sustainability

MDPI

Case Report

A Numerical Approach to Evaluating Groundwater Vulnerability to Seawater Intrusion on Jeju Volcanic Island, South Korea

Dongyeop Lee [1,2], Jonghoon Park [1], Hyun A. Lee [2] and Nam C. Woo [1,*]

[1] Department of Earth System Sciences, Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul 03722, Republic of Korea
[2] Groundwater Research Center, Jeju Research Institute, 253 Ayeon-ro, Jeju-si 63147, Republic of Korea
* Correspondence: ncwoo@yonsei.ac.kr

Abstract: Seawater intrusion (SWI) is a critical issue for coastal aquifers, especially in islands where groundwater is the sole source of water supply. The objective of this study was to develop a straightforward approach to evaluating groundwater vulnerability to SWI, using a statistical method with spatial analyses applied to the four basins of Jeju volcanic island. In this study, five factors were parametrized, including hydraulic conductivity, groundwater level, distance from shoreline to wells, well depth and groundwater use. These parameters were spatially interpolated and correlated with groundwater electrical conductivity as a proxy for groundwater salinization, resulting in three parameters with significant relations: groundwater use, well depth, and groundwater level. Then, a numerical model for the SWI vulnerability assessment was constructed using ratings and weights, and by evaluating the vulnerability as weak, moderate and high with a numerical index. Regional conditions, including major land-use types, industrial activities, population and the degree of urbanisation, could affect parameters differently at each region. Based on the percentage of area with a high vulnerability, regions of Jeju Island followed the order of eastern > northern > western > southern, indicating that preventive measures for SWI and its influencing parameters could be applied more effectively in certain regions.

Keywords: coastal aquifers; geostatistics; groundwater vulnerability; seawater intrusion; water resources; groundwater management

Citation: Lee, D.; Park, J.; Lee, H.A.; Woo, N.C. A Numerical Approach to Evaluating Groundwater Vulnerability to Seawater Intrusion on Jeju Volcanic Island, South Korea. *Sustainability* **2023**, *15*, 3081. https://doi.org/10.3390/su15043081

Academic Editor: Steve W. Lyon

Received: 17 November 2022
Revised: 11 January 2023
Accepted: 6 February 2023
Published: 8 February 2023

1. Introduction

Coastal areas contain important habitats and have experienced significant population growth, particularly those located in economic centres such as New York, Tokyo, Shanghai and Mumbai [1]. More than 45% of the world's population lives within 100 km of the coastline, and the average population density (87 people/km^2) is approximately four times higher in coastal areas than inland areas (23 people/km^2) [2]. In densely populated coastal areas, coastal aquifers act as a major source of freshwater supply [3]. However, due to the high demand for water and proximity to the coast, coastal aquifers may be affected by groundwater depletion and the resulting potential for seawater intrusion (SWI) [4]. In particular, SWI seriously impacts water use on islands and specific coastal areas where groundwater accounts for the majority of the freshwater supply; such sustainable groundwater management in coastal areas has emerged as a major concern [5].

In coastal aquifers, fresh and saline groundwater are in a natural equilibrium, with a transition zone sloping in the inland direction. When the groundwater level in the coastal aquifer drops due to excessive groundwater pumping and land-use changes that hamper groundwater recharge processes, seawater penetrates into the aquifer [6]. Consequently, SWI increases the salinity of groundwater, resulting in significant economic losses as the water loses its usability for drinking, agricultural and industrial purposes [7]. Therefore, a vulnerability assessment has been used to prevent and manage SWI into aquifers [8].

Vulnerability refers to the potential risk or sensitivity of a system to human or natural effects [9]. In many areas where groundwater is used as a major water resource, a vulnerability assessment has been employed for water resource management and land-use planning, and groundwater protection from pollution [10,11]. Assessment techniques based on numerical ranking systems have been developed, which intuitively illustrate the vulnerability of aquifers through spatial mapping. For example, DRASTIC [12] and SINTACS [13] are methods for assessing aquifer vulnerability to surface contaminants, while GALDIT [14–16] is a method for assessing vulnerability to SWI.

The DRASTIC method is one of the most widely used methods for the assessment of intrinsic aquifer vulnerability. DRASTIC uses seven hydrogeological parameters: depth to groundwater (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of the vadose zone (I), and hydraulic conductivity (C). The SINTACS method is a modification of the widely used DRASTIC method. The approach assesses intrinsic groundwater vulnerability through the seven hydrogeological parameters: water table depth (S), effective infiltration (I), unsaturated conditions (N), soil media (T), aquifer hydrogeologic characteristics (A), hydraulic conductivity (C), and topographic slope (S). DRASTIC and similar numerical methods are applicable to situations where potential contaminants at the surface are assumed to move downward through the recharge process and are affected by the amount of recharge and the physical properties of geologic materials. However, in coastal fresh groundwater interfacing with a saline water body (seawater and saline groundwater), the SWI process occurs horizontally along the interface between fresh and saline groundwater bodies. Therefore, the parameters for SWI vulnerability would be different from the methods (e.g., DRASTIC, SINTACS) that assume that intrinsic vulnerability is linked to vertical contaminant migration.

The GALDIT method assesses the vulnerability of large areas with complex geological settings to SWI using six factors: aquifer type (G), water conductivity (A), groundwater level (L), distance from the shoreline (D), the effect of seawater intrusion (I) and thickness (T). However, as factor (I) represents the effect of SWI as the molar ratio of chloride ions to bi-carbonate ions, the results of the GALDIT assessment intrinsically reflect the current state of SWI. Therefore, a map showing SWI potential based on the GALDIT method is actually a map of the consequences of SWI rather than the potential for SWI due to natural and anthropogenic factors.

With a population of approximately 697,000, Jeju volcanic island is located to the south of the Korean Peninsula, and around 92% of drinking, agricultural and industrial water is obtained from groundwater in the coastal areas of Jeju Island (https://www.jeju.go.kr/stats/index.htm, (accessed on March 2022)). This high intensity of groundwater use in coastal areas has the potential to cause a water-level decline due to groundwater depletion and cause subsequent SWI into the coastal aquifers. In some parts of eastern and western Jeju Island, these phenomena have been already reported [17,18]. Thus, vulnerability to SWI was assessed using a modified GALDIT method, replacing I factors with EC values [19]. Nevertheless, the issue of using parameters directly affected by the SWI as an input parameter of assessment for SWI still remains to be discussed.

Therefore, the aim of this study was to develop a vulnerability assessment model for SWI through the identification of factors affecting the SWI, while considering the hydrogeological environment of Jeju Island; this is characterised by volcanic geology, man-made factors related to the well construction and the amount of pumping that can be manageable through the institutional frameworks. This study introduces a simple and intuitive approach that can be applied in regions with various hydrogeological settings and anthropogenic factors that have a similar dependency on groundwater resources.

2. Materials and Methods

2.1. Study Area

Jeju Island is located at the south-western end of the Korean Peninsula (33°10′–33°34′ N, 126°10′–127° E) and covers an area of 1846 km^2. The island is elliptical, with distances of 73.3 km from east to west, and 41.0 km from north to south (Figure 1a). Mt. Halla, the main volcanic mountain at the centre of the island, is approximately 1950 m in elevation above mean sea level (amsl). The island is divided into coastal, mid-mountainous, and mountainous areas, corresponding to elevations less than 200 m, between 200 and 600 m, and greater than 600 m, respectively [20]. The topography of the Jeju island is controlled by volcanic eruption characteristics that show a gentle topography formed by low-viscosity basaltic lava flows on the east-west slope of Mt. Halla, and a relatively steep north-south slope formed by high-viscosity trachytic lava flows [20]. The water resources of the island are being managed by east, west, south, and north hydrologic basins, which are defined by surface topography [21].

