the 5 (five) classes determined beforehand. The levels of vulnerability of groundwater quality degradation were category I (very low vulnerability of groundwater quality degradation), II (low vulnerability of groundwater quality degradation), III (moderate vulnerability of groundwater quality degradation), IV (high vulnerability of groundwater quality degradation). The level of vulnerability of groundwater quality degradation was determined by the extent of influence that the spatial dynamics characteristics of the sand dune ecosystem posed. The smaller the influence was, the lower the vulnerability level would be, and vice versa (Figure 3).

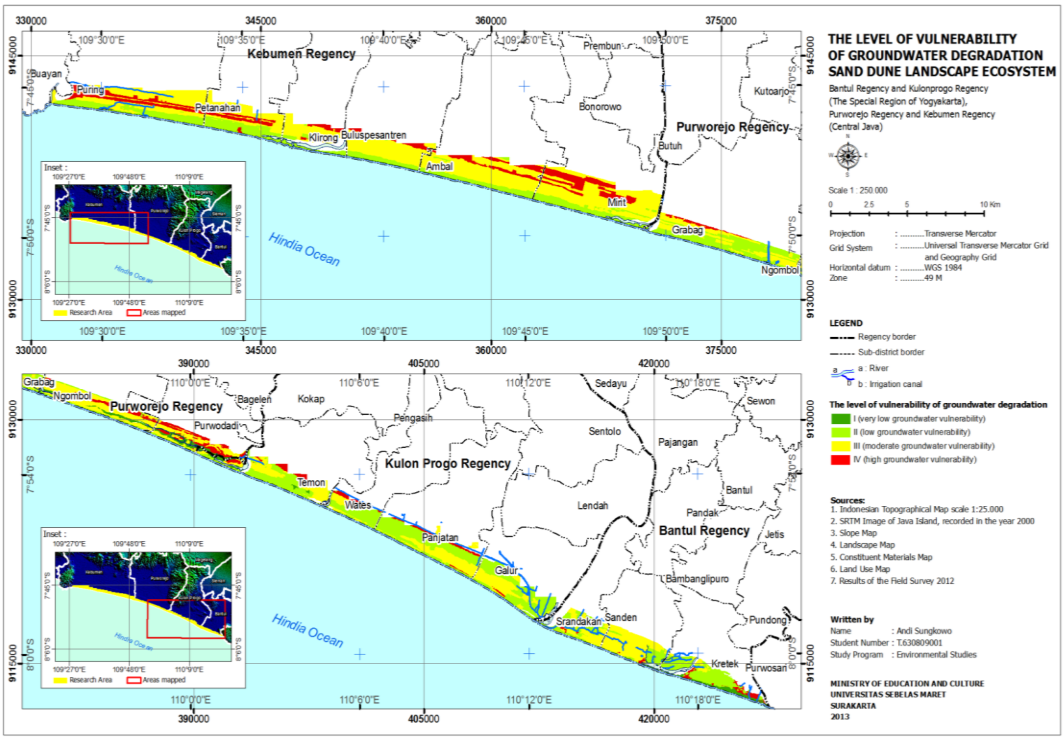

Figure 3. Map of the level of vulnerability of groundwater degradation

Based on the 4 (four) levels of vulnerability identified above, the vulnerability of groundwater quality degradation category III and IV proved problematic. The cause of the vulnerability of groundwater quality degradation problems were as follow:

a. The problems in the vulnerability of groundwater quality degradation category III were slow infiltration capacity, groundwater recharge deficiency, groundwater supply deficiency, and poor quality index. The problems in the vulnerability of groundwater quality degradation category IV were slow infiltration capacity, groundwater recharge deficiency, groundwater supply deficiency, and poor groundwater quality index.
b. The causes of the problems in the vulnerability of groundwater quality degradation category III and IV showed that: the decrease in infiltration capacity were an impact of agricultural land processing and the use of land for coastal settlement and resort areas; the changes in groundwater recharge was cause by the decrease in infiltration capacity; the decrease in groundwater supply was an impact of the decrease in infiltration capacity, groundwater recharge, and the limited width of field units; the drop in groundwater quality index, or in other words, the deterioration of groundwater quality, occurred due to agriculture activities and coastal settlements and resorts, which were pollutants that contaminate groundwater.

3. The model of environment management directives for sand dune landscape ecosystem is essential to ensure the continuous availability of groundwater supply.

The problems arising in sand dune landscape ecosystem, that caused the decline in groundwater quality, occurred in areas whose vulnerability of groundwater quality degradation was in category III or IV. The problems discussed were: disturbances in the groundwater supply system and contamination by domestic and agriculture waste. Therefore, the following managing means are essential:

a. In order to overcome the disturbances in the groundwater supply system, water infiltration well should be constructed in every settlement and coastal resort areas.
b. In order to reduce domestic waste pollution (in settlement and coastal resort areas), communal domestic waster processing should be encouraged. Similarly, in order to reduce pollution from the use of agricultural fertilizers, the fertilizers should be replaced by manure ameliorant blended with clay by 1:2 ratios.
c. Apart from the methods above, it is also essential to perform means of conservation on sand dune whose soil is covered and used as open fields and natural vegetations. Conservation is necessary in order to: a) maintain its function as rainwater catchment area, preventing seawater intrusion; b) allow the Aeolian process that is very important for Science; and c) act as a barrier against Tsunami.

