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Saline water intrusion toward groundwater: Issues and its control

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Abstract

Nowadays, saline water pollution has been gaining its importance as the major issue around the world, especially in the urban coastal area. Saline water pollution has major impact on human life and livelihood. It´s mainly a result from static fossil water and the dynamics of sea water intrusion.. The problem of saline water pollution caused by seawater intrusion has been increasing since the beginning of urban population. The problem of sea water intrusion in the urban coastal area must be anticipated as soon as possible especially in the urban areas developed in coastal zones,. This review article aims to; (i) analyze the distribution of saline water pollution on urban coastal area in Indonesia and (ii) analyze some methods in controlling saline water pollution, especially due to seawater intrusion in urban coastal area. The strength and weakness of each method have been compared, including (a) applying different pumping patterns, (b) artificial recharge, (c) extraction barrier, (d) injection barrier and (e) subsurface barrier. The best method has been selected considering its possible development in coastal areas of developing countries. The review is based considering the location of Semarang coastal area, Indonesia. The results have shown that artificial recharge and extraction barrier are the most suitable methods to be applied in the area.

Introduction

Water has an important role for human life and livelihood. Unfortunately water in the term of quality and quantity is getting worse over the time. The issues related to water quality and quantity have been increasing all over the world, including saline water pollution. Therefore, problems related to saline water pollution (as seawater intrusion) have become a crucial issue for the communities (Obikoya and Bennel 2010). The three major sources of fresh water are rainwater, surface water (rivers, lakes, and swamps) and groundwater. From these, the groundwater is the main contributor to our lives as source of drinking water. The usage of groundwater in human lives and other organisms on Earth is supported by its bigger availability compared to other sources. From all fresh water found on Earth (not including the ice in the polar region) 96% is groundwater (Todd and Mays 2005). Therefore, only four percent remains in reservoirs, lakes, rivers and as water vapor in the air. The abundance of groundwater represents its function as the major source of fresh water to fulfill the human population need. Unfortunately, the effect of human activities toward groundwater results in groundwater contamination, changing the chemical composition of water.

Saline water pollution is one type of groundwater contamination. It´s mostly caused by human activities. In coastal areas the cases of saline water pollution are dominated by seawater intrusion. Seawater intrusion occurred in urban coastal areas is caused especially by groundwater over pumping. In Indonesia groundwater over pumping led not only to seawater intrusion, but also to land subsidence (Marfai and King 2007; Marfai and King 2008a; Marfai and King 2008b; Marfai and King 2008c; and Marfai et al. 2009). Therefore the multiple impacts of groundwater over pumping must be prevented, specially seawater intrusion. This review aims to: (i) analyze the distribution of saline water pollution on urban coastal areas in Indonesia and (ii) analyze some methods in controlling saline water pollution, especially due to seawater intrusion in urban coastal areas. Analysis of the distribution of saline water pollution has been done using reference based studies for this research. Moreover, a case study on urban coastal area of Semarang-Indonesia has been applied to select the best method in controlling saline water intrusion in this area.

Groundwater contamination and its measurement

Pollution has increased rapidly due to development of urban areas. It´s defined as changing conditions of physical, chemical, and biological properties that are not desired from the mass of air, soil, or water in addition to biomass (Odum 1996). Groundwater contamination is mainly caused by human activities, especially due to excessive exploitation of groundwater for settlement, shrimp farming, and fisheries on the beach (Obikoya and Bennel 2010). Natural-environmental factors can also influence the occurrence of sea water intrusion. For example it can depend on the characteristics of the beach and rock constitution, strength of groundwater flow to the sea, and the fluctuation of groundwater in coastal areas (Custodio 1993). As one form of pollution the presence of saline water on the mainland has become serious problem mainly in coastal cities. The existence of saline groundwater on the mainland is also very harmful to society.The wells in urban settlements with saline groundwater on the mainlands can no longer being used as a source of drinking water. Therefore, the residents are forced to use different sources of fresh water.

The chemical most responsible for causing groundwater salinity is chloride ion (Saeni 1989). Chloride ion is categorized as a non-toxic material, but due the high level of salinity, excessive amount of chloride ion can lead to the decrease of water quality. Areas with very high salinity in groundwater are often found. Thus, this groundwater is not feasible to be used as source of domestic water and irrigation (Dayal and Chauhan 2010). Although chloride ion is the main source of water salinity, several other ions may also increase the salinity of water, such as sodium and sulfate ions (Abdel-Aal et al. 1996).

