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Assessment of vulnerability in the aquifers of rapidly growing sub-urban: a case study with special reference to land use

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Abstract

Groundwater vulnerability was assessed through the SINTACS-LU model to explore the aquifers which are more susceptible to contamination. The aquifers of the Palayamkottai taluk are at risk due to the uncontrolled agricultural practice and urbanization. As these aquifers are the source of water to most of the population, mitigation of the risk to the aquifer is essential. This proposed model uses eight parameters like water table depth, effective recharge, depth to unsaturated zone, soil media, aquifer media, hydraulic conductivity, topography, and land use to assess the vulnerability through index measurements. The index in the vulnerability map was reclassified through the cumulative score index (CSI) technique. Sensitivity investigation was done to survey the effect of each parameter over the vulnerability. Agricultural regions (185 km^2) and built-up regions (50 km^2) covering more than 50% of the land use exert pressure on the intrinsic resistance of the aquifers and put them at risk. The classified map has four classes according to vulnerability such as very high vulnerable zone (53.3 km^2), high vulnerable zone (81.95 km^2), moderate vulnerable zone (125.22 km^2), and low vulnerable zone (39.8 km^2). The vulnerability assessment made by the inclusion of land use in the intrinsic vulnerability can help in sustainable development of sub-urban regions.

Keywords SINTACS-LU · Vulnerability · DRASTIC · Land use/land cover · CSI · Sustainable

Introduction

Water in the aquifers is known as groundwater which is a comparatively secure and reliable source of good quality as compared to surface water. Rapid and over-extraction of groundwater lead to stress and deterioration in the quantity and quality of these precious resources (Samson and Elangovan 2015; Balamurugan et al. 2020a). The quality of groundwater in the aquifers is protected by the soil overburden

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present above the water table. Groundwater present in the shallow aquifers can lead to contamination due to the exposure to anthropogenic activities or unfavorable surface conditions. The land use in a region exerts pressure on the quality of surface water by the disposal of the domestic and other wastewater on the surface and near surface. Due to this, shallow aquifers are more sensitive to contamination activities like the action of seepage from the septic tank, effluent from the sewage system, and possibly pesticides and fertilizers applied in the agricultural land (Balamurugan et al. 2020b). It is impossible to restore polluted groundwater and its remediation is too expensive. To utilize the contaminated water, an enormous amount of energy, manpower, and money needs to be invested. Therefore, it is necessary to manage and utilize the groundwater in a sustainable manner.

The term vulnerability is defined as the liable nature of the soil properties such as porosity and tortuosity that leads to penetration and dispersion of impure surface water to the sub-surface reservoir (Machiwal et al. 2018). The vulnerability assessment is an effective way to understand the pollution potential by either quality or quantity. Vulnerability can be classified as intrinsic vulnerability (INV) and specific vulnerability (SV). The hydrogeological setting in a region can be

assessed by the degree of protection it offers to an aquifer which is named as INV. The land use activities and other natural processes that can pollute the aquifer, disturb the offered protection, which are named as SV. INV is due to the saturated depth of the water bearing zone, distance downward to groundwater level, depth of lateritic layer, and the aquifer character (Edet 2004). SV is due to specific contamination in consideration of the locations. The idea of vulnerability is an assumption that the resistance of the surface material that may offer some extent of safety to groundwater resources from pollution entering into the subsurface. In the past few decades, developments of GIS technology have permitted us to perform more activities like inventorying, archiving, retrieving, and display of spatial data (Samson and Elangovan 2015; Anand et al. 2017, 2020; Kirubakaran et al. 2019). The integration of spatial data with the numerical rating system and the conversion into parameters based on hydrogeological setting and its relative rating have resulted in the emergence of many index-based methods. There are numerous index methods available to evaluate aquifer vulnerability and environmental impact assessment. DRASTIC, SINTACS, AVI, and GOD are some of the index models that appeared to demarcate groundwater vulnerable regions (Ramos Leal et al. 2012). Index-based overlay methods merge all the layers that are identified as the controlling factor for the contaminant migration from the surface to the vadose zone. All parameters are independent and vary at different locations.

Assessment of vulnerability denotes the possibility of groundwater to be affected by pollutants and could not measure absolute level of contamination (Nahin et al. 2020). Index models design to produce scores of vulnerability for distinct location by combining thematic layers that summarizes different attributes with different influences. Numerous parametric models like DRASTIC, GOD, AVI, and SINTACS have been developed for mapping groundwater vulnerable areas in GIS environment. Many significant researchers (Neshat et al. 2014a; Babiker et al. 2005; Srinivasamoorthy et al. 2011; Neshat and Pradhan 2017) have used the DRASTIC model for their vulnerability evaluation study. Alam et al. (2014) adopted the DRASTIC-LU model for determining groundwater vulnerability which gave more accurate results compared to the conventional DRASTIC method. SINTACS model is one among the important models to evaluate the groundwater vulnerability. SINTACS model is an improved version of the US DRASTIC vulnerability assessment method which was introduced by Civita and De maio (Civita et al. 2000). This model is an Italian model and most widely used to assess the groundwater vulnerability (Civita and De Maio 2004; Sathees Kumar et al. 2013; Ashokraj et al. 2015; Machiwal et al. 2018). Generally, the SINTACS methodology uses seven parameters for demarcating vulnerable areas. All these parameters were prepared as layers in the GIS environment. Hybrid methods combine different assessment methods and can be

modified to improve the accuracy of vulnerability assessment (Neshat and Pradhan 2014). The land use (LU) exerts strong pressure on groundwater quality more extensively due to the industrial, urban, and vegetation land use. These land uses are a major threat to groundwater resources in any developing country. Therefore, the modified SINTACS-LU model has been used to estimate the vulnerability as a result of the use of the land use parameter in addition to the SINTACS model (Mobin Eftekhari and Mohammad Akbari 2020). The weights and ratings of the parameters can also be modified to improve the accuracy of vulnerability assessment (Neshat and Pradhan 2014). The major thematic layers such as soil, depth to the water table, slope, land use, and other SINTACS-LU themes are organized from a variety of records through a sequence of geo-processing function of GIS. In the current scenario, the statistical based sensitivity analysis was performed to improve the computational accuracy in groundwater aquifer vulnerability (GWAV) using geoinformation technology. Here, the cumulative score index (CSI) method is used to classify the vulnerable site. GIS an efficient environment that can handle large spatial data was used for the storage, analysis, and retrieval of spatial data. Study was carried out in Palayamkotai taluk, in which most of the rural and some of the urban population depend on groundwater resources for their needs. Agriculture has an important role in the economic aspect of the taluk. Commonly during the cultivation period, farmers apply fertilizers and pesticides for the crop to increase the yield often in an uncontrolled fashion. The constituents in the irrigated water will be a major source of pollution. These constituents enter into the subsurface and reduce the purity of groundwater resources. Therefore, the region needs more attention to groundwater vulnerability. By considering the importance of groundwater in the region, GIS-based assessment of vulnerability was carried out in the aquifers of Palayamkotai taluk. The taluk being a semi-arid region is located adjacent to the river Thamirabarani, a perennial river that has a significant role in the replenishment of the aquifer. It has a composition of urban and rural communities that depend on the groundwater. This taluk is composed of urban settlements and agricultural land use is a potential source for contamination. The riparian landscape has urban settlements and undergoes depletion of vegetation with rapid urbanization; therefore, LU layer was additionally incorporated in the SINTACS model to improve the vulnerability assessment.

Study area

The current study was conducted in Palayamkotai taluk situated in the district of Tirunelveli of Tamil Nadu, India. Taluk lies within longitude 77° 36′ 32″ and 77° 50′ 03″ and latitude 8° 35′ 12″ N and 8° 49′ 37″ N with an overall area of 300 km^2 (Fig. 1). It is one of the eleven taluks in the Tirunelveli district. The
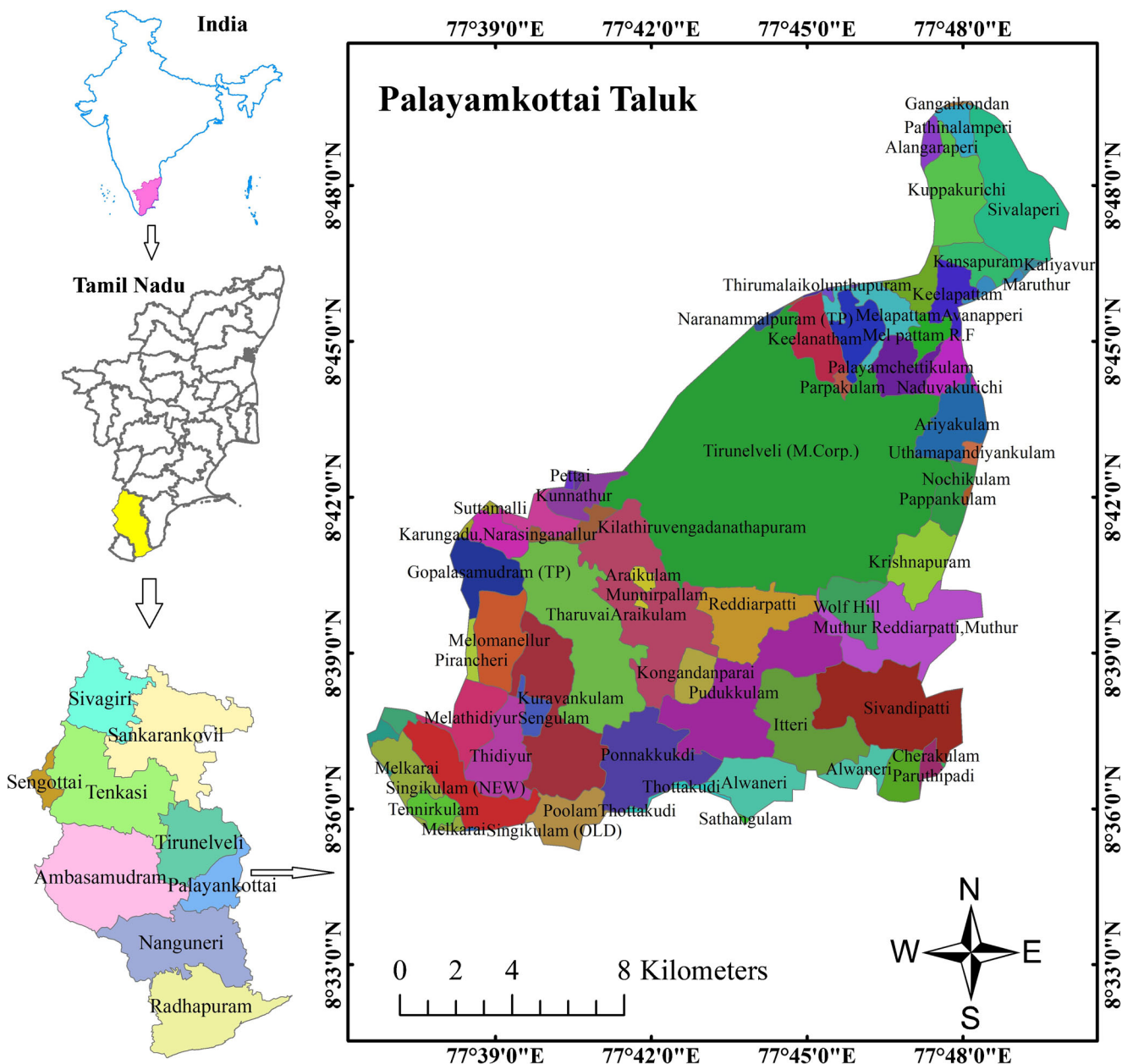
Fig. 1 Location map of the Palayamkottai taluk, Tirunelveli district, Tamil Nadu, India

