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Assessment of Seawater Intrusion Vulnerability in the Keta Strip Aquifer, Ghana, Using the GALDIT Model

Delaiah Antwi Nyarko [1] and Larry Pax Chegbeleh [2,*]

[1] Water Resources Commission, Cantonments, Accra P.O. Box CT 5630, Ghana; nyarkodelaiah4@gmail.com
[2] Department of Earth Science, University of Ghana, Accra P.O. Box LG 58, Ghana
* Correspondence: lpchegbeleh@ug.edu.gh

Abstract

Seawater intrusion presents a significant risk to coastal aquifers, particularly in low-lying locations where groundwater resources are intensively exploited. This study assesses the vulnerability of the Keta Strip aquifer in Southeastern Ghana to seawater intrusion using the GALDIT model; a widely applied index-based approach that evaluates seawater intrusion risk based on six key hydrogeological indicators: groundwater occurrence (G), aquifer hydraulic conductivity (A), groundwater level above sea level (L), distance from the shoreline (D), impact of existing intrusion (I), and aquifer thickness (T). These parameters were analyzed using data from 105 monitoring wells within a Geographic Information System (GIS) environment. The resulting vulnerability index was spatially grouped into four categories: low, moderate, high, and very high vulnerability. Results indicate that very high and high vulnerability regions are predominantly clustered along the coastal margins and central portions of the study area, driven mainly by low hydraulic gradients, proximity to the shoreline, and high hydraulic conductivity. Moderate vulnerability zones dominate inland areas, while low vulnerability zones are limited and confined to northern sections. Sensitivity analysis reveals that hydraulic head (L) and distance from shoreline (D) are the most influential parameters, whereas TDS exhibits relatively low contribution to overall vulnerability. The findings highlight the critical role of hydrogeological controls and anthropogenic pressures in shaping seawater intrusion risk and provide a scientific basis for sustainable groundwater management in the Keta Strip and similar coastal environments.

Keywords: seawater intrusion; GALDIT model; Keta Strip; coastal aquifers; groundwater

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1. Introduction

Seawater intrusion (SWI) is a major threat to coastal aquifers worldwide, especially in low-lying regions where groundwater is intensively exploited for household supply, irrigation, and economic activities. It occurs when the natural hydraulic balance between freshwater and seawater is disrupted, allowing saline water to encroach into freshwater zones. This process is driven by both natural factors and anthropogenic activities, especially excessive groundwater abstraction, which lowers hydraulic heads and promotes inland migration of saline water [1–5]. Once salinization occurs, it is often difficult and costly to reverse, posing long-term risks to groundwater sustainability and ecosystem integrity [6].

Coastal aquifers are inherently vulnerable due to their direct hydraulic connection with marine systems and their sensitivity to changes in recharge, land use, and climatic conditions. In addition to salinity, groundwater in these environments may also be affected by other contaminants such as nutrients, trace metals, and microbial pollutants, further

complicating water resource management [5,7–9]. These combined pressures highlight the need for effective vulnerability assessment frameworks to support sustainable groundwater management in coastal regions.

Over the years, several index-based methods have been developed to evaluate groundwater vulnerability, including the DRASTIC [10], GOD [11], AVI [12], ISIS [13], SINTACS [14], EPIK [15], and PI [16] models. Among these approaches, the GALDIT model has been specifically developed to assess seawater intrusion within aquifers along the coast [17,18]. The method incorporates six vital hydrogeological variables: groundwater occurrence, aquifer hydraulic conductivity, groundwater level above mean sea level, distance from the shoreline, influence of existing intrusion, and aquifer thickness, which directly control saltwater–freshwater interactions [19–22]. Comparative studies have demonstrated that GALDIT provides more reliable and physically meaningful results in coastal environments than general-purpose vulnerability models due to its process-oriented design [6,23–27]. The method has been applied across a range of coastal settings globally, including aquifers in South Korea [20,23], India [21,28], North Africa [24,29,30], Bangladesh [22], Italy [31,32], Greece [6,27], Benin [26], Mexico [5], and Finland [33], demonstrating its adaptability to diverse hydrogeological conditions.

The GALDIT method has been used both in its standard format and with modifications to suit different hydrogeological situations. For example, Kazakis et al. [34] developed the GALDIT-SUperficial Seawater Intrusion (SUSI) framework by incorporating the influence of surface water features, including lagoons, rivers, and wetlands, which can contribute to aquifer salinization but are not explicitly considered in the conventional GALDIT model. Similarly, Bordbar et al. [35] applied metaheuristic optimization algorithms like Grey Wolf Optimizer and Genetic Algorithm to make the GALDIT process less subjective and improve its accuracy using hydrochemical validation data. Chang et al. [20] and Kim et al. [23] modified the standard GALDIT framework for application on Jeju Island, South Korea, replacing the impact parameter with electrical conductivity and developing a seasonally averaged approach to better capture temporal variability in seawater intrusion. Other researchers combined GALDIT with additional methods: Kardan Moghaddam et al. [36] demonstrated that GALDIT produced a stronger correlation with TDS than DRASTIC in a coastal aquifer in northern Iran, while Hu et al. [37] applied both an AHP-modified DRASTIC model and GALDIT simultaneously in coastal China to distinguish between intrinsic groundwater vulnerability and seawater intrusion vulnerability. Lyu et al. [38] proposed a novel dynamic framework integrating GALDIT with the variable-density groundwater model SEAWAT to project monthly coastal vulnerability changes over a 30-year period under climate change and groundwater abstraction scenarios, demonstrating that over-abstraction is a more critical driver of vulnerability than precipitation changes. Winid and Maruta [39] integrated GALDIT with hydrochemical indicators, including seawater mixing indices and ionic ratios, to evaluate seawater intrusion vulnerability along the Polish Baltic coast. Their findings demonstrated that the integrated approach produced vulnerability patterns that differed from those generated by the GALDIT model alone. More recently, a systematic review by Bordbar et al. [40] confirmed that distance from the coastline and groundwater head above sea level consistently exert the greatest influence on vulnerability outcomes, while recharge, proximity to surface water bodies, and hydraulic gradient show strong potential as additional parameters for improving vulnerability mapping.

Despite its wide application, the GALDIT model typically provides a static representation of vulnerability under existing hydrogeological conditions and does not explicitly account for temporal changes driven by groundwater abstraction, land-use dynamics, or climate variability [38,41]. Nevertheless, it remains a robust and practical tool for identify-

ing vulnerable zones and guiding groundwater management decisions, particularly when integrated with geographic information system (GIS).

The Keta Strip, located in southeastern Ghana, represents a highly vulnerable coastal aquifer system characterized by a shallow unconfined freshwater lens overlying saline water. The area is bounded by the Atlantic Ocean, Keta Lagoon, Avu Lagoon, and the Volta River estuary, making it particularly susceptible to seawater intrusion. Groundwater in the area is extensively utilized for domestic supply and irrigation, with approximately 98% of shallow wells tapping the freshwater lens [42–44]. However, increasing population growth, urbanization, and climatic variability have intensified groundwater abstraction, leading to declining water levels and increasing salinity. Field observations and previous studies have reported elevated chloride concentrations and the abandonment of wells due to saline water intrusion, indicating ongoing deterioration of groundwater quality [45].

Several studies have investigated groundwater systems within the Keta Strip and surrounding areas, focusing on groundwater modelling, recharge estimation, hydrochemical characterization, and vulnerability assessment using index-based methods such as DRASTIC [42–44,46–50]. These studies have yielded meaningful information on aquifer properties, groundwater quality, and the delineation of the freshwater–saltwater interface. However, none has explicitly assessed seawater intrusion vulnerability using the GALDIT model. As a result, the spatial variability of intrusion risk and the relative influence of key hydrogeological controls remain insufficiently understood.

To address this gap, the present study applies the GALDIT model to assess the susceptibility of the Keta Strip aquifers to seawater intrusion. The objective is to generate a spatial vulnerability map, classify zones based on their level of risk, and identify the key hydrogeological factors influencing intrusion. The findings are expected to support improved groundwater management strategies, inform decision-making processes, and contribute to the sustainable protection of freshwater resources in this highly vulnerable coastal system. This study also represents one of the first applications of the GALDIT model in a low-lying coastal aquifer in Ghana and provides a useful framework for similar assessments in comparable environments.

2. Materials and Methods

2.1. Study Area

The Keta Strip is situated in the southeastern part of Ghana, bounded by the Keta Lagoon to the north and the Gulf of Guinea to the south (Figure 1). The area covers about 45 km^2 and is located about 160 km east of Accra.

Climatically, the Keta Strip lies within the dry coastal equatorial belt, recognized as one of the driest regions in Ghana, with an average temperature of about 28 °C [46,47,51]. The study area receives an average yearly rainfall of approximately 810–870 mm [47,49], with climatic conditions defined by two well defined periods: the rainy and dry seasons. The wet season is marked by a bimodal rainfall pattern, with a major peak occurring between April and July and a secondary peak between September and October, while June typically records the highest rainfall. Relative humidity is mostly elevated during the early morning and nighttime periods but decreases in the afternoon, with values ranging from 60% to 75%. The average annual temperature is approximately 27.5 °C [42–44,49].

Topographically, the Keta Strip (Figure 2) is a low-lying coastal plain, with elevations ranging from approximately 2.4 to 13 m above mean sea level (m amsl). Lower elevations are concentrated in the central and southern portions of the strip, while relatively higher elevations are observed towards the northeastern section. The Keta Basin can generally be divided into three main geomorphological zones: the narrow coastal strip, the central lagoon basin, and the northern plains [42–44]. The coastal belt is characterized by sandy

barriers and occasional sea cliffs along the shoreline. This zone is highly vulnerable to coastal erosion, with areas such as Keta, Kedzikope, Vodza, Kedzi, and Horvi experiencing significant impacts.

The Keta Strip is predominantly agricultural, characterized by subsistence farming such as vegetable production and irrigation farming, which is especially prominent in the northern regions and interior parts [42,52]. Fisheries and fish processing are common features within the coastal areas, following the importance that the region places on its marine and lagoonal resources [42,53]. The main residential and peri-urban activities are found in the towns of Keta, Kedzi, Vodza, and Kedzikope, where population density is high, leading to the extensive abstraction of groundwater as the main source of domestic water supply. The mining of salt is also an activity common in the area [53,54].

