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Appraisal of Groundwater Vulnerability Pollution Mapping Using GIS Based GOD Index in Tiruchendur, Thoothukudi District, India

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Abstract: Recently, groundwater resources have become the main freshwater supply for human activities worldwide, especially in semi-arid regions, and groundwater pollution from anthropological events is one of the chief environmental problems in built-up and industrial coastal areas. Many researchers around the world have conducted studies to evaluate the impact of groundwater management. For this study, GIS based GOD vulnerability models were used to assess the intrinsic impact and risk of pollution of coastal and irrigated areas in Tiruchendur Taluk, Thoothukudi district in Tamil Nadu. Here, GOD stands for G—Groundwater hydraulic confinement, O—Overlying aquifer strata, and D—Depth to groundwater. The parameters of G, O, and D show that 70% of the study area consists of an unconfined aquifer whose central part often consists of sandstone and fine to medium clay with sand along the coast that acts as an aquifer. The recorded value was 1–28 mbgl. The map of vulnerability using the GOD method shows that 32% of the medium vulnerabilities are located in the almost northern part of the study area, where the main source of pollution is from agricultural land and anthropological activities. A total of 39 groundwater samples were collected from different types of aquifers and used to validate the pollution map, using the EC concentration (230 to 15,480 µs/cm with an average of 2758 µs/cm) and NO_3^- concentration (2 to 120 mg/L with an average of 46 mg/L) in groundwater as indicators of pollution. Finally, we measured how the EC and NO_3^- parameters represent the medium vulnerability zone of the GOD model based on the pattern of their concentrations in groundwater. Therefore, the GIS with GOD model is the best model among these models for predicting groundwater vulnerability in Tiruchendur Taluk.

Keywords: groundwater vulnerability; GOD Index; GIS; EC and NO_3^- parameters

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1. Introduction

Groundwater is the most important water supply in the whole world, especially in coastal areas, and is considered as important as gold [1,2]. In northern India, there are many perennial rivers with surface water, but the source of surface water in southern India is very low, and coastal residents often rely on groundwater for drinking, irrigation, and all other uses. Water demand is increasing, especially in coastal and tropical regions of the world due to problems such as population growth, industrial development, and irrigation [3], and even in developed countries, groundwater pollution, as opposed to surface water pollution, poses a greater challenge for researchers on its origin, source, and pollution levels.

Groundwater vulnerability assessment has been reported in various climatic regions of the world, such as semi-arid regions, humid tropical regions, sub-tropical regions, temperate regions, and arid regions. The assessment has also been reported in various hydrogeological environments, i.e., karst aquifers, coastal region, alluvial aquifers, and hard rock aquifers [4]. The phenomenon of groundwater vulnerability is conceptualized assuming that the physical environment might act as a protector to groundwater against natural impacts to some extent, especially regarding the entry of contaminants into the subsurface [4–6]. The scope of aquifer vulnerability refers to the possibility of contamination of the aquifer by all contaminants in the surface and groundwater systems of the Earth [7]. The effectiveness and aspect of groundwater vulnerability valuation is essential for sustainable groundwater management and plays an important role in the study of high vulnerable regions [8].

There are different types of vulnerability systems to determine the vulnerability of groundwater in groundwater quality assessment, e.g., SINTACS [9], DRASTIC [10], SI [11], and GOD [12]. Among the mentioned methods, GOD was selected for this study as it is the easiest to evaluate and interpret based on the hydrogeological parameters of GOD, and all of these parameters had already been measured by the regional government and a private water authority, so we can ensure the accuracy and the quality of the data. There is a lot of background research on groundwater vulnerability indices using the GOD method, especially the studies of Akinlalu et al., in Nigeria [13]; Boufekane & Saighi, [14] and Kerzabi et al., [15] in Algeria; Lisboa et al., in Brazil [16]; and Islam et al., in Bangladesh [17]. Groundwater vulnerability is defined as the process of calculating the potential for contaminants to occur in a given event [18]. GOD [12] is an evaluation method to assess the vulnerability to various hydrogeological parameters such as G—the aquifer, O—the overlying lithology of the aquifer, and D—the depth of the water table. The result of the method for each classification varies from minimum vulnerability (zero) to maximum vulnerability (one) in the groundwater quality study.

Tamil Nadu has a high population density and is a coastal area, and nearly 90% of the people in Thoothukudi rely on groundwater as their main source of drinking water. This study focuses on groundwater contamination and helps to classify the Tiruchendur Taluk of Thoothukudi district based on its vulnerability studies. Many researchers have adapted various works to assess water quality using the WHO (World Health Organization) and Bureau of Indian Standards-based classification, irrigation codes, water quality index for drinking water and irrigation, health risk index, lake water mixing code, correlation methods, etc. [19–26]. However, this study is a new approach to identify the groundwater vulnerability zones in the coastal aquifers of Tiruchendur Taluk in Thoothukudi district using the GIS-based GOD method. The predicting groundwater vulnerability map can be further utilized as a base map for management of groundwater and its restoration of groundwater quality.

