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Assessment of groundwater vulnerability using SINTACS and modified-SINTACS methods in Burdur Çine Basin (Turkiye)

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ABSTRACT

Groundwater sensitivity studies are widely used to protect aquifers in basins from pollution elements and to take necessary precautions. In this study, the SINTACS model was used in conjunction with GIS and AHP to determine groundwater sensitivity. The SINTACS model is generally preferred in karstic lithologies. The Burdur Cine Basin (BCB) is located in the karstic area defined as the Taurus Limestone Belt in southwestern Turkey. In the basin where intensive agricultural activities are carried out, there is a university campus and numerous villages. The groundwater in the basin is used both for drinking water in Burdur province and for agricultural activities. In determining the sensitivity of groundwater; the parameters of water depth (S), infiltration (I), unsaturated zone (N), soil (T), hydrogeological features (C), and topographic surface (S) were used. These model parameters were weighted using normal and karstic SINTACS scenarios based on the characteristics of the basin. In the parameter weighting process with AHP, the geological, hydrogeological, meteorological, and land use characteristics of the region, particularly the karstic structure, were taken into account. The SINTACS index was found to be in the range of 26-222, while the modified SINTACS index was in the range of 63-269. The modified SINTACS method has provided higher index values due to the addition of two parameters. According to the modified SINTACS method, it has been determined that 44.36% of the basin has very high, 22.08% high, 13.02% moderate, and 10.17% extremely high sensitivity. The areas with very high and high sensitivity include areas where the slope is low and soil over the aquifer is permeable. This situation indicates that the groundwater aquifer in the basin is highly sensitive to pollution.

Keywords: Vulnerability Mapping; SINTACS; Geographic Information System (GIS); Hydrogeology; Turkey.

Evaluación de la vulnerabilidad de las aguas subterráneas mediante métodos SINTACS y SINTACS modificado en la cuenca de Burdur Çine (Turquía)

RESUMEN

Los estudios de sensibilidad de las aguas subterráneas se utilizan ampliamente para proteger los acuíferos en las cuencas de los elementos contaminantes y para tomar las precauciones necesarias. En este estudio, se utilizó el modelo SINTACS junto con SIG y AHP para determinar la sensibilidad del agua subterránea. El modelo SINTACS se prefiere generalmente en litologías kársticas. La Cuenca Burdur Cine (BCB) se encuentra en el área kárstica definida como el Cinturón de Caliza de Tauro en el suroeste de Turquía. En la cuenca donde se llevan a cabo actividades agrícolas intensivas, hay un campus universitario y numerosas aldeas. Las aguas subterráneas en la cuenca se utilizan tanto para el agua potable en la provincia de Burdur como para actividades agrícolas. Para determinar la sensibilidad de las aguas subterráneas, se utilizaron los parámetros de profundidad del agua (S), infiltración (I), zona no saturada (N), suelo (T), características hidrogeológicas (C) y superficie topográfica (S). Estos parámetros del modelo se ponderaron utilizando escenarios SINTACS normales y kársticos basados en las características de la cuenca. En el proceso de ponderación de parámetros con AHP, se tomaron en cuenta las características geológicas, hidrogeológicas, meteorológicas y de uso del suelo de la región, particularmente la estructura kárstica. El índice SINTACS se encontró en el rango de 26-222, mientras que el índice SINTACS modificado se encontró en el rango de 63-269. El método SINTACS modificado ha proporcionado valores de índice más altos debido a la adición de dos parámetros. Según el método SINTACS modificado, se ha determinado que el 44.36% de la cuenca tiene una sensibilidad muy alta, el 22.08% alta, el 13.02% moderada y el 10.17% extremadamente alta. Las áreas con sensibilidad muy alta y alta incluyen zonas donde la pendiente es baja y el suelo sobre el acuífero es permeable. Esta situación indica que el acuífero de aguas subterráneas en la cuenca es altamente sensible a la contaminación.