The Keta Basin is situated in the southeastern part of Ghana along the Gulf of Guinea and extends eastward into neighboring Togo and Benin [55]. It forms part of a series of Mesozoic–Tertiary sedimentary basins characterized by thick accumulations of both marine and continental deposits overlying older crystalline basement formations. The basal sedimentary units comprise Lower to Middle Devonian marine sequences, including shales, sandstones, and siltstones, which have been intruded by Jurassic dolerite sills [42–44,48]. These are overlain by Cretaceous to Eocene marine sediments consisting predominantly of limestone, shale, and glauconitic sandstones, which are exposed along the eastern margin of the basin near the Ghana–Togo boundary [46,50]. Two distinct limestone horizons are identified within the subsurface: an upper unit encountered in boreholes around Anyako and a deeper unit that outcrops in the Keta area. The lower limestone unit is interpreted to represent a regional hydrogeological formation that is likely recharged from higher inland areas. Above these formations lie Neogene continental deposits composed mainly of unconsolidated to semi-consolidated sands and gravels, particularly in the northeastern sections of the basin. The central and coastal zones are dominated by Quaternary marine deposits consisting of unconsolidated sands and gravels, with an average thickness of about 30 m, increasing towards the Volta River estuary [50]. The geological map of the area is as presented in Figure 3.

From a hydrogeological perspective, the Keta Basin exhibits a complex, multi-layered aquifer system [42,43,46,48]. Four principal aquifer units have been identified: (i) weathered aquifers developed within the Dahomeyan gneiss along the northeastern margin of the basin; (ii) Neogene continental sand aquifers distributed across the northeastern and central zones; (iii) Cretaceous–Eocene limestone and sandstone aquifers, which constitute the main deep and productive freshwater systems; and (iv) Quaternary coastal aquifers composed of marine sands and gravels, particularly within the Volta River estuary and Keta Lagoon areas.

The shallow Quaternary coastal aquifer is of particular importance for water supply, as it supports most domestic and agricultural activities in the region. This aquifer is unconfined and consists of unconsolidated sandy materials that host a thin freshwater lens floating above saline groundwater. It is estimated that nearly all shallow wells in the area exploit this freshwater lens [43,44]. Recharge to the aquifer occurs mainly through direct infiltration of rainfall. However, increasing pressure from population growth, urban expansion, and climatic variability has intensified stress on the system, raising concerns about its long-term sustainability and vulnerability to seawater intrusion, particularly in low-lying coastal zones [42–44].

This study specifically focuses on the shallow, unconfined Quaternary coastal sand aquifer, which is typically encountered at depths ranging from approximately 2 to 10 m and is predominantly composed of meteoric freshwater.

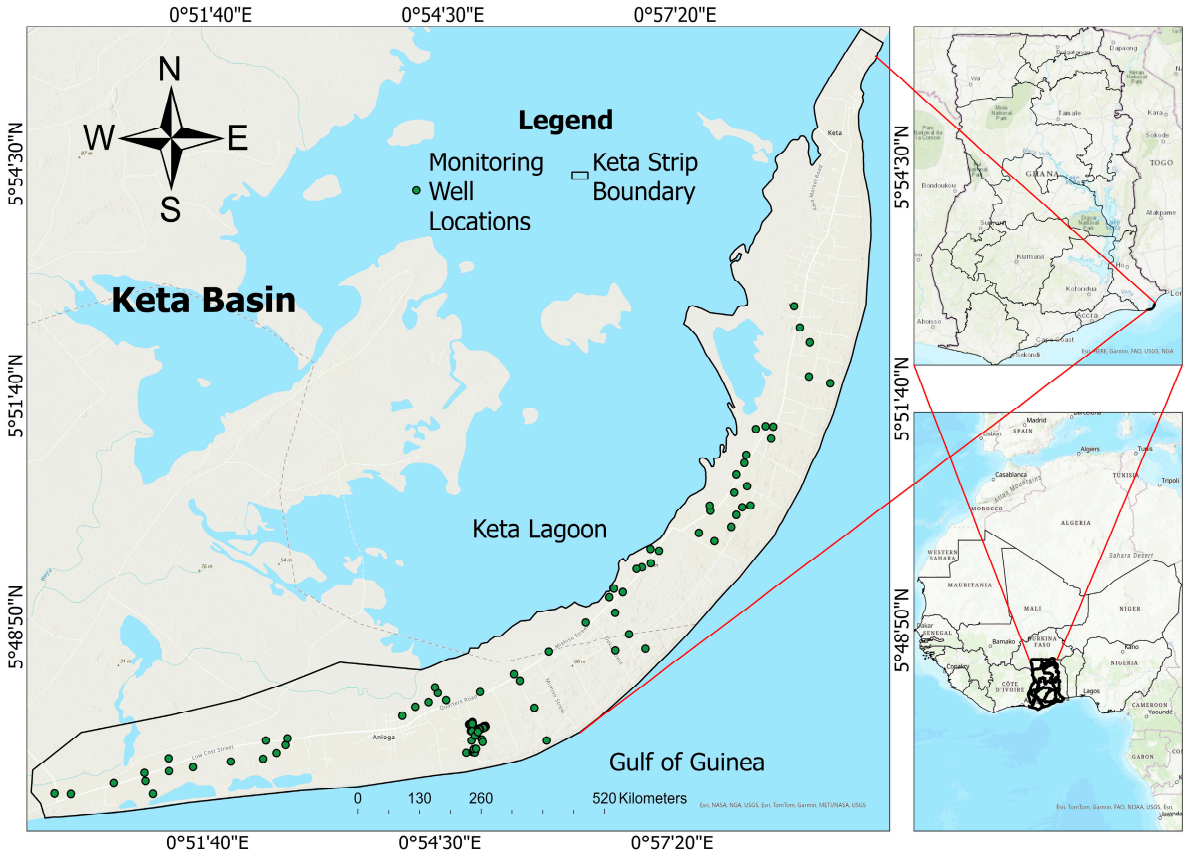


Figure 1. Location map of the study area showing the monitoring well locations (green points) used as the basis for all GALDIT parameter calculations in this study.

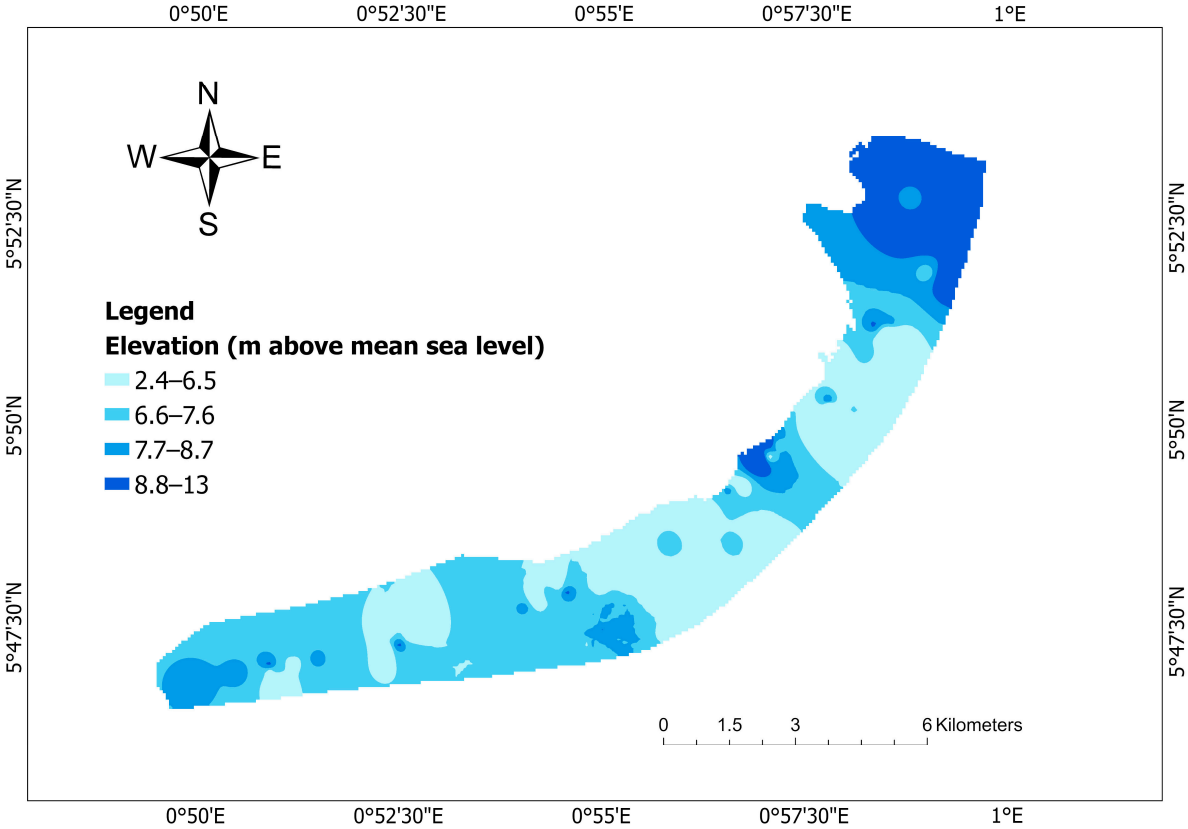


Figure 2. Elevation map (meters above mean sea level) of the Keta Strip.