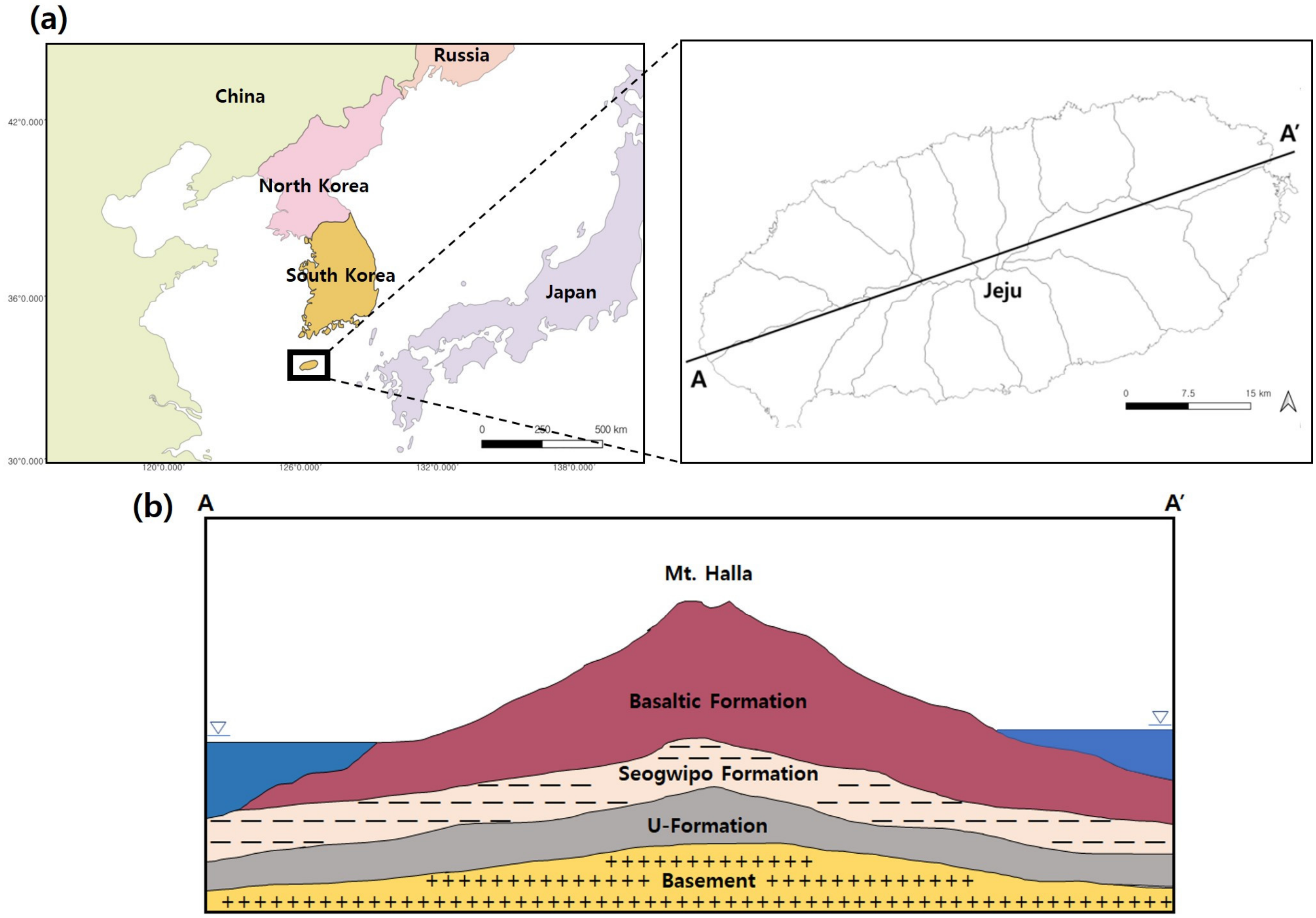

Figure 1. (**a**) Location of the study area, Jeju Island, South Korea, and (**b**) a schematic cross-section by crossline (A-A′) of its geology (vertically exaggerated without scale); modified from [22].

The geology of Jeju Island can be described as a macroscopic stratigraphy of bedrock, U Formation, Seogwipo Formation and basalts, ordered from bottom to top (Figure 1b). The bedrock consists of granite and volcanic rocks, and occurs at depths of 155–312 m below sea level. The U Formation consists of clay and fine sand with an average thickness of approximately 150 m. The Seogwipo Formation is a sedimentary layer comprising mudstone and sandstone with an average thickness of approximately 100 m. Basalts originating from lava flow are distributed from the top of the mountain to 150 m below sea level [21]. The surface geology of the island is dominated by basaltic bedrocks, and thus their physical properties have a significant effect on groundwater processes such as groundwater circulation through recharge and discharge, the hydraulic characteristics of the aquifer, the formation of and variation in groundwater storage, the distribution of natural springs, and water quality and vulnerability to contamination [21]. Due to its volcanic nature, Jeju Island has limited surface water resources, and groundwater formed through the precipitation recharge process is the sole source of water, with volcanic rocks connected by fractures serving as the primary aquifer.

Based on climate data from 2001 to 2010, coastal areas have a subtropical climate with an average annual temperature of 15.5 to 16.2 °C and an annual precipitation of 1200 to 1890 mm. Due to the influence of Mt. Halla in the center of Jeju Island, the amount of annual precipitation increases with an increase in altitude above sea level, and in high altitude areas, it is 4345–4539 mm, more than twice the amount of precipitation in coastal areas [21].

On Jeju Island, 6409 (91%) of the 7043 groundwater wells presently in use are located in coastal areas with elevations lower than 200 m amsl (https://water.jeju.go.kr/, accessed on March 2022). In a survey of groundwater levels in 250 wells, 39 wells (15.6%) had water levels below sea level, and water levels are above sea level in the remaining wells (Figure S1) [23]. If the groundwater level is below sea level, likely due to the over-exploitation of groundwater resources, the saline groundwater flow towards land increases, and subsequently increases the area's vulnerability to SWI [24]. Therefore, this study focused on the development of a groundwater vulnerability assessment model for SWI in coastal areas, where many wells are in use.

2.2. Data Acquisition

SWI refers to the inland movement of seawater along the coastal aquifer, and occurs horizontally along the interface between fresh and saline groundwater bodies due to the differences in hydraulic heads. Therefore, the driving force of SWI could be any factor that affects the hydraulic potential in the coastal aquifer; this includes natural factors, such as sea-level changes, tidal effects and the amount of precipitation recharge, and also anthropogenic factors, such as well development and groundwater pumping in the coastal aquifer. These factors vary both temporally and spatially. With the demand for groundwater supply continuously increasing in many coastal regions due to economic development, overexploitation of groundwater from the coastal aquifer has been reported to induce lower groundwater levels, subsequently driving SWI [25–30]. Therefore, both natural and anthropogenic factors should be considered to evaluate groundwater vulnerability to SWI.