Study Area

The study area covers an area of 8°22′ N–8°40′ N latitude and 77°14′ E–78°46′ E longitude in Tiruchendur Taluk of Tuticorin district with an area of 470 km^2 in Tamilnadu, India. Figure 1 shows the NDVI index of the region expressing water, land, shrub, and vegetation covers in Tiruchendur Taluk. Around the NW–NE, the year-round surface water source of the Thamiraparani River drains into the Bay of Bengal near the Punnakayal area, and the seasonal water source of the Karamaniyar Canal drains along the southern part of Tiruchendur. Selvam et al. [27] pointed out that the average rainfall in Tamil Nadu during the northeast monsoon is 94.3 cm, while the average rainfall in the study area is 87.7 cm, which is very low compared to the rainfall in Tamil Nadu. Wind speeds of 36 to 60 km/h were recorded during the months of June to September, while 20 to 40 km/h were observed during the months of October to December [28]. Tiruchendur Taluk is one of the major agricultural areas of Thoothukudi, and the major crops are cassava, coconut, banana, mango, cashew, sugarcane, cloves, cardamom, pepper, etc., and palm products are mainly grown in the study area [19]. In India, after Gujarat, the coastal areas of Tamilnadu around Thoothukudi and Tiruchendur are also heavily involved in the sea salt industry [28]. Most of the surveyed areas are surrounded by agricultural land, with the exception of wastelands, salt pans, and water bodies [20,24]. Groundwater and surface water in the region are affected by anthropological activities related to fishing, tourism, and industries [23].

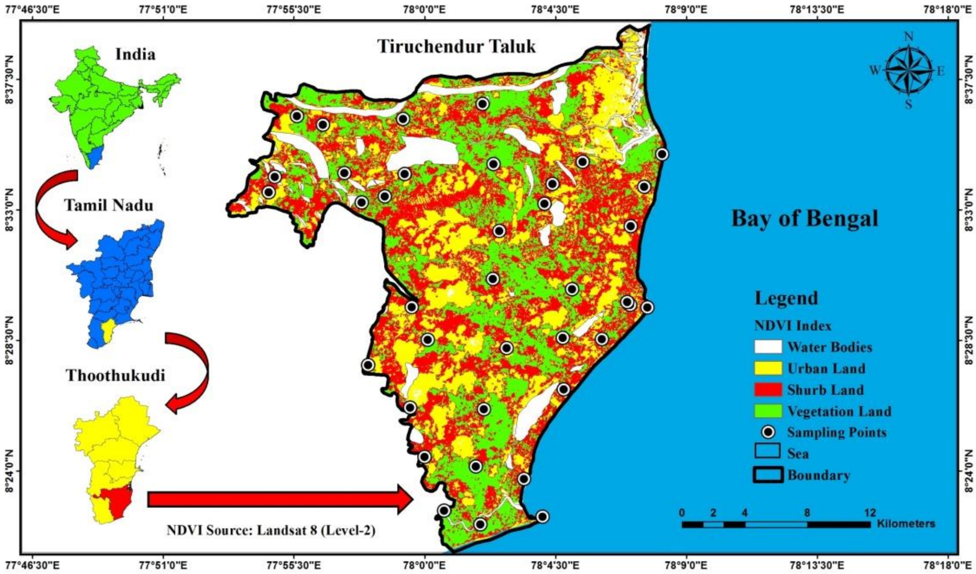

Figure 1. Study area map with NDVI Index classification.

The coastal region of Thoothukudi in Tamil Nadu has important industries such as chemicals, heavy water, petrochemicals and copper smelting (SPIC, TAC, and DCW), alkaloids, seafood, thermal power plants, port operations, and textiles. Dharangadara Chemical Works Ltd. manufactures caustic soda, liquid chlorine, trichloroethylene, refined illuminate, and PV resin. Drugs are mainly manufactured by Shantha Marine Biotechnologies (P) Ltd. Senna, and castor, corn, and cotton products are manufactured by Mother India Business Corporation. Rajashakthi & Co., a leading trader in Thoothukudi, manufactures palm jaggery, palm fruits, palm sap, palm leaves, palm candies, curry leaves, drumsticks, karnel, tari, and palmbakla. Chendhur Springs Pvt. Ltd., Manimala Water Supplier, K. Kumar Enterprise, and VVRM Water Supply are widely used for supplying quality drinking water in the study area.

2. Materials and Methods

2.1. Sampling and Analytic Techniques

Thirty-nine groundwater samples were collected in Tiruchendur Taluk, Thoothukudi district, to evaluate and verify the groundwater susceptibility system. According to the sampling guidelines, Arc-GIS 10.1 software package was used to create model stations at an equivalent distance of 1 km using GIS-based mapping and gridlines techniques. Groundwater levels from deep wells and open wells at depths ranging from 0.7 to 28 mbgl were monitored during sampling in the study area at Tiruchendur Taluk. Pre-cleaned HDPE bottles were used to collect 500 mL groundwater samples, and the water was extracted 10–15 min before sampling. Submitted water quality parameters of EC and TDS were measured during sampling using the Deluxe Water and Soil Analysis Equipment Kit multi-parameter probe (Model No. 191, Everflow Scientific Instruments, Chennai, India). All groundwater samples were then taken to a laboratory for physicochemical parameter analysis in accordance with American Public Health Association [29] standards.

