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# Factors of causing seawater intrusion in Kadatua Island, Southeast Sulawesi

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**Abstract.** In the last decade, there has been an increase in the population very rapidly not only in urban areas but throughout the villages of the region in Indonesia. This led to a huge increase in the need for clean water where the availability of surface water has begun not meet the needs, and groundwater ultimately plays an important role in meeting those needs. However, along with the increase in water use soil, there are negative effects that arise when groundwater exploitation becomes excessive and one of the impacts is the occurrence of seawater intrusion which destroys the quality and quantity of groundwater. It is hoped that the long-term objective of this research will be produced a report on the estimated intrusion of seawater that can be used as a reference to optimize the protection of groundwater resources. For that purpose short term in this research is to produce information/description regarding the current extent of seawater intrusion in Kadatua Island, Southeast Sulawesi based on data obtained from the identification results in the field.

## 1. Introduction

Kadatua Island is one of the small islands in the blacksmith archipelago in Southeast Sulawesi province, Indonesia. The island is located south of Muna Island to the north of Siompu Island to the west of Buton Island and to the east of Kabaena Island.

In the last decade, there has been very rapid population growth in the world, including in South Buton District, and this has caused the exploitation of underground water to continue to increase rapidly. This phenomenon has been a negative impact on the quantity and quality of groundwater, including a decrease in the groundwater level and the occurrence of seawater intrusion (IAL) in several areas including Kadatua Island, South Buton Regency. Thus it is necessary to make real and integrated efforts to deal with these negative impacts, both by the government, the public, and the private sector. This research focuses on the patterns of groundwater utilization and protection against seawater intrusion, especially for small islands.

The Phenomenon where seawater displaces fresh groundwater in coastal aquifers is named Seawater Intrusion (SWI). In previous studies, there are two recognized types of SWI: passive and active [1]. Inactive SWI, the hydraulic gradient slopes towards the land, and forces caused by density differences and fresh groundwater flow act in the same direction, causing more aggressive salinization. In passive



SWI, the hydraulic gradient slopes towards the sea. This results in density-induced forces acting in the opposite direction to fresh groundwater flow, creating the classical wedge-shaped seawater plumes that are traditionally associated with SWI. The current understanding of SWI is based primarily on studies that assume a steady-state condition [2]. In evaluating long-term extents of SWI, several studies use the shift in the interface between one steady-state condition and another, neglecting altogether transient effects and precluding the evaluation of active SWI processes. If the freshwater-saltwater interface moves slowly enough, steady-state solutions reproduce approximately the transient interface.

Previous studies of the transience of SWI have mainly considered passive SWI. For example, estimation of sea-level rise (SLR) and sea level decline in unrestricted coastal aquifers, and defines the SWI response time scale as the time taken for a foot freshwater-saltwater interface (ie, the inland limit of the saltwater wedge along with the aquifer basement) to reach 95% of the new steady-state condition [3]. They observed temporal asymmetry in the SWI responses to rises and falls in sea level, and discovered the phenomenon known as 'SWI overshoot'.

## 2. Previous empirical research studies

Some researcher provides an overview of the main realities of atoll freshwater groundwater aquifers. The factors that influence the susceptibility of these freshwater lenses are recommendations. The results indicated that following the salinization of groundwater with intrusive seawater, at least one year is required for full aquifer recovery. Of particular interest, it was found that despite the formation of strong salt plumes at relatively shallow depths, thin freshwater horizons are sometimes retained deeper in aquifers.

The impact of seawater intrusion (SWI) which involved salinization of the undersea domains of coastal aquifers. In this study, experimental physical modeling and numerical modeling were used to explore the salinization table water (WTS) associated with SWI in a variety of nontidal, not limited to coastal aquifer settings. The results indicate that WTS may be widespread in coastal aquifers that have experienced substantial groundwater subsidence over several years, although further evidence needed to identify WTS in field setting was conducted by [4].

