Assessing the Future Vulnerability of Coastal Salinity Intrusion Using the GALDIT Model and R: A Case Study from Negombo to Galle, Sri Lanka

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Abstract: *Coastal groundwater systems are increasingly threatened by salinity intrusion, where saline water encroaches into freshwater aquifers. This study investigates the critical issue of coastal salinity intrusion along the Negombo to Galle coastal line in Sri Lanka. The primary objective is to assess the future vulnerability of this area to salinity intrusion. The research employs a combination of empirical data analysis and predictive modeling using the GALDIT model and advanced statistical techniques in R. Salinity variations are analyzed using historical data (2016-2020) from multiple sample stations along the coast, with a focus on seasonal patterns and the influence of monsoon cycles. Subsequent regression analysis identifies key factors contributing to salinity changes, including GALDIT parameters (Groundwater occurrence, Aquifer hydraulic conductivity, depth of groundwater Level above the sea, Distance from the shore, Impact of existing seawater intrusion, and aquifer Thickness), and climate variability. Salinity intrusion of future years was predicted by using salinity data from 2016 to 2019. The findings reveal significant seasonal variations in salinity levels, with reduced contamination during monsoon periods compared to off-monsoon periods. Regression analysis indicates that the impact of existing seawater intrusion is a primary factor influencing salinity levels. A predictive analysis conducted using R to forecast salinity intrusion revealed no significant trends in salinity variation over the years, with the model demonstrating moderate accuracy at 52.93%. The implications of these findings are substantial for coastal water resource and coastal ecosystems management. The study highlights the necessity for long-term monitoring and the development of sustainable management strategies to mitigate the adverse effects of salinity intrusion.*

Keywords: coastal salinity intrusion, GALDIT model, regression analysis, predictive modeling.

Introduction

Coastal regions around the world are increasingly facing the critical challenge of salinity intrusion into freshwater aquifers, a phenomenon driven by both natural and anthropogenic factors. As populations grow and urbanization spreads, coastal communities have become more dependent on groundwater as a primary source of freshwater. However, the overextraction of groundwater combined with rising sea levels due to climate change has significantly increased the vulnerability of these aquifers to saltwater intrusion. In coastal areas, the balance between freshwater and seawater is delicate, and any disruption can result in the intrusion of saline water, rendering the groundwater unsuitable for human consumption, agriculture, and industry(Ranjan et al., 2009).

In Sri Lanka, the coastal belt stretching from Negombo to Galle is particularly vulnerable to salinity intrusion due to its geographical location, high population density, and reliance on groundwater. This coastal region supports a range of economic activities, including agriculture, tourism, and fisheries, all of which depend on reliable freshwater resources. The intrusion of saline water into the coastal aquifers not only threatens water security but also jeopardizes the livelihoods of local communities and the sustainability of the ecosystems in this area(Indika et al., 2022).

Groundwater salinity intrusion occurs when seawater encroaches into freshwater aquifers due to factors such as groundwater overextraction, sea-level rise, and reduced freshwater recharge. When groundwater is extracted at rates that exceed natural recharge, the hydraulic pressure of freshwater is reduced, allowing saline water to advance inland. Additionally, changes in precipitation patterns, temperature increases, and sea-level rise associated with climate change further exacerbate the risk of salinity intrusion, particularly in coastal zones (Ferguson & Gleeson, 2012)

To address the increasing threat of coastal salinity intrusion, it is essential to develop tools and models that assess the vulnerability of groundwater resources to this phenomenon. One of the most widely used models for assessing groundwater vulnerability to salinity intrusion is the GALDIT model. The GALDIT model is an acronym representing six key hydrogeological parameters: Groundwater occurrence (G), Aquifer hydraulic conductivity (A), Depth to groundwater level above sea (L), Distance from the shore (D), Impact of existing seawater intrusion (I), and Thickness of the aquifer (T). These parameters are integrated into a vulnerability index that helps quantify the risk of salinity intrusion in coastal areas(Gnanachandrasamy et al., 2019).

The application of the GALDIT model in coastal areas allows for a systematic evaluation of the factors contributing to groundwater vulnerability. By analyzing these factors, the model can identify regions at higher risk of salinity intrusion, thereby providing valuable insights for the development of management strategies aimed at mitigating the impacts of seawater intrusion. In addition to the GALDIT model, advanced statistical techniques such as regression analysis in R software can be used to enhance the predictive accuracy of salinity models and provide more detailed forecasts of future salinity trends.

a) Objectives

This study focuses on assessing the future vulnerability of the Negombo to Galle coastal region to salinity intrusion using the GALDIT model and empirical data analysis from 2016 to 2020. The analysis aims to identify key factors influencing salinity levels, such as geological formations, groundwater extraction rates, and climate variability. By combining historical salinity data with predictive modeling, the research aims to forecast salinity trends and determine the areas most at risk of seawater intrusion.

Literature Review

a. Introduction to Coastal Salinity Intrusion

Coastal salinity intrusion is one of the major threats to groundwater systems globally, especially in regions where groundwater is heavily relied upon for domestic and agricultural use. As seawater encroaches into freshwater aquifers, the balance between freshwater and saltwater is disrupted, posing significant risks to water availability, ecosystem sustainability, and agriculture. Coastal salinity intrusion is influenced by both anthropogenic activities, such as excessive groundwater extraction, and natural factors like rising sea levels caused by climate change(Mikunthan et al., n.d.).

The coastal belt from Negombo to Galle in Sri Lanka faces similar threats due to high population density, increased freshwater demand, and the region's dependence on groundwater resources for essential needs. This region’s vulnerability to salinity intrusion calls for thorough assessment and understanding of the processes involved, especially given the increasing pressure on groundwater resources.

b) Groundwater Vulnerability and Seawater Intrusion

Groundwater vulnerability assessments are essential for understanding the impacts of seawater intrusion (SWI) in coastal aquifers. Vulnerability can be described as the susceptibility of groundwater to contamination, including the intrusion of saline water from the sea. The importance of groundwater, particularly in coastal regions, is paramount due to its use in domestic, agricultural, and industrial sectors. Global estimates indicate that groundwater meets over 60% of the world's drinking water needs and a significant portion of industrial water demand(Indika et al., 2022).

However, groundwater in coastal regions is highly vulnerable due to overextraction and the encroachment of saline water, which renders it unsuitable for human consumption and agriculture(Yogesh, 2005). This global challenge is echoed in Sri Lanka, where coastal areas such as the Negombo-Galle region face increasing risk, necessitating robust groundwater vulnerability assessments.

c) Mechanisms of Seawater Intrusion

Seawater intrusion occurs through two primary mechanisms: lateral encroachment and upward migration(Uthayashangar et al., 2019). Lateral encroachment happens when saline water moves horizontally from the sea into coastal aquifers, often due to the overextraction of groundwater. Upward migration occurs when saline water moves vertically from deeper layers of the aquifer due to changes in hydraulic pressure. This phenomenon is exacerbated by climate change-induced sea-level rise, which increases the pressure of seawater on coastal aquifers, promoting further encroachment of saline water into freshwater systems (Ranjan et al., 2009).

In regions like Sri Lanka's western and southern coastlines, the combination of high population density, groundwater extraction for domestic use, and rising sea levels puts coastal aquifers at significant risk. The consequences of seawater intrusion are manifold, leading to reduced freshwater availability, agricultural land degradation, and long-term ecological impacts(Ferguson & Gleeson, 2012).

d) The GALDIT Model for Vulnerability Assessment

The GALDIT model is widely recognized for its applicability in assessing groundwater vulnerability to seawater intrusion. The model evaluates six key parameters—Groundwater occurrence (G), Aquifer hydraulic conductivity (A), Depth of groundwater level above sea (L), Distance from the shore (D), Impact of existing seawater intrusion (I), and Thickness of the aquifer (T)—to generate a vulnerability index. This index helps determine the susceptibility of coastal aquifers to SWI based on hydrogeological conditions (Gnanachandrasamy et al., 2019).

