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Analysis of Saltwater Intrusion and Mapping Using ArcGIS

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Abstract **- Saltwater intrusion is an arising problem worldwide. Sea level rise, anthropogenic actions, climatic change etc. are the major reasons behind Saltwater Intrusion (SWI). According to the report of Research Unit, Local Self Government (RULSG) Centre for Developmental Studies, Thiruvananthapuram, based of the study conducted in Thiruvananthapuram in 2017, the Vizhinjam-Poovar stretch showed more saltwater intrusion. For its effective management, SWI mapping is needed. Since there are multiple objective we can use Multi-Criteria Analysis (MCA). GALDIT is an overlay index method which we will be using to prepare saltwater intrusion index map based on 6 parameters: groundwater occurrence, hydraulic conductivity, level of water above sea level, distance from shore, impact of the existing seawater intrusion and thickness of aquifer. SWI vulnerability map will be prepared using SO4/Cl ratio and HCO3/Cl ratio from the field data using ArcGIS. Based on comparison between two maps SWI vulnerable area will be located. The following tests are to be conducted for mapping spatial distribution- sulphate,chloride,alkalinity and hardness. Modelling of SWI can be done using MODFLOW flux. Nowadays, various SWI management methods including abstraction and recharge, cut off wall, artificial landfill etc. are available. Out of these, the most suitable technique will be identified based on surrounding geology. There are so many management techniques to mitigate SWI, abstraction and recharge, cut off wall, artificial landfill etc. Thereafter, the aquifer behaviour will be analysed using MODFLOW flex. In this study, we are aiming to map the SWI in the study area and to suggest an effective management technique to mitigate it in future.**

Keywords:SaltwaterIntrusion(SWI),GALDIT,MODFLOWflux ,MultiCriteria Analysis(MCA), ArcGIS.

1. Introduction

SWI refers to the flow of salt water into fresh water. It results from either an increase in seawater levels or a reduction in groundwater levels. It happens as a result of either natural or human processes. Freshwater coastal aquifers are protected against saltwater intrusion by the natural migration of freshwater toward the sea. This saltwater-freshwater interface is preserved close to the coast or deeply below the surface of the land. Actually, freshwater and saltwater mingle in a diffuse zone called the interface. Excessive groundwater pumping and sea level rise are two variables that can restrict freshwater flow to coastal areas and draw saltwater into the freshwater zones of an aquifer.

SWI has a negative impact on agriculture and can change the quality of the soil. SWI reduces the amount of freshwater that can be stored in aquifers and, in extreme circumstances, may even cause wells to be abandoned. Coastal regions are particularly at risk.. Since 2/3rd of world's population lies on coastal areas and thus SWI is becoming a major threat. This demands the effective management of SWI in coastal areas. Since a third of the world's population lives in coastal regions, SWI is increasingly posing a serious hazard. This necessitates efficient SWI control in coastal locations.

The entry of salinewater into seawater is known as saltwater intrusion. Freshwater contamination may result from it. It is rising as a result of climatic change, human activity, and sea level rise.Due of its salinity, saltwater intrusion can contaminate groundwater.

In this case, the SO4/Cl ratio will be lower and the HCO3/Cl ratio higher. The water will get turbid as a result. Changes in ion concentration in the soil will affect its quality. As a result, it hinders cultivation and causes crop depletion. It may also result in health issues for people.

2. STUDY AREA

According to the RULSG study in Thiruvananthapuram in 2017, the Vizhinjam-Poovar section is more susceptible to saltwater intrusion. According to a preliminary report by the Kerala water authority for 2020, the study area chosen is more important because it is home to many people than the estimated 20714. Infiltration of saltwater taints groundwater and can change the flavour of water. Additionally, it may lead to changes in soil properties and crop degradation. The area is located at Latitude ranges from 8°19'3.80"N to 8°23'47.58"N & 77° 0'19.19"E to 77° 4'15.12"E. The stretch measures 15km.Average temperature of the area is 31/24℃|F.

3. IMPACT OF SALTWATER INTRUSION

Saltwater intrusion can result in the need for water utilities to increase treatment, relocate water intakes, or development of alternate sources of fresh water. Saltwater intrusion, through surface or ground water sources, may diminish the availability or quality of source waters for drinking water utilities. It can affect one well, or multiple wells in an aquifer, making the water unpotable to drink. People with hypertension should not drink groundwater with a high salt content. The health of plants and fertility of soil can be negatively impacted if irrigated with saline groundwater. Once saltwater intrusion occurs, the changes in the aquifer may be permanent or may take many years to recover.