In the study area, Jeju volcanic island, factors related to SWI were surveyed through the published and documented database from various government websites and reports [17,19]. Since the SWI vulnerability assessment was developed as a management tool for the local government, readily available data were combined to calculate the SWI vulnerability index. Figure 2 is a schematic diagram showing the equilibrium state between fresh and saline groundwater, along with natural and artificial factors that can cause the movement of the fresh–saline interface in the coastal aquifer.

To develop a vulnerability assessment model for SWI in this study, the following parameters and data were used:

1. Hydraulic conductivity of the aquifer (K): Based on pumping tests, hydraulic conductivity data for 296 wells were obtained from the Korea Water Resources Corporation [12] (Figure 3a).
2. Groundwater level (L): Water-level data observed in 393 wells were used, including 250 wells assessed by [12] in June 2018 and 143 wells monitored by the Jeju Special Self-Governing Province (https://water.jeju.go.kr/; Figure 3b).
3. Distance from the shoreline (D): SWI decreases with increasing distance from the shoreline [31]. In this study, a geographic information system (GIS) was used to calculate the shortest distance to the coastal boundary.

4. Well depth relative to mean sea level (W): Well depth generally represents the total depth of the borehole drilled for pumping wells measured from the land surface. However, where the well depth is above mean sea level (MSL), the impact of the water-level decrease on SWI is much smaller than that for wells that are open below MSL, as the pumping of wells that open deep in the aquifer directly induces fresh and saline groundwater flows. In addition, even for wells that are installed below MSL, the impact of pumping on SWI may be related to the screen length of the wells. A longer screen length below the MSL will lead to a stronger impact on SWI in a given aquifer. For this parameter, data from a total of 7043 registered wells were used. In the coastal areas of Jeju Island, most pumping wells tap into the primary aquifer comprising volcanic rocks. These wells have a structure of grouting in the unsaturated top portion, which prevents contaminant leakage from the land surface, and an open bore for water intake that accommodates groundwater inflows from as many fracture zones as possible. Therefore, considering the characteristics of the fractured aquifer and the well structures used in the study area, we defined a well depth that could affect the SWI as the length of the well below sea level. Considering this, with an increasing well depth, a well can draw more groundwater, both fresh and saline, and thus its impact on SWI increases. In this study, data from a total of 7043 wells across the island were used (Figure 3c; Jeju, 2022).
5. Groundwater use (U): Lowering of the water level due to groundwater pumping is one of the most important factors affecting SWI, and the amount of pumping directly impacts the intensity of SWI in coastal aquifers. However, accurately measured data on the amount of groundwater pumped from each well are not currently available. Therefore, in this study, we replaced the groundwater use data with the permitted withdrawal levels of those wells (https://water.jeju.go.kr/), including a total of 4566 fresh groundwater pumping wells and 1225 saline groundwater pumping wells. In addition, saline groundwater has been exploited in coastal areas for aquaculture. According to the Jeju Research Institute (2019), the local saline groundwater is a mixture of fresh and saline waters from the inland and seaward sides, with an average mixing ratio of fresh groundwater in saline groundwater of 13.4%, along with ratios of 11.8% in the east and 27.9% in the west. As saline groundwater has a total permitted intake 5.3 times greater than that of fresh groundwater, from the perspective of total groundwater usage on Jeju Island, the amount of fresh groundwater in the saline groundwater is nearly equal to the total amount of fresh groundwater pumping permitted. Furthermore, the amount of saline groundwater use per well for aquaculture, which accounts for 90.3% of total saline groundwater use, is approximately 22 times the amount of fresh groundwater pumped; thus, the drop in the groundwater level in the surrounding area and the resulting SWI cannot be overlooked [17]. Therefore, in this study, data from 4566 freshwater wells and 1225 saline groundwater wells were used as estimates of groundwater use (Figure 3d).
6. Electrical conductivity (EC): The consequences of SWI can be represented as an increase in EC, the total dissolved solids (TDS), or the major ions in groundwater [32]. In this study, considering data availability and the significance of spatial interpolation, the EC distribution in groundwater was used as an indirect indicator reflecting the influence of SWI, in order to validate the SWI vulnerability assessment model. EC data were obtained from 250 wells monitored by [23] and 1382 wells monitored by Jeju Special Self-Governing Province (Figure 3e).

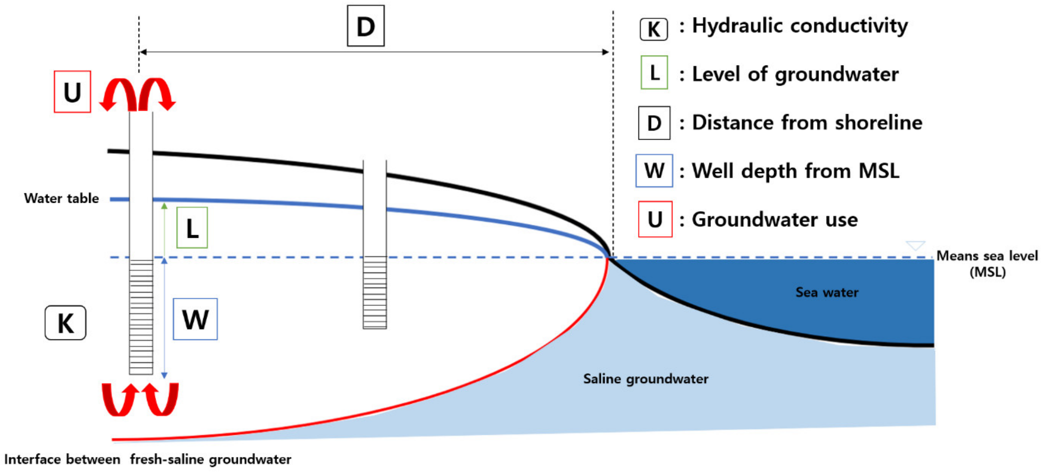

Figure 2. Schematic diagram of the parameters used in this study.