The GALDIT model has been applied in various regions worldwide, demonstrating its effectiveness in identifying zones at higher risk of salinity intrusion. For example, in coastal areas of Tunisia, the model was successfully used to assess vulnerability and suggest management practices for groundwater conservation (Trabelsi et al., 2016). Similarly, studies in India’s Kerala region have employed a modified GALDIT model to analyze the impacts of urban growth on seawater intrusion vulnerability (Salaj et al., 2022).

In Sri Lanka, the GALDIT model has been utilized in a limited number of studies, particularly in the Jaffna Peninsula. However, there is a gap in its application along the western and southern coastal belt from Negombo to Galle, an area heavily impacted by both natural and human-induced factors. The present study aims to address this gap by applying the GALDIT model to assess the vulnerability of coastal aquifers in this region and predict future trends using R software for statistical analysis and regression modeling (Gunaalan et al., 2018).

e) Statistical Analysis and Predictions

Statistical analysis plays a vital role in understanding the factors influencing seawater intrusion and predicting its future impacts. By using regression models and statistical tools like R software, researchers can assess the relationships between various parameters such as groundwater level, aquifer thickness, hydraulic conductivity, and salinity concentration. The correlation between these parameters helps in predicting how salinity intrusion might evolve under different scenarios, especially with the ongoing changes in sea level and groundwater extraction rates.

Predictive modeling through regression analysis is crucial in coastal groundwater studies as it helps quantify the potential risks and identify the most vulnerable areas. For example, using historical data on salinity, groundwater levels, and other relevant factors, predictions can be made regarding future SWI trends. In Sri Lanka’s coastal areas, predictive analysis can aid in understanding how future climatic changes and human activities will impact freshwater availability (Kazakis et al., 2018).

In similar studies, statistical analysis has been used to assess the accuracy of vulnerability maps created by models like GALDIT. By comparing predicted salinity levels with actual measured data, the reliability of the models can be validated. For instance, studies in the Mediterranean region have utilized regression analysis to validate GALDIT-based predictions, revealing significant correlations between predicted and observed salinity values (Kazakis et al., 2018). This method of validating model predictions enhances the accuracy of vulnerability assessments and informs decision-making regarding groundwater management (Trabelsi et al., 2016).

In this study, statistical analysis will be applied to evaluate the relationship between GALDIT parameters and observed salinity intrusion in the Negombo-Galle region. Predictive models will be developed using data from past years to forecast future salinity levels under various scenarios, including different rates of groundwater extraction and projected sea-level rise.

f) Impact of Climate Change and Human Activities

Climate change is a significant driver of seawater intrusion, particularly through sea-level rise and altered precipitation patterns. As sea levels rise, the hydraulic gradient between seawater and freshwater is reduced, allowing saline water to move further inland. In addition, changes in precipitation patterns and increased evaporation rates can reduce groundwater recharge, exacerbating the risk of SWI (Yang et al., 2022).

Human activities, such as groundwater extraction for agriculture and domestic use, further contribute to the vulnerability of coastal aquifers. Overextraction reduces the hydraulic pressure of freshwater in the aquifer, allowing saline water to migrate into freshwater zones. The combination of these factors poses significant challenges to groundwater management in coastal regions (Kazakis et al., 2018).

g) Responses to Groundwater Conservation

Effective groundwater management strategies are critical for mitigating the impacts of seawater intrusion. These strategies can include Managed Aquifer Recharge (MAR), the use of saltwater pumping wells, and the implementation of freshwater injection wells to maintain the balance between freshwater and saline water in coastal aquifers (Shah et al., 2000).

In Tunisia, for example, MAR has been employed to artificially recharge coastal aquifers with freshwater, reducing the risk of SWI (Saidi et al., 2013). In Sri Lanka, there is a need for proactive groundwater management, particularly in regions vulnerable to SWI. The GALDIT model provides a valuable tool for identifying areas at higher risk and informing the implementation of management practices. This study will build on previous research by applying the GALDIT model to the Negombo-Galle region and proposing long-term monitoring and conservation strategies to mitigate the impacts of seawater intrusion on coastal groundwater resources (Indika et al., 2022).

h) Regression Analysis in Salinity Intrusion Studies

Regression analysis is a widely used statistical technique for understanding the relationship between a dependent variable and one or more independent variables (Humpage, 2000). In coastal groundwater research, regression analysis has proven valuable for assessing the factors contributing to salinity intrusion and predicting future trends. This technique allows researchers to quantify the strength and significance of relationships between variables such as groundwater level, distance from the coast, and salinity concentrations. By fitting a mathematical model to observed data, the impact of various factors on salinity intrusion can be estimated, enabling more precise predictions and providing insights into the causal mechanisms driving these changes (Kazakis et al., 2018).

In the present study, regression analysis is used to analyze the correlation between salinity intrusion and related factors in the coastal belt from Negombo to Galle, Sri Lanka. By incorporating empirical data from the region, the analysis will help predict future salinity intrusion under different climate and human intervention scenarios. This method has been applied in several studies to assess the vulnerability of coastal aquifers, and the results have informed strategies for groundwater management and intervention (Trabelsi et al., 2016; Salaj et al., 2022).

Methodology

a) Study Area

The study area covers the western and southern coastal belt of Sri Lanka, extending from Negombo to Galle. This region is characterized by dense population, high industrial and domestic water demand, and coastal tourism activities. Due to its low-lying coastal nature, the area is vulnerable to seawater intrusion, especially under conditions of groundwater overextraction and rising sea levels.