Based on the discussion of the result of the research above, it can be concluded that spatial dynamics influence the groundwater quality by decreasing it. To prevent the decrease of groundwater quality, a model of environment management directives should be issued the phenomenon is summarized in Table 1.

Table 1. Summary of the result of the research and managing means directives

Spatial dynamics		Vulnerability category	Problem	Managing means directives
Movement	Perubahan change			
Human Activities	Controlling factors: slow infiltration capacity, groundwater recharge deficiency, groundwater supply deficiency, poor groundwater quality index	Class III (moderate), 57% out of the research area.	Disturbances in the groundwater supply system	Water infiltration well construction
	Damaging trigger factors such as agriculture activities, settlements & mixed garden and coastal settlements /resorts		Domestic and agricultural waste pollution.	The use of manure ameliorant blended with clay to overcome agricultural waste and taking communal measures to overcome domestic waste.
	Controlling factors: slower infiltration capacity, groundwater recharge deficiency, groundwater supply deficiency, shallow groundwater, poorer groundwater quality index	Class IV (high), 12.10% out of the research area.	Disturbances in the groundwater supply system	Water infiltration well construction
	Damaging trigger factors such as settlements & mixed garden, coastal settlements/resorts area, settlements		Domestic waste pollution	Taking communal measures to overcome domestic waste.

5. CONCLUSION

The result of the research can be summarized into several important points as follow:

1. The vulnerability of groundwater quality degradation was a result of the characteristics of the controlling factors prone to groundwater quality degradation and the characteristics of trigger factors that influenced the controlling factors.
2. In the research areas, 4 (four) classes of vulnerability was found out of the 5 classes determined beforehand. The vulnerability of groundwater quality degradation class III and IV showed a problem, which was the deterioration of the groundwater quality. Other problems were in the forms of disturbances in the groundwater supply system influenced the flushing process that increased groundwater quality, also agriculture and domestic waste pollution.
3. An environment management model is needed to ensure the continuous supply of groundwater. Measures in the models are: the construction of water infiltration wells to overcome the problems with groundwater supply system; manure ameliorant blended with clay to overcome the problems caused by agriculture waste, and communal waste processing for domestic waste.

ACKNOWLEDGEMENT

I would like to express my deepest gratitude to: the Directorate General of Higher Education of the Republic of Indonesia for granting me scholarship through the BPPS and Doctoral Dissertation Research programs. I would also like to express my gratitude to the Rector of Universitas Pembangunan Nasional "Veteran" Yogyakarta and the Rector of Universitas Sebelas Maret Surakarta and their officials, who have given me permission and support in taking this Doctoral Program. The gratitude also goes to my friends, colleagues and everyone who have supported me in every way, both morally and materially during the time I took to work on this research.

REFERENCES

[1] Asdak C., "Hidrologi dan Pengelolaan Daerah Aliran Sungai," Gadjah Mada University Press, 2007.
[2] Flint R. F., *et al.*, "Physical Geology," 2ed, John Wiley and Sons, Singapore, 1974.
[3] Karnawati D., "Gerakan Massa Tanah Di Indonesia dan Upaya Penanggulangannya," Jurusan Teknik Geologi, Fakultas Teknik, Universitas Gadjah Mada, Yogyakarta, 2005.
[4] Saaty T. L., "How to make a decision: The Analytic Hierarchy Process," *European Journal of Operational Research* 1990, Vol. 48, pp. 9-26.
[5] Saaty T. L., "Decision making with the analitic hierarchy process," *Int. J. Services Sciences*, 2008, Vol. 1, No. 1, pp. 83-98.
[6] Sianawati, "Kamus Istilah Hidrologi Teknik," P.T. Gramedia Pustaka Utama Jakarta, 2009.
[7] Strahler A. N., *et al.*. "Element of Physical Geography," John Wiley & Sons, New York., 1989.
[8] Sungkowo A., "*Ekosistem Gumuk Pasir Di Bagian Selatan Kabupaten Kebumen Berperan Sebagai Penghambat Hempasan Tsunami*," Seminar Nasional Fakultas Teknologi Mineral. Universitas Pembangunan Nasional "Veteran" Yogyakarta, 2007.
[9] Todd D. K., "Groundwater Hydrology," John Wiley and Sons, New York, 1980.
[10] Zuidam R. A., *et al.*, "Aerial Photo-interpretation in Terrain Analysis and Geomorphologic Mapping," Smith Publisher, The Haque, Netherlands, 1985.