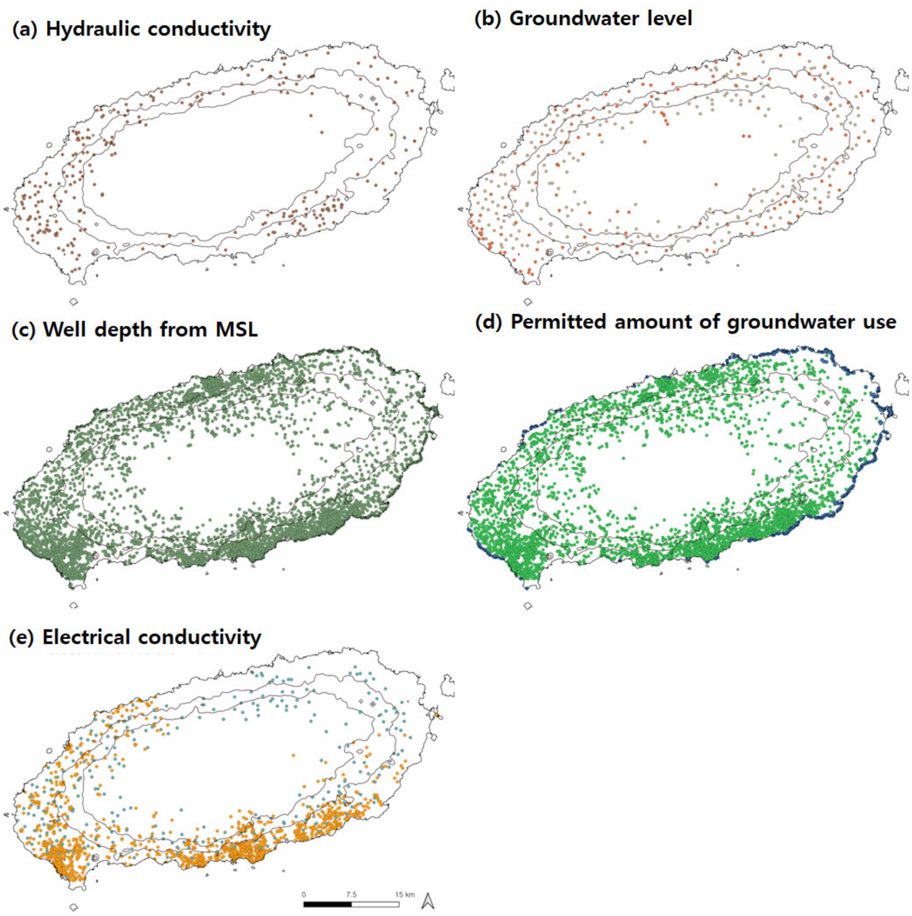

Figure 3. Distributions of wells on Jeju Island for each parameter: (**a**) aquifer hydraulic conductivity (data from [23]), (**b**) groundwater level (red dots: data from [23]; grey dots: data from Jeju Special Self-Governing Province, https://water.jeju.go.kr/), (**c**) well depth from sea level (data from Jeju Special Self-Governing Province, https://water.jeju.go.kr/, green dots for fresh groundwater wells and black dots for saline groundwater wells), (**d**) permitted amount of groundwater pumping (data from Jeju Special Self-Governing Province, https://water.jeju.go.kr/, green dots for fresh groundwater wells and black dots for saline groundwater wells), (**e**) electrical conductivity of groundwater (orange dots: data from [23]; blue dots: data from Jeju Special Self-Governing Province, https://water.jeju.go.kr/).

For aquifer type, parameter (G) of the GALDIT method, the hydrogeological characteristics of the volcanic rocks comprising the uppermost aquifer affected by SWI were assumed to be the same as those of the unconfined aquifer. Consequently, the aquifer type was excluded from the vulnerability model used to evaluate the spatial variations in SWI potential on Jeju Island. Nevertheless, if the method described in this study is applied to other regions, the aquifer type should be considered an essential parameter of coastal aquifers for SWI assessment.

The available well data used in this study vary depending on the specific objectives of government-funded projects and surveys. In this study, we used as many observations as possible from the available references to clarify the present conditions of coastal groundwater on Jeju Island. Consequently, the number of observations used differed among parameters, and the spatial distributions of data were interpolated using QGIS and geostatistical analysis.

2.3. Development of the Vulnerability Assessment Model

In the numerical ranking system used for the vulnerability assessment, parameters should be properly rated and weighted according to their variation ranges [33]. Thus, for this study, parameters were divided using the quartile system into ranges of the minimum to the first quartile, the first quartile to the median, the median to the third quartile and the third quartile to the maximum observed value, which were assigned rates of 2.5, 5.0, 7.5 and 10.0, respectively.

The weighting of parameters indicates their relative influences on SWI. Two methods are used for assigning weights: subjective weighting based on expert knowledge and experience, and objective weighting based on mathematical evaluation of data [34]. The DRASTIC method introduced by Aller (1985) is a typical example of an aquifer vulnerability model using the subjective method for seven parameters.

However, in this study, an expert evaluation of the parameters affecting SWI was not possible, and thus the objective weighting method, based on a geostatistical analysis of the parameters, was applied to derive the weights of the parameters impacting SWI. The weights were optimised in the order of the parameters' influence strengths identified in the geostatistical analysis, assuming dependence among the selected parameters (Figure S2).

Figure 4 shows a flow chart summarising the development of the groundwater vulnerability assessment model for SWI. This methodology is represented in the following steps:

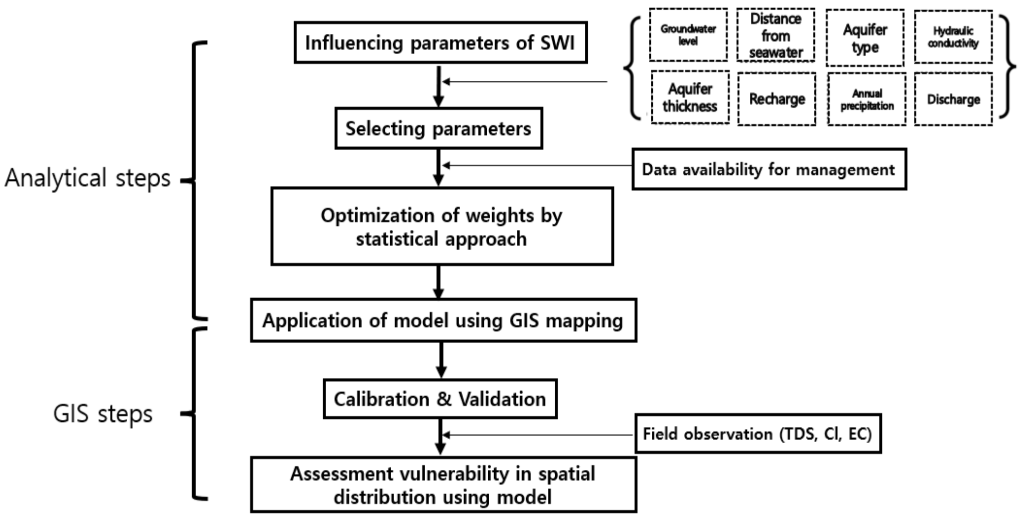

Figure 4. Flow chart of the development of the groundwater vulnerability model for seawater intrusion using the parameter weighting and rating methods.

(1) Parameters that may affect SWI were identified, and available data were collected from various references provided by the national and local governments. Parameters

related to groundwater were obtained from the registered pumping and monitoring wells, resulting in variations in well locations and their number of data depending on the period and method of investigation, which were adapted to the reports. In addition, the data show nonlinear characteristics reflecting the variability of nature. Logarithmic transformation of these data could alleviate these non-linearity problems for statistical analysis [35]. Therefore, log-transformation was performed for data that occur in a wide range (namely hydraulic conductivity, distance from the shoreline, permitted amount of groundwater and EC).

(2) Point data from wells were converted into a spatial distribution using the Quantum Geographic Information System (QGIS) software (https://qgis.org/, accessed on March 2022). The spatial distribution of observations differed among parameters. Thus, the inverse distance weighting method was used to reduce the influence of data density on the spatial interpolation (Supplementary Material S1). This method is a spatial interpolation technique across geographic space, wherein the characteristics of any given two points are connected, with their similarity being inversely proportional to the distance between the two positions [36–38].

(3) A non-parametric statistical approach that can be applied to data with non-normal distributions, Spearman's ρ correlation analysis, was applied to determine whether those influencing parameters actually affect SWI in the study area. The analysis was conducted after the log-transformation and spatial interpolation of data. Spearman's ρ measures the strength of the monotonic relationship between variables (Equation (1)), and thus could be used to verify the adequacy of the selected parameters, the reliability of weight optimisation, and subsequently the validity of the assessed vulnerability information [30]. Afterward, the relationships between parameters were interpreted based on Spearman's ρ correlation coefficients, as indicated in Table 1 [39].

$$P = \frac{\sum_{i=1}^{n}(Rx_i\ Ry_i) - n\left(\frac{n+1}{2}\right)^2}{n(n^2-1)/12} \tag{1}$$

where Rx_i is the ranking of i_{th} in variable x; Ry_i is the ranking of i_{th} in variable y; and n is the number of data.