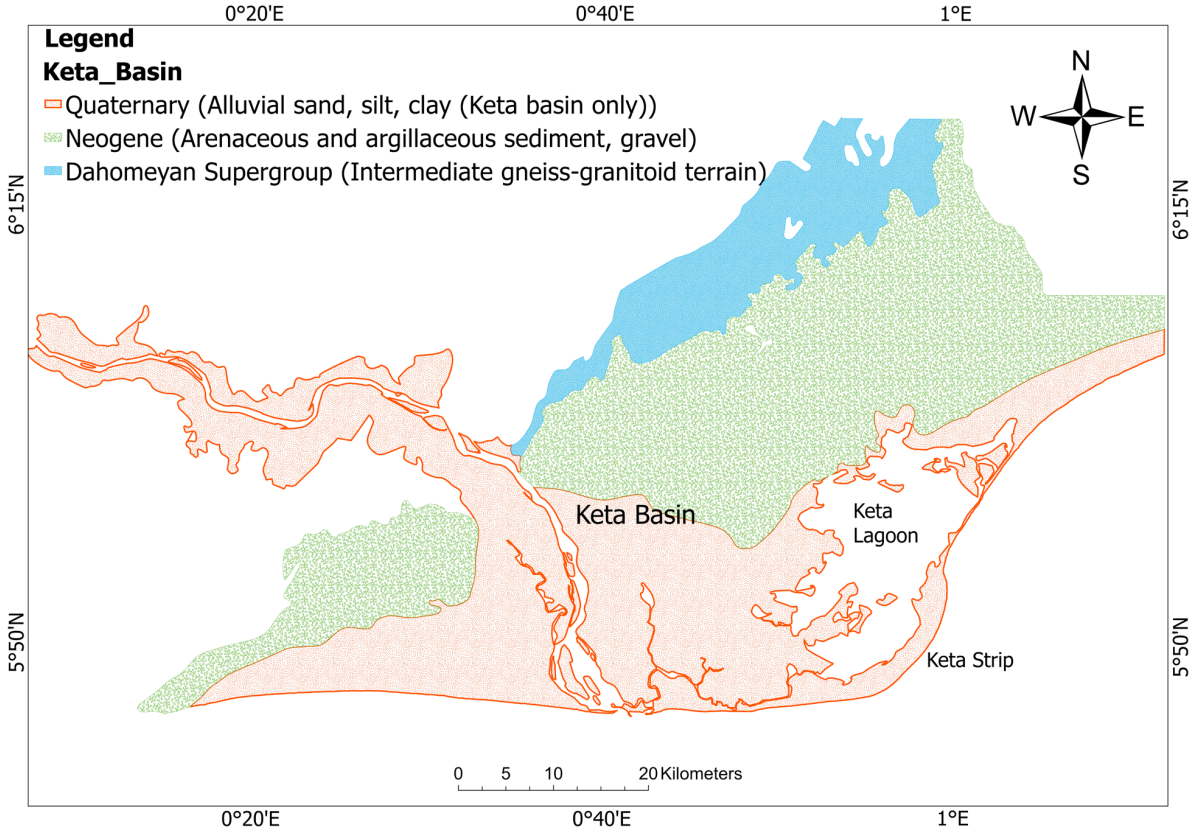


Figure 3. Geological map of the study area.

2.2. Model Development

This research employed a combined approach combining data collection, processing, and geospatial analysis to evaluate groundwater vulnerability to seawater intrusion within the research area. The analysis was based on primary and secondary data obtained from the Department of Earth Science, University of Ghana and Community Water and Sanitation Agency (CWSA) from 105 monitoring wells distributed across the Keta Strip aquifer. These wells are shallow hand-dug wells and boreholes penetrating the unconfined Quaternary coastal sand aquifer, typically at depths between 2 and 10 m below ground surface. Well locations span the full spatial extent of the study area from the coastal margin to the northern inland zone, providing representative coverage for spatial interpolation. Data obtained for each well include geographic coordinates (WGS 84 UTM Zone 31N), ground elevation derived from topographic surveys, static water levels (SWL), and groundwater quality parameters including Total Dissolved Solids (TDS).

Hydraulic conductivity was derived from pumping tests conducted; values for the remaining locations were obtained by spatial interpolation. Aquifer thickness was estimated using the Ghyben–Herzberg principle (Equation (3)). TDS measurements were obtained from groundwater samples collected during a multiple field campaign conducted in 2019.

The evaluation of seawater intrusion vulnerability was carried out employing the GALDIT index method. This approach is a widely applied index-based technique designed specifically to assess the susceptibility of coastal aquifers to saline intrusion. The GALDIT model identifies areas at varying levels of vulnerability by integrating key hydrogeological parameters that influence the interaction between freshwater and seawater [5,19,20,56]. The model incorporates six fundamental parameters: groundwater occurrence (G), aquifer hydraulic conductivity (A), height of groundwater level above sea level (L), distance from the shoreline (D), impact of existing seawater intrusion (I), and aquifer thickness (T). Each parameter is assigned a weight that reflects its relative significance in controlling seawater

intrusion processes, along with a rating that indicates its contribution to vulnerability. In this study, parameter ratings were categorized into four classes ranging from low (1) to very high (4), based on the spatial distribution and characteristics of the dataset. The assigned weights and ratings for each parameter are presented in Table 1 [17,33,57].

Table 1. Description of GALDIT parameters and their corresponding weights assigned according to their relative influence on seawater intrusion (adapted from [17]).

GALDIT Parameter	Description	Weight (W_i)
Groundwater occurrence (G)	Groundwater occurs within different aquifer systems, including unconfined, confined, semi-confined (weathered), bounded, and leaky confined aquifers. Among these, fractured confined aquifers and unconsolidated unconfined aquifers are generally more susceptible to seawater intrusion due to their hydrogeological characteristics.	1
Aquifer hydraulic conductivity (A)	It refers to the capacity of the aquifer to transmit water through a unit cross-sectional area and plays a key role in controlling the rate at which seawater can migrate within coastal aquifers.	3
Height above sea level (L)	The elevation of groundwater above sea level influences the hydraulic pressure exerted against seawater at the freshwater-saltwater interface. Higher groundwater levels enhance the seaward hydraulic gradient, thereby limiting the inland movement of saline water.	4
Distance from shoreline (D)	It describes the spatial separation of a given location from the coast. Areas located closer to the shoreline are more vulnerable to seawater intrusion compared to those situated further inland.	4
Impact of existing seawater intrusion (I)	It pertains to the effect of the saline water that already exists in the system of aquifers, causing a disruption in the natural interaction between the fresh water and seawater systems.	1
Aquifer thickness (T)	It refers to the vertical extent of the saturated zone, influences the potential for seawater encroachment. Thicker aquifers generally provide a larger zone for interaction between freshwater and saline water, making them more susceptible to intrusion compared to thinner aquifer systems.	2

According to Lobo-Ferreira and Chachadi [19], GALDIT parameter is defined by three key components: weight, range, and rating. The weight (W_i) represents the relative importance of a parameter in influencing seawater intrusion and typically varies between 1 (least influence) and 4 (highest influence). The range defines how each parameter is grouped into classes based on its spatial variability. In this study, classification was performed using the Natural Breaks (Jenks) method to ensure that class intervals accurately reflect inherent data patterns.

The rating (R_i) indicates the level of vulnerability associated with each class. While the original GALDIT framework employs a rating scale ranging from 2.5 to 10, a simplified scale of 1 to 4 was adopted in this study to ensure consistency across parameters and facilitate integration within a raster-based GIS environment. This adjustment maintains the relative ranking of vulnerability while improving computational efficiency.

The overall GALDIT index was calculated using a weighted linear combination approach, in which each parameter rating is multiplied by its corresponding weight. The final

index value is obtained by summing these weighted scores and normalizing by the total weight, as expressed in Equation (1):

$$\text{GALDIT Index} = \frac{\sum_{i=1}^{6}(W_i + R_i)}{\sum_{i=1}^{6} W_i} \quad (1)$$

where

W_i is the weight assigned to parameter i;
R_i is the rating assigned to parameter i;
i represents the six GALDIT parameters.

Using the modified rating scale (1–4), the resulting GALDIT index values range approximately from 1 to 4, with higher values indicating greater vulnerability to seawater intrusion (Table 2).

Table 2. Weights and importance ratings of GALDIT parameters adopted for the study area.

Parameter	Description	Weight (W_i)	Class	Range	Original Rating (Literature)	Modified Rating (This Study)
G	Groundwater occurrence	1	Unconfined		10	4
A	Aquifer hydraulic conductivity	3	Very High	>40	10	4
			High	10–40	7.5	3
			Medium	5–10	5	2
			Low	<5	2.5	1
L	Height above sea level	4	Very High	<1	10	4
			High	1–1.5	7.5	3
			Medium	1.5–25	5	2
			Low	>2.5	2.5	1
D	Distance from shoreline	4	Very Near	<500	10	4
			Near	500–750	7.5	3
			Moderate	750–1000	5	2
			Far	>1000	2.5	1
I	Impact of existing seawater intrusion (I)	1	Very High	>3000	10	4
			High	1500–3000	7.5	3
			Medium	500–1500	5	2
			Low	<500	2.5	1
T	Aquifer thickness	2	Very High	>10	10	4
			High	7.5–10	7.5	3
			Medium	5–7.5	5	2
			Low	<5	2.5	1

The processing of data in this study involved a combination of digitizing existing datasets, interpolating borehole data, and integrating hydrogeological parameters within a Geographic Information System environment. The workflow followed is illustrated in Figure 4. As a first step, the boundary of the aquifer was delineated from the map of the Keta Strip and used to define the spatial extent of the analysis. The study relied primarily on secondary borehole data obtained from the Community Water and Sanitation Agency, which included geographic coordinates, elevation, static water levels (SWL), and groundwater quality parameters. These data were organized in a spreadsheet format and subsequently imported into ArcGIS Pro (version 3.1.5) using the "XY Table to Point" tool to generate borehole point features. The spatial reference system was defined as WGS 84 UTM Zone 31N to ensure consistency with the study area.