eastern part of the Tirunelveli city Municipal Corporation (TMC) is located inside this taluk. The toposheets such as 58H/10, 58H/14, and 58H/9 are used in the present study that covered the taluk. Palayamkottai taluk consists of thirty villages and has a large irrigated area and well-distributed settlements. This taluk gains importance as it has a major portion of the sub-urban regions of TMC which was under rapid urbanization.

Materials and methodology

GIS-based statistical investigation of each model parameter was used to improve the efficiency of GWAV delineation in the Palayamkottai taluk. All the process involved in the study is discussed below.

Preparation of thematic layers

Hydrological parameters applied in the SINTACS-LU model are given in Table 1. Data necessary for the work were obtained as spatial and non-spatial data from different sources (Table 1). Spatial data used in the work was in the form of satellite data and published map of different agencies. Satellite data products from LANDSAT-8 OLI/TIRS and ASTER are used in the study. The published maps used in this study are obtained from the agencies such as soil map from European

Table 1 Data sources and values of weights for the parameters of SINTACS- LU model

SINTACS-LU parameters	Description of parameters	Data source	SINTACS-LU weight
S	Depth to water table	PWD, State government of Tamil Nadu	5
I	Effective infiltration	PWD, State government of Tamil Nadu	4
N	Unsaturated zone	Geological survey of India, Hyderabad	5
T	Soil media	European soils (Eusoils.jrc.ec.europa.eu)	4
A	Aquifer media	Geological survey of India, Hyderabad	3
C	Hydraulic conductivity	PWD, State government of Tamil Nadu	3
S	Slope	ASTER DEM (Aster web.jpl.nasa.gov)	2
LU	Land use/land cover	LANDSAT 8 (Landsat.usgs.gov)	5

digital archive soil atlas, toposheets from the Survey of India (SOI), and geological map from the Geological Survey of India (GSI). Generally, the non-spatial data are in the form of records and digital database. It was compiled and prepared into spatial data to carry further GIS analysis in efficient way. The thematic layers of this study were prepared with standard geographic coordinate systems and projections (Zone-43, Universal Transverse Mercator – World Geodetic System - 84) in the geographical information system.

Water table depth

Depth to water is the vertical distance between the terrain surface and the level of subsurface water (for unconfined and confined aquifer) (Chamanehpour et al. 2020). If depth to water table increases, the timespan for contaminant reach to aquifer will also increase and vice versa. Water level data were collected from the Public Works Department (PWD) of Tamil Nadu. After the compilation of data, the depth to water table layer was prepared through inverse distance weighting (IDW) technique in Arc GIS environment.

Effective infiltration

Infiltration is defined as the movement of surface water through soil to the groundwater in the aquifer (Linsley et al. 1988). Infiltration has a vital role in the GWAV assessment. It acts as a migrating process for the movement of surface contaminants into the aquifer (Civita and De Maio 2004). Infiltration is prime vehicle that is able to transport the pollutant downward to the groundwater and within the aquifer media. Increased pollution potential of groundwater resource is due to infiltration (Aller et al. 1987). It is a measure of net recharge rate. Net recharge rate can be estimated for a unit area by Piscopo method (Piscopo 2001) that is expressed in Eq. 1,

$$\text{Recharge Index} = \text{Percentage of slope (PS)}$$
$$+ \text{Effective annual rainfall } (P)$$
$$+ \text{soil permeability } (K) \tag{1}$$

Rainfall, slope, and permeability are the three vital parameters to determine recharge index. Advanced Space borne Thermal Emission and Reflection Radiometer Digital Elevation Model (ASTER-DEM) data in raster file format with 30-m spatial resolution was used to prepare the slope map of the taluk. Rainfall is the second major component next to slope in the estimation of the recharge index value. The spatially distributed rainfall map is generated based on PWD daily rainfall data using the Thiessen polygon method in GIS platform. Soil permeability has a key role in the determination of recharge index value and this layer was prepared based on the aquifer permeability data of PWD. The weighed grids of these three maps have been integrated to give the recharge index values.

Unsaturated zone

Unsaturated zone exists below the bare soil and extends up to the groundwater table; this is also known as vadose zone. The vadose zone is characterized into sand, fine sand, loamy sand, and silt according to the depth of weathering of the geological formation. If the vadose zone consists of karstified limestone, the zone is soluble in nature and more sensible to contamination. The reduction ability of the vadose zone was evaluated based on the hydro-lithologic features (Civita and De Maio 2004). Generally, unsaturated zone was appraised by the interpretation of geological maps, litho-logs of aquifer, and excavated trenches. Vadose zone layer was interpreted and digitized from the geology map and compared with well lithology data of PWD for validation purposes. The digitized vector layer was converted as a raster layer for carrying overlay analysis.

Soil media

Soil media is the topmost layer of the unsaturated zone and also the first layer to establish the physio-chemical exchange between the contaminant and the subsequent subsurface beneath soil. The presence of coarse-textured soil materials can enhance the infiltration. Generally, the fine-textured soil

materials (Al Kuisi et al. 2006) (clay and silts) can comparatively reduce soil conductivity and limit contaminant movement. The contaminant can utilize both these soil media of different grain sizes and tortuosity to reach the aquifer. The vector map of soil media for the Palayamkottai taluk was digitized from the "soil atlas" of European data archives that were classified based on USDA soil taxonomy (USDA 1999).

Aquifer media

The formation of fractured and weather rock-like substance which can store water and let water to be extracted is known as an aquifer. In vulnerability evaluation models, the nature of the aquifer will be considered a parameter that describes the susceptibility that occurs below the surface of the earth. Contaminants that reach the water table get dispersed in groundwater and get diluted. The concentration of contaminants in the groundwater gets reduced where the contaminants may have deposited in the soil particles during infiltration process (Rapti-Caputo et al. 2006). The aquifer media is prepared from the Geological Survey of India's published aquifer map. Lineaments are the places that have good potential for weathering and are possible entry points for the pollutants. The rocks are digitized as polygon features and the lineaments are digitized as a linear feature from the multi-dimensional Shaded relief map of ASTER DEM data. The buffered zones of these lineaments are overlaid (vector) with a digitized aquifer feature layer to get the improved aquifer media map.

Topography

The slope can be precisely expressed in both degree and percentage. The Slope can be subdivided into classes according to the rate of change of terrain surface elevation. The area which has a low slope represents that terrain has water retention capacity over the surface for a long time. The minimum amount of slope allows water infiltration or migration of contaminants vertically downwards. Larger slopes (steep slope) are areas having a huge amount of runoff and minimum amount infiltration capacity that leads the surface to less vulnerable to groundwater contamination. The Slope can be extracted from the ASTER DEM data acquired in the year 2011 using a spatial analyst tool in the GIS. The slopes of the study categorized into different categories of slope according to steepness of terrain.

Hydraulic conductivity

Hydraulic conductivity is the water transmission ability of earth materials, which pedals the groundwater flow rate in a given region's hydraulic gradient (Aller et al. 1987). Many physical factors such as porosity, particle size, shape, and distribution of particle arrangements have a

significant role in the hydraulic conductivity of soil or rock. Generally, hydraulic conductivity of clay exhibits low value whereas gravel has high value (Heath 2004). Normally, a high range of hydraulic conductivity 10 m/day. Pumping test hydraulic conductivity data was obtained from PWD to generate a hydraulic conductivity map. The thematic layer of hydraulic conductivity was generated by IDW techniques in GIS.

Land use/land cover

Groundwater quality in the taluk is at risk due to the increasing housing units and the expansion of the city. This taluk is located on the outskirts of the Tirunelveli Municipal Corporation; most of the housing layouts in the urban settlements are connected to the sewage system. In some regions, cultivations are practiced. Therefore, the aquifers in the taluk are vulnerable to agricultural and sewage pollution. The land use/land cover layer of the study area was prepared from LANDSAT-8 satellite image with 30-m spatial resolution using supervised classification technique of digital image processing and the correctness of classification was enhanced by the choice of more training pixels. Visual image interpretation approach was used to select the training pixels for the classification (classification scheme: level 1 classification) from the false color composite (FCC) satellite data. When the latest land use/land cover maps are unavailable, the available maps can be updated with the help of index map produced from recently available satellite data. Some of the popular indices that are used for land use/land cover map are Normalized Difference Vegetation Index (NDVI), Modified Normalized Difference Water Index (MNDWI), Normalized Difference Built-up Index (NDBI), and Normalized Difference Salinity Index (NDSI) (El-Zeiny and Elbeih 2019). The impact induced by the LU on the vulnerability was assessed by incorporating the LU parameter with the SINTACS model.