Table 1. Interpretation of correlations using Spearman's ρ [39].

Spearman's ρ	Correlation
≥0.70	Very strong relationship
0.40–0.69	Strong relationship
0.30–0.39	Moderate relationship
0.20–0.29	Weak relationship
0.01–0.19	No or negligible relationship

(4) A rate and a weight were assigned to each parameter using spatial analyses in the QGIS and the Spearman's ρ correlation analysis (Figure S2). Then, using these rates and weights, the vulnerability index was calculated as follows:

$$\text{Vulnerability index} = \sum(W_i\ R_i)/\sum W \tag{2}$$

where R_i is the rating of the i_{th} parameter, and W_i is the weight of the i_{th} parameter.

(5) The groundwater vulnerability map to SWI in the coastal areas of Jeju Island was produced, showing the spatial variation in SWI vulnerability. To prioritise groundwater management efforts to prevent SWI, the vulnerability index was classified into three groups: weak, moderate and high potential for SWI.

The vulnerability assessment model developed here was validated through the comparison of the model output, i.e., the map of SWI vulnerability, with the distribution of EC in coastal groundwater. SWI into the coastal aquifer could be identified from the concentration of TDS in groundwater, due to the salinity of seawater. On Jeju Island, the EC of groundwater is observed in real time through a groundwater monitoring network. Thus, EC monitoring data were used as an indicator of the effect and spatial distribution of SWI, and subsequently as field data to verify the vulnerability model developed in this study. The correlation between TDS and EC observations in [23] confirms their proportionality, with a correlation coefficient of 0.70 (Table S2, Figure S3).

3. Results and Discussion

3.1. Parameter Selection for Vulnerability Assessment

The descriptive statistics of SWI influencing the parameters of Jeju Island, including hydraulic conductivity (K), groundwater level (L), distance from the shoreline (D), well depth (W) and groundwater use (U), are presented in Table 2. The hydraulic conductivity, distance from the shoreline and groundwater use show large variations, covering four to five orders of magnitude. Thus, these data were converted to the natural log scale, and then a geostatistical analysis of their spatial variations was conducted (Figure 5).

To determine whether these influencing parameters affect SWI on Jeju Island, their data were correlated with EC. For this correlation analysis, a nonparametric correlation method using Spearman's ρ was applied. The local government of Jeju manages water resources as four hydrologic basins [21]; thus, the geostatistical analysis in this study was performed based on these four regions (Table 3). The results of the statistical analysis were evaluated based on the criteria provided in Table 1, indicating relatively strong relationships as bold.

The parameters with significant effects on SWI by region were as follows: groundwater level and groundwater use in the eastern region; groundwater level, well depth and groundwater use in the western region; groundwater use in the southern region; and groundwater level and distance from the shoreline in the northern region (Table 3).

In general, the effect of SWI increases as the hydraulic conductivity of a coastal aquifer increases [40]. However, fewer data for hydraulic conductivity were obtained in the field than for other parameters, resulting in weak or negligible correlations in all regions, likely due to the limitations of the interpolation method used to fill areas lacking data. Furthermore, SWI generally exhibits a negative correlation, decreasing as the distance from the shoreline increases [31]. However, no such relationship was clear in this study area, and the inverse relationship was observed in the northern region. As the groundwater EC values represent TDS, which could be derived from various natural and anthropogenic sources as well as SWI, these abnormal correlations between the distance from the shoreline and the groundwater EC may be a limitation of this study, based on the assumption that TDS is associated with SWI. Consequently, both hydraulic conductivity and distance from the shoreline were excluded from the parameters used to develop regional SWI vulnerability models in this study.

Table 2. Descriptive statistics of seawater intrusion influencing parameters on Jeju Island.

Parameter	Minimum	Median	Maximum
Aquifer hydraulic conductivity (K) [m/day]	0.2	33.2	1381.6
Groundwater level (L) [m]	−63.6	12.6	152.8
Distance from the shoreline (D) [m]	0.0	2395	10,278
Well depth below sea level (W) [m]	−103	31	126
Groundwater use (U) [m^3/month]	287	14,879	265,177

Table 3. Results of nonparametric correlation analysis of each parameter with electrical conductivity.

	Spearman's ρ				
	K	**L**	**D**	**W**	**U**
Eastern	0.14	**−0.48**	0.14	0.08	**0.32**
Western	−0.23	**−0.42**	−0.19	**0.53**	**0.51**
Southern	−0.01	0.09	0.26	0.13	**0.44**
Northern	−0.11	**−0.36**	**0.39**	−0.19	0.05