Seawater intrusion is often regarded as the only factor causing salt water contamination. Actually, there are other factors that also have a role in this issue. According to Todd and Mays (2005) and Custodio (1993), there are seven other causes of salinity in groundwater: (1) fossil water (connate water) which is the ancient sea water trapped in the mainland at past geologic time, (2) intensive evaporation in lagoons, swamps, lakes and other closed water bodies, (3) sea water splash along the coast due to the wind, (4)tidal and storm surges, (5) Ddissolution of salt dome and evaporite rock by groundwater, (6) reappearing saline-ancient-groundwater due to convection, (7) pollution from agricultural land, domestic and industrial waste (agricultural return flow).

Seawater intrusion is a phenomenon that occurs in the interface between groundwater and seawater. The sea water density is higher than fresh water so the seawater pushes the groundwater (Groend 1979). The interface is a zone where saline water and fresh water meet. It is not found in the form of thin-sharp plane, but it exists as an area where diffusion between fresh water and saline water has taken place (Figure 1a). The stronger the fresh groundwater pressure, the closer the interface to the sea. When the pressure is decreasing due to higher uptake of groundwater the sea water pushes the groundwater upward, so the interface is shallower.

The depth of the interface can be estimated by the Ghyben Herzberg equation. According to the equation the hydrostatic balance of fresh and saline water can be explained by the U-tube, as shown in Figure 1b. The depth of the interface can be calculated from (1) groundwater elevation above sea level, (2) the density of salt water and (3) the density of fresh water. Since saline water has a density of about 1.025 g/cm3 and fresh water has a density of about 1.000 g/cm3, the depth

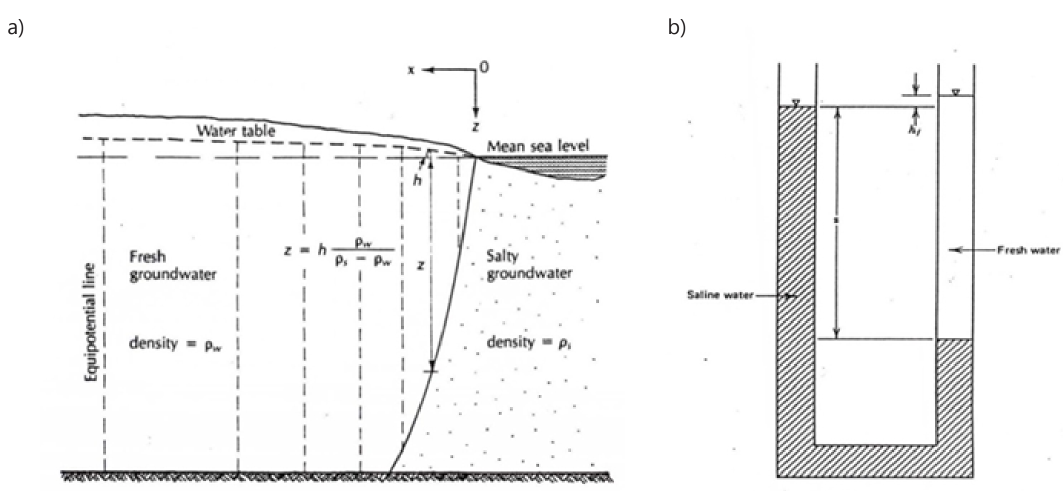

Figure 1. a) Fresh and salty groundwater in unconfined aquifer (Fetter, 1988); b) The U-tube (Todd and Mays, 2005)

of interface in coastal aquifer can be estimated as 40 times of the groundwater height above sea level (Todd and Mays 2005).

According to Todd and Mays (2005) the influence of saline water can be identified by observing the changes in groundwater chemical composition. Revelle (in Todd and Mays 2005) suggests to use a ratio between chloride ions with bicarbonate and carbonate ions to evaluate the effects of saline water. The criteria of saline water influence level, as mentioned by Revelle, is shown in Table 1.