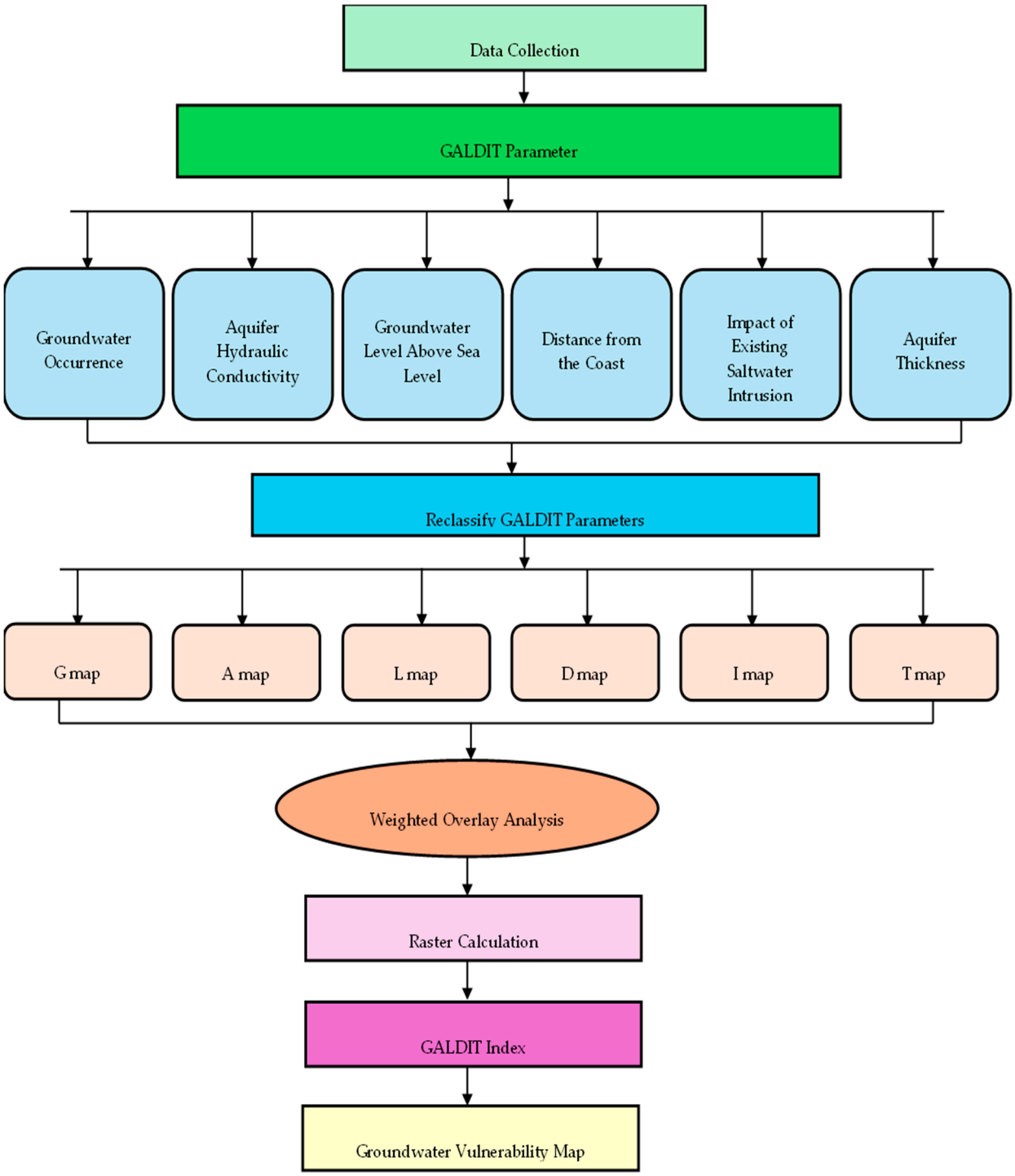


Figure 4. Methodological flowchart for assessing groundwater vulnerability.

Following data importation, continuous raster surfaces were generated from the borehole datasets through spatial interpolation. To ensure compatibility during spatial analysis, all raster datasets were standardized to a common cell size, spatial extent, and alignment using a snap raster within the ArcGIS environment. This step ensured accurate overlay and minimized spatial discrepancies between datasets. Subsequently, all parameter rasters were reclassified into four vulnerability classes using the Natural Breaks (Jenks) classification method, which reflects the inherent distribution of the data. Rating values ranging from 1 (low vulnerability) to 4 (very high vulnerability) were assigned based on the relationship of each parameter with seawater intrusion. Parameters such as hydraulic head and distance from

the shoreline, which exhibit an inverse relationship with seawater intrusion, were assigned higher ratings at lower values, whereas parameters such as aquifer thickness and TDS, which have a direct relationship, were assigned higher ratings at higher values. The final GALDIT vulnerability index was computed using a weighted linear combination of all parameters. Each reclassified raster was multiplied by its corresponding weight, and the results were summed and normalized using raster-based map algebra. The resulting GALDIT index map was subsequently classified into four vulnerability zones: low, moderate, high, and very high. A detailed description of each parameter is provided below:

2.2.1. Groundwater Occurrence/Aquifer Type (G)

The nature of groundwater occurrence plays a fundamental role in controlling the susceptibility of aquifers to seawater intrusion (SWI). Aquifer systems are generally classified as confined, unconfined, leaky confined, or bounded, and each type responds differently to saline water encroachment [58–60]. The degree of intrusion is strongly influenced by this classification. For instance, unconfined aquifers are typically more vulnerable because they are directly exposed to atmospheric conditions and lack protective confining layers. In contrast, confined aquifers, which are under pressure greater than atmospheric conditions, may exhibit some resistance to intrusion, although excessive groundwater abstraction can create cones of depression that enhance their susceptibility [61]. Leaky confined aquifers may maintain some level of hydraulic balance due to vertical leakage from adjacent units, potentially reducing their vulnerability. Accurate characterization of aquifer type is therefore essential when assigning weights and ratings within the GALDIT framework. In addition, aquifer heterogeneity, controlled by factors such as grain size distribution, aquifer geometry, stratification, permeability variations, hydraulic conductivity, transmissivity, and flow connectivity, also influences the movement of saline water [62,63]. In this study, the aquifer system was identified as unconfined throughout the study area. Consequently, the groundwater occurrence parameter was treated as spatially uniform and assigned a consistent rating.

2.2.2. Aquifer Hydraulic Conductivity (A)

Hydraulic conductivity is a key parameter influencing the rate and extent of seawater intrusion. Aquifers with higher hydraulic conductivity facilitate more rapid groundwater flow, thereby allowing the saline front to advance further inland. Under pumping conditions, high conductivity zones tend to develop broader cones of depression, which can enhance the landward movement of seawater, especially in coastal settings.

Within the GALDIT framework, hydraulic conductivity is assigned a relatively high weight due to its significant influence on intrusion processes. Rating values typically range from low (1) to very high (4), depending on the magnitude of conductivity. Previous studies have shown that areas with hydraulic conductivity values exceeding 40 m/day exhibit the highest susceptibility, whereas values below 5 m/day are associated with lower vulnerability [19,20,26,56].

In this study, hydraulic conductivity was estimated from pumping test data from 59 well locations distributed across the study area. The pumping tests were conducted between 2017 and 2020. Transmissivity values were analyzed using the Cooper–Jacob straight-line method where applicable and converted to hydraulic conductivity using Equation (2). The resulting 59-point dataset was then spatially interpolated using the Inverse Distance Weighting (IDW) technique to generate a continuous hydraulic conductivity raster over the study area.

Hydraulic conductivity was estimated from pumping test data using the relationship:

$$K = \frac{T}{b} \quad (2)$$

where K is hydraulic conductivity (m/day), T is transmissivity (m^2/day), and b represents the saturated thickness of the aquifer (m). The resulting values were interpolated and converted into raster format, after which appropriate weights were applied within the GIS environment.

2.2.3. Height of the Water Table Above Sea Level (L)

The elevation of groundwater relative to average sea level is one of the most critical factors in evaluating seawater intrusion, as it governs the hydraulic gradient between freshwater and seawater. Higher groundwater levels generate a stronger seaward hydraulic gradient, which helps to repel saline water intrusion, while lower heads reduce this resistance and increase vulnerability. Groundwater head values were calculated as the variation between ground elevation and observed static water levels, representing the height of the water table above sea level. The parameter values were spatially interpolated employing the Inverse Distance Weighting (IDW) technique to produce a continuous surface. Aquifers with higher hydraulic heads are generally less susceptible to intrusion because they promote freshwater discharge toward the coast, thereby limiting the inland movement of saline water. Conversely, areas with low hydraulic head are more prone to seawater encroachment, particularly under conditions of reduced recharge or increased abstraction [5,64].

2.2.4. Distance from the Shore (D)

Distance from the coastline is a vital controlling factor in seawater intrusion, as the influence of saline water typically diminishes with increasing distance inland. Areas located close to the shoreline or tidal channels experience the greatest impact, while inland zones are relatively less affected under natural conditions. In this study, the distance parameter was classified into four categories based on proximity to the coast, with ratings ranging from 1 (farthest) to 4 (nearest). This classification assumes relatively undisturbed hydrogeological conditions, where groundwater abstraction has not significantly altered the natural balance between freshwater and seawater. The relationship between distance and vulnerability is generally considered to be inversely proportional, with vulnerability decreasing inland.

2.2.5. Impact of Existing Status of Seawater Intrusion (I)

The parameter representing the current level of seawater intrusion reflects the extent to which groundwater quality has already been affected by salinity. Disruption of the natural equilibrium between freshwater and seawater, often due to excessive pumping in coastal zones, can lead to increased salinization. Traditionally, the GALDIT method uses the molar ratio of chloride to bicarbonate ions as an indicator of seawater intrusion [19]. However, alternative indicators such as electrical conductivity (EC) have also been commonly applied because of their simplicity of measurement [20].

TDS values were obtained entirely from in situ field measurements conducted in 2019. A total of approximately 70 samples were measured directly by using a portable field meter, while the remaining 30 data points were sourced from CWSA field records for the same year.

In this study, Total Dissolved Solids (TDS) was adopted as a proxy for assessing the impact of seawater intrusion [21,33,65–67]. TDS is a widely accepted indicator of groundwater salinity, as it represents the total concentration of dissolved substances in

water. Elevated TDS values in coastal aquifers are commonly associated with the mixing of freshwater and seawater. The use of TDS is particularly appropriate in this study due to the absence of detailed ionic data such as chloride concentrations. Previous studies have demonstrated that TDS can effectively capture spatial distribution of salinity and serve as a reliable tool for identifying zones influenced by seawater intrusion [6,68].

2.2.6. Aquifer Thickness (T)

Aquifer thickness, defined as the saturated thickness of the aquifer, is a key parameter influencing seawater intrusion. It represents the vertical extent of freshwater storage and determines the volume of water available for interaction with saline water. In coastal aquifers, thicker freshwater zones can affect the position and stability of the freshwater-saltwater interface. Analytical approaches such as those proposed by Glover [69], Lau [70], and Vacher [71] have been used to estimate aquifer thickness. In systems characterized by a relatively sharp interface between freshwater and seawater, the Ghyben–Herzberg principle provides a practical approximation of the depth to the saline interface. This approach has been successfully applied in various coastal aquifers [72–76].

In this study, aquifer thickness was estimated at all 105 monitoring well locations using the Ghyben–Herzberg relationship:

$$T = 40 \times h \tag{3}$$

where h represents the hydraulic head above mean sea level derived from point measurements of static water level (SWL) and ground surface elevation at each well. This relationship assumes a density disparity between freshwater and seawater and provides an approximation of the depth to the saline interface under equilibrium conditions.