SINTACS-LU model

LU influences groundwater vulnerability (Noori et al. 2019). Eight parameters of SINTACS-LU model were used to assess the vulnerability index of the taluk through the weighted overlay analysis. SINTACS-LU index which measures the pollution potential was computed using Eq. 2:

$$
\begin{aligned}
\text{SINTACS-LU}_{\text{Index}} = {} & S_r S_w + I_r I_w + N_r N_w + T_r T_w \\
& + A_r A_w + C_r C_w + Sl_r Sl_w \\
& + LU_r LU_w
\end{aligned}
\tag{2}
$$

where

S_r rating of S
S_w weight of S
I_r rating for I
I_w weight of I
N_r ratings of N
N_w weight of N
T_r ratings of T
T_w weight of T
A_r ratings of A
A_w weight of A
C_r ratings of C
C_w weight of C
Sl_r ratings of Sl
Sl_w weight of Sl
LU_r ratings of LU
LU_w weight of LU

Sensitivity analysis

Sensitivity analysis (SA) was performed to appraise the sensible nature of each model parameters using statistical methods (Hasan et al. 2019). Here, sensitivity analysis was utilized to analyze the SINTACS-LU parameters in the GIS platform. The output of sensitivity analysis indicated the layers that are more significant for analysis. Sensitivity analysis can show the users about the reliability of the parameter. This analysis enhances the efficiency of the GWAV index (Napolitano and Fabbri 1996). The two types of SA engaged in these studies are map removal analysis and single variable analysis.

Map removal SA

Map removal sensitivity was carried out by the removal of one variable at a time to find the effect on the model output, i.e., the impact of each parameter over the vulnerability map. The weights of SINTACS-LU parameters are recomputed through the appropriate groundwater vulnerability index values. These values are used to determine individual parameter sensitivity towards groundwater vulnerability. The sensitivity analysis is performed by map removal sensitivity analysis using the map algebra toolbox in the GIS environment. The sensitivity of the variable under test can be expressed as Eq. 3 (Kumar and Pramod Krishna 2019).

$$S = \left(\frac{\frac{V}{N} - \frac{V'}{n}}{V} \right) * 100 \tag{3}$$

where

S sensitivity of specific parameter

V total GWAV index
V' GWAV index values of specific parameter
N total number of SINTACS-LU parameters involved in the GWAV index
n total number of parameters involved in V'

This sensitivity analysis is performed as a local operation that was done on cell by cell basis. A cell may have a high or low influence on the resulting index respectively. The rated parameters of SINTACS-LU model are evaluated individually and also combined together (Babiker et al. 2005). To derive the sensitivity of each parameter, the arithmetic operations of layers are prepared in the GIS environment and the statistical quantity like minimum, maximum, standard deviation, and arithmetic mean was measured.

Single-parameter SA

Single-parameter SA is a type of investigation basically performed to appraise the influential degree of individual parameters for vulnerability to groundwater. Comparison of real weights can be made against the theoretical weights of each parameter used in the SINTACS-LU model. Equation 4 is used for the analysis of single-parameter sensitivity (Napolitano and Fabbri 1996).

$$W = \frac{(P_r P_w)}{v} \tag{4}$$

W effective weight of feature class of parameters
P_r respective rating of particular parameters
P_w respective weight of particular parameters
v total vulnerability index

Cumulative score index and validation

Cumulative score index (CSI) is a statistical method used for classifying the resultant SINTACS-LU index prepared for the taluk. The categorization of the index map depends on the mean (μ), standard deviation (σ), and the scores of each map (Kirubakaran et al. 2016). Ranks are assigned to the different classes of the parameter layer based on the significance. The score of individual layer classes was estimated by the product of rank and the weights of corresponding layer (Kirubakaran et al. 2016). Cumulative scores are obtained by the overlay analysis of raster layers to produce the groundwater vulnerability map. Groundwater vulnerability map was categorized into four types of vulnerable zones namely very high, high, moderate, and low vulnerable zone (VZ). The vulnerability map was related with the quality characteristics of groundwater in the wells. Water collected from the wells in and around the taluk was assessed for water quality parameters by

adopting American Public Health Association (2012). The water quality parameters such as TDS, chloride, sulfate, bicarbonate, and other parameters are compared with the vulnerability index and results were used to validate.

Results and discussion

Water table depth

Water level data of Palayamkottai taluk was acquired from wells that are used for public supply, domestic, and monitoring purposes. Water table depth (S) was used to determine the depth at which water resources are available. In the taluk, there are seven PWD observation wells including bore wells and dug wells. Water levels from different wells were collected from the field and compared with the government records to analyze the historical behavior of the water level in the wells. Among these wells, few wells are only in common and had a 10-year record. Therefore, the wells in common are used for the purpose of map preparation to improve the credibility of the study. The map representing the spatial distribution of S is shown in Fig. 2. The average water level data for the period of

10 years from 2009 to 2018 was used for the study. This observational data showed that the study area has a relatively shallow water table and depth to water level ranged from 4.6 to 15.2 m. IDW method was used for the interpolation and the adoption of other methods can change the results of the water table layer. IDW method has some advantage over the other interpolation methods, i.e., krigging method that can be significantly affected by variability and spatial structure of the data and by the choice of variogram models, search radius, and number of the neighboring points used for estimation (El-Zeiny and Elbeih 2019). Among the wells, only one well from Thidiyoor village makes contact with surface water in the post monsoon season. The water level in the shallow aquifer of Palayamkottai within the Corporation limit had the minimum depth and Sivanthipatti had the maximum depth. The raster layer of S was reclassified into two classes by assigning ratings which are listed in Table 6. The maximum depth was assigned low ratings (Ghosh et al. 2015) within a limit of 1 and the minimum depth was assigned higher ratings within a limit of 10. Since the water level in the taluk ranged at moderate depth, the region was classified into two, i.e., 4.6 to 9.1 m and 9.1 to 15.2 m, and ranks 7 and 5 are assigned respectively. Rapid urbanization increases the demand for

**Fig. 2** Depth to water level map of the Palayamkottai taluk
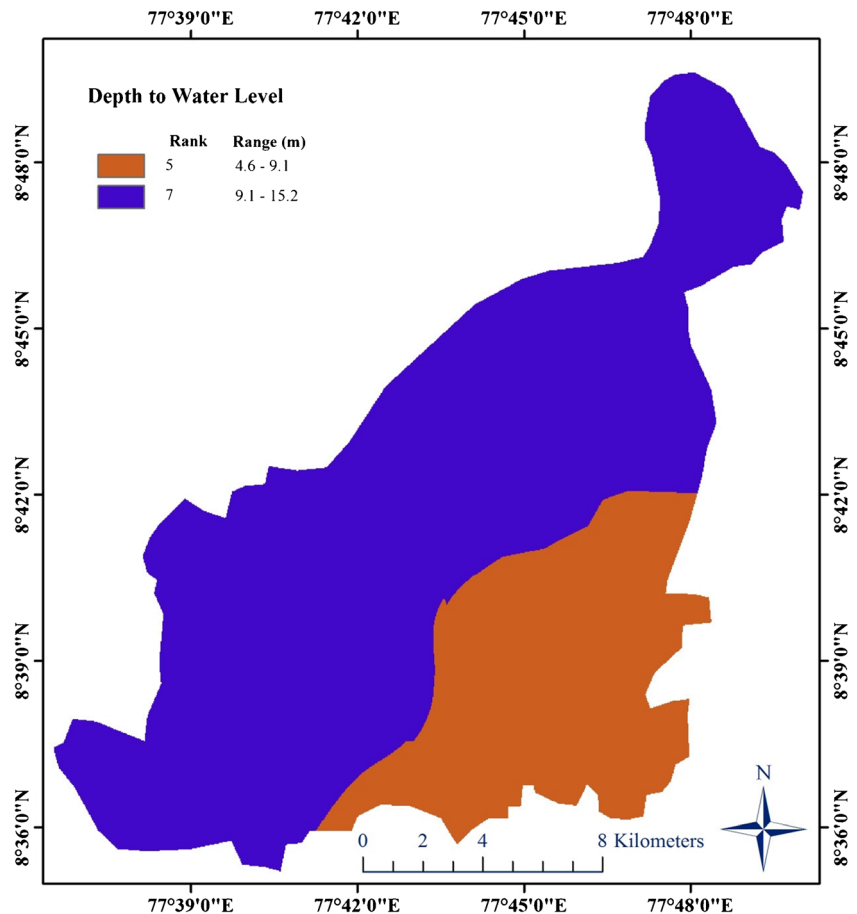
groundwater and this may encourage groundwater exploitation and decrease the depth to water table and this may decrease the vulnerability of the aquifer.