4. METHODOLOGY

The study's methodology mainly consists of three steps: creating a map of SWI vulnerability using the GALDIT method; creating a map of spatial variation in the ratios of SO4 to chlorine and HCO3 to chlorine; validating the SWI vulnerability map using the above maps; and numerically simulating SWI using MODFLOW.
Thematic maps showing groundwater occurrence, hydraulic conductivity, aquifer thickness, distance from the shore, the effect of saltwater intrusion, and the level of groundwater above mean sea level are created as part of the creation of the SWI Vulnerability Map.

For mapping spatial variation and for GALDIT method the following details are to be collected from field- latitude& longitude, water level with respect to ground,& distance from shore. 4 tests are to done for spatial variation mapping – Alkalinity, hardness, sulphate & chloride.

4.1 METHODS FOR IDENTIFICATION OF SALTWATER INTRUSION

4.1.1 Alkalinity

The alkalinity of water is a measure of its capacity to neutralize acids. It is primarily due to salts of weak acids, although weak or strong bases may also contribute. Alkalinity is usually imparted by bicarbonate, carbonate and hydroxide. As per IS 10500-2012 Maximum Acceptable limit of total alkalinity for drinking water is 200mg/L.

4.1.2 Hardness

Hardness is the ability of water to cause precipitation of insoluble calcium and magnesium salts of higher fatty acids from soap solutions. The principal hardness causing cations are calcium, magnesium, strontium, iron and manganous ions associated with bicarbonates, carbonates, chlorides and sulphates. The determination of hardness of water is important in assessing its suitability for domestic and industrial use. The acceptable limit of hardness for drinking purpose as per IS 10500-2012 is 200 mg/l.

4.1.3 sulphate

The Turbidimetric method of measuring sulphates is based upon the fact that Barium sulphate tend to precipitate in a colloidal form and that this tendency is enhanced in the presence of NaCl-HCl solution containing glycerol and other organic compounds. The absorbance of Barium sulphate solution is measured by a Nephelometer or turbidimeter and the sulphate ion concentration determined by comparison of the reading with a standard curve. As per IS 10500-2012 Maximum Acceptable limit for drinking purposes is 200mg/L.

4.1.4 Chloride

If water containing chlorides is titrated with silver nitrate solution, chlorides are precipitated as white silver chloride. Potassium chromate is used as indicator, which supplies chromate ions. As the concentration of chloride ions approaches extinction, silver ion concentration increases to a level at which reddish brown precipitate of silver chromate is formed indicating the end point. The acceptable limit of chloride for drinking purpose is 250 mg/L.

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4.2 SPATIAL VARIATION MAP OF SO4/Cl RATIO AND HCO3/Cl RATIO

Chemical testing will be done on the water samples taken from the study region, and the results will be used to calculate the SO4/Cl ratio and HCO3/Cl ratio for each sample. Significant saltwater intrusion is indicated by high SO4/Cl and Cl/HCO3 ratios. Based on the findings of this research, a SWI vulnerability map will be created in ArcGIS, and its accuracy will be compared to the map produced using the GALDIT method.

4.3 SWI VULNERABILITY MAP USING GALDIT METHOD

GALDIT is an index-based vulnerability model that uses the six key parameters of Groundwater Occurrence (G), Aquifer Hydraulic Conductivity (A), Groundwater Level Above Mean Sea Level (L), Point Distance from Shore (D), Impact Magnitude of the Existing SWI (I), and Aquifer Thickness (T) to identify areas that are vulnerable to different types of SWI (T). To evaluate saltwater intrusion, GALDIT will be used to create a numerical ranking system. Weights, ranges, and ratings make up the system's three key components. The relative importance of each GALDIT element will be assessed in relation to the other factors. Experts will decide how much importance to give to each factor. Following weighting, variables will be given relevance ratings on a scale from 2.5 to 10, based on their relative importance to the seawater intrusion process. The GALDIT Index will next be calculated by assessing each indicator's score and adding them together according to the formula:

$$\text{GALDIT Index} = \frac{\sum_{i=1}^{6}(W_i \times R_j)}{\sum_{i=1}^{6} W_i}$$

Where Wi is the weight and Ri are the importance rating of the ith indicator.

The final Vulnerability to Saltwater Infiltration Decision Criteria will be this value. The area will be divided into different categories of seawater intrusion sensitivity when the GALDIT-Index has been determined. All of the thematic maps will be overlaid to create the final map.

Occurrence of Groundwater (G): The type of aquifer or groundwater occurrence has a big impact on how much SWI there was. Out of all the aquifer types, the restricted aquifer was given the most thought. Because the unconfined aquifers of Jeju were the focus of this investigation, all sites received a significance value of 7.5.

