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Investigation of groundwater-seawater interactions: a review

A Purwoarminta¹, N Moosdorf², and R M Delinom¹

¹Research Center for Geotechnology, Indonesian Institute of Sciences, Bandung, Indonesia
²Leibniz Center for Tropical Marine Research, Bremen, Germany
E-mail: ananta.purwoarminta@lipi.go.id

Abstract. This paper is to review how to investigate the interactions between groundwater and seawater. Those interactions divide into two, which are submarine groundwater discharge and seawater intrusion. This investigation is important because the interactions can give impact to coastal aquifer and marine ecosystem. On land, fresh groundwater is vulnerable to seawater disturbance. Coastal aquifer is under pressure from abstraction caused by population, industry, and agriculture. The pumping can induce seawater intrusion and land subsidence. Then in marine, seawater mixes with freshwater and it decreases salinity. Low salinity will influence marine ecosystem. The ecosystem will be disturbed by groundwater discharge if that water is contaminated. Based on the argue investigation of groundwater-seawater interactions is important and must be accurate because the results are used for coastal water management. To investigate the interactions data, i.e., lithology, pumping tests, hydrochemical data, sea level rise estimates, precipitation data, geophysics, environmental isotopes, and drilling information, should be compiled. The interaction can feed a model to determine how much groundwater extraction happening on coastal areas to prevent seawater intrusion and land subsidence. Water resources management on coasts should consider groundwater-seawater interactions.

1. Introduction
A coast is an area formed by land and ocean interactions. This area has strategic position with large natural resources. Coastlines in some countries were developed as large cities including in Indonesia, and most of them also have high population [1]. The high population will increase fresh water demand for daily life and groundwater is one of fresh water sources. Excessive groundwater pumping in coastal areas could trigger seawater intrusion, even creating land subsidence. Seawater intrusion and upconing make coastal aquifer vulnerable to salinization [1]. Groundwater as a source of drinking water has potential to be contaminated by seawater, especially in the shallow aquifer. So, salinization will disturb drinking water supplies and coastal waters [2].

The interactions between groundwater and seawater can be divided into two water flows: groundwater flows into the ocean (submarine groundwater discharge), and seawater flows into an aquifer (seawater intrusion). The groundwater flows depend on stratigraphy and human activities. The boundary between fresh groundwater and seawater is called interface, which is Ghyben-Herzberg relationship theory. Ghyben and Herzberg concept is when two fluids with different constant densities (fresh and saline water) create a mixing zone [3]. The boundary in mixing zone is known as interface or zone of dispersion (Figure 1). The interface is very dynamic, depending on its physical characteristic.
Figure 1. Fresh groundwater and seawater interaction
(Source: https://water.usgs.gov/ogw/gwrp/saltwater/salt.html)

1.1. Submarine Groundwater Discharge
Groundwater flowing out across the sea floor is submarine groundwater discharge [4]. Submarine groundwater discharge is a significant source of nutrients, contaminants, and trace elements that affects the ocean. The impacts of the interaction are saltwater intrusion into fresh aquifers and quality of groundwater discharge to the saltwater ecosystems [2]. Coastal ecosystems are sensitive to the salinity and nutrient concentrations of coastal waters. Several environmental issues linked to coastal ecosystems such as red tides, fish death, loss of sea grass habitats, and destruction of coral reefs, can be attributed to the introduction of excess nutrients from freshwater discharges [2]. Submarine groundwater discharge is a media to deliver pollution, particularly in the shallow aquifer. The shallow aquifer has known as a dynamic and significant source of nutrients to coastal waters [5–7].

1.2. Seawater Intrusion
Seawater intrusion into groundwater may affect the quality and availability of fresh water. It will cause stress to coastal aquifer [8]. Saltwater intrusion is the movement of saline water into freshwater aquifers. The physics of the saltwater intrusion system can be divided in two ways: first by the sharp-interface approach and second the density-dependent approach [3]. Two major factors thought to contribute to saline water intrusion are the excessive pumping of groundwater and the decrease of groundwater gradients [9]. The natural balance between freshwater and saltwater in coastal aquifers is disturbed by groundwater withdrawals and other human activities that lower groundwater levels, decrease groundwater flow to coastal, and cause saltwater to intrude coastal aquifers [2].

2. Investigation Methods
Many methods can be used to investigate groundwater-seawater interactions. Based on Yi [8] and Moore [6], they are:

- Remote Sensing
  Satellite imagery is used to separate groundwater and seawater based on temperature, color composites, geology, and geomorphology. Seawater intrusion and submarine groundwater discharge are controlled by geology. Lithology and geomorphology can identify the intrusion using satellite images or infrared then correlate them with groundwater and seawater
interaction. Different water temperature also can be identified from satellite images, and it can find submarine groundwater discharge zone.

- **Seepage and Piezometers**
  Seepage meter is a method to investigate submarine groundwater discharge and seawater intrusion. Seepage meters are used to investigate groundwater seepage rates into surface water bodies. This equipment is using chamber (drum) then it is inserted open end down into the sediment. Water seeping through the sediment will displace water trapped in the chamber forcing it up through the port into the plastic bag. The change in volume of water in the bag over a measured time interval provides the flux measurement [4].

- **Tracers and hydrochemical data**
  Natural tracers can be equipped as a tool to estimate submarine groundwater discharge and seawater intrusion. Radon, radium, and other isotopes can be used as a tracer. Isotopes and chemical data can identify mixing zones and make the saltwater mixing patterns more understandable [10]. Groundwater discharge can be detected and calculated by separating fluxes by the radon concentration of the groundwater [4, 11–13].

- **Hydrologic models**
  Numerical models have become a valuable tool to understand groundwater flows from aquifers [14]. Numerical model is the best method to estimate submarine groundwater discharge and seawater intrusion within a study area by interpolating and extrapolating field measurement both in space and time [15].

- **Geophysical data**
  Resistivity can record the subsurface condition and separated saltwater-fresh water. Resistivity method is an efficient tool to investigate saltwater-freshwater boundary in coastal areas [9].

3. **Coastal water management**

Water in coastal areas is not only seawater but also groundwater and in some locations including river water. The interactions of groundwater and seawater could give impacts for fresh groundwater salinization and degradation of the marine ecosystem. An assessment of the interaction can solve the coastal problems such as intrusion, water pollution, and ecology. Water management is a challenge for all cities in coastline. The combined effects of demographic, socio-economic, climatic, and political changes on the coastal groundwater resources negatively impact both the availability and sustainability of potable groundwater [16]. Water management in coastal areas should consider the interactions of groundwater and seawater.

4. **Conclusions**

Water management in the coastal area should consider the interaction between groundwater and seawater. The consideration could protect marine ecosystem and fresh water supply for the community. Regulation and management strategy for coastal areas should be published to keep environmental sustainability.

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