2.2. Groundwater Vulnerability Assessment

In this study, the evaluation method GOD was mainly used to assess the vulnerability of groundwater in the coastal region of Tiruchendur. This is the best parametric technique that uses few parameters associated with the DRASTIC method, and this method has been accepted by many researchers [13,30,31]. The simplest and most pragmatic vulnerability assessment system for GOD was developed in England [12] by using three hydraulic and hydrological parameters such as groundwater occurrence (G), overall aquifer lithology (O), and depth to water table (D); Table 1 shows all types of each parameter (G, O, and D) with their individual estimated weights for vulnerability calculation [3]. The results of the index GOD are classified into five headings ranging from 0 to 1 [13]. The GOD index is calculated using the following equation, and GOD is defined by the multiple of the three parametric indices G (groundwater occurrence), O (overlying lithology), and D (water depth) (Equation (1)).

$$\text{GOD Index} = G_c \times O_c \times D_c \tag{1}$$

where Gc represents the weight of the aquifer occurrence parameter, Oc represents the weight of the aquifer lithology, and Dc represents the weight of the depth of the water table. In this measure, if two parameters have the value of 1, the result of the impact indicates the value of the third parameter. Finally, the results of GOD were classified into six categories, from pristine (0) to most vulnerable (1) Table 2; [31,32]. For example, if the sampling station classified under the unconfined aquifer (Gc = 1), fractured limestone acts as an overlying lithology (Oc = 1), then we can get the depth of water in between 10–20 mbgl (Dc = 0.7), and it will be classified under high vulnerable zone.

Table 1. Ratting of GOD model indicators.

Parameters	Type	Ratting
GroundwaterOccurrence (G)	No aquifer	0
	Aquifer confined and artesian	0.1
	Confined and non-artesian aquifer	0.2
	Semi-Confined Aquifer	0.3
	Aquifer with fairly permeable cover	0.4-0.6
	Unconfined aquifer	0.7–1
Overlyinglithology ofaquifer (O)	Residual soil	0.4
	Alluvial silt, clay, marl, fine limestone	0.5
	Wind, silt, tuff, igneous rock, and fractured metamorphic	0.6
	Sand and gravel, sandstone, tuff	0.7
	Gravel (colluviums)	0.8
	Limestone	0.9
	Fractured or karst limestone	1
Depth to the groundwater(D)	0–2	1
	2–5	0.9
	5–10	0.8
	10–20	0.7
	20–50	0.6
	50–100	0.5
	>100	0.4

Table 2. Vulnerability Classification.

Vulnerability Class	GOD Index
0	No Vulnerability
0–0.1	Negligible
0.1–0.3	Low Vulnerability
0.3–0.5	Medium Vulnerability
0.5–0.7	High Vulnerability
0.7–1	Very High Vulnerability

2.3. Computation of GOD's Indicators

Based on the GOD parameters according to Foster [12] and Foster and Hirata [33], the following parameters are used to measure vulnerability: Groundwater occurrence, class of overlying aquifer, or depth to water table. Finally, a hazard map was created that combines as well as interprets the above parameters (groundwater occurrence, class of overlying aquifer, and depth to groundwater level).

2.3.1. Groundwater Occurrence (G)

Parameter (G) refers to the types of aquifers that function as aquifers at a given depth in the study area. For this study, groundwater event data were collected from pumping test data and water level mapping reports from the CGWB and PWD departments. The IDW-based spatial map of aquatic media identifies four types of aquifers: confined (10%), unconfined (5%), semi-unconfined (70%), and semi-confined (15%) (Figure 2). Therefore, shallow bodies of water, primarily in coastal and riverine plains, have been used to extract groundwater for drinking and irrigation purposes.

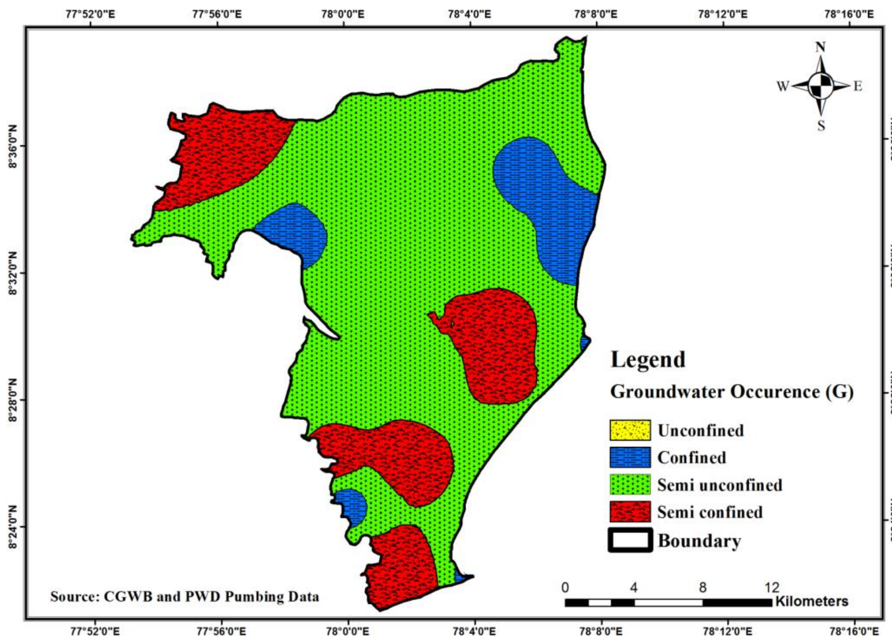

Figure 2. Groundwater occurrence spatial map in study area.