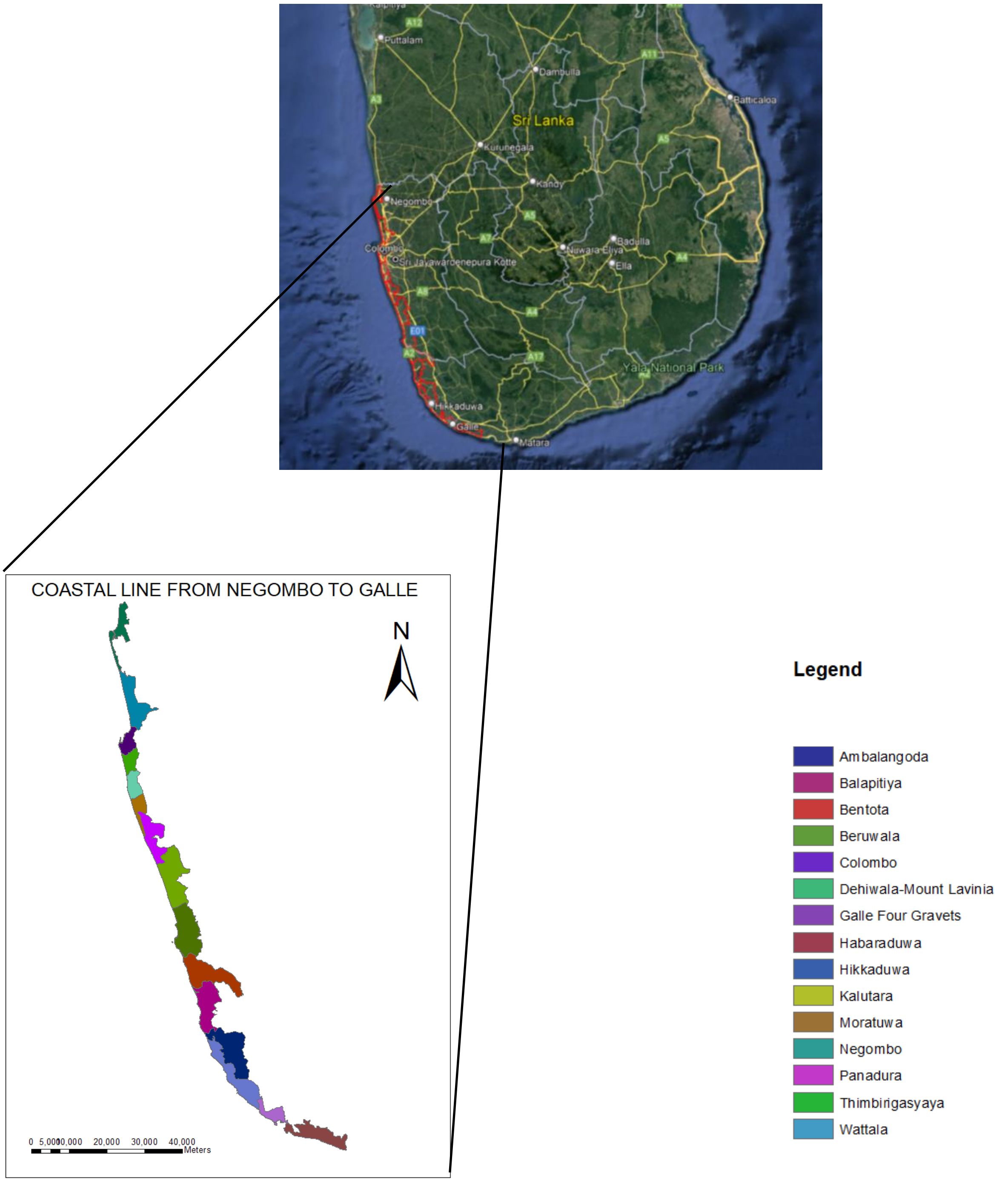


Figure 1:Study Area - Coastal line from Negombo to Galle

b) Data Collection

Table 1:Data Types and Sources for Assessing Coastal Groundwater Vulnerability

Data Type	Purpose	Source
Groundwater Occurrence	Identifying the type and presence of groundwater in the coastal areas	Water Resources Board, Sri Lanka
Depth Below Ground Level	Used to calculate the depth of groundwater level above sea	Water Resources Board, Sri Lanka
Location Data of Water Samples	Calculating the distance inland perpendicular from the shoreline (Distance from the shore)	Water Resources Board, Sri Lanka
Electric Conductivity Data	Assessing the impact of existing seawater intrusion in the area	Water Resources Board, Sri Lanka
Depth Below Ground Level	Estimating the thickness of the aquifer being mapped	Water Resources Board, Sri Lanka
Salinity and Total Dissolved Solids (TDS) Data	Validating the model output with measured salinity and TDS levels	Water Resources Board, Sri Lanka
Soil Type Data	Used to determine the aquifer hydraulic conductivity	Water Resources Board, Sri Lanka
SRTM Data (Shuttle Radar Topography Mission)	Used to calculate the depth of groundwater level above sea	USGS Earth Explorer

The methodology for this research follows a systematic approach to assess the vulnerability of coastal groundwater to salinity intrusion using the GALDIT model and statistical analysis in R. The flowchart below illustrates the step-by-step process, starting with data collection from various sources, followed by the application of the GALDIT model to determine vulnerability indices. The model’s output is then validated using field data, including salinity measurements. Finally, predictive analysis is conducted to forecast future trends in salinity intrusion, integrating the regression results from R software. Each stage of the methodology is crucial for understanding the current and future impact of seawater intrusion on coastal groundwater resources.

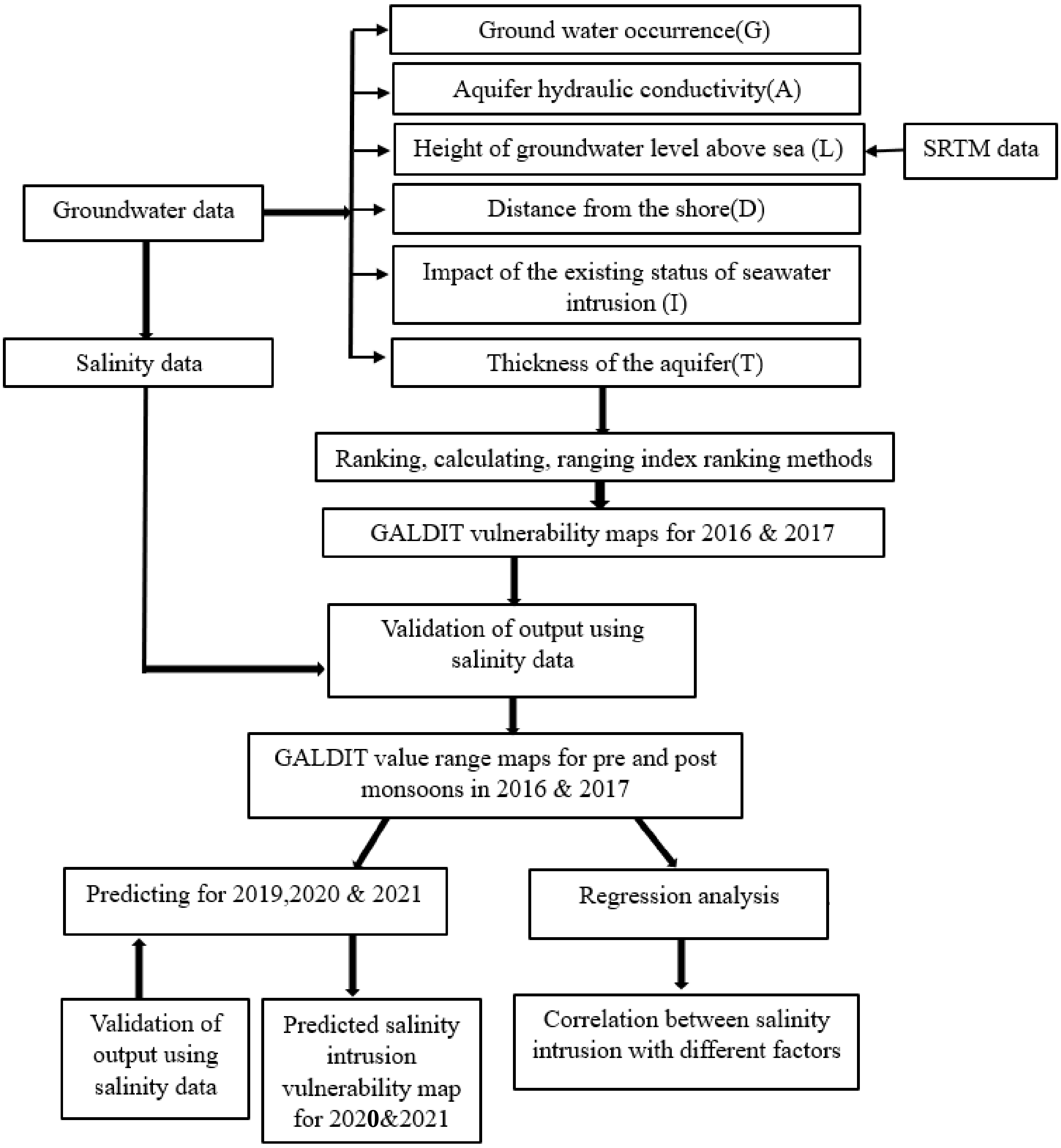
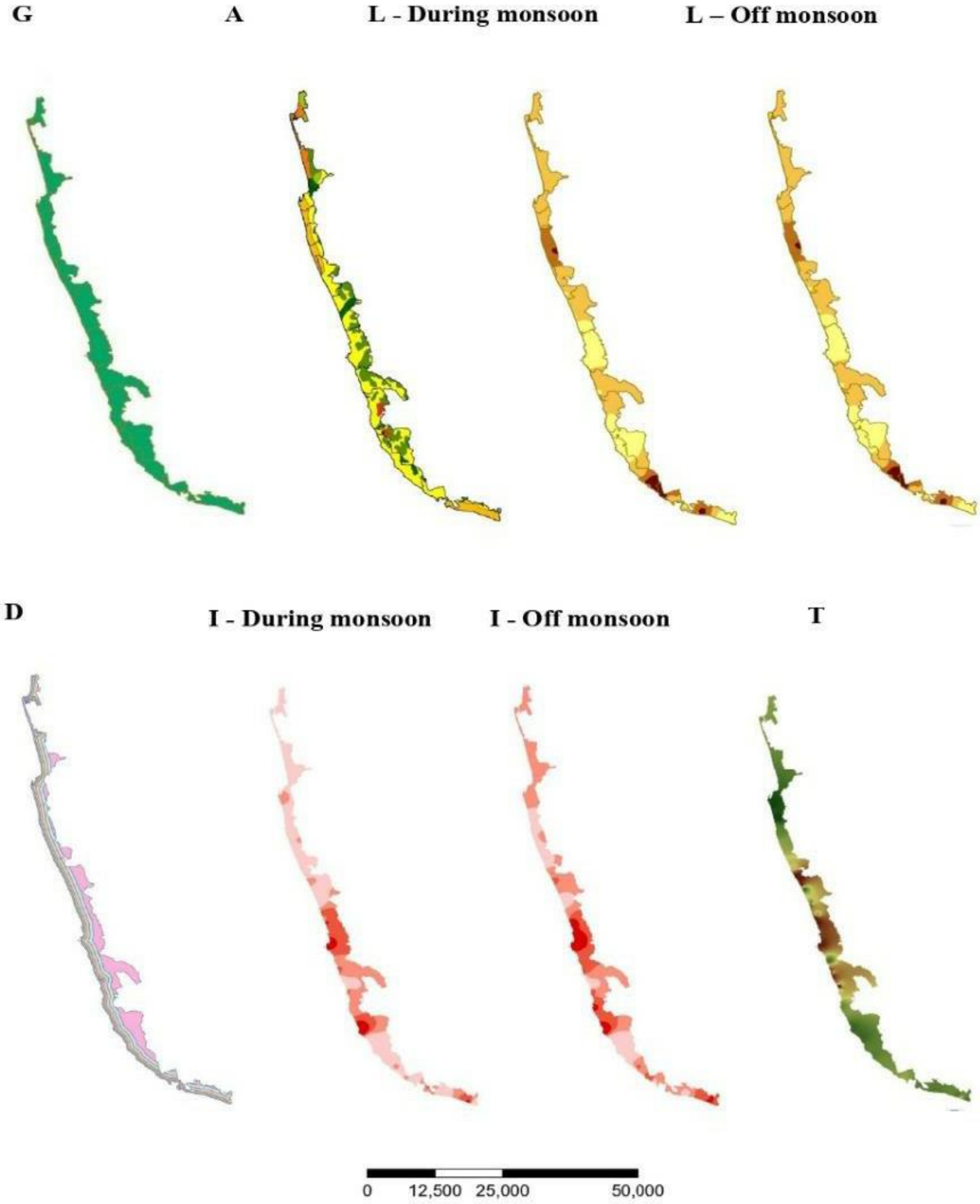