2.3. Mapping GALDIT Vulnerability Index

The GALDIT vulnerability map was developed to spatially represent the susceptibility of the coastal aquifer to seawater intrusion. The computed GALDIT index values were grouped into four distinct categories: low, moderate, high, and very high vulnerability. Higher index values indicate greater susceptibility of groundwater to salinization and, consequently, a higher risk of seawater intrusion within the aquifer system. The overall procedure used to develop the vulnerability map is illustrated in the flowchart presented in Figure 4.

2.4. Sensitivity Analysis of the GALDIT Vulnerability Index

A sensitivity analysis was conducted to evaluate the robustness of the GALDIT model by evaluating the influence of assigned weights and ratings on the final vulnerability index. This analysis helps determine the relative contribution of each parameter to the overall assessment and provides insight into the reliability of the model outputs [21,26,64].

Furthermore, sensitivity analysis serves as a diagnostic tool for identifying the most influential parameters controlling seawater intrusion within the study region. In this research, two (2) widely recognized techniques were applied: single-parameter sensitivity analysis (SPSA) and map removal sensitivity analysis (MRSA). These approaches, originally proposed by Napolitano et al. [77] and Lodwick et al. [78], respectively, are commonly used in groundwater vulnerability studies to evaluate parameter significance and model stability.

2.4.1. Single-Parameter Sensitivity Analysis (SPSA)

The SPSA technique was used to quantify the contribution of each individual variable to the overall vulnerability index. This approach helps reduce uncertainty in the GALDIT model by examining how variations in parameter weights affect the computed vulnera-

bility. It also provides a clearer understanding of the relative importance of each factor in controlling seawater intrusion.

The effective weight of each parameter was calculated using Equation (4):

$$W = \frac{P_r P_w}{V} \times 100 \quad (4)$$

where W represents the effective weight of a parameter, P_r is the rating assigned to the parameter, P_w the corresponding weight, and V is the overall GALDIT index value derived from Equation (1).

2.4.2. Map Removal Sensitivity Analysis (MRSA)

The MRSA approach was applied to evaluate the influence of each parameter by systematically removing them one at a time and recalculating the vulnerability index [79]. This method measures the degree of change in the model output resulting from the exclusion of individual parameters, thereby indicating their relative importance.

The sensitivity index is computed using Equation (5):

$$S = \frac{\left(\frac{V}{N} - \frac{V'}{n}\right)}{V} \times 100 \quad (5)$$

where S represents the sensitivity of a given parameter, V is the original GALDIT index value calculated using all parameters, V' is the recalculated index after removing a parameter, N is the total number of parameters used in the original model, and n is the number of parameters used after removal.

3. Results and Discussion

3.1. GALDIT Parameters

To calculate the GALDIT index, the six (6) variables were first developed as thematic layers. The parameter layers were analysed applying ArcGISPro (3.1.5) software in raster format environment. Where necessary, spatial interpolation was carried out using the Inverse Distance Weighting (IDW) technique, which has been widely applied in similar studies [6,80]. The results of each parameter mapping were subsequently visualized and integrated for further analysis.

3.1.1. Groundwater Occurrence (G)

This parameter accounts for aquifer type and its hydrogeological properties, which govern its susceptibility to seawater intrusion. The groundwater occurrence within the Keta Strip is characterized entirely by an unconfined aquifer system, as shown in Figure 5. Unconfined aquifers are directly exposed to atmospheric conditions and are therefore highly susceptible to external influences such as recharge, contamination, and seawater intrusion. Due to the absence of a confining layer, seawater can easily migrate into the aquifer under conditions of hydraulic imbalance, particularly in coastal environments where the freshwater–saltwater interface is sensitive to changes in groundwater levels. This condition significantly increases the intrinsic vulnerability of the aquifer to saline intrusion. In the GALDIT framework, the unconfined nature of the aquifer is assigned a high vulnerability rating, reflecting its limited natural protection against seawater encroachment. Since this condition is uniform across the study area, it contributes consistently to the overall vulnerability index.

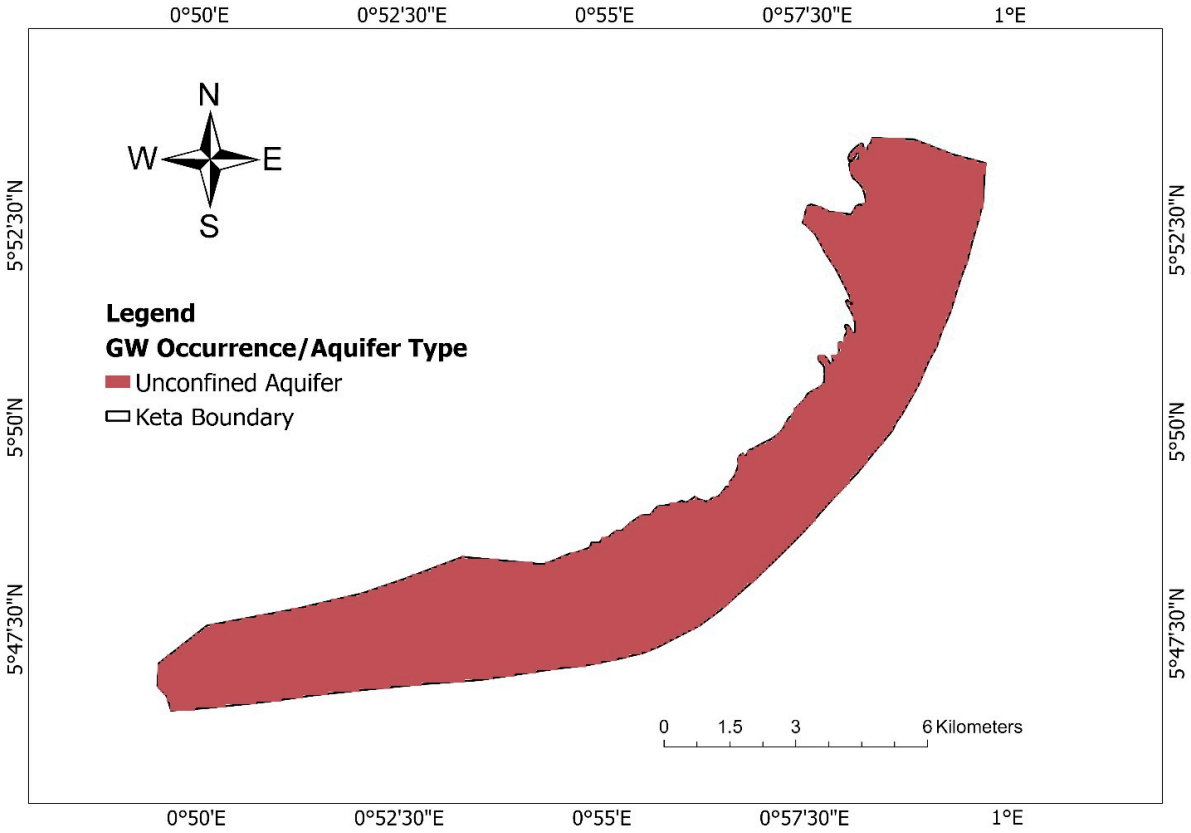


Figure 5. Groundwater occurrence (G).

3.1.2. Aquifer Hydraulic Conductivity (A)

As illustrated in Figure 6, hydraulic conductivity in the Keta Strip ranges from low to very high, corresponding to ratings of 1 to 4 for parameter (A). The values are categorized into four classes: low, medium, high, and very high. Areas characterized by high to very high hydraulic conductivity are predominantly observed along the central to eastern portions of the study area, while low to medium conductivity zones occur mainly in the western sections. High hydraulic conductivity indicates that the aquifer materials (likely sands and gravels) allow rapid groundwater movement. This enhances the ease of saline water migration, thereby increasing the susceptibility of these zones to seawater intrusion. Conversely, areas with low hydraulic conductivity, which are typically associated with finer materials such as silts or clays, tend to restrict groundwater flow and may offer some degree of protection against saltwater encroachment. The observed spatial pattern suggests that zones with elevated hydraulic conductivity represent potential pathways for seawater intrusion, particularly when combined with other influencing factors such as proximity to the coast and groundwater abstraction.

3.1.3. Height of Ground Water Level Above Sea Level (L)

This variable plays a critical role in determining aquifer vulnerability to seawater intrusion. The spatial distribution of groundwater level above mean sea level in the Keta Strip shows distinct variations that significantly influence vulnerability to seawater intrusion. In this research, lower hydraulic head corresponds to higher vulnerability, while higher head indicates lower vulnerability. The map (Figure 7) indicates that areas with very high vulnerability zones (head < 3 m) are predominantly observed along the coastal and central portions of the Keta Strip, with notable extensions into the eastern sector. These zones represent regions where groundwater levels are close to sea level, thereby reducing the freshwater hydraulic gradient that normally prevents seawater from encroaching inland. As a result, these locations

exhibit a high level of susceptibility to seawater intrusion. The high vulnerability zones (3–5 m) are also widely distributed, especially across much of the southern and central sections of the study area. These regions still exhibit relatively low hydraulic heads, suggesting limited resistance to saline water movement. In contrast, moderate vulnerability zones (5–8 m) occur mainly in the northern parts, indicating a relatively improved hydraulic gradient that can partially restrict seawater intrusion. The low vulnerability zones (>8 m) are sparsely distributed and confined to small patches within the northern sector. These areas have sufficiently high groundwater levels, which enhance freshwater outflow toward the sea and act as a natural barrier against saline intrusion.

3.1.4. Distance from Shoreline (D)

Distance from the shoreline is a key controlling parameter in seawater intrusion, as zones located nearer to the coastline are more directly influenced by marine processes and saline water encroachment. The spatial distribution of this parameter (Figure 8) within the Keta Strip shows a clear gradient pattern extending inland from the coastline. Zones classified as very high vulnerability are located immediately adjacent to the shoreline, which was rated as, where the influence of seawater is strongest. These locations exhibit a high level of susceptibility to seawater intrusion due to their proximity to the ocean, which facilitates the lateral movement of saline water into the aquifer system. Moving inland, high to moderate vulnerability zones are observed, indicating a gradual reduction in the influence of seawater. These transitional zones may still be affected by intrusion, particularly under conditions of groundwater over-extraction or reduced recharge. Areas classified as low vulnerability are found farther inland, where the influence of seawater intrusion is minimal. In these zones, the greater distance from the shoreline provides a natural buffer against saline water encroachment. The consistent inland decrease in vulnerability highlights the strong spatial control of proximity to the coast on seawater intrusion processes within the Keta Strip aquifer.