Study on active SWI caused by the decreased freshwater head (FHD) characterized using numerical modeling of various coastal aquifers not limited to ideal settings. The relation between the main features of active SWI (e.g., interface characteristics and SWI response time scale) and problem parameters (e.g., terrestrial FHD, sea-water density contrast, dispersivity, hydraulic conductivity, porosity, and aquifer thickness) were explored for which the first time. The sensitivity analysis showed that the SWI response time scale in an active SWI situation was influenced by the difference in the head's initial and final limits. The interface was found to be steeper under stronger advection (eg, due to terrestrial FHD), higher dispersivity and hydraulic conductivity, and lower aquifer thickness, seawater density, and porosity. Faster interface motion and wider mixing zone with greater hydraulic conductivity, differences in seawater-freshwater density, and aquifer thickness, and with lower porosity. nondimensional parameters (sum of pellets and mixed convection ratio) of the previous steady-state analysis only offer limited application to passive SWI control factors, and not applicable to active SWI. Current studies on active SWI highlight important functional relationships that enhance the general understanding of SWI, which previously has been established mainly at steady-state and passive SWI was conducted by [5].

Some researchers suggest that the essence of many groundwater management problems are Traditional water tenure rights inherent in land tenure and conflict between the terms of urban communities and the traditional values and rights of subsistence communities living in groundwater reserves. Resource limitations and geographic isolation limit the potential for increasing wealth through crop exports. Water governance reform and provision of knowledge to communities are essential. Regional water organizations, supporting self-help, are key to developing island-owned solutions.

Another researcher suggests the factors affecting FGL in small, two-layer islands experiencing SLR were investigated. Analytical solutions that describe FGL in circular islands, consisting of two geological layers, were developed for simplified cases of steady-state and interface-sharp conditions. The application of the developed model has been shown to estimate the FGL thickness of several real-

world islands by comparison with existing FGL thickness data. Furthermore, numerical modeling was applied to extend the analysis to consider the dispersion effect and to confirm comparable results for both cases. The methodology presented in this study provides water resource managers with a rapid assessment tool for evaluating the possible impact of SLR and the accompanying LSI on FGL.

Indonesian researchers researched groundwater management systems in Jakarta. The model used for the management of aquifer coastal groundwater systems is called the quasi-three-dimensional simulation and optimization (OPT-Q3D) groundwater model. Model simulation and optimization are quasi-three-dimensional computer models with finite difference methods used for seawater infiltration operations. This model can simulate groundwater flow, head of freshwater and saltwater, and describe the interface movements of freshwater and seawater. The model can also optimize single or multi-layered aquifer systems. The Jakarta Groundwater Basin is assumed to consist of three aquifer layers separated by an impermeable layer. Application of groundwater simulation models in Jakarta can provide information on groundwater balance, freshwater head, saltwater head, saltwater and freshwater interfaces, saltwater distribution maps, and bargains in each; each aquifer. Here, after optimization, the model will generate various information that can be used for consideration to manage the optimal amount of groundwater pumping for each area in each aquifer layer, the optimal pumping amount, the optimal freshwater head, the optimal saltwater head, and the infiltration map.