Effective infiltration

The maximum amount of recharge has the maximum ability to migrate the contaminant. The slope map was classified to have four classes in the consideration of natural break system. Low slope value attains larger rating and maximum slope attains minimum ratings due to the retention behavior of the terrain allowing more infiltration. The rainfall map showed average annual rainfall that ranged from 597 to 819 mm from rain gauge stations such as Tirunelveli, Palayamkottai, Moolkarapatti, Ambasamudram, Cheranmadevi, and Alagiapandiapuram (CGWB 2009). Since most of the gauge station was outside the taluk, the Thiessen polygon method was used to interpolate the rainfall in the unknown regions. However, the influence of rain gauges from Palayamkottai and Cheranmahadevi was felt in the taluk. Rainfall data of the taluk was classified to have two classes by adopting equal interval method. It is observed from PWD data that soil permeability was found to be minimum ranging from 0.4 to 12.3 m/day in the taluk. The spatial variations of net recharge

potential characteristics are given in Fig. 3. The value of recharge index was a sign of the infiltration event that was related to the water storage characteristics of the vadose zone (Rimon et al. 2007). Each class in the recharge index had appropriate ratings with the range of 1–10 (Piscopo 2001). The parameters used in the present study were limited when compared to Achu et al. (2020) in the study conducted for the identification of recharge potential zone, the thematic classes such as lithology, available space for recharge, geomorphology, slope, lineament density, soil texture, land use/land cover, annual average rainfall, sand percentage, and drainage density. Therefore, to further improve the outcome of the model, other parameters can be used. The layer of net recharge was reclassified into five classes with equal intervals that ranged from 1 to 11. The value greater than 9 indicated the area with comparatively elevated recharge rate and was assigned rating of 10 while area that had little index value (less than 5) showed meager recharge, and assigned rating value as 1. The remaining class was assigned by suitable rating value with the consideration of their potential recharge characteristics. The southeastern part of the region had moderate recharge with a value of 3. Net recharge of water in the taluk was in the range of 5–96 mm. Recharge in a rapidly growing urban environment gets decreased due to the impermeable structures, roads,

Fig. 3 Net recharge map of the Palayamkottai taluk
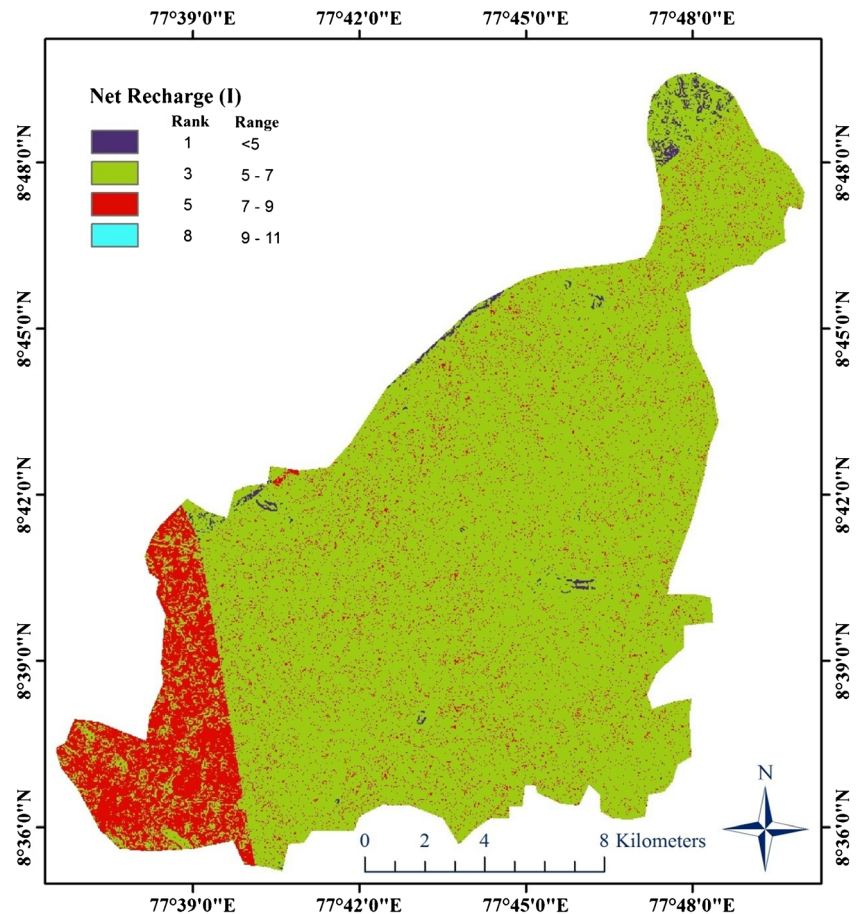
Fig. 4 Impact to vadose/
unsaturated zone map of the
Palayamkottai taluk
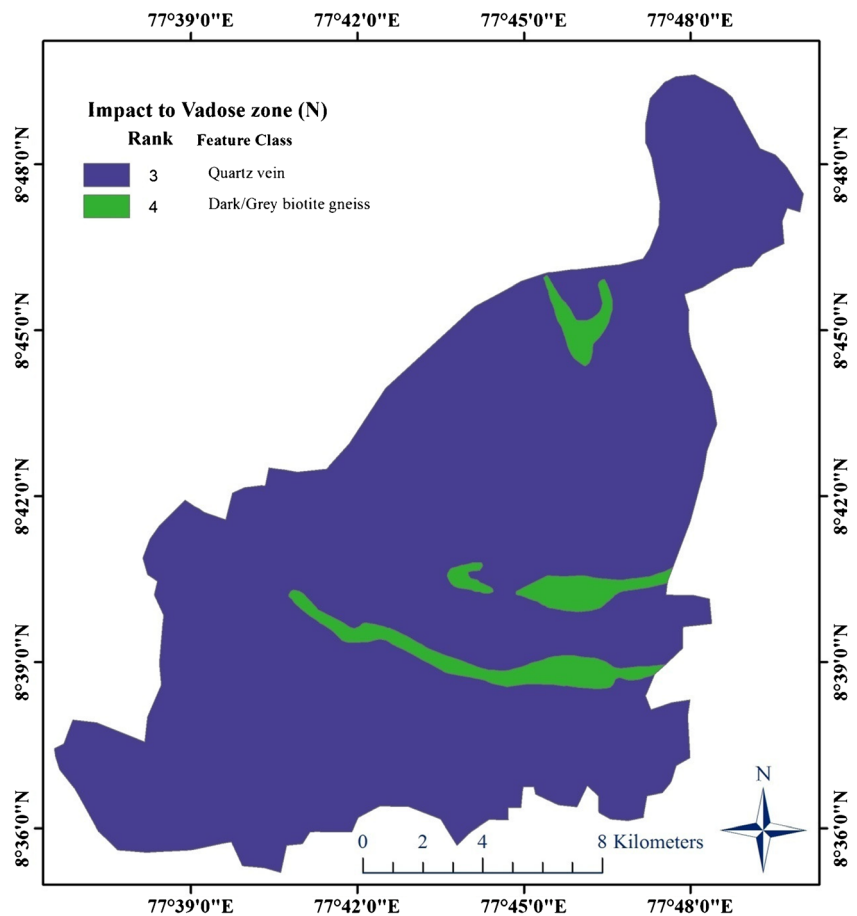
and pavements. Limitation in recharge reduces the opportunity of contaminant infiltration.

Unsaturated zone

Unsaturated zone was mainly dominated by the vadose zone that contains beds of different soil and lithological units that vary in the hydrogeological characteristics (Kapelj et al. 2013). The distribution of the unsaturated zone is shown in Fig. 4. Taluk comprises two major lithological units such as dark/gray biotite gneiss and granite gneiss. This layer acted as a medium of interaction between the water in the root zone and the aquifer (Rimon et al. 2007). Granitic gneiss covers a larger area compared to the biotite gneiss and quartz veins were present in some regions. All these formations have undergone different levels of weathering with some lineaments and subsurface fractures. The presence of some linear hills in Reddiyarpatti has folded rocks with alternate layer bedding of quartz veins and biotite gneiss dipping at angles indicated the presence of shallow and deep aquifer. Quartz veins that lie in the region of the southern part of Munirpallam, Muthur, and Reddiarpatti have similar characteristics, and hence, a low rating of 3 was assigned. The taluk has undergone fluvial

processes over the years and mainly drained by the river Thamirabarani (Rajamanikam et al. 2016). The presence of pediment and shallow weathered pediplain in the south of the taluk makes this region more reliable on deep bore wells. The shallow flood plains are present in the regions adjacent to the river Thamirabarani (Rajamanikam et al. 2016) which can be observed on the northern side of the taluk. Soil overburden of shallow depth ranged from 0.5 to 3 m and the weathered formation of rocks ranged from 2 to 40 m had water. During rainy season, water infiltrates through this zone and the depth of the zone gets decreased and enhances vertical flow. In the dry season, water table retreats and the depth of zone gets increased. The vadose zone offers a degree of resistance to the contaminants and restricts infiltration. The poorly developed soil formation in the taluk and the gneissic materials below the soil overburden are poor in adsorption of contaminants, that too in a relatively poor infiltration zone. The major geological formation of gneissic rock was assigned a lower rating value of 4 (Ghosh et al. 2015). Construction of urban infrastructures causes settlements and higher consolidation of the unsaturated zone. This overburden pressure consolidates the vadose zone materials and decreases the vulnerability of the aquifer.