Table 1. The criteria of saline water influence level (developed from Revelle)

[Cl-]/([HCO3-]+ [CO32-]) (meq/l)	Level of Saline Water Influence
≤ 0.50	There are no saline water influence
0.51 - 1.50	Low saline water influence
1.51 - 3.00	Moderate saline water influence
3.01 - 6.50	High enough saline water influence
6.51 - 15.50	High saline water influence
> 15.50	Very high saline water influence

Source. Revelle (in Todd and Mays, 2005)

Saline water contamination can also be identified by using piper quadrilateral diagram (Kloosterman 1989). This diagram has six groups of water types, named evaporite water, fossil water, saline water from seawater intrusion, sulfate water, and bicarbonate spring water and bicarbonate fresh water. The first three types are categorized as salty, while sulfate can be considered either fresh or saline depending on its measurement. Electrical conductivity can also be used to identify the presence of saline water contamination. Electrical conductivity of water represents the ability of water to conduct electricity, which is highly dependent on concentration of the ions. Identification of saline groundwater can also be carried by dissolved solid measurement (Total Dissolved Solid). According to Carrol (in Todd and Mays 2005) the classification can be done based on Table 2.

Table 2. Results of physicochemical parameters

Type of Saline Water	Total Dissolved Solids (mg/l)
Fresh water	0 – 1,000
Brackish water	1,000 – 10,000
Saline water	10,000 – 100,000
Brine	> 100,000

Seawater intrusion in Indonesian Coastal Area

The phenomenon of seawater intrusion has occurred in some regions and countries. Damsarkho and Akkar areas in Syria, also Beirut in Lebanon are some examples of cities in Middle East Asia experiencing seawater Intrusion. (Makalani 1993; Majdalani 1993) In South Asia seawater intrusion occurred in the Eastern Kolkata (Saha and Chodhury 2005), whereas in Southeast Asia, the capital of Bangkok has experienced seawater intrusion (Soenarto 1988). According to Cat and Duong (2006), seawater intrusion also occurred in river water, for example the estuaries in Red-Thai Binh River, Vietnam. In Africa, seawater intrusion occurred in the lagoon of South-Western Nigeria, between Ebute Metta – Lagos State and Ori-oke Iwamino-Ondo State (Emmanuel and Chukwu 2010). Seawater intrusion also occurred in Egypt and Tunisia (Hefni 1993; Rekaya 1993). In Europe, several cities in Cyprus and Turkey also suffered by seawater intrusion (Iacovides 1993, Gunay 1993). In addition, Cambrian-Vendian aquifer system on Kopli Peninsula, Northern Estonia also experienced seawater intrusion (Marandi and Vallner 2010). In Australia, seawater intrusion occurred in Lower Muray River, Southeastern Australia and Burdekin River Delta in Northeastern Australia (Holland et al. 2006; Fass et al. 2007).

Indonesia, as an archipelago with more than 81,000 kilometers of coastline. It has very dynamic processes occurring in the coastal area. The physical-dynamic processes includs coastal inundation, land subsidence and seawater intrusion. In Indonesia, seawater intrusion also occurred in some areas, including Java, Bali, Borneo, and Sumatra Island. In Java Jakarta is,the most affected area, where the intrusion reaches up to 3-50 meters/year. Moreover, land subsidence due to the groundwater over pumping was identified in this area. Other towns in Java Island dealing with groundwater pollution are Semarang and Surabaya. In Semarang, it is known that the saline groundwater is not mainly caused by seawater intrusion, but by fossil water and evaporite water (Purnama 2005). However, the intrusion of seawater also occurred in the coastal area and downtown area (Figure 2). Although Regional Water Company (PDAM) is supplying fresh water for urban residents, some of them still take the advantage from the fresh water in semi confined aquifer, which until now has not been contaminated by salty water.