Hydraulic conductivity of the aquifer (A): The intrusion's size was influenced by the aquifer's hydraulic conductivity. When the hydraulic conductivity of the aquifer is higher, the saltwater front moves farther inland. Chang et al. (2019) performed a SWI sensitivity test using a cross-sectional simplified model and showed that the saltwater wedge was positioned deeper in an aquifer with higher hydraulic conductivity. Locations with a hydraulic conductivity of more than 40 m/day received the highest vulnerability rating, and those with a hydraulic conductivity of less than 5 m/day received the lowest vulnerability grade.

Groundwater level above sea level in feet (L): The long-term temporal change in the groundwater level must be considered. Low SWI risk was associated with groundwater aquifers located well above sea level. According to earlier study, locations with groundwater levels greater than 2 m should receive the lowest risk rating, while areas with groundwater levels less than 1 m should receive the highest vulnerability rating. An area with a higher groundwater level was included to the study's range. In this study, the range was altered, with a region's groundwater level greater than 2 m receiving the lowest vulnerability rating and one with a level less than 0 m receiving the highest.

Distance inland perpendicular from the shoreline (D): As one walks further inland perpendicular to the shoreline, the influence of SWI frequently decreases away from the shoreline (D). The inland perpendicular distance from the shore and the height of the groundwater level above sea level have the biggest effects on the SWI potential, and their combined maximum weight is four. In this study, a location closer to the beach was rated 10.0 and a location farther away was rated 2.5 (i.e., lowest vulnerability rating) (i.e., greatest vulnerability rating)

Impact of current seawater intrusion in the area (I): This option considers the most recent SWI. The amount of seawater intrusion into a coastal aquifer was measured using the molar ratio of chloride ions to bicarbonate ions in standard GALDIT research. Since EC data are currently being collected by a groundwater monitoring network in Jeju, EC was chosen as a GALDIT index parameter in this study rather than the molar ratio or Cl content. How well the groundwater conducts electricity was revealed by measuring the electrical conductivity (EC), which was based on the quantity of dissolved ions.

Aquifer thickness (T): This statistic reveals the thickness of a saturated aquifer. Thick aquifers are more impacted by SWI than are thinner aquifers. Their investigation used the distance between the groundwater level and the basalt aquifer's bottom to calculate the aquifer's thickness (or top elevation of the Seogwipo Formation). A region with an aquifer thickness greater than 10 m received the highest vulnerability rating, and one with a thickness less than 5 m received the lowest grade.

4.4 NUMERICAL MODELLING OF SWI USING MODFLOW

The groundwater flow equation is solved by a computer programme called MODFLOW, which is a finite-difference

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flow model. The simulation of groundwater movement through aquifers is done with this application. It is regarded as a global benchmark for modelling and forecasting groundwater conditions and groundwater/surface water interactions. The aquifer behaviour under various saltwater intrusion management approaches is examined in this case using MODFLOW.

5. MEASURES TO REDUCE SALTWATER INTRUSION

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Remediation of brackish or saline groundwater using biological, chemical, and physical techniques is a very expensive process and can take a long time, depending on the source and level of salinity. Therefore, sustainable water resources management in coastal areas can be achieved through the use of different arrangements and rates of external sources or sinks of water and physical barriers. To control SWI problems, a seaward hydraulic gradient should be maintained, and, hence, a proportion of the fresh or brackish water should be allowed to flow into the sea. This seaward hydraulic gradient provides a hydraulic barrier against SWI. Each of these hydraulic (and physical) approaches has its own advantages and limitations in terms of practical operation and control of SWI. The available control approaches are categorized into three different groups: (i) conventional methods, (ii) physical barriers, and (iii) hydraulic barriers. These methods include reduction of pumping rates, relocation of pumping wells, use of physical surface or subsurface barriers, natural or artificial recharge (pressure or positive barriers), pumping
of saline water along the seacoast (abstraction or negative barriers), and combination techniques(mixed barriers).

1.Conventional/Temporary methods

1.1. Reduction of Pumping

Reduction of abstraction from pumping wells is the simplest, most direct and cost-effective
measure to maintain the groundwater balance in aquifers and control SWI problems. However, the possibility of reducing the abstraction can be restricted in some regions in terms of water demand requirement, and of course a supplemental source of water should be provided to substitute the imposed reduction on the groundwater pumping plan.

1.2. Relocation of Pumping Wells

In this approach, the pumping wells are commonly relocated further inland away from the coast to provide a proper seaward hydraulic gradient, by keeping the groundwater levels above the sea level in the vicinity of the shoreline and reducing the excessive losses of fresh groundwater by outflow. This approach could also be limited in some cases due to unavailability of land or conflicts with other strategic projects in the public sector, or even with private infrastructures that will terminate the process. In some cases, and under high levels of contamination, the size (length) of the aquifer needed to accommodate the new locations of wells far from the intruded seawater wedge is another obstacle to manage with SWI. Moreover, the cost associated with transportation and in-lieu delivery of water from the new pumping wells (far enough from the coastline) to the predeveloped areas near the coastline (susceptible zones) could be another constraint. Therefore, this technique might also be regarded as a temporary solution.