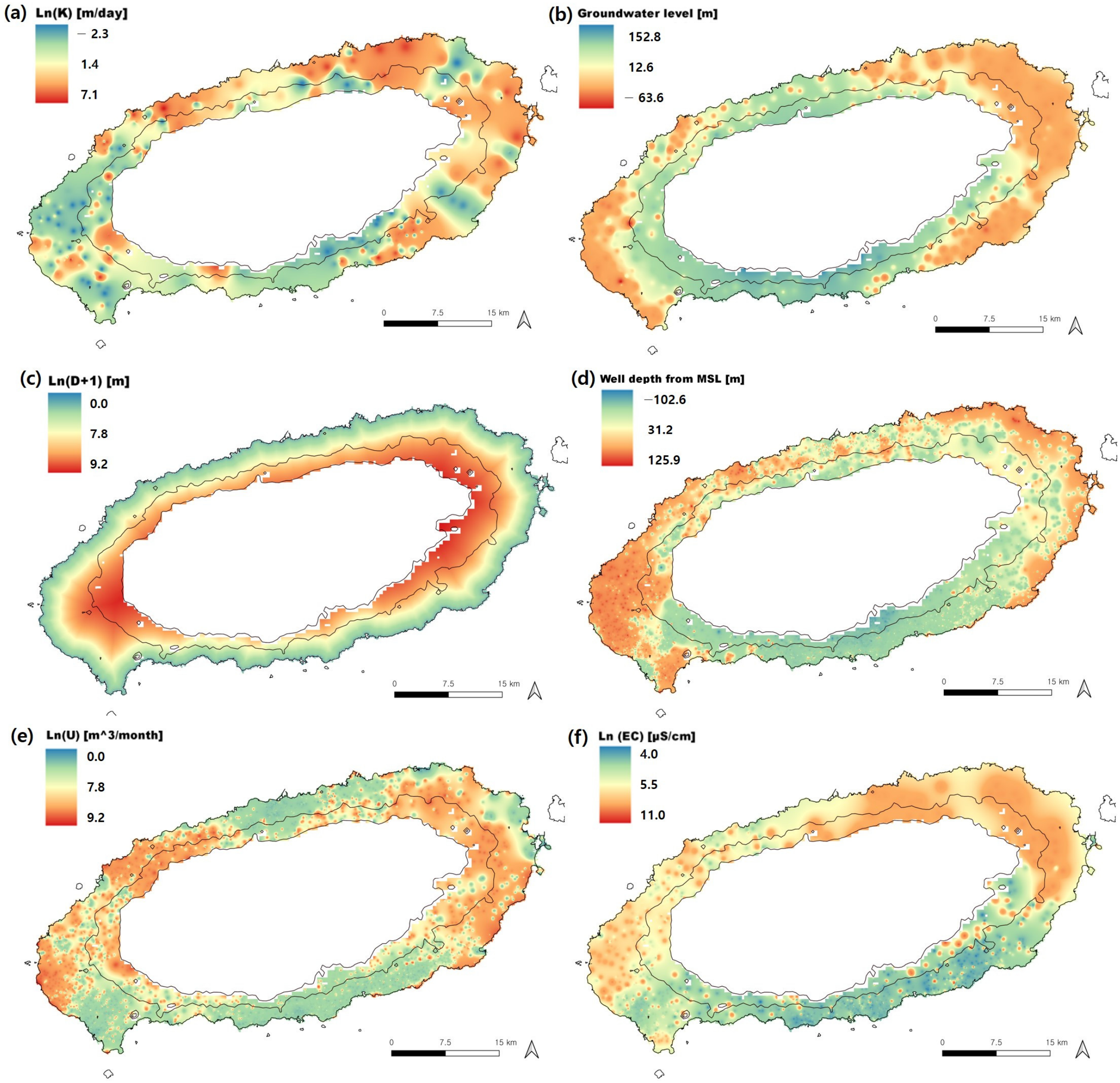

Figure 5. Spatial distribution of each parameter affecting seawater intrusion with electrical conductivity obtained from QGIS using inverse distance weighting: (**a**) hydraulic conductivity, (**b**) groundwater level, (**c**) distance from the shoreline, (**d**) well depth from mean sea level, (**e**) groundwater use and (**f**) electrical conductivity of groundwater.

3.2. Assigning Ratings and Weights to Parameters

To expand the point groundwater data from wells to spatially continuous data, coastal areas lower than 200 m in elevation were divided into a grid of 100 m × 100 m. For grid cells with no observations, the inverse distance-weighted interpolation of observation data was applied to obtain numerical data (Figure 6). Then, ratings of 2.5, 5, 7.5 and 10 were assigned to each parameter, based on the quantiles of the range in the observed data (Table 4).

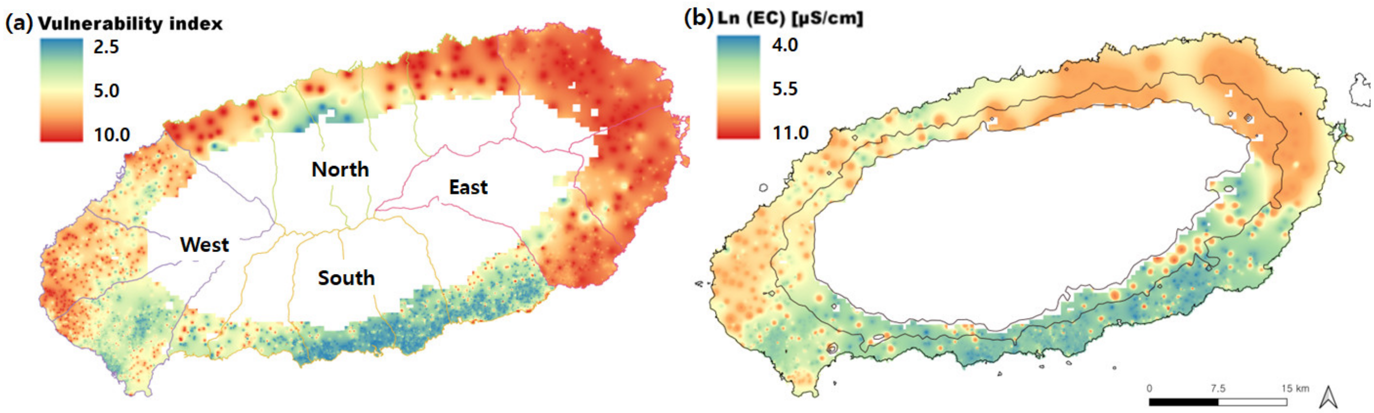

Figure 6. Spatial distributions of (**a**) vulnerability index and (**b**) electrical conductivity in the study area.

Table 4. Data range of each parameter used for rating.

Parameter	Range	Rating
Groundwater level above sea level (m)	<7.2 7.2–12.6 12.6–25.0 >25.0	10 7.5 5 2.5
Well depth from mean sea level (m)	>38.1 31.2–38.1 25.9–31.2 <25.9	10 7.5 5 2.5
Groundwater use (m^3/month) * Data: ln(U)	>9.2 8.7–9.2 8.2–8.7 <8.2	10 7.5 5 2.5

The weights of influencing parameters on SWI indicate the relative influences of each parameter. Therefore, based on the relative influences identified from the correlations between each parameter and EC, a weight optimisation operation was performed for each region (Table 5). In the eastern region, the weights of groundwater level and the groundwater use, optimised in terms of their relative influences on SWI, were 4.5 and 1.0, respectively. In the western region, the weights of groundwater use, well depth and groundwater level were 1.7, 1.6 and 0.4, respectively. In the southern and northern regions, single parameters were found to influence SWI, namely groundwater use and groundwater level, respectively. Thus, the weights of these single parameters were set to 1 for calculating the vulnerability index.

Then, the spatial distribution of the SWI vulnerability index in the coastal area was calculated following Equation (2). The results showed significant and strong correlations with the distribution of EC data, suggesting an effect of SWI, with correlation coefficients of 0.58, 0.67, 0.44 and 0.36 in the eastern, western, southern and northern regions, respectively.

Table 5. Optimised weights and relative effects of each parameter on seawater intrusion, and the explanatory power based on Spearman's ρ of selected parameters affecting seawater intrusion potential.

	Weight (Relative Weight)			Spearman's ρ
	L **	W **	U **	
Eastern	4.5 (81.8%)	-	1.0 (18.2%)	0.58 *
Western	0.4 (10.8%)	1.6 (43.2%)	1.7 (45.9%)	0.67 *
Southern	-	-	1.0 (100.0%)	0.44 *
Northern	1.0 (100.0%)	-	-	0.36 *

*: $p < 0.05$, **: L, W, and U denote groundwater level, well depth, and groundwater use, respectively.

3.3. Vulnerability Assessment of Jeju Island

Using a GIS technique, a vulnerability map of SWI in the coastal areas of Jeju Island was constructed through the integration of a regional vulnerability index (Figure 6). To prioritise groundwater management efforts to prevent SWI, the vulnerability index was classified into three groups: weak (<5.0), moderate (5.0–7.5) and high (>7.5) potential for SWI.

In the western region, approximately 29% and 62% of the area had high and moderate vulnerability to SWI, respectively (Table 6). In contrast to the eastern region, SWI in this region was affected by three parameters: groundwater use (relative influence: 46%), well depth (43%) and groundwater level (11%; Table 5). These impacts are likely due to intensive agricultural activity (Figure S3) and large amounts of saline groundwater use for aquaculture along the coast (Figure 3d). SWI was reported in this region in 2009, 2011 and 2017 [17]. If the current method of using or developing groundwater resources is maintained, SWI is expected to expand. Thus, to prevent further SWI in this region, management policies to reduce groundwater usage should first be applied to agricultural and aquacultural activities that depend on groundwater resources; these include shifting toward crops with lower water demands and micro-irrigation in the dry season, the application of managed artificial recharge in the rainy season, and the management of saline groundwater usage. In addition, the amount of groundwater pumping and the depths of groundwater-pumping wells should be properly managed. The local government of Jeju Special Self-Governing Province has enacted a local groundwater management law in the form of a permitting system, which controls the amount of groundwater development; this also requires a specific well design to prevent contaminant inflow through the borehole wall.