2.3.2. Overlying Aquifer Class (O)

The overlying layers of the aquifer are one of the most important factors in evaluating the groundwater's impacts because the upper layers of an aquifer can provide information about the porosity and permeability of the aquifer system [33]. As part of this study, pumping, geophysical, and lithologic well data from the CGWB and PWD fields were used to produce a spatial map of the overlying strata (Figure 3), which shows that the Tiruchendur area is mostly covered by topsoil (5%), sand with clay (13%), sandstone (20%), clay (19%), clay with shale (16%), sand (12%), and weathered granitic gneiss layers (15%). In the coastline, sandy loam and sand acted as overlying layers.

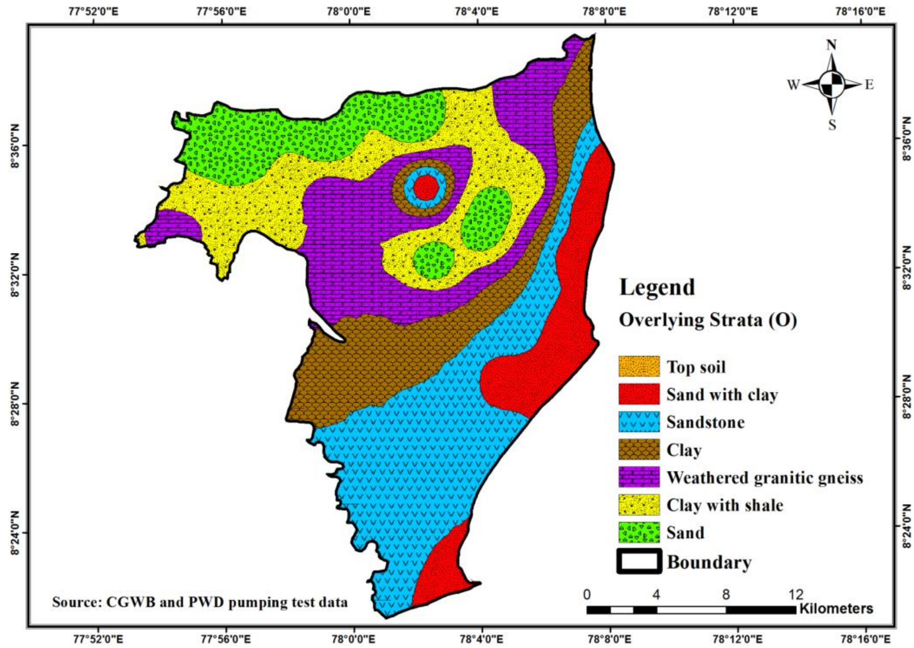

Figure 3. Overlying strata spatial map of the study area.

2.3.3. Depth to Groundwater (D)

The depth to groundwater regulates the risk of contamination as it relates to the thickness of the subsurface material. The depth to the groundwater determines the risk of contamination as it relates to the thickness of the subsurface material that must be traversed by the infiltrated water before it reaches the groundwater saturation zone. Particularly in coastal areas, the depth from the ground surface to the water level affects groundwater contamination because groundwater contamination increases with decreasing depth [34]. In the present study, this parameter was determined using 39 groundwater samples collected from open wells and drilled wells at depths ranging from 1 to 28 mbgl (Figure 4). The shallow depth of the water level (0–2 mbgl) was observed along the coast, and the deep groundwater level (20–28 mbgl) was observed beyond the coastline in the study area.

