Impact of Brackish-water Aquaculture Activity on Groundwater Vulnerability in Coastal Alluvial Plain: An evaluation to reach sustainability

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論文の要旨 (Abstract)

Brackish-water aquaculture, also known as coastal aquaculture, is an aquatic organisms' cultivation in brackish-water. It is well-known in Southeast Asia countries, particularly Indonesia. Although the activity gives a positive contribution to food production and economic growth, its affects may cause groundwater quality deterioration. The chemicals from the ponds, such as salt and nutrients, may infiltrate to subsurface and contaminate groundwater systems. Additionally, coastal alluvial plains generally have fertile soil and large groundwater storage capacity, making this location a target of urbanization. Meanwhile, coastal groundwater also is facing twofold problems: (i) it is naturally vulnerable to contamination (i.e., seawater intrusion) and (ii) urbanization potentially trigger groundwater quality deterioration (i.e., due to over-exploitation, leakage of industrial and household wastewater` network).

Previous studies have confirmed that geological settling, excessive groundwater pumping, wastes from industrial, agricultural, and household activities are the leading causes of contamination. Research on the environmental effect of brackish-water aquaculture activity, in the meantime, is still very limited to date, and the information about the deterioration of groundwater quality is not well addressed yet even from recent studies.

This thesis provides a comprehensive evaluation of brackish-water aquaculture impact on the vulnerability of coastal alluvial groundwater in Indonesia, which has not been studied comprehensively to date. By understanding the groundwater vulnerability and actual data from the fields, it is expected that the Indonesian government can take proper strategies to maintain sustainability.

There are three crucial groundwater quality aspects that become the focus, which are suspected to derive from brackish-water aquaculture activities, namely: (1) saline water contamination, (2) metals contamination, and (3) nitrogen contamination. Water quality analysis is carried out for major cations (consist of Na^{+}, K^{+}, Ca^{2+}, and Mg^{2+}) and anions (consist of Cl^{-}, SO_4^{2-}, and HCO_3^{-}); bromide ion (Br^{-}); dissolved arsenic (As), iron (Fe^{2+}) and manganese (Mn^{2+}); dissolved inorganic nitrogen (comprise of NH_4^{+}–N, NO_3^{-}–N, and NO_2^{-}–N); stable isotopes in water ($\delta^{2}H$ and $\delta^{18}O$), sulfate ($\delta 3^{4}S$ and $\delta^{18}O$), and ammonium

($\delta^{15}N$); and coliform bacterial. The land-uses and geology features are also evaluated to understand environmental factors that potentially contributed to high saline water, metals, and nitrogen concentrations.

As the representative, the area under study is Indramayu, located in the north of West Java, Java Island, Indonesia. The fisheries production from brackish-water culture in Indramayu is the highest in Java Island and the second highest in Indonesia. Despite the groundwater in this region is essential to support livelihood and aquaculture activities, comprehensive information on groundwater condition is limited. The groundwater samples are collected from two categorizes of land-uses: brackish-water aquaculture region, hereinafter written as a lower coastal region (LC), and agriculture and residential areas, hereinafter written as an upper coastal region (UC).

Samples are collected for sediments and groundwater. The sediments samples are collected at different depths from two boreholes in UC and LC areas to understand the geological conditions of the aquifer system. Groundwater samples are collected two times, in August 2017 (dry) and November 2019 (very dry). There are 18 groundwater samples (5 from LC; 13 from UC) and 28 groundwater samples (10 from brackish-water aquaculture area; 18 from agriculture and settlement areas) collected in the first and second sampling periods.

The examination of the geological profile demonstrates that LC sediment contains thicker marine clay than UC sediment. Both LC and UC sediment comprise high exchangeable cations and cation exchange capacity on average. The groundwater quality analysis results show that the LC site has been contaminated with saline water and dissolved iron and manganese. In the meantime, although no indication of dissolved inorganic nitrogen, LC groundwater is potentially vulnerable to elevated concentration of ammonium-nitrogen. Moreover, the contents of chemicals parameters are generally higher in the very dry period than in the dry period. However, the characteristics of groundwater do not significantly change.