Figure 2:Methodology

c) MAKING INPUT MAPS FOR GALDIT MODEL

There were six input map layers that should be created. They were Groundwater occurrence(G), Aquifer hydraulic conductivity(A), Depth of groundwater Level above sea(L), Distance from the shore(D), Impact of existing status of seawater intrusion in the area(I) and Thickness of the aquifer(T) which is being mapped. These maps were created from Arc map and ArcGIS pro software. Depth of groundwater Level above sea(L) and Impact of existing status of seawater intrusion in the area(I) maps were created according to year wise for both during and off monsoons.



G

A

L - During monsoon

L – Off monsoon

D

I - During monsoon

I - Off monsoon

T

Figure 3: Input Maps for GALDIT method

d) Modeling Vulnerability using the GALDIT Method

The GALDIT model is a weighted overlay method used to calculate the vulnerability index of the coastal aquifer to seawater intrusion. The model integrates the following parameters, with each assigned a weight depending on its contribution to salinity intrusion. The vulnerability index was calculated using the equation(Yogesh, 2005):

$$\text{GALDIT} = 1(G) + 3(A) + 4(L) + 2(D) + 1(I) + 2(T) \qquad \text{Equation 1}$$

Each parameter was assigned a ranking based on predefined classes to develop vulnerability maps for the study area. The Raster Calculator tool in ArcGIS Pro was used to compute the GALDIT vulnerability index maps for different years (2016, 2017) during both monsoon and off-monsoon seasons.

e) Statistical Analysis and Prediction of Future Vulnerability

R software was employed to perform the statistical analysis of the relationship between salinity and the GALDIT factors. Linear regression models were developed to assess the correlation between parameters such as aquifer thickness, distance from the shore, and depth to groundwater level, and salinity levels. This analysis was instrumental in validating the GALDIT model's predictive capability for salinity intrusion.

The model was extended to predict future salinity trends using historical data from 2016 to 2019. Salinity values for 2019 were predicted based on the data from 2016 and 2017, and this prediction was validated against the actual measured salinity data through regression analysis. The model's accuracy was assessed by calculating the Mean Absolute Error (MAE), Root Mean Squared Error (RMSE), and R-squared values for both the monsoon and off-monsoon periods.

The multiple regression model used for prediction followed the equation:

The model was further used to predict salinity trends for the years 2020 and 2021, using the data from 2017 and 2018, following the same regression method.

f) Validation of GALDIT Maps

To validate the GALDIT model output, salinity maps were generated from the field data collected during both the monsoon and off-monsoon periods of each year. The predicted salinity values from the model were compared with the measured salinity values using R software. The accuracy of the GALDIT model was assessed through regression analysis, where the correlation between salinity levels and the six GALDIT parameters was examined.

Results and Discussion

a) Salinity Variations and Seasonal Patterns (2016–2020)

The study analyzed salinity data from multiple sample stations along the Negombo to Galle coastal line, focusing on the period from 2016 to 2020. The results indicate significant seasonal variations in salinity levels, with noticeable differences between the monsoon and off-monsoon periods. During the monsoon seasons, increased rainfall and groundwater recharge led to a marked reduction in salinity levels, while off-monsoon periods showed heightened salinity due to reduced recharge and increased seawater intrusion. Here salinity of June 2017 and the salinity of August 2016 indicate the salinity during the monsoon. The salinity of October 2017 and the salinity of January 2016 indicates the salinity during off monsoon.

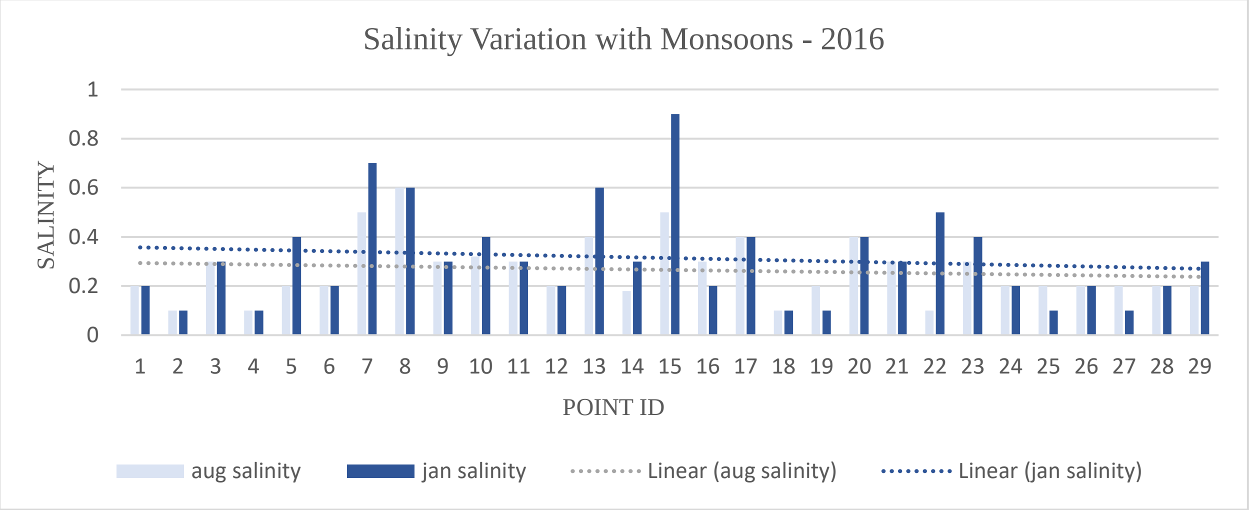


Figure 4: Salinity variations across different sample stations during monsoon and off-monsoon periods in 2016