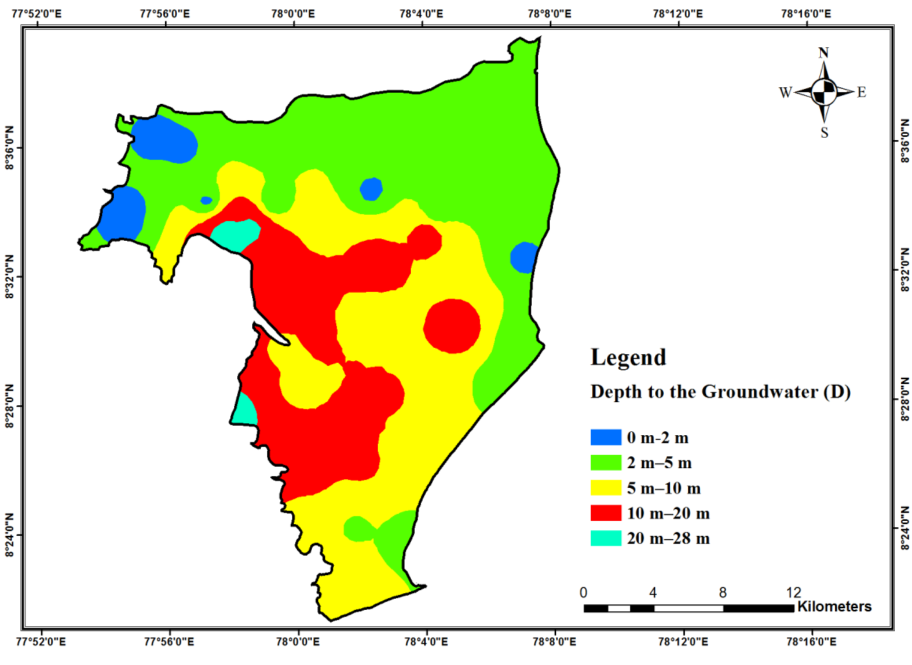

Figure 4. Spatial map of depth to the groundwater of the study area.

2.4. Method to Model Validation

Evaluating a method means that we further validate the result, which is essential for research [35,36]. No one uses a specific model for vulnerability map assessment, so most authors use the method that is most appropriate for them [37,38]. At the same time, in the field of groundwater pollution assessment, the groundwater vulnerability system is reviewed by storing data on the source of a pollutant that is abundant in the study area [35]. In the study by Jesuraja et al., [19,20] the DWQI, IWQI, and groundwater pollution index were used to determine the level of groundwater in the vicinity of Tiruchendur Taluk that is not suitable for drinking water and irrigation. Selvam et al., [22] also confirmed the presence of nitrate and fluoride pollution in the study area. Agricultural activities play an important role for the population of the study area, so in this study, it was decided to check the results of ultimate GOD susceptibility using nitrate (NO_3^-) and electrical conductivity (EC).

3. Results and Discussion

3.1. Geochemical Assessment for Drinking and Irrigation

The significant and analyzed water quality parameters of electrical conductivity (EC) and nitrate (NO_3^-) are classified according to their concentrations in groundwater (Table 3). The EC and NO_3^- concentrations were classified for drinking water [39–41] and irrigation purposes [41,42] respectively. A specific range of EC was found in groundwater, ranging from 230 to 15,480 (µs/cm) EC. According to the estimate of EC, 44% of groundwater samples were harmful for drinking and irrigation purposes (3000 µS/cm). The observed NO_3^- concentrations from open wells and deep wells in the study area ranged from 2 to 120 mg/L, and 32% of the samples were above the limits for drinking water use. NO_3^- concentration measurements are classified as useful (25–50 mg/L) in 24% of the samples and harmful for drinking water use (>50 mg/L) in 21% of the groundwater samples, and harmful for irrigation purposes (50–100 mg/L) in more than 21% of the samples.

Table 3. EC- and NO_3^--based water classification for drinking and irrigation.

Scale of Category	EC in µS/cm				NO_3^- in mg/L			
	Drinking [39–41]		Irrigation [41,42]		Drinking [39–41]		Irrigation [41,42]	
	Grade	% of Samples	Grade	% of Samples	Grade	% of Samples	Grade	% of Samples
Very good	0–180		0–250		0–10	31	0–10	31
Good	180–400	3	250–750	13	10–25	24	10–30	24
Usable	400–2000	50	750–2000	40	25–50	24	30–50	24
Usable with caution	2000–3000	3	2000–3000	3			50–100	18
Harmful	>3000	44	>3000	44	>50	21	>100	3

According to the geochemical parameters in the coastal areas, high EC concentrations were found in groundwater and abnormal NO_3^- concentrations in agricultural areas of the study area. In the southern coastal areas of Thoothukudi region in Tamil Nadu, many researchers have identified the reasons for the high number of pollutants in water quality, and the details to improve the specific parameters are given in Table 4.

Table 4. Identified groundwater pollution sources in the study area.

Year	Pollution Source	Flagged Pollutants and Parameters	Reference
1993	Over exploitation	Groundwater salinity and quality	[43]
2009	Domestic effluents	Groundwater Contamination	[44]
2011	anthropogenic contamination (likesalt pans and fertilizer)	To enhance the Na^+ and Cl^-	[45]
2011	Industrial activities	Fluoride contamination	[21]
2012	Infiltration process from sewers canals, unprotected drains and industrial effluents	To increase the TDS > 1500 mg/L	[46]
2012	Salt pans	Enhance alkaline nature	[47]
2012	Industrial effluents	Metal pollution	[45]
2012	Agricultural return flow, domestic sewage, septic tanks or other anthropogenic activities	Nitrate pollution	[46]
2013	Seawater influence or salt pan deposits or ionic exchangeprocess	Increase Na^+ in groundwater	[48]
2014	Owing to the modern day issues of sea level rise, irregular patterns of rainfall due to climate change	Increased demand of groundwater	[49]
2014	Chemical industries, salt, flower dying, copper wire, copper alloy, alkali chemicals and fertilizers, petro-chemicals & plastics industries	Overall groundwater quality	[21]
2018	Urbanization, Over exploitation and Industrialization	To decrease the groundwater quality	[50]
2019	Rural and private septic systems, sinkholes, municipal sewage systems and tourism	To increase micro plastic in groundwater	[23]
2020	Fishing industries	High organic compounds in the groundwater	[51]