**Fig. 5** Soil media map of the Palayamkottai taluk
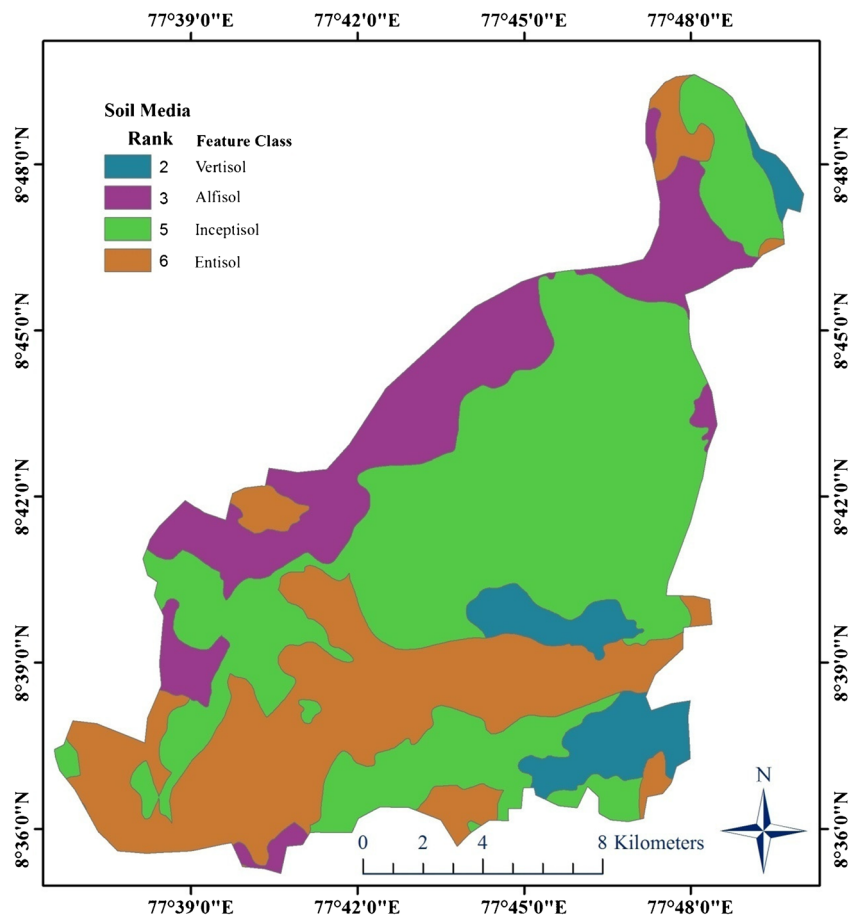
Soil media

Soil media in the taluk has been classified into alfisol, entisol, inceptisol, and vertisol shown in Fig. 5. Alfisol has been seen in some of the regions near the banks of the river such as Chittar and Thamirabarani. The distribution of alfisol was found along northwestern sides of the region covering an area of 51 km^2 (Ashokraj et al. 2015). This soil was fertile and rich in aluminum and iron content and widely used for cultivation (USDA 1999). Entisol has been seen in some of the regions poorly formed on top of quartz and biotite gneiss. The distribution of entisol was found on the southern side of the taluk covering an area of 79 km^2. Inceptisol has been seen in most of the regions moderately formed on top of quartz. The distribution of inceptisol was about 50% in the taluk covering an area of 148 km^2 (Ashokraj et al. 2015). These soils were almost left uncultivated and some regions are being used for cultivation. Vertisol present in some regions such as Sivanthipatti, Reddiyarpatti, and Sivalaperi covered an area of 19 km^2. By considering the infiltration nature, the ratings assigned to soil media are 2, 3, 5, and 6 for reserve vertisol, alfisol, inceptisol, and entisol respectively (Colins Johnny et al. 2016). As the taluk was a hard rock terrain, the geomorphical process has not developed good soil formation,

and hence, the soil in the vadose zone (Kapelj et al. 2013) has to play a major role in the dilution of the contaminant. Presence of clay-rich soils was also observed in some regions. Availability of clay can delay the time for water to get infiltrated and increases the time to be counted as recharge to the water table that indicated more purification (Nahin et al. 2020). Impermeable structures in an urban area accelerate the runoff and supports soil erosion. Removal of loose soil in the surface in due course of time can decrease the thickness of soil layer. Reduction in the thickness can increase the vulnerability of the aquifer.

Aquifer media

Aquifer media map represented the material matrix of aquifer, influence of lineament (Masoud and Osta 2016), and aquifer depth. It has water capturing capacity within it and water can also penetrate through the aquifer materials. The aquifer media with assigned ratings are shown in Fig. 6. In the taluk, aquifer media has components such as dark gray biotite gneiss and quartzite vein. Biotite gneiss is the high grade of metamorphic rock; biotite gneiss exists in two forms either with or without lineament structures. The rating index value assigned to biotite gneiss in presence of lineament was 6 and the

**Fig. 6** Aquifer media map of the Palayamkottai taluk
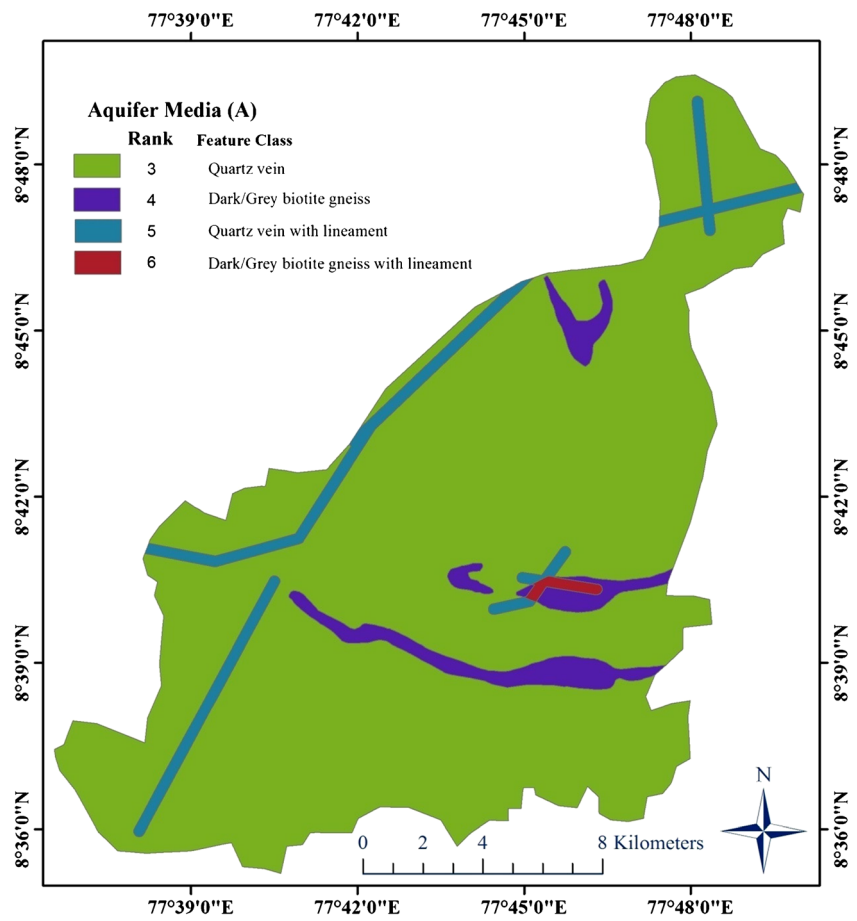
absence of lineament was 4. Gneiss covers more than 90% of the taluk with an area of 285.56 km^2. Quartzite vein with lineaments occupying an area of 14.12 km^2 was assigned a rating of 5. The aquifer media was also responsible for the contaminant attenuation in the aquifer. The gneissic rock with variants such as granitic and biotite was mostly the bedrock in the taluk except in the central parts of Tirunelveli Municipal Corporation where charnockite was the bed rock. The weathering in the taluk has resulted in the weathered formations in the order of 30 to 40 m. The aquifers near the river are replenished by the river Thamirabarani. However, other places are rain fed. The dug wells in the southern regions of the taluk may get dried when there was a failure in the monsoon. The aquifer media played an important role in the contaminant attenuation (Kumar and Pramod Krishna 2019). However, in the taluk, the attenuation capacity was poor due to the poorly developed soil and moderately weathered rocks. Rapid urbanization can alter the aquifer media due to the over exploitation of groundwater in the aquifer and may support dissolution of minerals and increases the vulnerability of the aquifer.

Hydraulic conductivity

Hydraulic conductivity was determined through the pumping test data from 38 observation wells of PWD. The spatial variation map of the conductivity is shown in Fig. 7. The villages like Kunnathur, Karungadu, Thiruvengadanathapuram, and Narasinganallur recorded greater value of hydraulic conductivity compared to other villages. Hydraulic conductivity of the taluk varied in the range between 0.4 and 12.3 m/day. The northwestern and northeastern parts of the taluk had poor hydraulic conductivity. The hydraulic conductivity of the taluk was classified into two categories such as 0.04 to 4.1 m/day and 4.1 to 12.3 m/day and the ratings were assigned values such as 3 and 6 respectively (Colins Johnny et al. 2016). The larger values of hydraulic conductivity occupied smaller area and were found near the river Thamirabarani. In general, urban growth has increased impervious surfaces such as parking lots, roadways, and rooftops and has altered the hydrological characteristics by preventing surface flow and infiltration (Sahoo and Sreeja 2012). The taluk had gneissic rock type that was weathered and fractured in different depths having

Fig. 7 Hydraulic conductivity
map of the Palayamkottai taluk
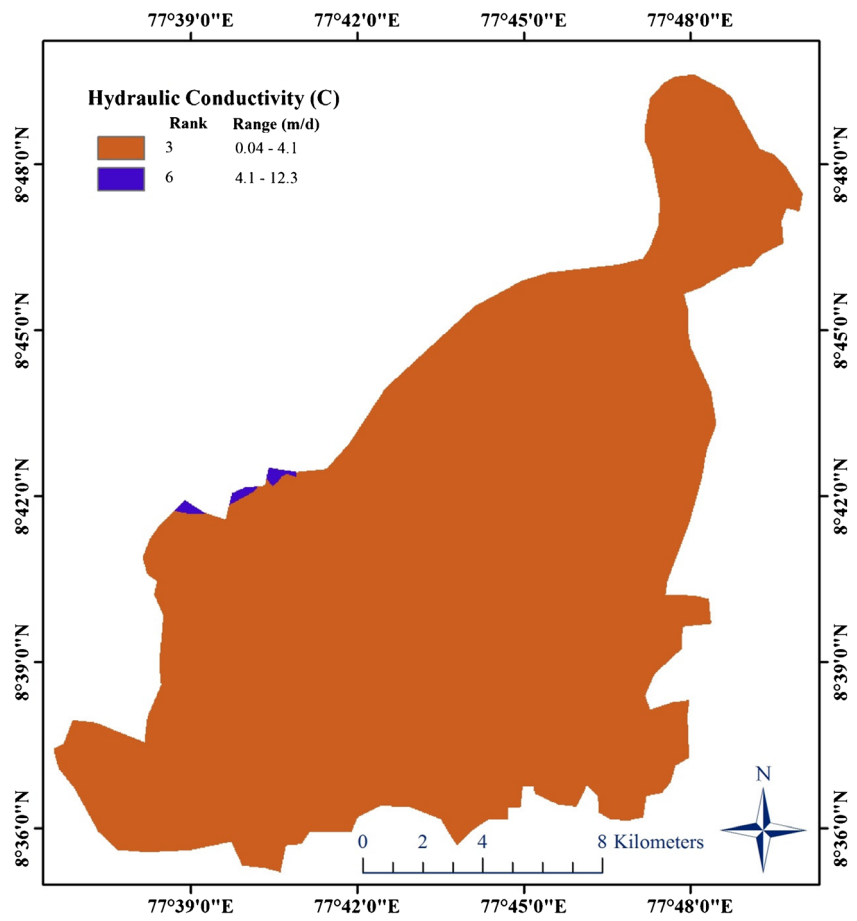
a poor hydraulic conductivity. The consolidation of the soil particles caused due to the urban infrastructure can reduce the hydraulic conductivity of the soil. When there is a curtailment in the permeability, the possibility of the surface contaminant to reach the aquifer also gets decreased and decreases the vulnerability of the aquifer.