Table 6. Vulnerability index values in each region.

Vulnerability	Percentage of Area			
	Eastern	Western	Southern	Northern
Weak	0.5%	9.3%	62.3%	7.4%
Moderate	10.1%	62.2%	34.0%	37.8%
High	89.4%	28.5%	3.7%	54.8%

In the southern region, with Seogwipo City located at its centre, groundwater use was the most important parameter affecting SWI. This region has been developed for decades for tourism, with abundant facilities for travel and leisure, in addition to traditional farms growing Mandarin oranges. The over-exploitation of groundwater has caused SWI into the coastal aquifer. Nevertheless, more than 62% of the region showed weak vulnerability to SWI and only around 4% of the area had high vulnerability (Table 6). This pattern is likely due to the hydrogeological characteristics of the region, where thick sedimentary layers with relatively low hydraulic conductivity, namely the Seogwipo Formation comprising mudstone and sandstone, are exposed above sea level (Figure 5a).

The northern region contains Jeju City and the main facilities of the Jeju local government. For the last several decades, most of this region has rapidly urbanised, with increases in both the resident population and tourists. As water for drinking and domestic use is supplied through a piped distribution system in most of this region, groundwater level, as an influencing parameter of SWI, could be driven by the water-level decrease; this is caused by the reduction in groundwater recharge due to rapid urbanisation, the expansion of pavement, preventing the infiltration of precipitation through the land surface, as well as population growth, leading to greater water demand. Consequently, approximately 93% of the region showed moderate to high vulnerability to SWI (Table 6). Various techniques could be applied to enhance precipitation recharge, including managed artificial recharge or the development of a building code that provides sufficient recharge area.

4. Conclusions

This study was conducted to develop a vulnerability assessment model for SWI in the coastal aquifers of Jeju volcanic island. The model was developed via the following steps: the collection of the available groundwater data, the transformation of groundwater point data into continuous spatial data using the inverse distance weighting method and QGIS, the identification of SWI influencing parameters based on correlations with EC as a proxy for SWI, the assignment of ratings and weights to data ranges and determining their relative influences on SWI, and the interpretation of SWI potential, based on the estimated vulnerability index values.

The geostatistical analysis of data was conducted separately for the eastern, western, southern and northern regions, as these regions have significant differences in their major land-use types, industrial activities, population and degree of urbanisation. As a result, three SWI influencing parameters were identified: groundwater level, well depth and groundwater use. However, each region showed differences in SWI influencing parameters and their relative impacts on vulnerability, likely due to differences in their regional characteristics.

SWI vulnerability was classified as weak, moderate or high. The percentage of high vulnerability areas for each region was ranked in the order of eastern > northern > western > southern. High vulnerability to SWI in the eastern region indicates that the present empirical management of avoiding groundwater resource development in this region appears to be scientifically appropriate. In contrast, more than 90% of the areas of the northern and western regions had a moderate to high vulnerability; thus, preventive management of SWI is urgently needed for sustainable water supply. The southern region had a lower vulnerability than the other regions. As groundwater use was identified as the most important parameter, continuous efforts to control the amount of groundwater pumping through institutional regulations are needed.

The SWI potential determined in this study is a simple and intuitive method that used statistical and geospatial analyses of the available data in the study area. The results of this study could provide local government with a simple and intuitive measure in order to manage coastal aquifers efficaciously, using extensive groundwater monitoring data and fast-decision making processes. However, it could also have limitations; these include the irregular distribution of well data (Figure 5) and the replacement of actual pumping data with permitted groundwater use. These limitations could be minimised through expanded surveying and the continuous monitoring of groundwater pumping in the future.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15043081/s1, S1: Inverse distance weighting method; Table S1: The mixing ratio of fresh-groundwater to saline groundwater in each region; Table S2: Spearman's ρ correlation analysis between electrical conductivity and TDS; Figure S1: Plots of groundwater level according to the elevation of wells in each region of Jeju island (data from MOE and K-water, 2018) title; Figure S2: Flow chart of the optimization method; Figure S3: Correlation plots of the total dissolved solids against electrical conductivities of groundwater.

Author Contributions: D.L. and N.C.W. conceived and designed the research; D.L. performed the data collection and analysis; J.P. and H.A.L. reviewed the data and geostatistical approach. D.L.