Palabras clave: Mapa de vulnerabilidad, SINTACS, Sistema de Información Geográfica (SIG), Hidrogeología, Turquía.

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1. Introduction

Groundwater is one of the most important sources of freshwater necessary for the survival of all living organisms and agricultural activities. In recent years, the quality, quantity and availability of water have been the main problems with groundwater. The most important factors limiting the use of surface water and groundwater are agricultural, industrial and domestic pollution sources. Unlike surface waters, the processes of groundwater being affected by pollution elements take time and are more difficult (Foster and Chilton, 2003; Jackson et al., 2001). However, the cleaning of polluted groundwater is very difficult and time-consuming compared to surface waters and, in some cases, even impossible (Soyaslan, 2022). For these reasons, it is of great importance to take the necessary measures to protect groundwater from pollution sources. To take these measures, it is necessary to determine the pollution potential of groundwater. The assessment of groundwater pollution potential is carried out to determine the possible consequences of potential pollution. For this purpose, it is necessary to determine the topographical, geological, hydrogeological and hydrological characteristics of the environment through which the pollutant elements pass. One of the methods frequently used in determining the pollution potential of groundwater is groundwater vulnerability studies (Soyaslan, 2020; Kirlas et al., 2022). The factors to be considered in these studies are the spread of pollution depending on the groundwater flow mechanism and the economic value of groundwater in the region (COST, 2003). Groundwater aquifers are crucial for providing water for several applications, including potable, agricultural, and industrial needs. Mathematical simulation techniques are employed to ascertain the response of groundwater aquifers to pollution sources. Understanding the hydrological characteristics of an aquifer is essential in this domain. Numerous researches employing various methodologies have demonstrated that the most sensitive criterion for internal groundwater sensitivity is the depth of the groundwater level (Ansarifar et al., 2020).

To take measures to reduce and prevent groundwater pollution, the relationship between pollution sources and groundwater vulnerability should be revealed. Groundwater vulnerability maps prepared using models integrated with GIS are very useful for regional and local groundwater utilization planning (Taheri et al., 2023).

The concept of groundwater vulnerability was initially articulated in 1968 as 'the susceptibility of groundwater to pollution' (Margat, 1968). The word vulnerability became prevalent in the early 1970s to denote the susceptibility of aquifer groundwater systems to contamination (Albinet and Margat, 1970). The phrase gained broader usage among numerous researchers in the 1980s (Haertle, 1983; Aller et al., 1987; Foster, 1987; Forster and Hirata, 1988). The notion of groundwater vulnerability refers to the susceptibility of groundwater to contamination (Gogu and Dassargues, 2000). The evaluation of groundwater contamination potential cannot be ascertained immediately by field research (Alfonso et al., 2008).

The terms origin, channel, and target articulate a triadic model for environmental management in aquifers, which forms the foundation of the notion of groundwater vulnerability. The origin is the location from which the pollutant emanates. The pathway encompasses all components, from the pollution source to the route taken until it reaches the groundwater. The objective is to safeguard the groundwater table (COST, 2003). Groundwater vulnerability can be assessed using two sub-concepts: intrinsic and particular vulnerability. Intrinsic vulnerability considers the geological, hydrological, and hydrogeological attributes of the aquifer region, reflecting the groundwater's susceptibility to pollution. Nonetheless, it fails to include contamination scenarios resulting from potential contaminants affecting groundwater. The specific vulnerability takes into account the attributes of a specific contaminant as well as the inherent vulnerability of groundwater (COST, 2003). Index methodologies employed to assess groundwater vulnerability might be important in safeguarding aquifers at risk from pollution sources and in implementing requisite remedies. These index approaches classify the parameters influencing the probability of groundwater pollution on a scale and assign a score that indicates the impact (Foster, 1987). Numerous research studies employing various methodologies have demonstrated that the depth of the groundwater level is the most sensitive indicator for assessing internal groundwater sensitivity (Ansarifar et al., 2019).