Topography

The slope of the topography varies with its relative steepness (Ahirwar et al. 2020). The slope of the taluk has severe undulation in few regions and moderate to gradual undulation in most of the regions. Slope map is represented in Fig. 8. Elevation in taluk ranged from 28 m present near the river Thamirabarani to 160 m present near the hills of Reddiyarpatti. The higher elevation regions are found in the southern parts of the taluk and residual hills are found in Melapattam, Kunnathur, and Reddiyarpatti. The lower elevation regions are present in the northern regions. The river Thamirabarani drains the taluk by covering the three sides of the taluk. The river runs through the periphery of the taluk by entering the west side then meandering north and then to south. More than 75% of the taluk comes under a moderate slope. Kunathur, Kuppakurichi, Nachankulam, Vaigaikulam,

Melapattam R. F, Alwaneri, Singikulam, and the southern part of Tirunelveli Municipal Morporation area have moderate slope steepness. The reclassified layer of the slope raster was categorized into four types such as a moderate slope that covered an area of 278 km^2, a gentle slope (4 km^2 area), a steep slope (1 km^2 area), and a very steep slope (17 km^2 area). The curvilinear hills of gneissic rocks that run east west were the elevated regions and were eroded in the north south direction sloping towards the riverside. The moderately sloped regions dominate the taluk and reduced the influence of topography over the vulnerability. The process of urban development alters the topography and hence the slope of a region; this alteration can affect the time of residence of the water that gets stagnated in the surface. This disturbance in the topography affects the infiltration of water.

Land use/land cover

Knowledge of land use dynamics is essential to understand the root cause of natural and environmental changes at the local and regional levels (Kumari et al. 2019). The LU pattern in the taluk was in the form of agricultural land, barren land, built-up regions, surface water bodies, and forest (Fig. 9). Improper coordination of anthropogenic activities in the developing

Fig. 8 Slope map of the
Palayamkottai taluk
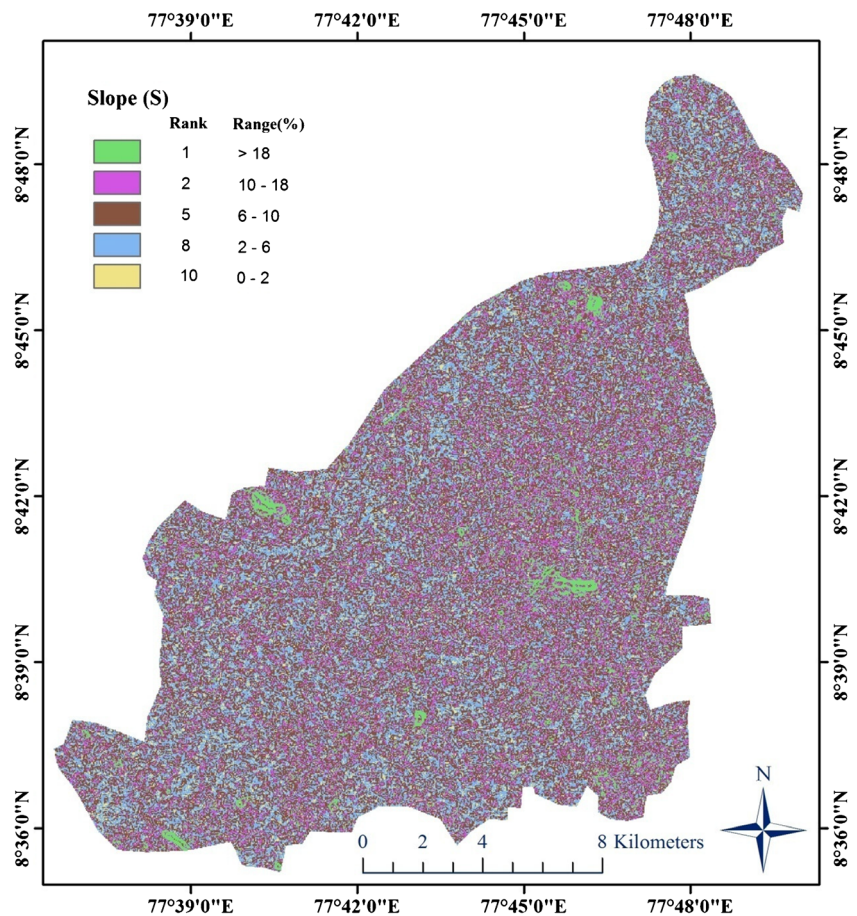
countries has caused land use/land cover change with an im-
pact on environmental (Seto 2002). Land use/land cover (LU)
showed that most of the taluk falls in the category of agricul-
tural land. Agricultural land involving wet crops such as pad-
dy, dry crops such as groundnut, plantations such as banana,
and other crops occupied 185 km^2 which are considered to be
harmful due to the agricultural activities such as usage of
pesticides, herbicides, fertilizers, etc. in the taluk. A major
challenge to the land use program in India is to improve food
production while at the same time reducing environmental
degradation from land use and land change (Meiyappan
et al. 2017). The problems related to agricultural land use such
as poor management of crop residue. Higher ratings of 10
were assigned due to the agricultural practice that was in-
volved in the application of fertilizers and pesticides, hence
posing a threat to groundwater (Noori et al. 2019). Urban and
rural settlements are found in the taluk where the urban settle-
ments are considered to be harmful due to the threat for the
groundwater caused by residential, public, and commercial
activities. Palayamkottai town and Melapalayam town that
comes under the Tirunelveli Municipal Corporation are the
rapidly growing towns in the Palayamkottai taluk. The popu-
lation density in the taluk was very higher in some areas of
Melapalayam with 1180 persons per hectare (PPH) and in

Palaymkottai urban area about 348 PPH (TNT&CP 2004).
Land use change is an issue of regional scale that helps in
the understanding of interactions of the human activities with
the environment (Etefa et al. 2018). Due to the rapid urbani-
zation in the peripheral regions of the corporation, the land
value gets increased. Sivanthipatti, Araiklam, Ariayakulam,
Nochikulam, Krishnapuram, Tharuvai, Reddiyarpatti,
Munnerpallam Mela, and Keela Pattam are the prominent vil-
lages that are included in the vicinity area of local planning.
The fully developed city has good solid waste management
and well connected with the underground drainage system.
Built-up land occupied only 6% and it is nearly equal to
50 km^2 that was assigned a rating value of 3. Forest covers
an area of 28 km^2 in the taluk that comprised a minimum area
compared to other LU patterns in the taluk. Waste land obtains
the last rank in usage of LU pattern and it contained only
6 km^2. Since these areas were left unutilized, these regions
were assigned the least score (Kumar and Pramod Krishna
2019). Surface water bodies are found in these regions that
occupied a substantial area of 31 km^2 and were assigned with
a rating value of 5 because they have a threat of contaminants
in the surface and agricultural wastes carried during surface
runoff resulting from precipitation. Most of the water bodies
are ephemeral in nature and a few are system tanks of the river

Fig. 9 Land use/land cover pattern map of the Palayamkottai taluk
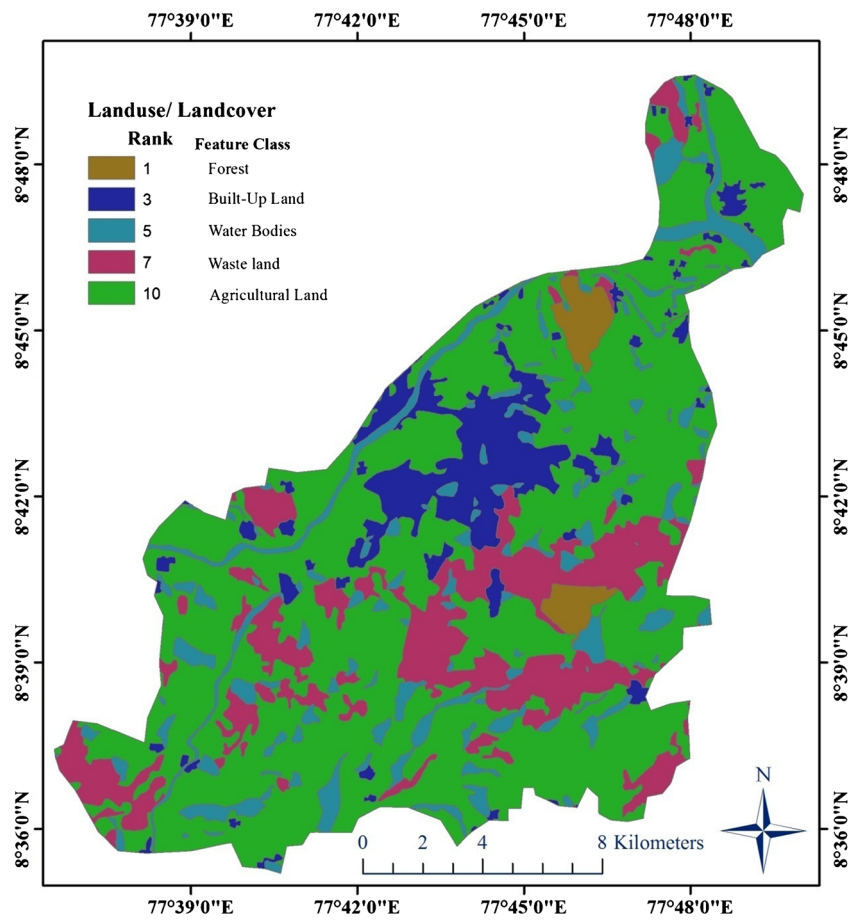
Table 2   Range, rating, and index values of the parameters of SINTACS-LU