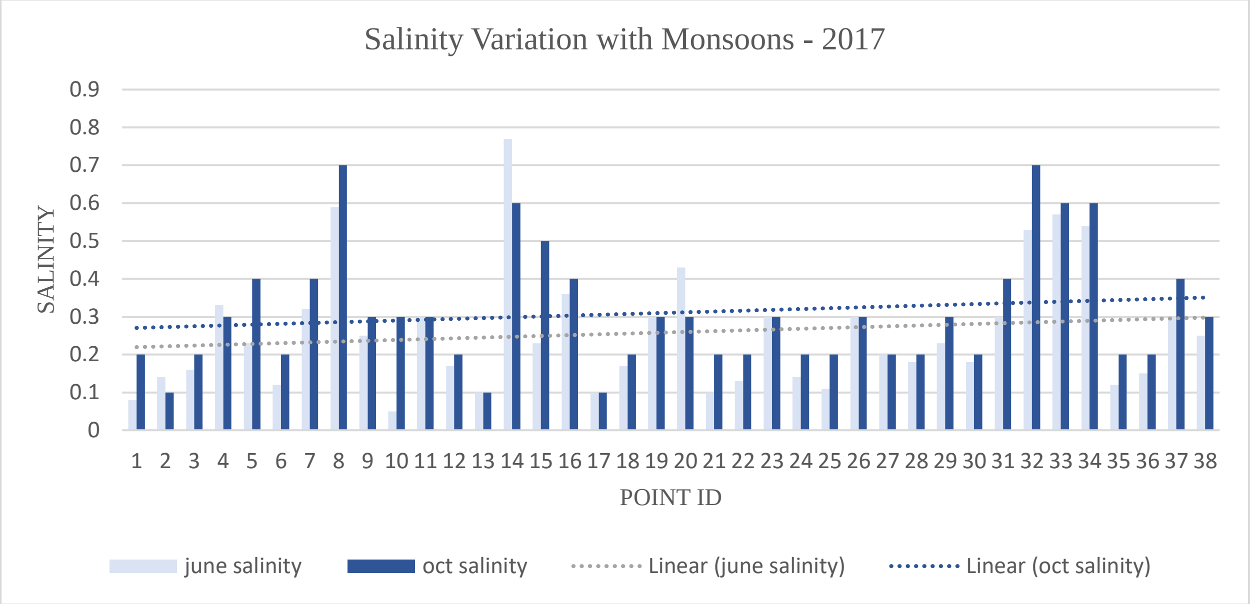


Figure 5: Salinity variations across different sample stations during monsoon and off-monsoon periods in 2017

The findings indicate that seasonal patterns, particularly monsoon cycles, have a profound impact on salinity levels in coastal aquifers. The monsoon rains facilitate groundwater recharge, thereby diluting salinity levels and pushing back the saline water interface. This suggests that coastal groundwater systems are particularly vulnerable during off-monsoon periods, when groundwater extraction peaks and saline water intrusion becomes more pronounced. The Southwest monsoon plays a protective role, temporarily reducing the intensity of salinity intrusion.

b) Influence of Monsoon Cycles

Monsoon cycles play a pivotal role in regulating salinity levels in coastal groundwater. As expected, the Southwest monsoon (May–September) leads to significant freshwater inflow, diluting salt concentrations in the aquifers. In contrast, during dry seasons, groundwater extraction rates remain high, exacerbating seawater intrusion. Salinity levels were consistently lower during the monsoon periods across the study years, which reinforces the role of seasonal rainfall in buffering groundwater systems against salinity intrusion.