The evaluation from hydrochemical characteristics and stable isotopes in water (δ^2H and $\delta^{18}O$) and sulfate ($\delta^{34}S$ and $\delta^{18}O$) confirm a strong impact of saline water in the LC region. The groundwater is characterized by dominant contents of Na^+ and Cl^-, strong correlation between Na^+ and Cl^-, relatively high ratio of Mg^{2+}/Ca^{2+} and significantly low ratio of HCO_3^-/Cl^-, and the ratios of Br^- and Cl^- in LC groundwater indicates similar trend with seawater. Meanwhile, evidence of groundwater salinization in the UC area is not widely found. Furthermore, δ^2H and $\delta^{18}O$ values tell that both LC and UC groundwater are originally from rainwater. However, the low values of $^{\delta 2H}$ and $\delta^{18}O$ in LC region imply that groundwater experiences saline water enrichment. In agreement with this finding, $\delta^{34}S$ and $\delta^{18}O$ values indicate the seawater presence in LC groundwater. The high salinity possibly arises from the brackish-water pond and marine clay.

An evaluation of As, Fe^{2+}, and Mn^{2+} shows that groundwater in LC and UC sites is naturally vulnerable to Fe^{2+} and Mn^{2+} contamination. As concentrations, meanwhile, are very low or under the threshold of drinking- water regulation. There are two most critical environmental factors that are responsible for elevated concentrations of Fe^{2+} and Mn^{2+} in the study site: high salinity and low redox environment. High salinity, in this case described by high Cl^- and SO_4^-, is suspected of supporting Fe^{2+} and Mn^{2+} leaching from minerals and soils through ion-exchange processes. Then, the reduced environment, indicated by low ORP, and DO and NO_3^-–N reduction, promotes the dissolution of Fe^{2+}

and Mn^{2+} from soils and minerals to groundwater. In line with salinity conditions, the most vulnerable area with trace metals contamination is recognized in the LC region.

Analysis of dissolved inorganic nitrogen analysis shows that ammonium-nitrogen (NH_4^+–N) is the predominant dissolved inorganic nitrogen species, compared to nitrate-nitrogen (NO_3^-–N) and nitrite-nitrogen (NO_2^-–N) in almost groundwater samples, particularly in LC site. The combined parameters of $\delta^{15}N_{NH4}$, coliform bacteria, land use, and geology successfully depict that the sources of NH_4^+–N in LC and UC groundwater are different. The LC groundwater has a narrow range of $\delta^{15}N_{NH4}$ values over a wide range of NH_4^+–N concentrations. The $\delta^{15}N_{NH4}$ values indicate that NH_4^+–N potentially derived from mineralization of organic nitrogen to ammonium. Furthermore, ammonium has a significantly positive relationship with sodium indicating the exchangeable ammonium is mobilized to groundwater via cation exchange. On the contrary, UC groundwater has a wide range of $\delta^{15}N_{NH4}$ values over a narrow range of NH_4^+–N concentrations. The isotopic ratios of $\delta^{15}N_{NH4}$ signify NH_4^+–N attenuation from several sources namely manure, mineral fertilizer, sewage, and pit latrines. Also, the presence of *E. coli* confirms the indication of human and animal waste contamination. However, since ammonium has no relationship with sodium, cation exchange is not feasible and NH_4^+–N flows into the groundwater from anthropogenic sources along with liquid wastes. The comparison of NH_4^+–N concentrations and $\delta^{15}N_{NH4}$ compositions between LC and UC groundwater showed that the LC groundwater is potentially more vulnerable to NH_4^+–N contamination. Interestingly, the relatively high NH_4^+–N in LC groundwater is mainly from natural sources and attributable to high salinity.

There is nearly 2 x 10^6 m^3 confined groundwater in brackish-water aquaculture region is contaminated by Cl^- and trace metals contaminations, and vulnerable to elevated NH_4^+–N. From a drinking-water point of view, the LC groundwater is not recommended to directly use as clean water. The concentrations of Cl^-, SO_4^{2-}, Na^+, Fe^{2+}, and Mn^{2+} are significantly higher than the guidelines regulated by the World Health organization and Indonesian Government. Therefore, Indonesian government should consider groundwater resources carefully in developing brackish-water aquaculture activity because the sustainability of this resource is possibly problematic in the future.