Depth to water table (S)			Hydraulic conductivity (C)			Unsaturated/vadose zone (N)		
Range (m)	Rating (D_r)	Index	Range (m/day)	Rating (C_r)	Index	Lithology	Rating (I_r)	Index
4.6–9.1	7	35	0.04–4.1	1	3	Quartz vein	3	15
9.1–15.2	5	25	4.1–12.3	2	6	Dark/gray biotite gneiss	4	20
Weight (S_w): 5			Weight (C_w): 3			Weight (N_w): 5		
Topography/slope (S)			**Land use/land cover (LU/LC)**			**Effective infiltration (I)**		
Range (%)	Rating (T_r)	Index	Feature class	Rating (LU_r)	Index	Range (mm/year)	Rating (R_r)	Index
0–2	10	20	Forest	1	5	<5	1	4
2–6	8	16	Water bodies	3	15	5–7	3	12
6–10	5	10	Waste land	5	25	7–9	5	20
10–18	2	4	Built-up land	7	35	9–11	8	32
>18	1	2	Agriculture	10	50			
Weight (S_w): 2			Weight (LU_w): 5			Weight (I_w): 4		
Aquifer media (A)						**Soil media (T)**		
Hydrological setting		Rating (A_r)	Index			Soil type	Rating (D_r)	Index
Quartz vein		3	9			Entisol	6	24
Dark/gray biotite gneiss		4	12			Inceptisol	5	20
Quartz vein with lineament		5	15			Alfisol	3	12
Dark/gray biotite gneiss with lineament		6	18			Vertisol	2	8
Weight (A_w): 3						Weight (T_w): 4		

Thamirabarani. The ephemeral water bodies often face the problem of encroachment and if not conserved may succumb to the pressures exerted due to urbanization. Therefore, the restoration and renovation of wetlands and the framework and management plans for the conservation and wise use of wetlands and their resources are important for the sustainability of the wetlands (MoEF&CC 2019).

Sensitivity analysis

The rating, weight, and index values assigned to different parameters of the SINTACS-LU model are shown in Table 2. Sensitivity analysis (SA) of the SINTACS-LU factors was evaluated for the influence of each layer on the vulnerability of groundwater. The statistical summary of the reclassified model parameters is given in Table 3. It showed that the maximum risk for contamination in Palayamkottai taluk may be due to LU pattern with mean value (MV) = 8.13 followed by recharge index (MV = 6.73), depth to water table (MV = 6.47), and slope (MV = 6.08). The parameters like aquifer media (MV = 4.95), soil media (MV = 4.72), and unsaturated zone (MV = 3.04) imply the moderate risk of contamination. Hydraulic conductivity (MV = 1.00) had a lower risk of contamination. The topography, land use, soil, and depth to water table are highly variable with a coefficient of variation (CV) values of 42.76%, 32.47%, 25.64%, and 13.76% respectively. Other parameters had a lower CV in the order aquifer media (CV = 9.69%), recharge index (CV = 8.62%), unsaturated zone (CV = 6.91%), and hydraulic conductivity (CV = 5.00%). The rates and weights that are used for the overlay analysis can be optimized to overcome differences that are generally observed in the classes and parameters in different methods (Neshat et al. 2014b). Sensitivity was measured through the value of rating and weights allocated to the SINTACS-LU layers of every unique parameter and the degree of the dissimilarity generated on the removal of parameter (Babiker et al. 2005) is discussed below.

Map removal sensitivity analysis

Actual impact of any parameter over vulnerability was determined by removing the parameter from the calculation. The variation in the index was derived by the removal of one parameter for every iteration as given in Table 4. This map removal sensitivity analysis (MRSA) was carried out by the removal of single or additional parameters of model output at a time (Colins Johnny et al. 2016). The effect of the removal of each parameter can be attained with the aid of statistical measures, namely minimum, maximum, mean, and standard deviation. After the removal of each parameter, the mean, and other indicators of vulnerability, LU pattern (mean variation index = 1.82) was recognized as highly responsive parameter to vulnerability. Though S and N were also given the same theoretical weight, the influence was felt slightly lesser in the Palayamkottai, but this did not disagree with the weights assigned to the parameter. The effective weight of the parameter was compared with the theoretical weight of that respective input parameter through coefficient of variation that can be seen in Table 5. The difference in the vulnerability index that is obtained by the removal of one parameter every time was used to derive the variation index of the parameter (Babiker et al. 2005). Results clearly indicate large difference in index value (mean value was 10.40) after the removal of the slope parameter in SINTACS-LU model. Soil and recharge layers are the parameters which have the nearly same mean variation index (1.44% and 1.47%). The vulnerability variation index value was moderately responsive to the elimination of depth to water table (3.2%) and the hydraulic conductivity layer (3.17%). The order of sensitivity of parameters over the map removal sensitivity analysis was hydraulic conductivity, soil, depth to water table, recharge impact of vadose zone, topography, and aquifer media (Anim et al. 2019).

Single-parameter SA

Single-parameter SA (SPSA) was used to appraise the inspiration of each and every parameter over the GWAV.

Table 3 SINTACS-LU model parameters' statistical summaries

Parameters	Statistical measurement				
	Min	Max	Mean	Standard deviation (SD)	Coefficient of variation
Water table depth (S)	5	7	6.47	0.89	13.76
Effective infiltration (I)	4	8	6.73	0.58	8.62
Unsaturated zone (N)	3	4	3.04	0.21	6.91
Soil media (T)	2	6	4.72	1.21	25.64
Aquifer media (A)	3	6	4.95	0.48	9.69
Hydraulic conductivity (C)	1	2	1.00	0.05	5.00
Slope (S)	1	10	6.08	2.60	42.76
Land use (LU)	1	10	8.13	2.64	32.47

Table 4 Statistical significance of every parameter during the map removal SA (removal of single model parameter at a time)

Parameters	Variation index (%)			
	Min	Max	Mean (μ)	Standard deviation (σ)
Water table depth (S)	0	2.70	1.04	0.49
Effective infiltration (I)	0	2.65	0.57	0.29
Unsaturated zone (N)	0	1.09	0.44	0.28
Soil media (T)	0	1.57	0.27	0.36
Aquifer media (A)	0	1.48	0.47	0.29
Hydraulic conductivity (C)	0.657	2.09	1.463	0.29
Slope (S)	0	2.22	0.71	0.52
Land use (LU)	0	3.68	1.82	0.87

Computation of the vulnerability index has been supplied with appropriate facts on the highly dominant model parameter involved in the GWAV assessment. The order of influence of every parameter with that of the other parameters was distinguished by the weights. The theoretical weight assigned to the parameter by the model failed due to the area specific conditions. The vulnerability assessment done through intrinsic vulnerability model may be unreliable due to the area-specific variation feature, feature ratings, and weights of the model. Therefore, to improve the trustworthiness, modification of the DRASTIC model was attempted (Neshat et al. 2014b). The contrast between the theoretical weight and the effective weight is shown in Table 6. The order of influence in the study that was estimated through the effective weight was land use, water table depth, effective infiltration, soil media, unsaturated zone, aqifer media, slope, and hydraulic conductivity. The study conducted by Neshat et al. (2014a) showed that an order of influence of effective weight calculated by the single-parameter sensitivity analysis was impact of vadose zone, recharge, aquifer media, hydraulic conductivity, soil, depth to water table, and topography that was deviated from the theoretical weight. The order of influence of the parameters used in the model varies from region to region, and therefore, the effective weights vary with respect to the region of study. The overall observation of theoretical and effective weights showed that the LU was more sensitive towards vulnerability.

SINTACS-LU

The SINTACS-LU model index was estimated through the summation of product of ratings and weights assigned to every parameter. The rating value of classes in a particular model parameter varied from 1 to 10. Parameters of SINTACS-LU model with ratings and ranges of each unique layer are illustrated in Table 6. Vulnerability index map revealed that areas sensible to vulnerability are in the range of 85–190. South west and north east represented that they are more vulnerable to contamination in spite of good vegetation cover. Rosenmeier et al. (2002) have showed the impact of vegetation cover on surface runoff reduction and groundwater recharge. The aquifers of villages that are less vulnerable to contamination are regions such as Melapattam, Reddiyarpatti hill, and its surrounding pediments, Sivanthipatti, and some parts of Tirunelveli Municipal Corporation. The most possible reason for the degradation of water quality in the wells may be due to the urban and agricultural activities (El-Zeiny and Elbeih 2019). Most of the regions of the taluk belong to the category of the moderate vulnerable zone. Spatial representations of vulnerability index in the taluk are shown in Fig. 10. Monitor and management of groundwater are essential to develop *land use policies related to recharge and seepage of chemicals from farming, waste disposal, and industrial activities to minimize possible contamination.* The knowledge of potential threats of pollution to groundwater resources especially in vulnerable areas and the issues related to health should be imparted to the public (Anim et al. 2019). Therefore, identification of highly vulnerable aquifers is necessary for the groundwater management, public awareness, and the consequential health-related issues.