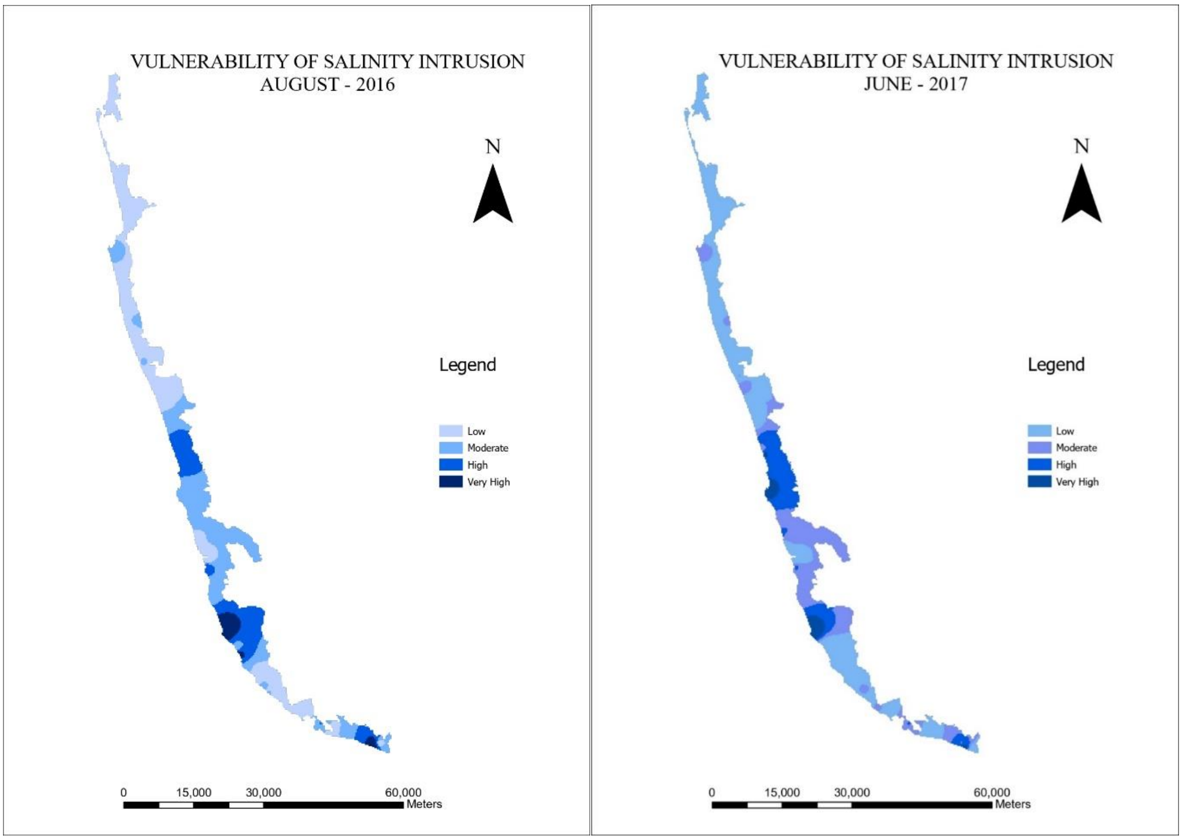


Figure 6:Spatial maps of average salinity levels during monsoon in 2016 & 2017

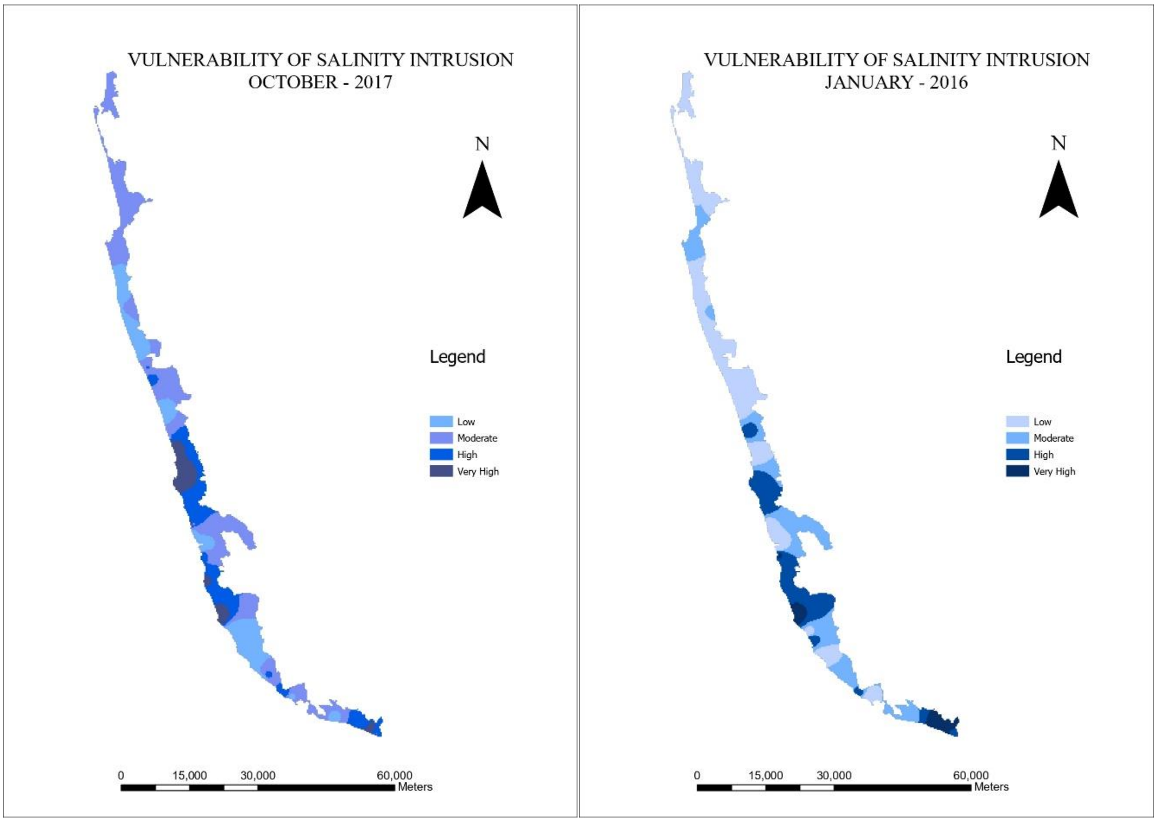
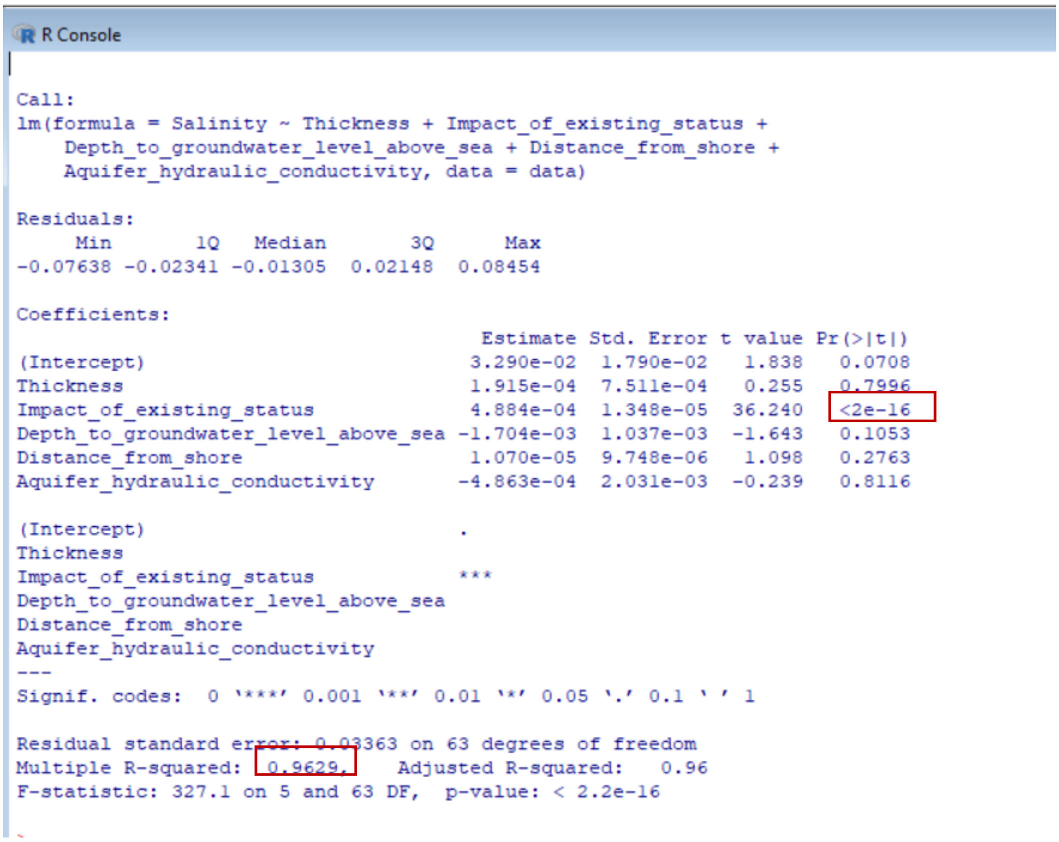


Figure 7:Spatial maps of average salinity levels during off monsoon in 2016 & 2017

c) Regression Analysis and Key Contributing Factors

The regression analysis identified key factors that contribute to salinity changes, with the impact of existing seawater intrusion (I) emerging as the most significant variable influencing salinity levels. Other important factors included aquifer hydraulic conductivity (A) and distance from the shore (D), as these parameters were found to correlate strongly with salinity levels in the groundwater. The GALDIT model parameters showed a significant correlation with salinity levels, indicating the model's applicability in assessing coastal salinity vulnerability. Groundwater occurrence (G) and aquifer thickness (T) were less influential compared to other factors, but their contributions were still relevant in areas with thin aquifers and confined groundwater occurrences.

The overall model has a high R-squared value of 0.9629, indicating that the model explains a large proportion of the variance in Salinity. However, the Adjusted R-squared value is slightly lower at 0.96, indicating that the model may be slightly overfitting the data. The reason for that is the insufficient training data and the making assumptions instead of actual data. The F-statistic is very large, with a corresponding very small p-value, indicating that the overall model is highly significant (Sykes, n.d.; Wang & Lu, 2018)



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Call:
lm(formula = Salinity ~ Thickness + Impact_of_existing_status +
    Depth_to_groundwater_level_above_sea + Distance_from_shore +
    Aquifer_hydraulic_conductivity, data = data)

Residuals:
     Min       1Q   Median       3Q      Max
-0.07638 -0.02341 -0.01305  0.02148  0.08454

Coefficients:
                                       Estimate Std. Error t value Pr(>|t|)
(Intercept)                           3.290e-02  1.790e-02   1.838   0.0708
Thickness                             1.915e-04  7.511e-04   0.255   0.7996
Impact_of_existing_status             4.884e-04  1.348e-05  36.240   <2e-16
Depth_to_groundwater_level_above_sea -1.704e-03  1.037e-03  -1.643   0.1053
Distance_from_shore                   1.070e-05  9.748e-06   1.098   0.2763
Aquifer_hydraulic_conductivity       -4.863e-04  2.031e-03  -0.239   0.8116