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3.2. GOD Vulnerability Map

The flowchart of this study shows how the maps were preferred and the specific process used to generate the spatial distribution of each responsible parameter (Figure 5). According to the weight of vulnerability and the evaluation process, each indicator was evaluated to determine the extent of vulnerability. From the interpolation of all G, O, and D parameters, a master map of GOD vulnerability was created for each indicator using GIS software (version 10.1). The GOD index impact map was created by overlaying the water table, topsoil, groundwater depth, and soil type maps. The final map of hazard GOD shows that the study area was classified into three hazard classes from negligible to a medium hazard, with values ranging from 0.08 to 0.50. The percentage results of the studied aquifer show that the study area was classified as very low risk (3%), low risk (65%), and moderate risk (32%) (Figure 6). According to the results, most of the study areas are in the low hazard zone, while the northern part of the study area is in the high and moderate zone, especially on the Punnakayal bank of the Thamiraparani River. At the same time, no area is affected that is not classified in the highest and most sensitive zone. Shallow water levels were found in the coastal and reverie levels, which may increase the vulnerability of the aquifer compared to other lithological factors and the overlying layers of the aquifer, as shallow water is very favorable for groundwater pollution and anthropological activities [3,17,31].

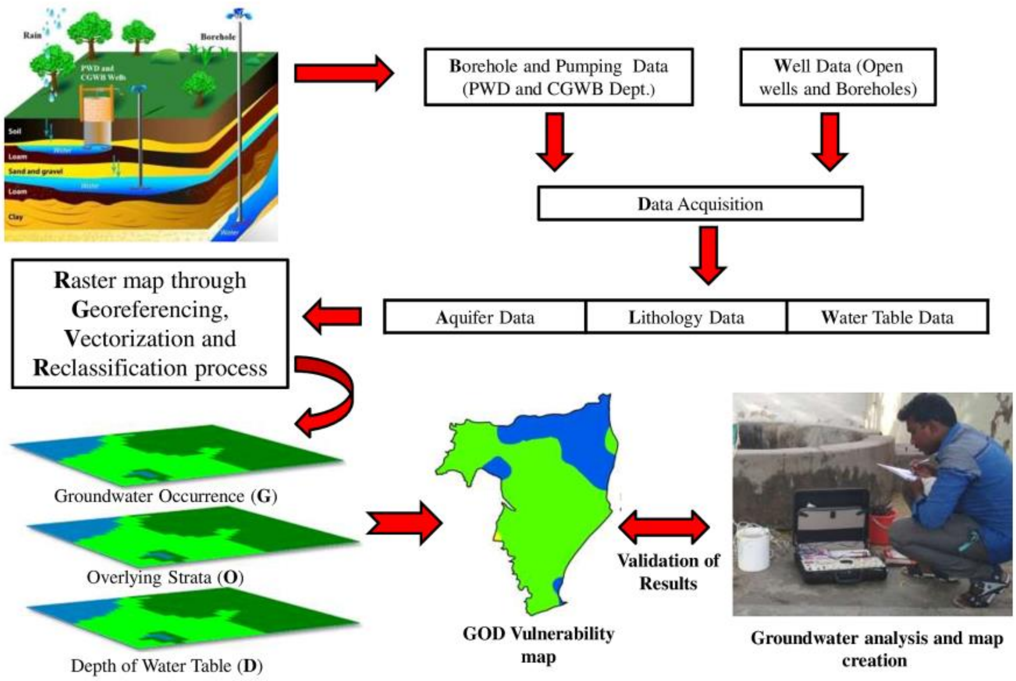

Figure 5. Flow chart of the GOD model working methodology.