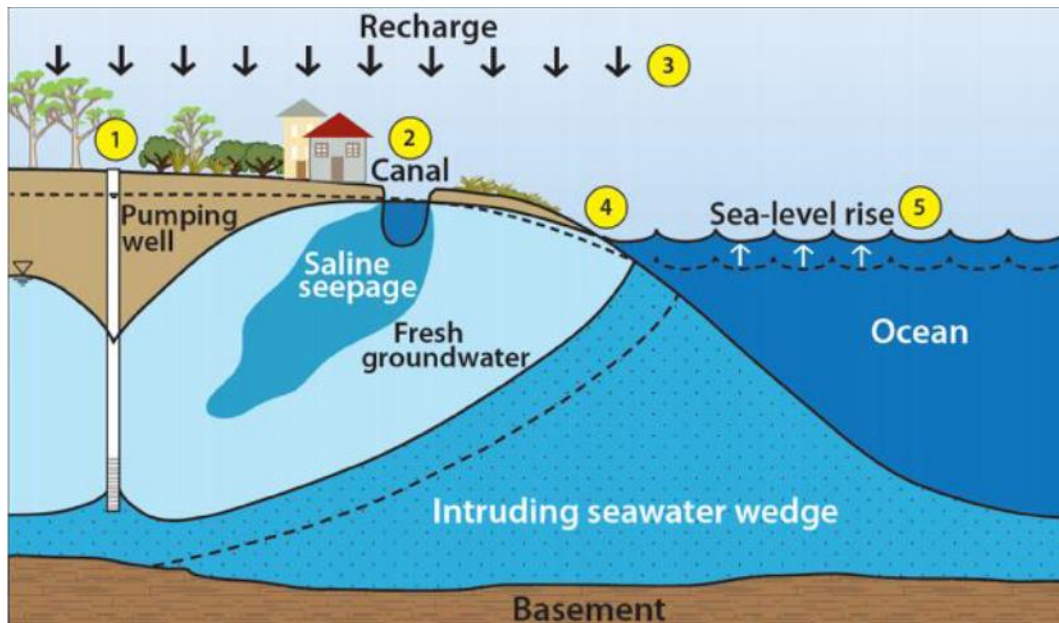
Another Indonesian researcher researched in the coastal area of Ketah Beach which is one of the coastal areas in Situbondo Regency which has the potential to experience seawater intrusion because the problem of seawater intrusion is often one of the problems in the coastal area. Based on the test results, the overall quality of pumped water used by the Pesisir Ketah community for their daily needs is not suitable for consumption and must be processed/cooked first because it has exceeded the maximum level allowed by the Ministry of Health of the Republic of Indonesia 2010 including point 8 with a pH level of 8.73, point 5 with an iron content of 0.48 mg / L, point 4 with a hardness level of 760 mg / L, and according to PAHIAA 1986, the water quality in the Ketah coastal area is not suitable for consumption because it has an average conductivity value of 1751.78  $\mu\text{s} / \text{cm}$  and included in the slightly brackish water category, while the average chloride was 410,169 mg / L, TDS was 20,074 mg / L and was still in the freshwater category.

Research on Pramuka Coral Island, which is one of the islands that has a strategic function as the capital of the Thousand Islands Regency, DKI Jakarta was conducted by some researchers. The ongoing development to support its function as a capital city, as well as a tourist destination, has resulted in high population growth and increased demand for water resources. This condition can cause the threat of seawater intrusion to be even higher because the amount of groundwater extraction will increase. This study aims to determine the impact of seawater intrusion on groundwater in Pramuka Coral Island. The method used is the analysis of the electrical conductivity (DHL) of groundwater and the ratio of chloride ions and carbonate ions in groundwater. The data used in this study are the DHL value, the content of chloride and bicarbonate ions taken from groundwater samples. Samples were taken systematically based on a grid measuring 100 meters x 150 meters. The total samples of groundwater are 23 samples. The results of the study showed that 15 samples of groundwater indicated that the intrusion had a significant effect on groundwater, while 8 samples indicated that the intrusion had a major effect on groundwater in Koral Pramuka Island.

### **3. Sea Water Intrusion (SWI)**

The coastal area is an area that is topographically lowland and seen morphologically in the form of a coastal plain. Geologically, the rocks that make up the plains are generally alluvial deposits consisting of clay, sand, and gravel resulting from the transportation and erosion of rocks in the upstream part of the river. Generally, rocks on the plains are less compact, so the groundwater potential is quite good. Good aquifers in the coastal plain are generally confined aquifers, but free aquifers can be a good source of groundwater, especially in coastal areas. The main problem in coastal areas is the diversity of aquifer systems, the position, and distribution of seawater both naturally and artificially due to the extraction of groundwater for domestic, fishermen, and industrial needs. In coastal aquifers, changes in the

hydrogeological area of the coast can cause the movement of seawater towards the land which pollutes groundwater in the aquifer and is known as IAL seawater intrusion, sees figure 1.



**Figure 1.** Cross-sectional illustration of the confluence of freshwater and seawater in an aquifer underlying the IAL process

Historically, the occurrence of EIs has generally been caused by over-pumping of groundwater or extracting groundwater and this can cause significant losses in groundwater availability in coastal aquifers around the world [6]. However, the effects of climate change (eg sea level rise and decrease in groundwater recharge) can also cause EIs. Therefore, the vulnerability of coastal aquifers to climate change increased volumes of groundwater pumping, and sea-level rise must be considered integrally in groundwater management investigations.