Table 5 Statistical significance in the SINTACS-LU model during the removal of layers in SA

Model parameters	Variation index (%)			
	Min	Max	Mean (μ)	SD (σ)
SITACS-LU	0	2.22	0.71	0.52
SIACS-LU	0	3.94	1.44	0.74
SACS-LU	0	4.76	1.47	0.66
ACS-LU	0	5.68	3.2	1.01
AS-LU	0	5.68	3.17	1.01
S-LU	1.48	9.77	6.65	0.81
LU	2.22	17.52	10.40	0.46

**Table 6** Table of comparison between theoretical and effective weights of parameters of SINTACS-LU model

Parameters	Percentage of theoretical weight (TW)	TW	Effective weight (EW)			
			Min	Max	Mean (μ)	SD (σ)
Water table depth (S)	16.12	5	12	31	19.35	3.07
Effective infiltration (I)	12.90	4	11	28	15.97	1.85
Unsaturated zone (N)	16.12	5	7	19	8.87	1.34
Soil media (T)	12.90	4	4	19	11.05	3.02
Aquifer media (A)	9.67	3	4	17	8.62	1.34
Hydraulic conductivity (C)	9.67	3	1	4	1.22	0.417
Slope (S)	6.45	2	1	16	6.83	2.99
Land use (LU)	16.12	5	3	44	23.87	6.96

Cumulative score index

The aquifer vulnerability was estimated by weighted overlay analysis based on SINTACS-LU model. The output of the model was a map representing the groundwater vulnerability as an index of values within a range of 85–190. In the present groundwater vulnerability study, the cumulative score index (CSI) of a statistical approach was used to classify the vulnerability (Kirubakaran et al. 2016). This method uses mean and standard deviation of vulnerable index values of the layers of SINTACS-LU model to categorize the vulnerable zones. The statistical classification summary of model layers is represented in Table 7. The region was classified into four zones depending upon the vulnerability to contamination such as low, moderate, high, and very high vulnerable regions. Riparian landscape with impervious formation was dominated by depletion of vegetation and is vulnerable to flash floods (Mohamed and Worku 2020). The vulnerability of the aquifer

Fig. 10 GWAV index map of the Palayamkottai taluk
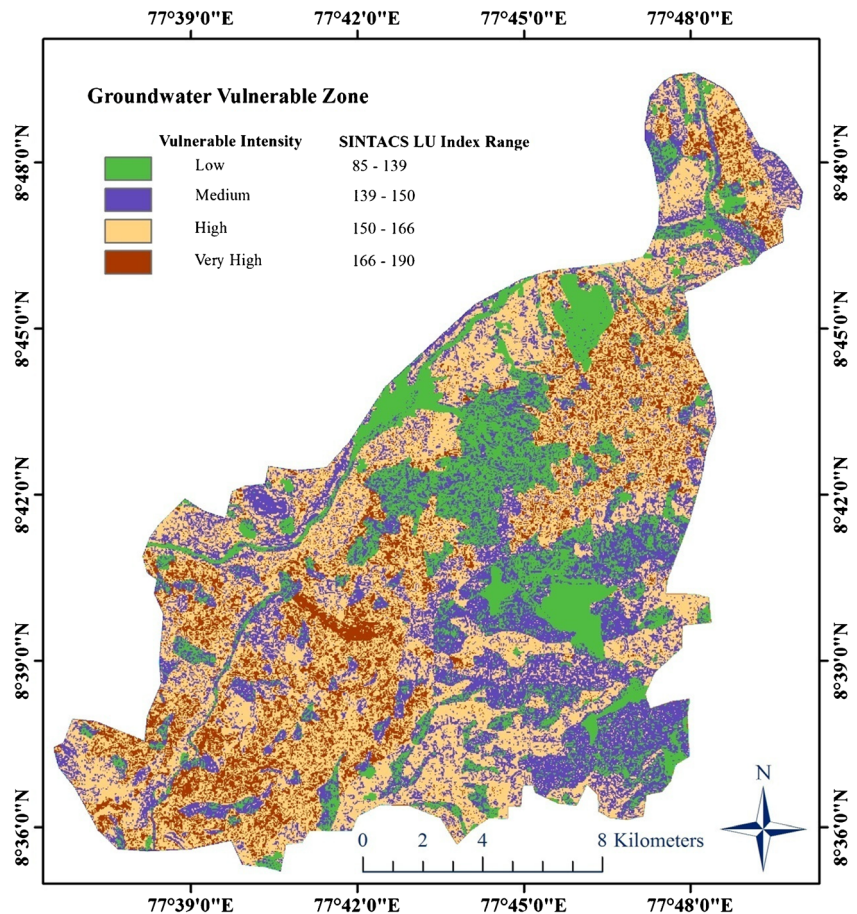
Table 7 Classification of vulnerability based on cumulative score index in SINTACS-LU model

Sl. No.	Vulnerability index	Area (km^2)	Vulnerable intensity
1	85–139	50.21	Low vulnerable zone
2	139–150	114.21	Moderate vulnerable zone
3	150–166	54.31	High vulnerable zone
4	166–190	81.19	Very high vulnerable zone

to contamination will be severely altered by the irregular flow of water that happens during the flash flood.

Validation

Groundwater vulnerability map was used to relate the vulnerability index of the SINTACS-LU model with that of the hydrochemical parameters of the taluk. This groundwater quality data of different wells obtained from the PWD was used for the analysis of the hydrochemical property of the well. Groundwater in the deep bore wells is moderately good than that in the dug wells of the taluk. The concentration of the hydrochemical parameters was compared with the standards of the World Health Organization (WHO 2008). Total dissolved solids (TDS) in the taluk ranged from 277 to 1319 mg/L. Total dissolved solids (TDS) in the taluk has less salinity, i.e., less than 2000 mg/L, and can be utilized for irrigation (El-Zeiny and Elbeih 2019). Wells in the Ariyakulam, Nochikulam, and Gonganthanparai have TDS less than the desirable limit with fresh water. The freshwater with the presence of salts was mainly due to the weathering of rocks and the dissolution of minerals in the rocks. The presence of bicarbonate was observed to be relatively more in these wells. Ariyakulam being close to the river Thamirabarani with limited settlements had good quality of water. Other wells had TDS greater than 500 mg/L, with the hydrochemical property of the water being modified by other agents of pollution. The chemical constituents such as nitrate, chloride, and TDS are generally high in the district (CGWB 2009). The influence of hardness of the wells was comparatively more in the wells of Thidiyoor, Palayamkottai town, and Sivanthipatti. By the observation of the concentration values of nitrate (6 to 42 mg/L), potassium (2 to 40 mg/L), sulfate (14 to 149 mg/L), and chloride (65 to 533 mg/L), the influence of irrigation return flow in the taluk appears to be moderate. Being an area dominated by agricultural activities, nitrate concentration is less. However, higher nitrate concentration was expected due to the effect of surface recharge over long periods (Neshat et al. 2014a). To find the wells that are influenced by the anthropogenic activities, the ratio of chloride to bicarbonate was used. The ratio ranged from 0.4 to 2.7, where the lower values show less anthropogenic and high values show high anthropogenic influence. Thidiyoor,

Palayamkottai town, and Sivanthipatti showed a higher value of the ratio, demonstrating the influence of anthropogenic activities. Thidiyoor (0.96) and Palayamkottai town (1.06) had a value close to 1, and Sivanthipatti had a ratio of 2.7. However, the deep bore wells in the Palayamkottai town showed a lower influence with a value of 0.5. The vulnerability in the Palayamkottai taluk ranged from very high VZs to low VZs. Major parts of the region in the taluk fall in the high to very high VZs. The wells that are influenced by anthropogenic activities fall in the highly sensitive VZs, whereas other wells from Ponnakudi, Ariyakulam, and Goganthanparai also were found in the same zone. Nochiklam falls in the medium VZ. Agricultural land where inorganic fertilizers are used is a potential source for nitrate contamination. The leaching of nitrate from the surface soil to the groundwater increases the concentration of nitrate (Neshat et al. 2014a). Though these regions are covered with agricultural lands, the concentration of nitrate was found to be less in the groundwater. Some wells despite of falling into high and very high vulnerable zones, had a good quality of groundwater indicating less contamination.

Conclusion

The study attempted to assess the present condition of the vulnerability of groundwater through the inherent nature of aquifer and LU. SINTACS-LU model uses eight spatial parameters to assess the GWAV. Almost 55% of the regions fall in the low to moderate vulnerability and are found to be safe for further development. Other regions need to be carefully examined before the development and proper investigation are needed at the field level. These regions need careful planning especially for industrial development as 45% of the regions were high to very high vulnerable regions. Remediation of the contaminated aquifer is more difficult, expensive, and time consuming and needs periodical monitoring even after the implementation. Therefore, avoidance of polluting activities is most needed in the effective management of groundwater and saves a lot of resources. Palayamkottai taluk has a major portion of the Tirunelveli Municipal Corporation and the sub-urban that has a wide scope of urbanization in the future. The development plans such as master plan of the city have included several villages in the taluk, and therefore, this sub-urban area has to be sustainable for future development. The impact of LU over the vulnerability was found to be high and needs to be considered for the assessment of vulnerability in this taluk. The aquifers in these villages are the main source of water and will continue to be so for the future. The quality of groundwater in some regions of the taluk was getting deteriorated and planning of any development activities should include the LU parameters to preserve the groundwater in the aquifers. Therefore, all the parameters used in this study could be

included in any LU planning to achieve the sixth goal of sustainable development of United Nations Environment Program. Under unavoidable circumstances, proper protection strategy should be adopted to prevent the aquifer from contamination. This work helps planners to achieve sustainable development goals and will be very useful for decision-makers involved in aquifer protection and urban development.

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