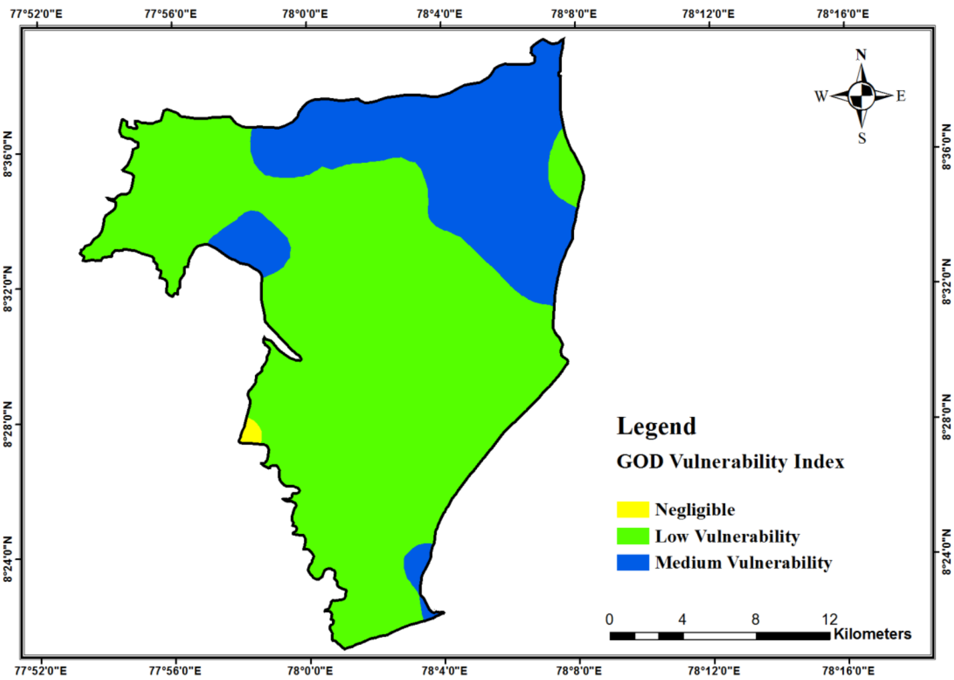

Figure 6. Spatial distribution of the GOD intrinsic vulnerability map of the study area.

3.3. GOD Model Validate with Geochemical Parameters

According to Singha et al., [52], the results of the vulnerability zones give us a little more confidence when validating the retention of the geochemical values obtained. Nitrate (NO_3^-) and EC are the most confirmed anthropogenic contamination indicators of the study area's groundwater resources, so its concentration in groundwater could correlate with the GOD risk index [21,22]. The reason for choosing NO_3^- is that the chief sources of nitrate in groundwater are numerous anthropogenic activities, such as fertilizers used in agriculture, which show the salinity and pollution of groundwater [53–57]. According to the WHO 2017, the maximum adequate nitrate concentration for human health is 50 mg/L [58], but it is known that a nitrate absorption >3 mg/L in groundwater indicates anthropogenic pollution [59]. The nitrate concentration of groundwater in the northern portion of the study area and in the agricultural area of Thamiraparani River was more than 60 mg/L.

It can be resolved that the increase in nitrate absorption in this area, particularly in the north, is likely to be related to pollution input from agricultural fertilizers in this area. The spatial correlation diagram clearly shows that the trends in NO_3^- concentrations are consistent with the indices of GOD vulnerability in the north, and that the higher NO_3^- concentrations in the study area represent the intermediate vulnerability zone. With the exception of the estuary, low NO_3^- concentrations often represent a low hazard zone because of the absence of agricultural activities compared to other areas (Figure 7).

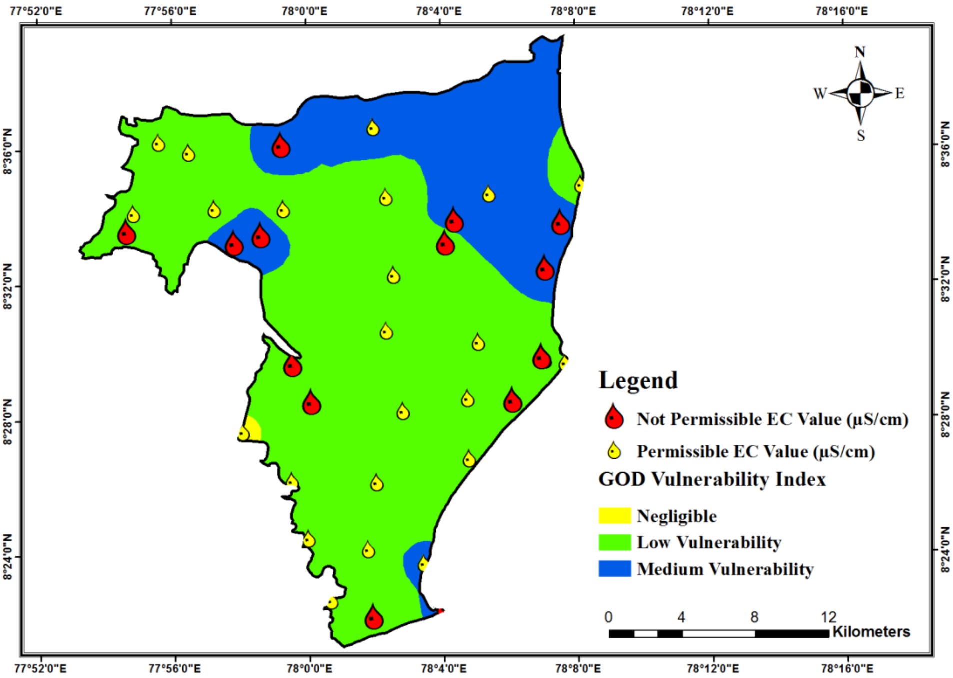

Figure 7. Spatial distribution of the GOD intrinsic vulnerability with an EC concentration.

EC concentration describes the general quality and suitability of groundwater. As with nitrate, the value of EC increases not only in river basins but also in other areas, indicating unsuitable concentration. However, high EC concentrations are observed in the moderately vulnerable areas of the NE and NW, as well as in coastal areas (Figure 8), as high EC values indicate not only agricultural mismanagement but also secondary salts and seawater leaching [59].

3.4. Mitigation of Groundwater Sources from Vulnerability

It is not always adequate to know the status of the fault memory and water quality, which is always present in the field of water conservation research. So it can be said that the next step is to do what needs to be done to improve groundwater resources so that what the public and researchers can have a positive impact on society. Therefore, the following describes ways to reduce groundwater contamination in the coastal and agricultural areas of Tiruchendur.