SWI is a complex process involving variable-density flow, solution transportation, and hydrochemical processes, which makes groundwater assessment relatively difficult and expensive [7]. As a result, the assessment of the vulnerability of coastal aquifers to SWI on a large scale generally only uses qualitative methods such as GALDIT and CVI which only consider some of the factors that are considered to have an impact on SWI [8,9]. Also, these methods are generally lacking on a theoretical basis and are subjectively more focused on selecting only one element related to SWI. This method is based on steady-state conditions, the Strack equation (1976) which assumes that the meeting between seawater and freshwater in an aquifer is a sharp-interface, so this method involves the physical mechanics of SWI even though it is very ideal conditions. Meanwhile, to get a condition that is close to the real condition in predicting SWI, numerical modeling is needed which assumes that the meeting between seawater and freshwater in an aquifer is a mixing zone.

In this study, the analytical method and numerical modeling methods in predicting EI in Kadatua sub-district in South Buton Regency applied using [10]. South Buton Regency is one of the regencies in Southeast Sulawesi, Indonesia which is positioned on the seashore and it is very possible to experience the SWI process because groundwater in the district has long been used for domestic and irrigation purposes.

#### 4. Conceptual model

A schematic representation of a simple unconfined coastal aquifer and identified key parameters are adopted in quantifying the main features of active SWI is shown in figure 1. Because of more often support freshwater extraction given their shallow occurrence relative to confined systems the analysis

applied to unconfined aquifers. Each left and right sides of the conceptual model are the coastal and inland boundaries.  $Q_0$  [L<sup>2</sup>/T] is discharged fresh water to the sea, and  $Of$  [L] is the depth of freshwater that is discharged to the shoreline (i.e., 'outflow face'), as the distance from the water table to the 5% relative salinity on the ocean boundary. Clearly to define freshwater,  $Of$  is dependent on the choice of relative salinity value. The regional head difference ( $hfs$  [L]) is the advective force driving groundwater flow between the boundaries and is represented by  $hf - h_s$ , where  $h_s$  [L] is the depth of the horizontal aquifer base below sea level, and  $hf$  [L] is the inland freshwater head. For simplicity, surface recharging is neglected. As shown by replenishment creates a mitigating effect on water table salinization during active SWI. Therefore, the results of the analysis may overestimate the possible surface salinization of water in areas experiencing significant and continuous recharging. Three different salinity values (i.e., 5%, 50%, and 95% of seawater) referred to as 'relative salinity' in what follows provide the basis for evaluating the behavior of the interface, and both the interface tip ( $x_{tip}$  [L]) the interface toe ( $x_{toe}$  [L]) are reported. The horizontal length between the 5% and 95% relative salinity contours are adopted as the width of the dispersion zone, which is calculated both at the interface toe ( $W_{toe}$  [L]) and at the water table (i.e., the interface tip) ( $W_{tip}$  [L]). The interface slope ( $h$ ) then is obtained from a straight line connecting the interface toe and tip.

Several relationships between key hydrogeological parameters and the nature of active SWI are expected based on direct application of Darcy's Law, and given studies with higher hydraulic conductivity ( $K$ ), lower effective porosity ( $n$ ), steeper hydraulic gradient and greater density difference between freshwater and seawater the interface will migrate faster. Also, in models that adopt higher values of dispersion parameters will have a wider mixing zone. However, other aspects of active SWI behavior remain unclear, including relationships between time-scales and parameter combinations, the factors that control the steepness of the interface during active SWI, and the links between density differences and the mixing zone width. More generally, the investigation is warranted of the relative contributions of dispersion, advective, and buoyancy forces in controlling the nature of active SWI.

Underactive SWI, because of the interface toe eventually intrudes into the inland boundary, there is no final steady-state condition. Unlike passive SWI, in which seawater eventually restabilizes to a new location. SWI will reach the inland boundary unless  $h_f$  exceeds the equivalent freshwater head at the base of the coastal boundary ( $h_{base}$ ) based on sharp-interface theory. Here,  $h_{base} = \rho_s / \rho_f$ , where  $\rho_s$  [M/L<sup>3</sup>] is saltwater density and  $\rho_f$  [M/L<sup>3</sup>] is freshwater density. Active SWI occurs if  $h_f < h_s$ .