(Intercept)                          .
Thickness
Impact_of_existing_status            ***
Depth_to_groundwater_level_above_sea
Distance_from_shore
Aquifer_hydraulic_conductivity
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.03363 on 63 degrees of freedom
Multiple R-squared:  0.9629,    Adjusted R-squared:   0.96
F-statistic: 327.1 on 5 and 63 DF,  p-value: < 2.2e-16
```

Figure 8: Results of the regression analysis – Checking accuracy of GALDIT model

The following regression plots show the relationship between salinity levels and key GALDIT parameters (G, A, D, I, L, T). According to the correlations between factors and salinity, only Impact of existing status Vs Salinity Intrusion has the r value nearly equal to 1. It had r=0.98. Other factors had low r values which were nearly equal to 0. It means among GALDIT factors only Impact of existing status of seawater intrusion in the area sufficiently effects to sea water intrusion(Sykes, n.d.). This finding aligns with previous research, which suggests that once seawater has encroached into coastal aquifers, it continues to have a lasting impact, especially in areas with high hydraulic conductivity and close proximity to the shoreline(Gnanachandrasamy et al., 2019). The reason for that is, groundwater is invariably under stress and that stress, and that stress has modified the natural hydraulic balance between Groundwater and seawater. Then selective ion exchange scenario is happening through the interface.

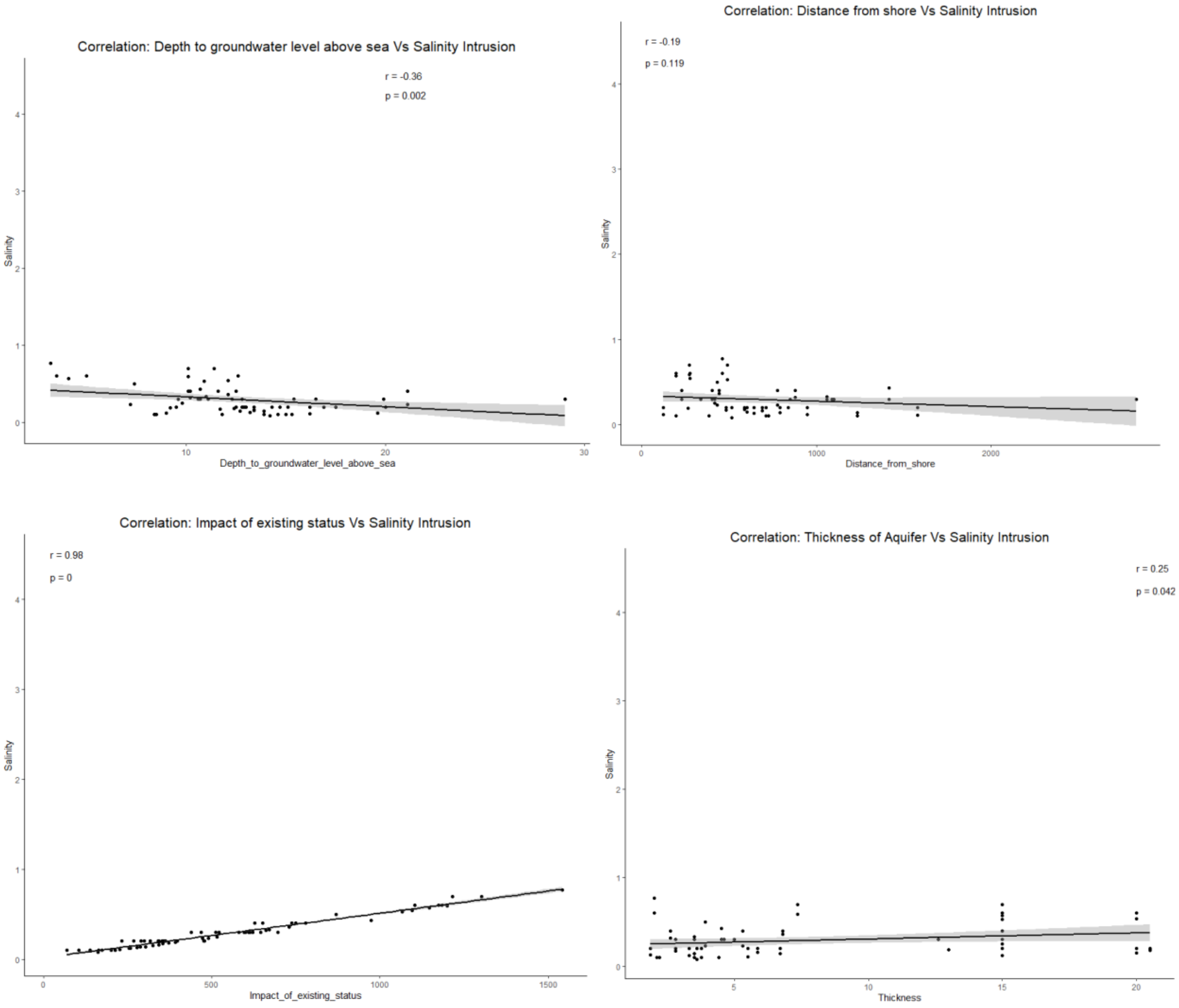

Figure 9:Regression plots of the relationship between salinity levels and key GALDIT parameters

d) Prediction of Future Salinity Intrusion

Salinity data from 2016 to 2019 were used to predict salinity levels for 2020 and beyond. The predictive model demonstrated moderate accuracy, with an overall prediction accuracy of 52.93%. The regression model suggested that no significant trends in increasing salinity levels were evident over the years; however, local variations were observed. Predictions for future salinity levels under different scenarios (varying groundwater extraction rates, rainfall patterns) suggest that salinity may stabilize during monsoon seasons but could worsen during dry periods if groundwater extraction continues unchecked.

Table 2: Predicted salinity values for 2020 and 2021 during monsoon season

ID	latitude	longitude	salinity_2016	salinity_2017	salinity_2018	salinity_2019	salinity_2020	salinity_2021
1	6.76684729	79.89932951	0.200319	0.2291009	0.2346954	0.2366522	0.25436	0.2551728
2	6.75461774	79.90557439	0.200679	0.2308968	0.2357214	0.2333809	0.254786	0.2535288
3	6.7364035	79.906355	0.200525	0.21957	0.2367234	0.2279268	0.254647	0.2499452
4	6.74290859	79.93575797	0.201174	0.2336451	0.2396817	0.2298126	0.259075	0.254127
5	6.71728	79.90955	0.2	0.2000059	0.2380547	0.219637	0.255069	0.2451707
6	6.72755659	79.93992122	0.201221	0.2359698	0.2437613	0.2240569	0.260593	0.250819
7	6.69917361	79.91463987	0.200368	0.2459998	0.2395736	0.2097566	0.254204	0.2398656
8	6.706834	79.92796228	0.200598	0.2432598	0.2585693	0.2043429	0.265275	0.2385302
9	6.687697	79.92042	0.200024	0.2064834	0.3250616	0.2294848	0.296714	0.2473042
10	6.68932	79.9223	0.200005	0.292013	0.2986316	0.2106652	0.282022	0.2390878
11	6.67602593	79.9252978	0.20073	0.2849616	0.2228705	0.2300082	0.244946	0.2499553
12	6.68551814	79.9374545	0.200821	0.2680465	0.2562267	0.2103116	0.263332	0.2413002
13	6.662718	79.92830167	0.201899	0.3994977	0.4496337	0.4509739	0.351946	0.3513552
14	6.66886513	79.9374545	0.20202	0.3246263	0.2199144	0.215719	0.243372	0.2439279
15	6.67552634	79.94844548	0.201946	0.2757169	0.2393038	0.234108	0.255489	0.253865
16	6.68618426	79.96543156	0.203058	0.2579543	0.2409212	0.2371863	0.259017	0.2576237
17	6.6478	79.938883	0.20001	0.2005294	0.251946	0.2649176	0.261027	0.2660593
18	6.65354436	79.94894508	0.201315	0.2367367	0.2426309	0.2539759	0.256933	0.2623032
19	6.66003904	79.96143483	0.203241	0.2554266	0.2384402	0.2503678	0.256052	0.2622728
20	6.66969778	79.97792132	0.204977	0.2576498	0.2362051	0.2504973	0.257108	0.2645884
21	6.62856484	79.94727977	0.204733	0.2141192	0.2295883	0.2751766	0.249631	0.2714129
22	6.63570482	79.95917627	0.205711	0.2257229	0.2306385	0.2695999	0.251448	0.2702702
23	6.64247011	79.97400786	0.208357	0.2366548	0.2299669	0.2663746	0.252723	0.2705912
24	6.60592	79.9554	0.200026	0.1987809	0.2138477	0.2772613	0.241956	0.2724153
25	6.61488856	79.97010481	0.209358	0.1946647	0.2219215	0.287844	0.247963	0.2793395
26	6.63050076	79.99014046	0.214393	0.245372	0.2308092	0.2916554	0.253907	0.2838524
27	6.596783	79.954042	0.206405	0.0049716	0.1922224	0.1996555	0.235613	0.2345858
28	6.58106213	79.96229871	0.256815	0.2400694	0.2360021	0.3134626	0.251059	0.2888224
29	6.59277128	79.98207416	0.238046	0.2491351	0.2428668	0.3055718	0.256814	0.2874579

30	6.56707	79.973917	0.299883	0.300459	0.2514684	0.3159416	0.257504	0.2900666
31	6.57611826	79.99092107	0.262133	0.3267459	0.2621741	0.3134451	0.264275	0.2908042
32	6.554117	79.969	0.268481	0.3049158	0.3113914	0.3303018	0.285329	0.2943627
33	6.55075	79.970417	0.246273	0.3978858	0.3847389	0.520748	0.318648	0.3851036
34	6.540867	79.97501667	0.177754	0.6960025	0.6223797	0.6216948	0.426735	0.4282265
35	6.54853671	79.99716595	0.205652	0.4315671	0.2851083	0.3104666	0.271968	0.2879283
36	6.51705211	79.98597721	0.115257	0.4800067	0.312185	0.3232332	0.281092	0.2906234
37	6.52720004	80.00991591	0.17978	0.437028	0.3014363	0.3177005	0.279911	0.2911803
38	6.473933	79.98251667	0.297532	0.5995867	0.4290397	0.3890239	0.332258	0.317029
39	6.47959366	79.99840452	0.284267	0.5319932	0.3390103	0.3167141	0.29208	0.2860227
40	6.48719378	80.02390184	0.25504	0.4338211	0.3192691	0.3171155	0.287916	0.2897081
41	6.41795	80.006133	0.399863	0.3001092	0.31793	0.3408004	0.285025	0.2957036
42	6.383317	80.011483	0.200433	0.4874384	0.5143274	0.4238621	0.374541	0.329889
43	6.38278	80.013367	0.200433	0.4874384	0.4562612	0.391792	0.346471	0.3158978
44	6.39113286	80.03933096	0.248466	0.3232947	0.2790061	0.3170774	0.267445	0.2870535
46	6.37985992	80.04341709	0.236846	0.301399	0.2570837	0.3060291	0.257133	0.2820297
47	6.39490292	80.08570013	0.264716	0.315477	0.2488218	0.3032242	0.257876	0.2859793
48	6.33988	80.035033	0.10033	0.1015767	0.098742	0.1580349	0.182083	0.2109819
49	6.35424615	80.06537175	0.234521	0.2634216	0.1929344	0.2740982	0.227727	0.2689374
50	6.37498111	80.10724822	0.267817	0.3048359	0.2322817	0.29575	0.251207	0.2838649