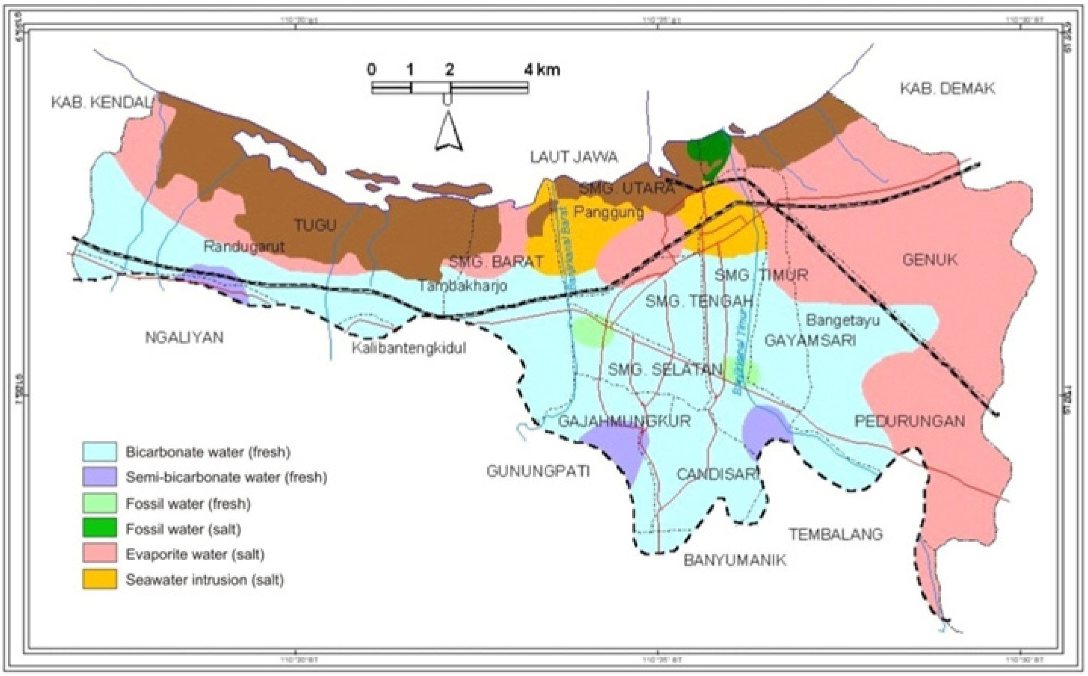

Figure 2. Distribution of salt water in Semarang coastal area (Purnama 2005).

In Surabaya, the appearance of saline groundwater and brackish groundwater caused by fossil water also has been identified. Saline water can be found in various soil layers and distances from the coastline. Confined aquifer containing fresh water is not found in this city (Purnama and Sulaswono 2006). Cilacap, located in the south coast of Central Java, has a quite interesting phenomenon related to seawater intrusion. From the results of geoelectrical research the interface has been detected and monitored. From 1977 to 1996, it was found that the interface depth became shallower (Purnama 1996). It is predicted that when the depth of the wells has penetrated to this layer sea water pollution would occur.

The interface found in southern coast of Central Java also has been measured (Simoen et al. 1993). In South Kroya the interface reached a depth of 40 to 70 meters from the land surface. Meanwhile, in the east side (West part of Kali Ijo), the interface reached from 45 to 60 meters. Further in the east the interface is found in South Kutowinangun Kebumen and ends up in Kutoarjo. The interface can be detected again in Glagah Area, Kulon Progo. In Rembang the existence of saline water in some coastal areas also has been detected (Sudaryatno and Purnama 1997). This pollution is caused by the pressure of fossil water and the excessive water pumping for farming. However, in confined aquifers the fresh water can still be found. In the entire region of the northern coast in Central Java, almost all regions have been contaminated with saline water that was generally caused by fossil water (Simoen 2000). However, the changes of interface depth were also detected, which are generally associated with groundwater pumping for fishpond/aquaculture. Since 1989 to 1996 the interface was continuously becoming shallower and needed to be monitored.

In Bali Island, areas affected by seawater intrusion are South Denpasar, Gilimanuk, Southern Negara, and Northern Singaraja (Purbohadiwijoyo 1972). This phenomenon needs to get serious and direct attention because most of the island has low to very low groundwater resources. Unfortunately, groundwater pumping has been increasing due to development of tourism. In Borneo, one of large cities experiencing seawater intrusion is Samarinda and Mahakam River. This condition has been reducing the availability of fresh water used for drinking water by the city population. Besides Borneo, seawater intrusion also struck the island of Sumatra. In Lampung Bay seawater intrusion has reached several meters from the coastline. This phenomenon is exacerbated by the expansion of pond areas around the coastline. In Indragiri Hilir, Riau, intrusion of seawater has infiltrated to the peat, disrupting agriculture and plantation. Although its impacts to the groundwater are not clearly mentioned, the intrusion of sea water in the area has reached 3-4 km from the coast. The map of saline water intrusion in Indonesia is shown in Figure 3.