The aquifer nature of the base case reflects that used by Lu and Werner. Which means, the coastal aquifer is homogeneous and isotropic,  $K$  is 10 m/d,  $n$  is 0.3, specific yield is 0.25, distance to the inland specified head boundary ( $x_b$ ) is 1000 m and  $h_s$  is 30 m. The values of  $q_s$  and  $q_f$  are 1025 kg/m, respectively. The longitudinal dispersivity ( $\alpha_L$ ) is 1 m and the transverse dispersivity ( $\alpha_T$ ) is one-tenth of  $\alpha_L$ . Molecular diffusion ( $D_m$ ) is  $8.64 \times 10^{-5}$  m<sup>2</sup>/d).

## 5. Numerical model

To conduct numerical experiments of SWI in two-dimensional cross-sections, variable-density groundwater flow, and transport code SEAWAT version 4 was used [11].

The base case model domain is 35 m high and 1000 m long. The mesh Peclet number ( $Pem$  [-]) was used in specifying the discretization of the model domain suggested by [12]. The formula is shown in equation 1.

$$Pem = \frac{\Delta L}{\alpha_L} < 4 \quad (1)$$

where  $\Delta L$  [L] is the grid spacing. Initially, a uniform grid size of  $\Delta x = 1.0$  m and  $\Delta z = 0.5$  m was used, resulting in a grid of 70,000 cells and a  $Pem$  of 1. A grid-dependence test was conducted using both passive and active SWI base cases, and considering alternative levels of discretization, namely ( $\Delta x$ ,  $\Delta z$ ) equal to (0.5 m, 0.5 m), (0.5 m, 0.25 m) and (2 m, 1 m). The simulation results showed the differences of less than 1% in the transient interface locations between the finer grid spacing and initial grids, and more than 5% compared to the coarser grid model. Therefore, this study adopted the initial

grid spacing (1.0 m, 0.5 m). For Case 65 (the field case), the domain height was 47 m, and a uniform grid size of  $\Delta x = 10$  m and  $\Delta z = 0.5$  m (i.e.,  $Pem = 1$ ) was applied.

Seawater and freshwater hydrostatic conditions are represented by the left and right boundaries of the model, respectively defined by specified-head boundary conditions. The solute boundary condition at the coastal boundary is one where inflowing water has the concentration of seawater, whereas outflowing water is assigned the ambient concentration of groundwater at the boundary. The base of the domain is a no-flow condition. By running transient simulations for 150 y the initial steady-state condition was obtained by which time no change was observed in salinity distributions in all cases. Instantaneous inland FHD simulations were conducted using SEAWAT's CHD package which was assigned only to the part of the inland boundary that remained fully saturated after the FHD.

## 6. Conclusions

This study is an attempt to characterize the saltwater-freshwater interface during active SWI conditions. Apart from adjusting to some of the active SWI observations, our sensitive analysis reveals another important feature of active SWI. As while the slope of the interface gradually becomes shallower during passive SWI, interface trends during SWI simulation are complex. An active SWI can usually lead to faster movement of the interface tip following the interface speed.

The interface ends are ultimately following a footstep, particularly for the increasingly active SWI, which also causes the mixing zone widening with time, particularly at the interface end. Then the toe and interface end move faster and the mixing zone is wider with a higher  $K$  and a lower  $n$ , both of which create a higher flow velocity. This observation of active SWI fits well for passive SWI.

SWI in coastal aquifers can produce WTS, which can lead to soil salinization via capillary rise. There is currently limited guidance on the extent to which FSW may occur as a secondary impact of SWI. Laboratory experiments and corresponding numerical simulations indicate that significant WTS can occur under active SWI due to the cessation of fresh groundwater flow to shore. Under passive SWI conditions, minor WTS may occur under certain conditions (i.e., high  $aL$ , high  $K$ , and low  $q_0$ ) and as a result of dispersive processes, where the water level may exceed 5% of the salinity of seawater around the sea boundary.

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