3.1.5. Impact of Existing Seawater Intrusion (I)

The impact of existing seawater intrusion was assessed using Total Dissolved Solids (TDS) as an indicator of groundwater salinity. TDS is widely used as a proxy for seawater intrusion because elevated concentrations often reflect the mixing of freshwater with saline water. The spatial distribution of TDS within the Keta Strip in Figure 9 reveals distinct zones of varying salinity levels. Areas classified as high to very high impact are scattered across the aquifer, indicating zones where groundwater has already been significantly affected by saline intrusion. These zones may be associated with proximity to the coastline, over-abstraction of groundwater, or localized hydrogeological conditions that facilitate saltwater encroachment. Moderate impact zones dominate a substantial portion of the study area, suggesting transitional conditions where freshwater is beginning to show signs of salinization. In contrast, areas classified as low impact indicate relatively fresh groundwater conditions with minimal influence from seawater intrusion. The heterogeneous distribution of TDS highlights the complex interaction between natural processes and anthropogenic activities influencing groundwater quality. The presence of high-impact zones confirms that seawater intrusion is already occurring in parts of the Keta Strip, emphasizing the need for careful groundwater management.

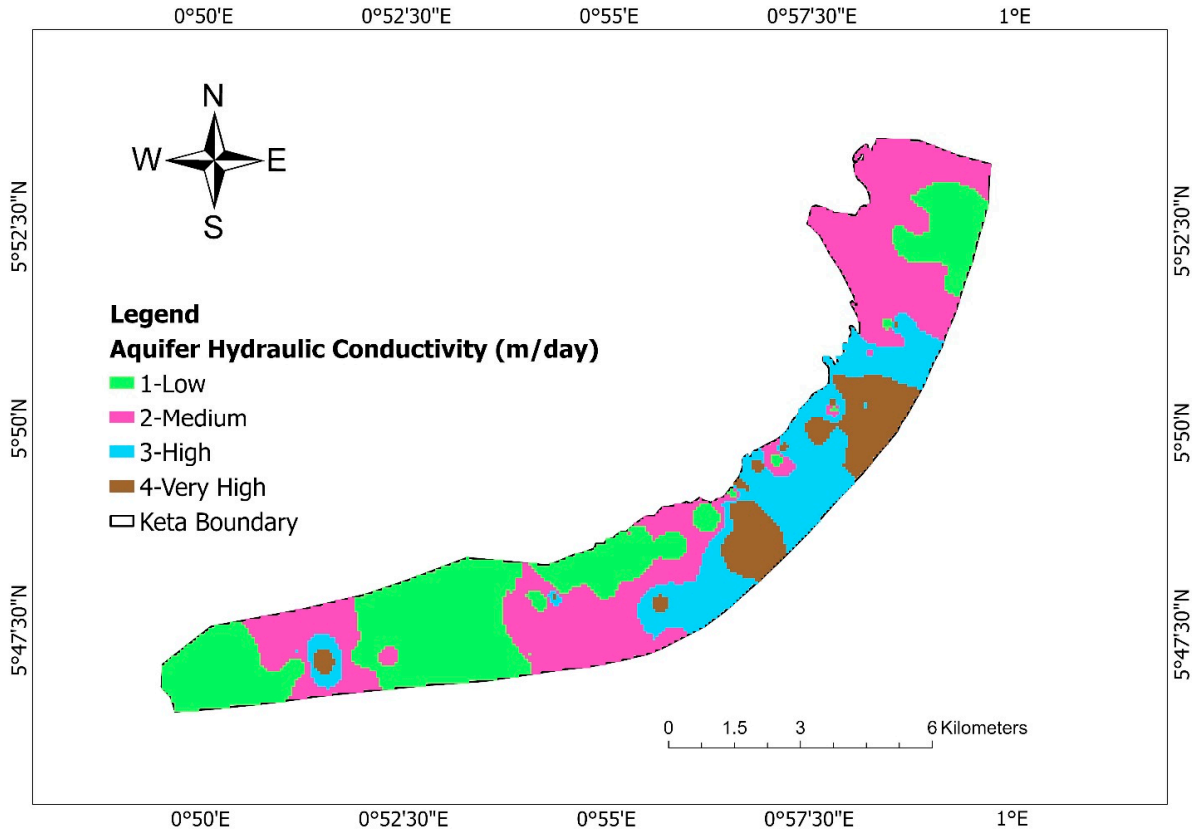


Figure 6. Aquifer hydraulic conductivity (A).

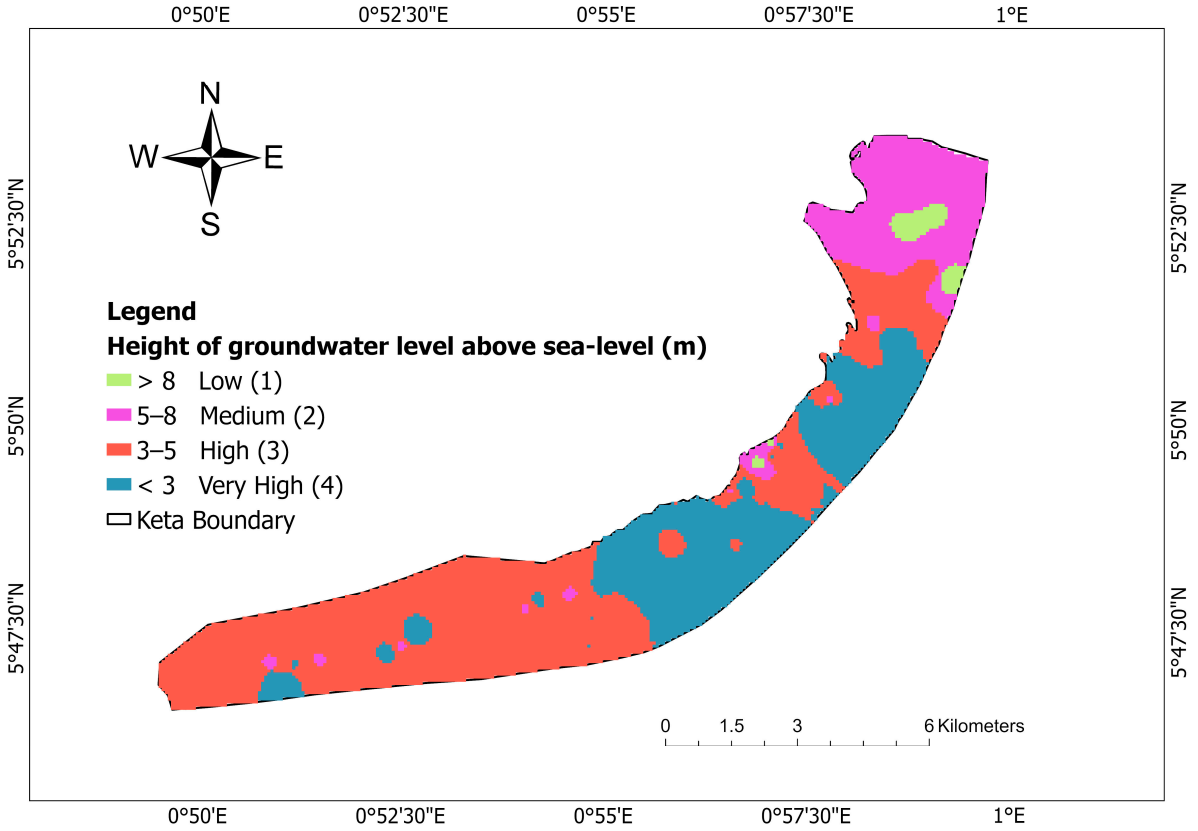


Figure 7. Height of ground water Level above sea level (L).

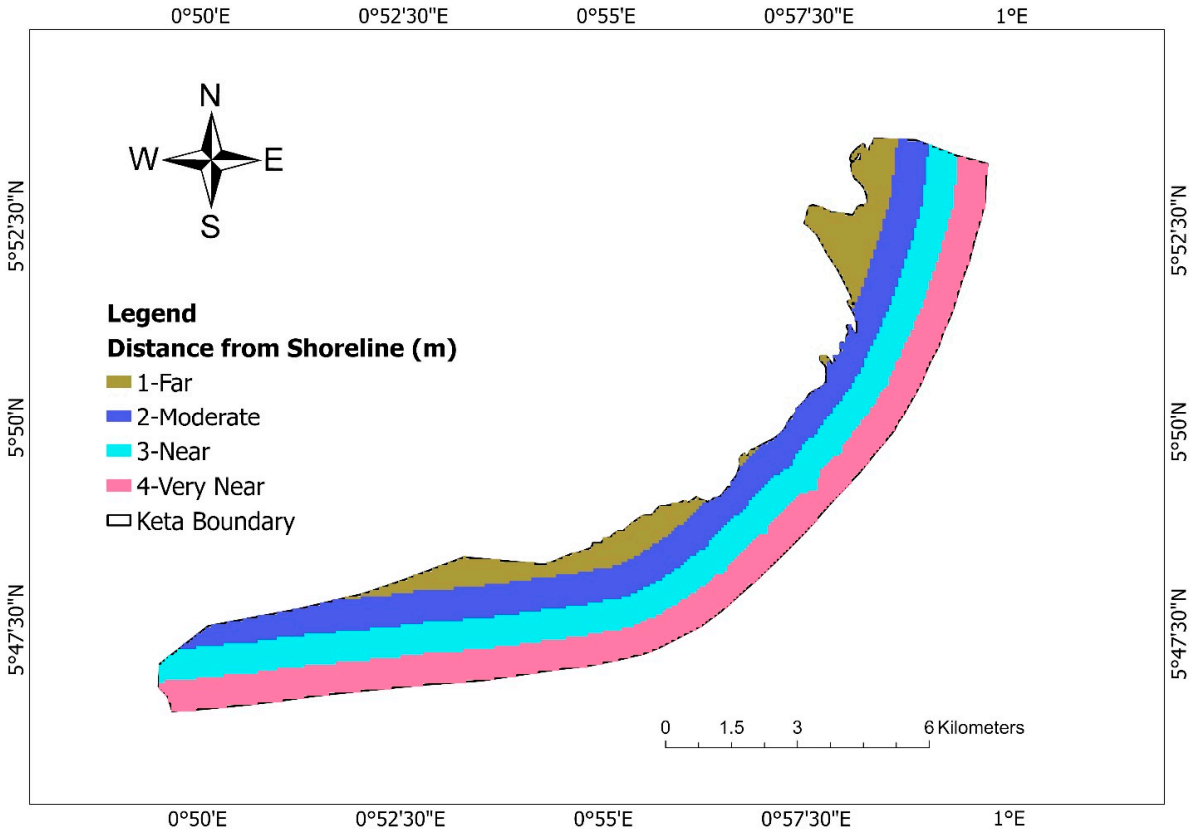


Figure 8. Distance from shoreline (D).