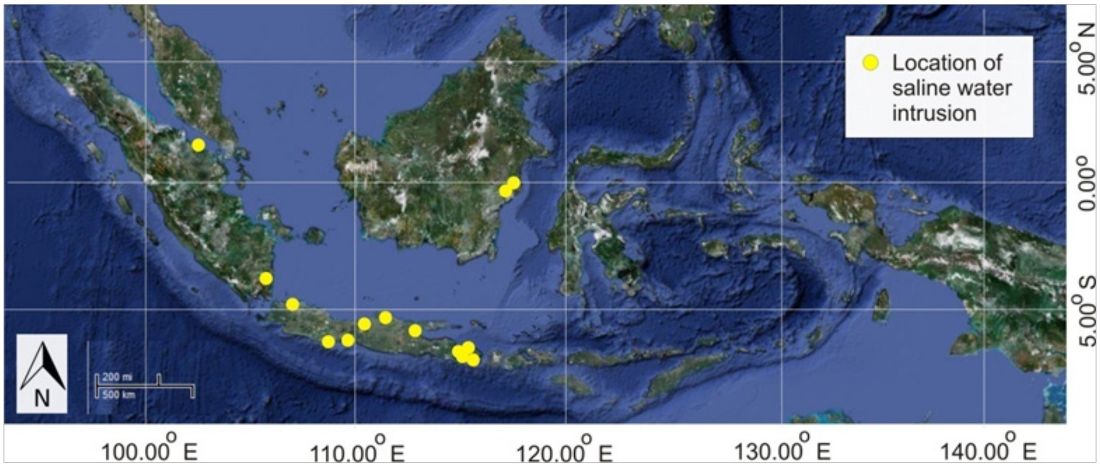

Figure 3. Distribution of saline water intrusion in Indonesia (Purnama and Sulaswono 2006; Simoen et al. 1993; Sudaryatno and Purnama 1997; Simoen 2000; Purbohadiwijoyo 1972)

Controlling seawater intrusion in Indonesian Coastal Area: A case study of Seamarang

Semarang is one of the biggest cities located in the northern part of Central Java, Indonesia. This city is the capital city of Central Java Province the administrative area extends to 373.4 km2. Semarang coastal area is flat, consists of low lying area as the adjacent to the Java Sea (Figure 4). The growing population of the city, which is now around 1.5 million people, has resulted in the groundwater over pumping in the coastal area. Groundwater over pumping is the main source of seawater intrusion in Semarang coastal area, which is now getting bigger due to increasing urban population.

Seawater intrusion can be controlled by several methods considering the source of intrusion, the affected area, geological conditions, water usage, and economic factors. There are several methods proposed