51	6.32305	80.034683	0.398938	0.3980627	0.099222	0.2809965	0.17402	0.2698088
52	6.33635718	80.06862429	0.254119	0.2711082	0.1700651	0.2656181	0.215779	0.2647429
53	6.36237751	80.12310435	0.270597	0.3094096	0.2284324	0.2942845	0.25015	0.2841756
54	6.27297	80.0396	0.300014	0.4996794	0.182801	0.2808287	0.209926	0.2654432
55	6.28350338	80.06293234	0.301706	0.397429	0.1798706	0.2780035	0.213975	0.267082
56	6.25016483	80.05398785	0.320922	0.4278944	0.1983699	0.285737	0.219501	0.2676702
57	6.25476718	80.07262491	0.323247	0.4016425	0.1989964	0.2853007	0.222599	0.2695844
58	6.4487777	80.00020478	0.310583	0.4112757	0.3372363	0.3204787	0.292724	0.2864114
59	6.4580833	80.02346877	0.289474	0.4076946	0.3381371	0.3268837	0.296117	0.2923697

The following table represents the values of metrics for the prediction.

Table 3: Metric values of prediction

Metric	Value
Multiple R-squared	0.5293
Adjusted R-squared	0.4938
P-value	3.197e-08

e) Validation

Comparison of Measured and Modeled Salinity Data:

To ensure the reliability of the GALDIT model, directly measured salinity data from multiple sample stations along the Negombo to Galle coastline were compared with the salinity levels predicted by the model. Field data were collected during both monsoon and off-monsoon periods. The directly measured salinity levels were then plotted against the predicted values from the GALDIT model to evaluate the consistency between empirical observations and model outputs.

The comparison revealed that the model was able to capture general trends in salinity variation, with predicted values closely aligning with measured data in areas where existing seawater intrusion was the dominant factor. However, some discrepancies were observed, particularly in regions where groundwater extraction rates and local geological formations had a greater influence, which were not fully accounted for in the model.

Validation of GALDIT Model Predictions:

The validation of the salinity prediction model involved a multi-step process utilizing R software to analyze the statistical relationship between salinity values from the years 2016 through 2019. Initially, the model predicted the salinity values for the year 2019 using the data from 2016 and 2017. To assess the accuracy of these predictions, the predicted values were compared against the actual measured salinity data through regression analysis. This comparison allowed for the evaluation of the model's performance and accuracy.

Continuing with this approach, salinity values for the year 2020 were predicted based on the data from 2017 and 2018. This method involved using salinity data from two consecutive years to forecast values for the subsequent year, establishing a pattern for prediction. Following this trend, predictions for the year 2021 were made using the salinity data from 2018 and 2019.

Conclusion and Recommendation

The GALDIT model, combined with the analytical power of R, offers a comprehensive approach to evaluating and managing coastal salinity intrusion risks. This study's application of the GALDIT model to the coastal stretch from Negombo to Galle aims to contribute to the growing body of knowledge on salinity intrusion in Sri Lanka and to provide actionable insights for sustainable water resource management.

The analysis of salinity variations along the Negombo to Galle coastal line from 2016 to 2020 reveals distinct seasonal patterns and the substantial impact of monsoon cycles on groundwater salinity levels. The study demonstrates that monsoon rains contribute significantly to the reduction of salinity in coastal aquifers by enhancing groundwater recharge and mitigating seawater intrusion. Conversely, during off-monsoon periods, reduced rainfall and heightened groundwater extraction lead to increased salinity due to intensified seawater intrusion.

The regression analysis highlights the critical role of existing seawater intrusion as the most influential factor affecting salinity levels. The GALDIT model parameters, particularly the impact of seawater intrusion, show a high correlation with observed salinity changes, reinforcing the model's effectiveness in assessing coastal salinity vulnerability. The model's strong R-squared value (0.9629) indicates a high explanatory power, although a slightly lower Adjusted R-squared value suggests potential overfitting due to limited training data.

Future predictions based on salinity data from 2016 to 2019 indicate that salinity levels may remain stable during monsoon seasons but could deteriorate during dry periods if groundwater extraction rates continue to rise. The predictive model achieved moderate accuracy (52.93%), reflecting local variations rather than significant long-term trends in salinity levels.

Validation against measured salinity data confirms that the GALDIT model effectively captures general trends, though some discrepancies highlight the need for further refinement, particularly in areas influenced by local groundwater extraction and geological conditions.

Recommendations

Based on the study's findings and additional insights, several future recommendations can be made. For regions with limited data, such as countryside areas, it is advisable to use alternative methods like the DRASTIC model to effectively model salinity intrusion. The GALDIT method, while suitable for highly salinized coastal areas, requires a large amount of data to provide accurate results. Incorporating geological data into modeling approaches is crucial to enhance the realism and accuracy of predictions related to salinity intrusion.

To address groundwater depletion, several solutions can be implemented based on the study's findings. Recharge with imported surface water and rainwater can help replenish groundwater resources, while vegetative treatment of catchments can enhance water retention and reduce runoff. Additionally, promoting domestic rainwater harvesting systems can reduce reliance on groundwater.

The study's insights should be leveraged to develop sustainable adaptation strategies for managing and conserving coastal groundwater resources. These strategies should include integrated water resource management approaches and community engagement to ensure long-term sustainability. Expanding data collection efforts and conducting long-term studies will further improve the accuracy of models like GALDIT and help assess the effectiveness of implemented solutions over time.

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