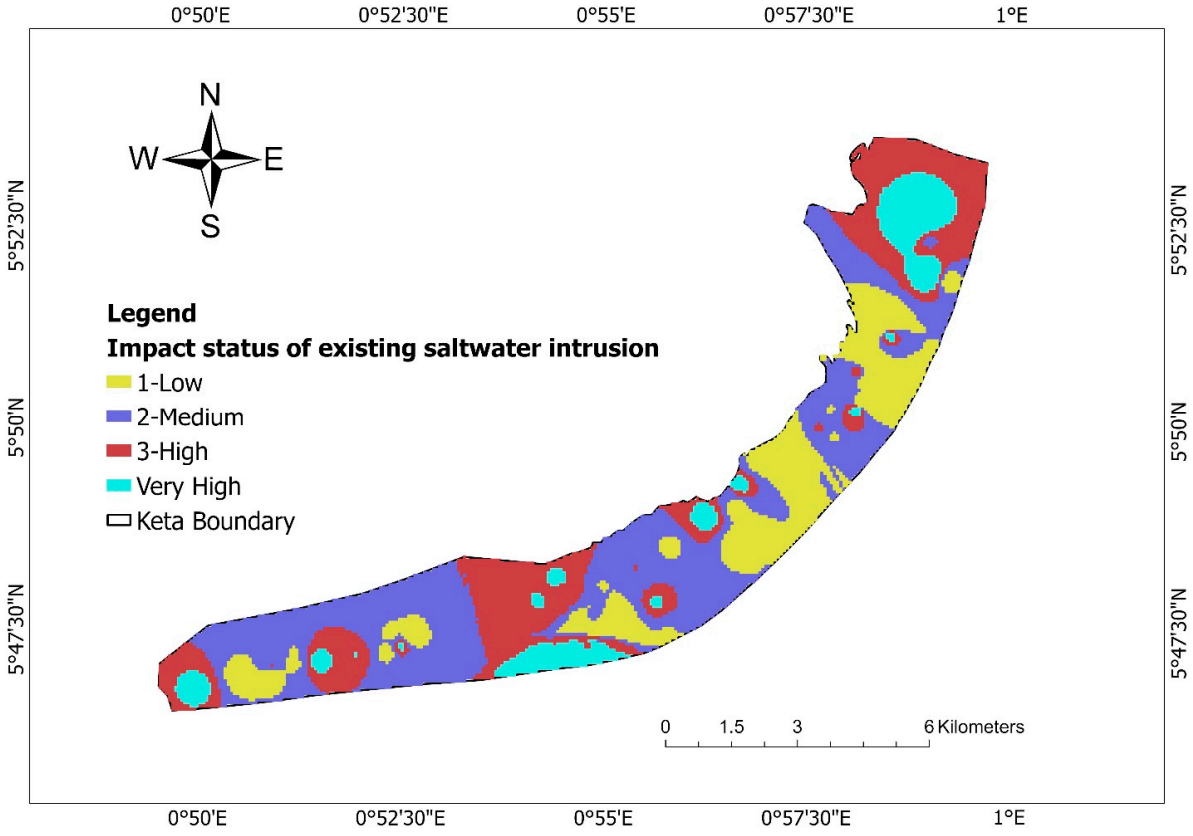


Figure 9. Impact of existing seawater intrusion (I).

3.1.6. Thickness of the Aquifer (T)

Aquifer thickness plays a critical role in controlling seawater intrusion, as thicker aquifers generally provide a larger freshwater reserve and a stronger hydraulic barrier against saline water encroachment. The spatial distribution of aquifer thickness (Figure 10) indicates that low aquifer thickness is predominantly observed along the central to south-eastern coastal stretch, forming a continuous band. These areas represent relatively thin saturated zones, which limit the volume of freshwater storage and reduce the buffering capacity of the aquifer against saline encroachment.

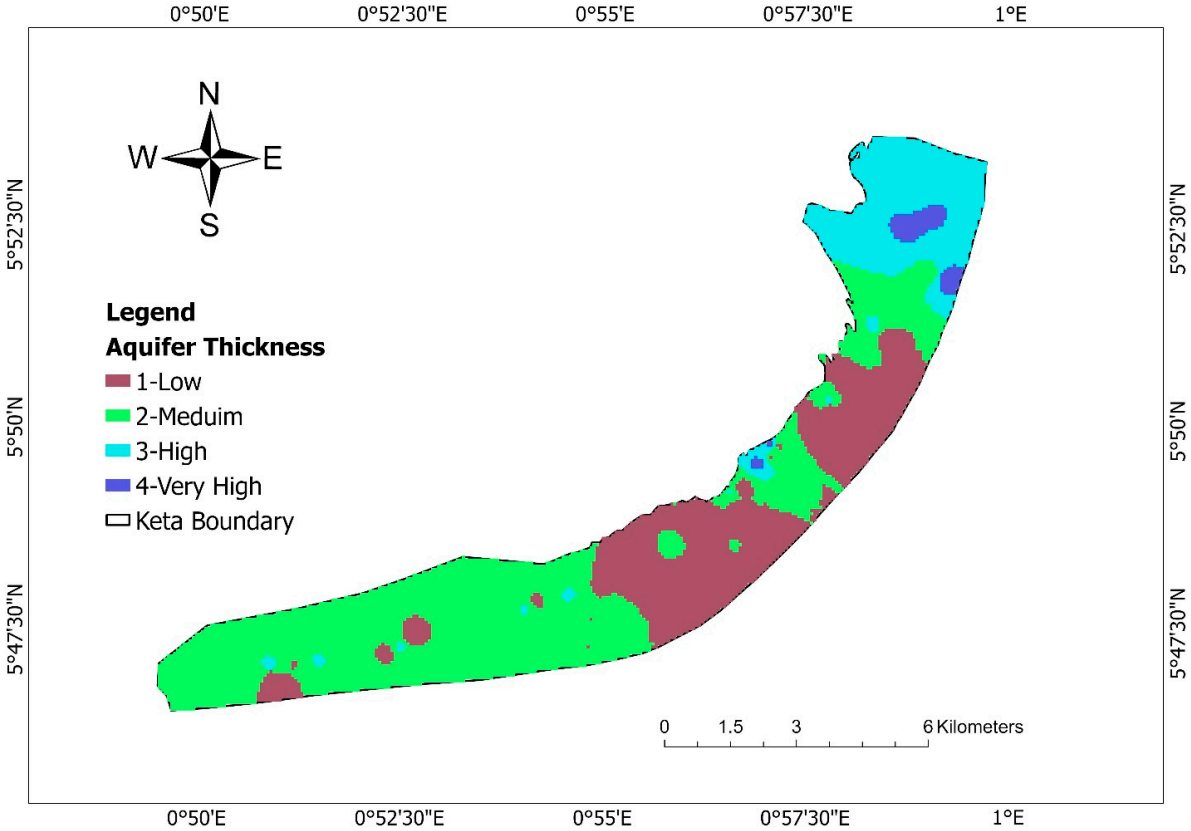


Figure 10. Thickness of the Aquifer (T).

Moderate thickness zones are more widespread, particularly across the western and central portions of the study area. These regions indicate intermediate conditions where the aquifer can support some level of freshwater storage but remains vulnerable under stress conditions such as excessive abstraction. High to very high aquifer thickness is mainly concentrated in the northeastern sector, with isolated pockets scattered across the central zone. These thicker aquifer sections provide a larger saturated zone, which enhances the potential for interaction between freshwater and saline water. As a result, such areas may be more susceptible to seawater intrusion, particularly where other controlling factors such as hydraulic conductivity and proximity to the coast are favorable. Overall, the spatial pattern suggests that aquifer thickness increases inland toward the northeastern part of the study area, while thinner aquifers dominate the coastal margin.

3.2. Calculation of GALDIT Index and Vulnerability

Figure 11 presents the spatial distribution of the GALDIT index derived from data obtained from 105 monitoring wells. The computed index values were averaged and subsequently categorized into four vulnerability classes: low (1), moderate (2), high (3) and very high (4). Very high vulnerability zones are predominantly concentrated along

the coastal margin, forming a continuous belt parallel to the shoreline. These areas are characterized by conditions that strongly favor seawater intrusion, including proximity to the coast, relatively low hydraulic gradients, and evidence of existing salinity.