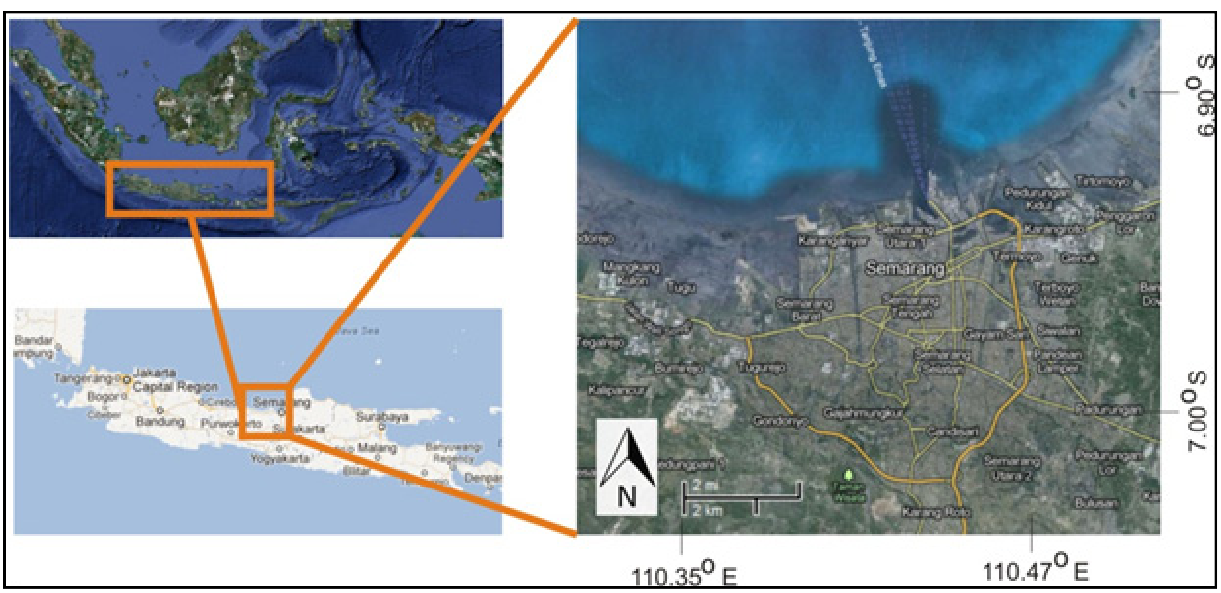

Figure 4. Location of Semarang coastal area

by Todd and Mays (2005) and Soenarto (1988) to control seawater intrusion; (1) changing the pumping pattern, (2) artificial recharge, (3) extraction barrier, (4) injection barrier, and (5) subsurface barrier. Each method has advantages and weaknesses when compared to each other. One method might be suitable to be applied in one specific location, while in other location might not. Therefore, when each method is compared to be applied in coastal cities, especially in developing countries, there are some aspects to be taken into account. The comparison of each method when trying to be applied in urban coastal area of Semarang is shown in Table 3.

Table 3. Comparison of the methods in controlling saline water intrusion

Factors to be considered	Methods				
	Changing the pumping pattern	Artificial recharge	Extraction barrier	Injection barrier	Subsurface barrier
Difficulties in construction/ implementation	√				√
Expensive cost to build		√	√	√	√
Difficulties in maintenance				√	√
Requirement of additional resource and energy			√	√	
Environmental obstacle	√				√

Changing the pumping pattern

Changing the location of groundwater pumping higher to the upstream will increase the hydraulic gradient toward the sea, so the groundwater pressure will be higher. If this method is combined with the reduction of pumping rate, seawater intrusion will be reduced. Therefore, the location of the pumping area that should be reduced needs to be properly determined, as well as the area that can still be pumped.If it´s applied in Semarang, there might be some obstacles in the application, especially due to the flat topography over the area. Moreover, some difficulties might be emerging when trying to change the habit of local community on pumping the groundwater, as it´s required for drinking and other domestic activities. As a solution, deep-saline non-drinking water to reduce seawater intrusion can be used as suggested by Cook (2007).

Artificial recharge

Groundwater level can be increased by applying artificial recharge. For unconfined aquifer, it can be done when rain water enters to well-made ground surface that spreads water, or through pond/ artificial lake. For confined aquifer, it can be done using recharge wells (injection wells) that penetrate the aquifer. According to Soenarto (1988), artificial recharge can be done in: (1) areas with very deep groundwater table, (2) areas where the groundwater is saline, and (3) areas with poor groundwater quality. Adding groundwater presvents not only seawater intrusion, but also reduces the runoff. Artificial recharge, such as ponds, can be added to the polder system, which has been built in Semarang to reduce the flooding (Figure 4). Moreover, compared to the other methods, the cost is lower. Therefore it´s considered as one of the most suitable method to be applied in coastal cities of Semarang. In general, this method is best suited in developing countries due to its low cost.

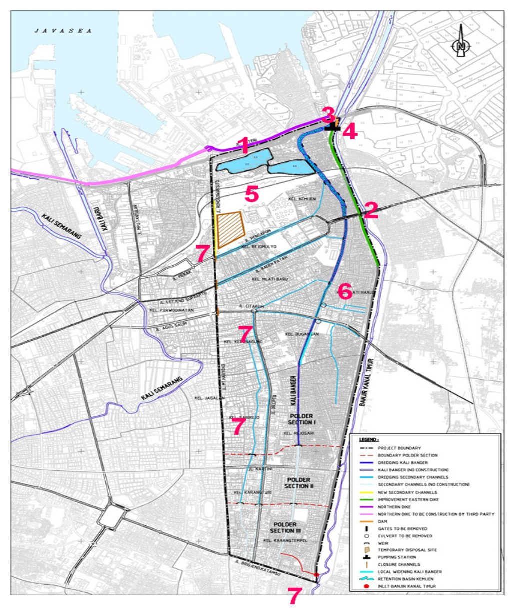

Figure 4. Design of artificial recharge (ponds) in Banger polder system, Semarang (Witteveen & Bos 2007)