Proper disposal of domestic waste in the residential areas of the coastal regions of Tiruchendur and Thoothukudi is essential.

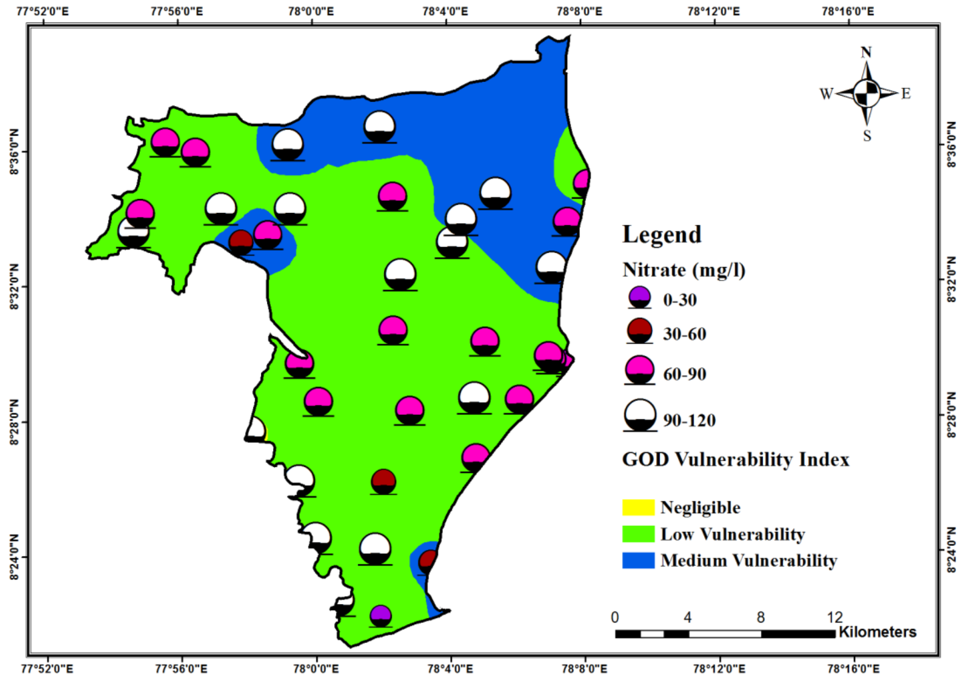

Figure 8. Spatial distribution of the GOD intrinsic vulnerability with an NO_3^- concentration.

Establishment of a special team to monitor and manage tourism, especially to mitigate the local surface water levels at the mouth of the Punnakayal Thamiraparani River.

Develop the separate guidelines based on the local environment for the companies linked to the wastewater treatment system.

Reducing fertilizer use, especially on agricultural land and informing producers of the impact.

Upgrading a large number of monitoring wells by state and central water management agencies to collect accurate data near industrial and fish factories.

Part of this is ensuring water quality for a private team and all types of private sector employees to provide safe drinking water for public schools and hospitals.

Conducting public education programs about water pollution and raising awareness about groundwater management.

Mandate rainwater collection in residential areas to reduce storm water runoff.

Sustainable water management is integral to the future of food and agriculture such as drip irrigation systems.

Sewage water treatment in high populations areas such as Tiruchendur, Punnakayal, Udangudi, Kulasai, etc.

Desalination is a process that takes away mineral components from saline water for companies not drinking.

With support from the communities, structures are built for soil and water conservation to reduce the volume and velocity of runoff for better protection against topsoil loss and to improve soil moisture retention.

Require many businesses in Thoothukudi district to set up their own coastal pollution monitoring commission, as wastewater is discharged directly into the Bay of Bengal.

4. Conclusions

In the field of groundwater chemistry, this study is the first attempt to investigate the impact on groundwater using a GIS-based GOD exposure method in TiruchendurTaluk of South Thoothukudi district. The vulnerability map of the GOD system confirms that almost 32% of the Thamiraparani River plain and northern coastal areas are classified as medium vulnerability. The remaining areas (65%) are less vulnerable, reflecting aquifer degradation in the study area. In this assessment of the GOD index, geological systems and water bodies contribute to pollution compared to the shallow layers of this region. In the zones of medium vulnerability, we can observe shallow groundwater levels of less than 5 mbgl, which is very conducive to agricultural and human pollution of groundwater. To further evaluate the susceptibility of evolution measurements, this study compares the significant geochemical parameters of EC and NO_3^- concentrations with the GOD susceptibility map. Both parameters are closely related because high concentrations were observed in the zones of medium vulnerability, which ensure that water easily combines with various geochemical components derived from noxious pesticides and their widespread use in agricultural lands and anthropological activities. Therefore, high-risk activities should not be allowed in high-risk areas to achieve economic benefits and to reduce the risk of pollution. To reduce the risk of pollution in moderate-risk areas, a precautionary measure should be taken before exploiting aquifers and before starting extensive agricultural activities in the area. The GIS-based GOD model can be used to classify areas susceptible to groundwater quality management in the Thoothukudi coastal area and serve as one of the latest databases for the government.

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