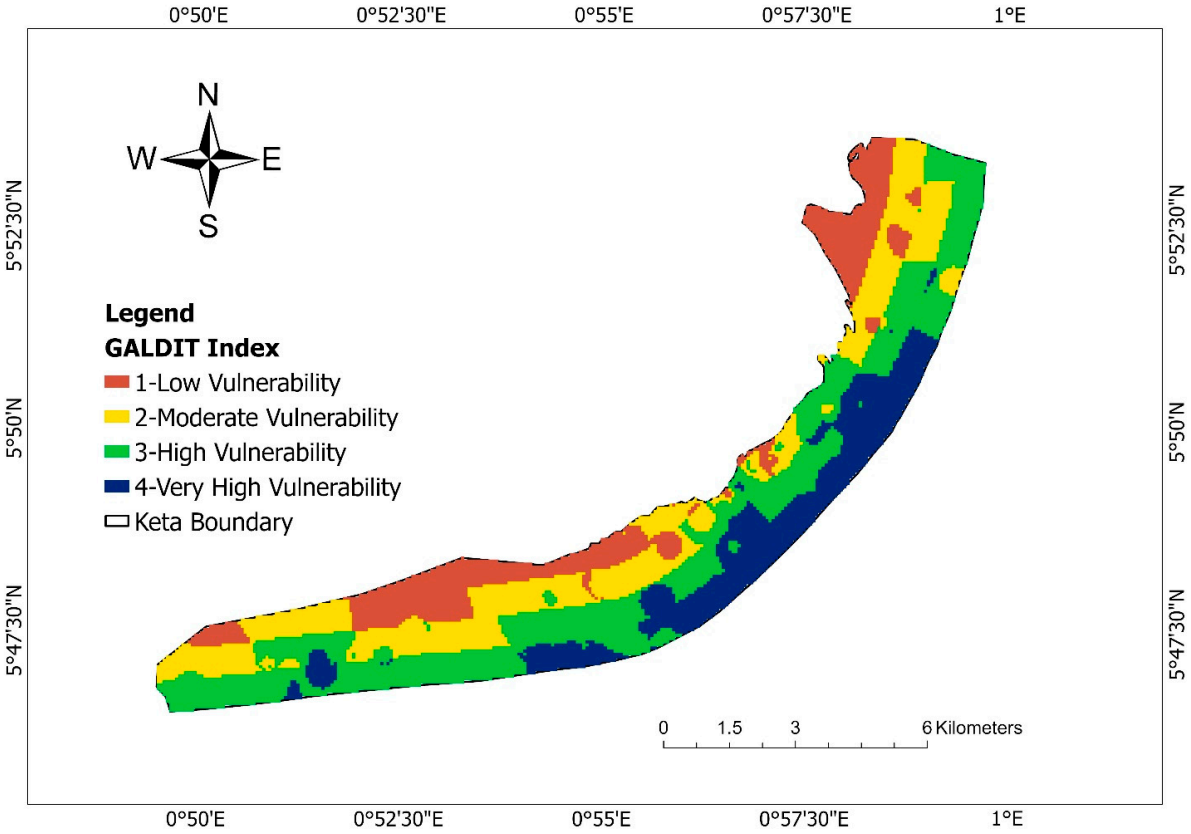


Figure 11. GALDIT vulnerability index map.

High vulnerability zones extend inland from the coastal belt, particularly across the central portions of the study area. These areas represent zones where seawater intrusion is likely under increased groundwater abstraction or reduced recharge conditions. Moderate vulnerability zones are widely distributed across the western and central sections, indicating transitional conditions where the aquifer is not currently highly impacted but remains sensitive to environmental and anthropogenic changes. Low vulnerability zones are mainly confined to the northern and northeastern parts of the study area. These regions are relatively distant from the coastline and are characterized by more favorable hydrogeological conditions, including higher groundwater levels and reduced influence of saline intrusion.

3.3. Sensitivity Analysis of the GALDIT Model

To evaluate the robustness of the GALDIT model and the relative influence of individual parameters on seawater intrusion vulnerability, both single parameter sensitivity analysis (SPSA) and map removal sensitivity analysis (MRSA) were conducted.

The statistical summary of GALDIT parameters (Table 3) highlights both their relative magnitude and spatial variability in controlling seawater intrusion vulnerability, with n representing the number of observation points. Groundwater occurrence (G) shows a constant mean rating (R_i = 4) with no variability (CV = 0%), confirming a uniformly unconfined aquifer and an inherently high baseline susceptibility across the study area. Among the variable parameters respectively, groundwater level above sea level (L) and distance from the shoreline (D) exhibit the highest mean ratings (R_i = 3.09 and 2.77), indicating a strong overall contribution to vulnerability, despite their moderate variability

(CV = 23.62% and 36.82). In contrast, aquifer thickness (T) has a lower mean rating (R_i = 1.91) but the high spatial variability (CV = 38.21%), suggesting that while its average influence is moderate, it exerts localized control on saline intrusion. Similarly, aquifer hydraulic conductivity (A) (R_i = 2.03; CV = 47.29%) and impact of existing intrusion (I) (R_i = 2.25; CV = 40.89%) show moderate mean contributions but high spatial variability, reflecting their role in defining spatial patterns of vulnerability. Overall, parameters such as L and D dominate in terms of magnitude of influence, whereas A, I, and T primarily control the spatial heterogeneity of seawater intrusion risk.

Table 3. Statistical summary of GALDIT parameters map.

Parameter	*n*	Max	Min	Mean (R_i)	SD	CV%
G	N/A	4	4	4	0	0
A	59	1	4	2.03	0.96	47.29
L	105	1	4	3.09	0.73	23.62
D	N/A	1	4	2.77	1.02	36.82
I	100	1	4	2.25	0.92	40.89
T	105	1	4	1.91	0.73	38.21

3.3.1. Single Parameter Sensitivity Analysis

The SPSA was applied to quantify the relative contribution of each GALDIT parameter to the overall vulnerability index. This was achieved by comparing the effective weight of each parameter, computed as the ratio of the product of its assigned weight and rating to the total weighted sum of all parameters. The statistical summary of the calculated effective weights and variability for each parameter is presented in Table 4. The results indicate that the assigned theoretical weights differ from the derived effective weights for the individual parameters.

Table 4. Single parameter weight sensitivity analysis.

Parameter	Assigned Weight (X_{wi})	Assigned Weight (%)	Calculated Weight (X_{wi})	Average Calculated Effective Weight (%)
G	1	6.67	4.00	10.10
A	3	20.00	6.09	15.38
L	4	26.67	12.36	31.21
D	4	26.67	11.08	27.98
I	1	6.67	2.25	5.68
T	2	13.33	3.82	9.65

The results (Table 4) indicate that the height of groundwater level above mean sea level (L) and distance from the shoreline (D) are the most influential factors, contributing approximately 31.21% and 27.98%, respectively, to the overall GALDIT index. This highlights the dominant role of hydraulic gradient and proximity to the coast in controlling seawater intrusion within the Keta Strip aquifer. Moderate contributions were observed for hydraulic conductivity (A) (15.38%), groundwater occurrence (G) (10.10%) and aquifer thickness (T) (9.65%) indicating that aquifer properties also play a significant role in facilitating or restricting saline water movement. In contrast, the impact of existing seawater intrusion (I) represented by TDS (5.68%) exhibited relatively low contributions. The low influence of TDS suggests that the present distribution of salinity does not strongly control the spatial variability of vulnerability but rather reflects localized or secondary effects.

3.3.2. Map Removal Sensitivity Analysis

The MRSA was conducted by systematically removing one parameter at a time and recalculating the GALDIT index to evaluate the resulting variation. The outcomes of the map removal sensitivity analysis, highlighting the effect of excluding each parameter on the vulnerability index, are summarized in Table 5.

Table 5. Map removal sensitivity analysis.

Parameter Removed	Min	Max	*V′* (Without)	STD	Sensitivity
NO_G	1.79	3.50	2.54	0.42	−2.58%
NO_A	1.92	3.42	2.79	0.37	−4.47%
NO_L	1.36	3.81	2.48	0.46	−2.12%
NO_D	1.82	3.45	2.59	0.31	−2.95%
NO_I	1.93	3.57	2.67	0.44	−3.56%
NO_T	1.77	3.92	2.75	0.52	−4.17%

The sensitivity values range from −2.12% to −4.47%, indicating low variability among the parameters. The highest sensitivity is associated with aquifer hydraulic conductivity (A) (−4.47%), followed by aquifer thickness (T) (−4.17%) and the impact of existing seawater intrusion (I) (−3.56%). The remaining parameters: distance from shoreline (D), groundwater occurrence (G), and hydraulic head (L) show comparatively lower sensitivity.

The low magnitude of these values suggests that the GALDIT model is stable and not overly dependent on any single parameter. The negative values indicate that removing a parameter reduces the vulnerability index, confirming that all parameters contribute positively to the model.

Comparison with the single-parameter analysis shows that while hydraulic head (L) and distance (D) dominate in proportional contribution, hydraulic conductivity (A) has the greatest influence when excluded. Overall, seawater intrusion vulnerability is primarily controlled by hydraulic gradients and coastal proximity, with secondary influence from aquifer properties.

4. Conclusions

This research applied the GALDIT index model within a GIS framework to evaluate the vulnerability of the Keta Strip aquifer to seawater intrusion using six hydrogeological parameters derived from 105 monitoring wells. The results reveal a clear spatial pattern of vulnerability, with very high and high-risk zones concentrated along the coastal margins and extending into central parts of the aquifer. These areas are primarily controlled by low groundwater heads, high hydraulic conductivity, and close proximity to the shoreline, which collectively favor saline water encroachment. In contrast, moderate to low vulnerability zones are mainly distributed inland, where relatively higher hydraulic gradients provide some resistance to intrusion.

Sensitivity analysis confirms that groundwater level above sea level (L) and distance from shoreline (D) are the dominant controlling factors, while aquifer hydraulic conductivity (A) shows the greatest influence when excluded from the model. The relatively low contribution of TDS explains its weak spatial agreement with the final vulnerability map, indicating that salinity reflects localized conditions rather than overall system behaviour.

Overall, the GALDIT model demonstrates robustness and reliability in assessing seawater intrusion vulnerability in the study region. The findings underscore the importance of managing groundwater abstraction and maintaining adequate recharge to mitigate intrusion risks. This study provides a valuable framework for coastal groundwater management and offers a baseline for future studies incorporating dynamic modeling and climate change scenarios.

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Data Availability Statement: The dataset used to support the findings of this study are available online [81].

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Abbreviations

The following abbreviations are used in this manuscript:

A	Aquifer hydraulic conductivity
CWSA	Community Water and Sanitation Agency
D	Distance from shoreline
EC	Electrical Conductivity
GIS	Geographic Information System
G	Groundwater occurrence
GALDIT	Groundwater occurrence, Aquifer hydraulic conductivity, Level of groundwater above sea level, Distance from shoreline, Impact of existing seawater intrusion, Thickness of aquifer
IDW	Inverse Distance Weighting
I	Impact of existing seawater intrusion
L	Height of groundwater level above sea level
MRSA	Map Removal Sensitivity Analysis
R_i	Rating of parameter i
SWI	Seawater Intrusion
SWL	Static Water Level
SPSA	Single Parameter Sensitivity Analysis
TDS	Total Dissolved Solids
T	Aquifer thickness
UTM	Universal Transverse Mercator
W_i	Weight of parameter i

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