Extraction barrier

Extraction barrier can be created by pumping saline water continuously to the wells already exposed to seawater intrusion. By pumping the saline water, the interface can´t move toward the mainland. Therefore, the pumping will form a basin, in which the seawater and groundwater will flow into the basin. Moreover, it will form a stable boundary of seawater to halt seawater entering the mainland. If it´s applied in Semarang, it´s recommended to use the integration of several wells so this treatment can be done in a bigger scale. However, since the movement of water in the interface is very low, the effect of this effort can´t be perceived immediately in the area. In addition, this method also requires high cost and effort, which can be major a obstacle to the Semarang government. Some innovations might be required to reduce the cost, in which the actual cost could be compensated by using the saline water for other purposes. Saline water can be used for cooling turbine engine, as applied in Suralaya, Banten-Indonesia.

Seawater can also be used in the circulation of conditioner air made from rust resistant materials in hotels and factories. For some coastal tourism areas where the sea is very dangerous for swimming, the salty water can be used to fill swimming pools and other activities related to water, such as waterparks and other attractions related to water. Salt water fishpond or seawater aquarium can also be constructed along with the manufactured salt water fountain (Soenarto 1988). With respect to its effect to groundwater in surrounding area, when the cost can be reduced this method can also become one of the most suitable methods to be applied in Semarang coastal area. This method can also be combined with other methods, such as artificial recharge, to improve its effectiveness in controlling sea water intrusion.

Injection barrier

Injection barrier can be created by filling the fresh water into injection wells located at the coastline. The infiltrated water would raise the groundwater level below the wells, which function as a barrier preventing sea water move further to the mainland. Until now, this method is considered difficult to be implemented in Semarang, because (1) the cost is very expensive, (2) the injection process requires continuous energy from electricity and diesel power, (3) the requirement of fresh water with good quality, in which water with high turbidity will clog the house pump and injection well, (4) the requirement of long pipe with appropriate filter, and (5) the discharge of injected water is highly dependent on soil texture (Soenarto 1988),

Subsurface barrier

Subsurface barrier is a barrier placed under the ground and functioned as a boundary between saline water and fresh water. It can consist of clay, concrete, bentonite, or asphalt (Todd and Mays 2005). Due to expensive cost and complex engineering construction, it is also very difficult to be implemented in Semarang coastal area.

Conclusion

Sea water intrusion is considered as one of the factor causing the increase of saline water contamination in fresh water. The existence of saline water on the mainland is very harmful to the society. The wells in urban settlement can no longer being used as source of drinking water due to high concentration of chloride, sodium and sulfate ions. This condition is faced by Semarang City as the research area.

Generally, sea water intrusion is faced coastal urban area due to groundwater over pumping. While in Semarang City, characteristics of the beach and rock formation, strength of groundwater flow to the sea, and the fluctuation of groundwater in coastal area also influence the occurence of this phenomenon. There are many method to indentify sea water intrusion i.e. (1) Ghyben Herzberg equation, (2) ratio between chloride ions with bicarbonate and carbonate ions, (3) piper quadrilateral diagram, (4) electrical conductivity and (5) dissolved solid measurement. Selection of method is depend on the area condition. The second, third and fourth method is successfully to be applied in the research area of Semarang City.

Besides Semarang City, several areas in Indonesia are also suffering by sea water intrusion. The areas are including parts of Java, Bali, Borneo and Sumatra Island. Indeed, these are mainly urban coastal areas located in low lying areas with flat topography similar to Semarang City. The dinamic nature of saline water contamination due to intrusion of sea water is considered to be dangerous, it should be anticipated early. From some proposed method to control sea water intrusion, i.e.: (1) changing pumping pattern, (2) artificial recharge, (3) extraction barrier, (4) injection barrier and (5) sub-surface barrier, the combination of artificial recharge and the extraction barrier is considered the most suitable to be applied in Semarang City. In general, both methods are well suited to coastal areas in developing country due to its low cost.

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