2. Physical barriers

2.1. Physical Subsurface Barriers

In physical subsurface barriers, concrete, grout, bentonite, slurry walls, and sheet piles are
commonly designed in front of seawater along the coast. The efficiency of injecting cement
grout was examined by in Okinawa-Jima Island in Japan following experimental and numerical simulations, including experimental sand box tests and finite difference modelling. Although, the development of such barriers has high initial installation and material costs, they have still been suggested to be the most cost-effective strategy, since they do not require maintenance and repair activities over their life time.

2.2. Physical Surface Barriers (Land Reclamation)

Coastal land reclamation involves the artificial extension of the coastline towards the sea. In this technique, new land is introduced by artificial filling of the appropriate type of soil at the desired geometry and slope (Figure 2). It is mainly constructed to provide the land area required to meet growing urbanization and population increase. However, from a hydraulic point of view, coastal reclamation creates a foreland that may develop a new zone for a freshwater body, helping to delay the advancement of SWI [42]. In this framework, and in order to maintain the hydraulic equilibrium of the system, the freshwater body starts to penetrate into the newly reclaimed soil, and hence it delays the inflow rates of saline water.

3. Hydraulic Barriers

The application of hydraulic barriers to control SWI has gained more popularity than other
management strategies. Recharge, abstraction, and combination of abstraction and recharge are the three main types of hydraulic barriers. Treated wastewater (TWW), desalinated seawater, and desalinated brackish water are three possible sources of water that can be used to recharge aquifers.

3.1. Artificial Recharge

Within the positive or pressure barriers, the aquifer is artificially recharged by high-quality water(e.g., surface water, rainwater, extracted groundwater, treated wastewater, or desalinated water) to maintain the seaward gradient in the system by increasing the inland piezo metric heads. Generally, the artificial recharge of water aims to reduce flood flows, store freshwater water in aquifers, raise groundwater levels, relieve over-pumping, and finally, improve water quality and suppress the saline water body.

3.2. Abstraction Barriers

In negative barriers, the brackish or saline water is continuously pumped through deep abstraction wells located near the coast. The extracted water can be directly disposed of into the sea or it may be used as a water source for desalination plants.

3.3. Combined Barriers

The combination of some of the aforementioned strategies can help to better control SWI by combining the merits of the individual methodologies. For instance, the combination of reduction in the pumping rates and recharge barrier and controlling the pumping rate with artificial recharge has been reported as a possible solution for SWI.

3.3.1. Aquifer Storage and Recovery (ASR)

Aquifer storage and recovery (ASR) is a technique that has been widely used in many countries for management of water resources as an alternative to surface water storage in dams and reservoirs. ASR is one of several techniques used for management of aquifer recharge. ASR methodology involves continuous storage of excess water by deep injection through recharge wells into deep aquifers or other water-bearing formations, either when water is available or during the wet and low demand season of the year. The stored water is then recovered when needed using the same wells to meet the water demand of the community, and during the next dry or high demand season of the year.

3.3.2. Abstraction, Desalination, and Recharge (ADR)

ADR is based on continuous abstraction of brackish water near the coast, desalination of the abstracted brackish water (e.g., using reverse osmosis), and using the excess desalinated water as a source of artificial recharge through injection wells, while the rest of the desalinated water is used to meet some of the water demand. They showed that this method represents an effective and economic method for controlling SWI.

3.3.3. ADRTWW

The abstraction, desalination, and recharge by treated wastewater (ADRTWW) methodology concerns the use of more economic sources of water, such as biologically treated wastewater (TWW) and collected rainwater, or transferring good quality water from rivers, canals, lakes, and ponds that exist in the vicinity of the coastal regions. The ADRTWW methodology consists of three steps: (a) abstraction of brackish water from the saline wedge using deep negative barriers (abstraction wells); (b) desalination of the extracted brackish water using a small-scale reverse osmosis (RO) plant and use of the desalinated water as a supplement for an urban water supply system; and finally (c) recharge of the aquifer using an external source of TWW.

7. CONCLUSION

It has been found that saltwater intrusion is present in several regions of the study area. The extent of intrusion may increase in the coming future also. It results in the deterioration of water quality and makes the water unfit for drinking. Hence, effective measures are to be adopted so as to reduce the existing intrusion and to prevent further intrusion.

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