performed GIS visualization and wrote the draft. N.C.W. revised the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2017R1A6A1A07015374).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This paper was published as a part of D.L's master's thesis at Yonsei University, 2022.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Nicholls, R.J. Planning for the impacts of sea level rise. *Oceanography* **2011**, *24*, 144–157.
2. Fernandino, G.; Elliff, C.I.; Silva, I.R. Ecosystem-based management of coastal zones in face of climate change impacts: Challenges and inequalities. *J. Environ. Manag.* **2018**, *215*, 32–39.
3. Kaliraj, S.; Chandrasekar, N.; Peter, T.S.; Selvakumar, S.; Magesh, N.S. Mapping of coastal aquifer vulnerable zone in the south west coast of Kanyakumari, South India, using GIS-based DRASTIC model. *Environ. Monit. Assess.* **2015**, *187*, 4073.
4. Van Camp, M.; Yohana, M.; Mjemah, I.C.; Bakundukize, C.; Walraevens, K. Investigating seawater intrusion due to groundwater pumping with schematic model simulations: The example of the Dar es Salaam coastal aquifer in Tanzania. *J. Afr. Earth Sci.* **2014**, *96*, 71–78.
5. Bremer, L.L.; Elshall, A.S.; Wada, C.A.; Brewington, L.; Delevaux, J.; El-Kadi, A.I.; Voss, C.I.; Burnett, K.M. Effects of land-cover and watershed protection futures on sustainable groundwater management in a heavily utilized aquifer in Hawai 'i (USA). *Hydrogeol. J.* **2021**, *29*, 1749–1765.
6. Duerrast, H.; Srattakal, J. Geophysical Investigations of Saltwater Intrusion into the Coastal Groundwater Aquifers of Songkhla City, Southern Thailand. In *Groundwater in the Coastal Zones of Asia-Pacific*; Springer: Dordrecht, The Netherlands, 2013; pp. 155–175.
7. Lee, Y.K.; Lee, H.S. Numerical modeling of seawater intrusion in coastal aquifer. *Tunn. Undergr. Space* **2004**, *14*, 229–240.
8. Lappas, I.; Kallioras, A.; Pliakas, F.; Rondogianni, T. Groundwater vulnerability assessment to seawater intrusion through GIS-based Galdit method. Case study: Atalanti coastal aquifer, central Greece. *Bull. Geol. Soc. Greece* **2016**, *50*, 798–807.
9. Stigter, T.Y.; Ribeiro, L.; Dill, A.M.M. Evaluation of an intrinsic and a specific vulnerability assessment method in comparison with groundwater salinisation and nitrate contamination levels in two agricultural regions in the south of Portugal. *Hydrogeol. J.* **2006**, *14*, 79–99.
10. Samake, M.; Tang, Z.; Hlaing, W.; Mbue, I.N.; Kasereka, K.; Balogun, W.O. Groundwater vulnerability assessment in shallow aquifer in Linfen Basin, Shanxi Province, China using DRASTIC model. *J. Sustain. Dev.* **2011**, *4*, 53.
11. Hashimoto, T.; Stedinger, J.R.; Loucks Reliability, D.P. Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. *Water Resour. Res.* **1982**, *18*, 14–20. [CrossRef]
12. Civita, M. *Le Carte della Vulnerabilità degli Acquiferi all'inquinamento: Teoria & Pratica*; Pitagora Editrice: Bologna, Italy, 1994; 325p.
13. Aller, L. *DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings*; Robert, S., Ed.; Kerr Environmental Research Laboratory, Office of Research and Development, US Environmental Protection Agency: Ada, OK, USA, 1985.
14. Chachadi, A.G.; Lobo Ferreira, J.P.; Noronha, L.; Choudri, B.S. Assessing the impact of sea-level rise on salt water intrusion in coastal aquifers using GALDIT model. *Coastin A Coast. Policy Res. Newsl.* **2002**, *7*, 27–32.
15. Chachadi, A.G.; Lobo-Ferreira, J.P. Assessing aquifer vulnerability to sea-water intrusion using GALDIT method: Part 2–GALDIT Indicators Description. In Proceedings of the 4th Inter Celtic Colloquium on Hydrology and Management of Water Resources, Guimarães, Portugal, 11–13 July 2005.
16. Lobo-Ferreira, J.P.; Chachadi, A.G.; Diamantino, C.; Henriques, M.J. Assessing aquifer vulnerability to seawater intrusion using galdit method. Part 1: Application to the Portuguese aquifer of monte Gordo. In Proceedings of the 4th Inter Celtic Colloquim on Hydrology and Management of Water Resources, Guimarães, Portugal, 11–13 July 2005.
17. JRI. *Analysis of the Causes of Seawater Intrusion in the Western Area and Preparation of Appropriate Management Plan*; JRI: Needham, MA, USA, 2019.
18. Kim, Y.; Lee, K.S.; Koh, D.C.; Lee, D.H.; Lee, S.G.; Park, W.B.; Koh, G.W.; Woo, N.C. Hydrogeochemical and isotopic evidence of groundwater salinization in a coastal aquifer: A case study in Jeju volcanic island, Korea. *J. Hydrol.* **2003**, *270*, 282–294. [CrossRef]
19. Chang, S.W.; Chung, I.M.; Kim, M.G.; Tolera, M.; Koh, G.W. Application of GALDIT in assessing the seawater intrusion vulnerability of Jeju Island, South Korea. *Water* **2019**, *11*, 1824. [CrossRef]
20. Koh, G.W.; Park, J.B.; Monn, D.C. *Geology and Groundwater Occurrence of Volcanic Island*; JPDC: Jeju, Republic of Korea, 2017.
21. Won, J.H.; Lee, J.Y.; Kim, J.W.; Koh, G.W. Groundwater occurrence on Jeju Island, Korea. *Hydrogeol. J.* **2006**, *14*, 532–547. [CrossRef]

22. Koh, G.W.; Prak, J.B.; Son, Y.G.; Yoon, S.H. *Geological Logging Guide of Drilling Core in Jeju Island*; JPDC: Jeju, Republic of Korea, 2017.
23. K-Water. *A Basic Study on Groundwater in Jeju Area*; K-Water: Korea, Republic of Korea, 2018.
24. Jasechko, S.; Perrone, D.; Seybold, H.; Fan, Y.; Kirchner, J. Groundwater level observations in 250,000 coastal US wells reveal scope of potential seawater intrusion. *Nat. Commun.* **2020**, *11*, 3229.
25. Barlow, P.M. *Ground Water in Fresh Water-Salt Water Environments of the Atlantic Coast*; U.S. Geological Survey: Denver, CO, USA, 2003.
26. Vengosh, A.; Rosenthal, E. Saline groundwater in Israel: Its bearing on the water crisis in the country. *J. Hydrol.* **1994**, *156*, 389–430. [CrossRef]
27. Ozler, H.M. Hydrochemistry and salt-water intrusion in the Van aquifer, east Turkey. *Environ. Geol.* **2003**, *43*, 759–775.
28. Han, D.M.; Cao, G.L.; McCallum, J.; Song, X.F. Residence times of groundwater and nitrate transport in coastal aquifer systems: Daweijia area, northeastern. *China Sci. Total Environ.* **2015**, *538*, 539–554.
29. Chatton, E.; Aquilina, L.; Petelet-Giraud, E.; Cary, L.; Bertrand, G.; Labasque, T.; Hirata, R.; Martins, V.; Montenegro, S.; Vergnaud, V.; et al. Glacial recharge, salinisation and an-thropogenic contamination in the coastal aquifers of Recife (Brazil). *Sci. Total Environ.* **2016**, *569*, 1114–1125.
30. Vallejos, A.; Daniele, L.; Sola, F.; Molina, L.; Pulido-Bosch, A. Anthropic-induced sali-nization in a dolomite coastal aquifer. *Hydrogeochemical processes. J. Geochem. Explor.* **2020**, *209*, 106438. [CrossRef]
31. Sophiya, M.S.; Syed, T.H. Assessment of vulnerability to seawater intrusion and potential remediation measures for coastal aquifers: A case study from eastern India. *Environ. Earth Sci.* **2013**, *70*, 1197–1209.
32. Mondal, N.C.; Singh, V.P.; Singh, V.S.; Saxena, V.K. Determining the interaction between groundwater and saline water through groundwater major ions chemistry. *J. Hydrol.* **2010**, *388*, 100–111. [CrossRef]
33. Vrba, J.; Zaporozec, A. *Guidebook on Mapping Groundwater Vulnerability*; Heise: Hanove, Germany, 1994.
34. Sahoo, M.; Sahoo, S.; Dhar, A.; Pradhan, B. Effectiveness evaluation of objective and subjective weighting methods for aquifer vulnerability assessment in urban context. *J. Hydrol.* **2016**, *541*, 1303–1315. [CrossRef]
35. Muralidharan, K.A. note on transformation, standardization and normalization. *IUP J. Oper. Manag.* **2010**, *9*, 116–122.
36. Yu, J.S.; Shin, J.Y.; Kim, T.W. Evaluation of extended inverse distance weighting method for constructing a flow duration curve at ungauged basin. *J. Korean Soc. Hazard Mitig.* **2015**, *15*, 329–337.
37. Sayl, K.N.; Sulaiman, S.O.; Kamel, A.H.; Muhammad, N.S.; Abdullah, J.; Al-Ansari, N. Minimizing the impacts of desertification in an arid region: A case study of the West Desert of Iraq. *Adv. Civ. Eng.* **2021**, *2021*, 5580286. [CrossRef]
38. Hashim, H.Q.; Sayl, K.N. The application of radial basis network model, GIS, and spectral reflectance band recognition for runoff calculation. *Int. J. Des. Nat. Ecodynamics* **2020**, *15*, 441–447. [CrossRef]
39. Dancey, C.P.; Reidy, J. *Statistics without Maths for Psychology*; Pearson Education: London, UK, 2007.
40. Strack, O.D.L.; Stoeckl, L.; Houben, G.; Ausk, B.K.; Lange, W.J. Reduction of saltwater intrusion by modifying hydraulic conductivity. *Water Resour. Res.* **2016**, *52*, 6978–6988. [CrossRef]