For distinct aquifers, groundwater vulnerability assessments employ several methodologies with GIS assistance (Khemiri et al., 2013; Assefa and Dinka, 2023). Among the most prevalent methods are DRASTIC (Aller et al., 1987), GOD (Foster, 1987), the AVI rating system (Van Stempvoort et al., 1992), SINTACS (Civita, 1994; Civita and De Maio, 1997; Doerfliger and Zwahlen, 1995; Hölting et al., 1995; Vias et al., 2002; Goldscheider et al., 2000), EPIK (Doerfliger and Zwahlen, 1995), GERMAN (Hölting et al., 1995), COP (Vias et al., 2002), PI (Goldscheider et al., 2000), and the ISIS method. The nomenclature of these methods typically includes the initials of the parameters employed. There are ongoing discussions about the best way to do things, but the DRASTIC method is used for alluvial aquifers and the SINTACS method is used for karstic aquifers to figure out how likely they are to become contaminated (Taheri et al., 2023; Jahromi et al., 2021). Research indicates that methodologies employing numerous criteria in groundwater vulnerability assessments yield more trustworthy outcomes (Kazakis et al., 2015). Table 1 presents the parameters of various approaches employed in groundwater vulnerability assessment. Furthermore, irrespective of the approach employed, the paramount stage in groundwater risk assessment is the allocation of weights (Pacheco et al., 2015; Soyaslan, 2020). The disadvantages of these methods include their process-based nature, challenges in data acquisition, difficulty in calculations, and the necessity for expertise and experience in their implementation. Consequently, statistical methods are predominantly employed in groundwater vulnerability assessments rather than alternative approaches (Al-Abadi et al., 2017; Neshat et al., 2014). Table 1. Parameters of several methodologies employed in groundwater vulnerability assessment (Polemio et al., 2009).

The primary advantage of the SINTACS approach compared to the DRASTIC method is the simultaneous application of varied weights across multiple cells (Goyal et al., 2021). The SINTACS method can be used for both medium- and large-scale mapping, and it is more flexible than the DRASTIC method when it comes to choosing the input parameters' proportions and weights (Ramos Leal et al., 2010; Majandang and Sarapirome, 2013; Goyal et al., 2021). Consequently, the weights utilized in the SINTACS technique are established more completely by taking into account all hydrogeological variables, allowing its application in areas with varying hydrogeological characteristics within the same basin (Kumar et al., 2013).The concentrations of NO_3^- and SO_4^{2-} obtained in the field are utilized to assess the groundwater vulnerability to anthropogenic sources and to validate thematic maps generated using the SINTACS approach (Eftekhari and Akbari, 2020). Land use is regarded as an extra factor to enhance the precision of the groundwater vulnerability assessment (Soyaslan, 2020; Busico et al., 2017). Intrinsic vulnerability assessment is typically favored in karst basins utilized as drinking water supplies and agricultural regions when employing the SINTACS approach (Kapelj et al., 2013; Aschonitis et al., 2014; Boufekane and Saighi, 2013; Kumar et al., 2013; Marsico et al., 2004). The SINTACS method is specifically employed in the evaluation of groundwater vulnerability in karst aquifer systems (Khemiri et al., 2013; Busico et al., 2017). The updated SINTACS model has been developed and extensively utilized by incorporating lineament and land use parameters alongside the seven components of the original SINTACS technique (Busico et al., 2017; Eftekhari and Akbari, 2020).

The groundwater vulnerability study of Torka province in Ghana, utilizing the SINTACS model, revealed that over 50% of the aquifer is very sensitive due to mining and industrial operations (Ewusi et al., 2017). A groundwater sensitivity research study employing the SINTACS model in southern Italy revealed that the application of nitrogenous fertilizers elevates groundwater sensitivity (Busico et al., 2017). The groundwater sensitivity study in the Nong Rua region of Thailand, conducted using the SINTACS approach, identified six distinct groundwater sensitivity zones. Regions exhibiting high and medium groundwater sensitivity were identified as those with elevated infiltration rates and shallow groundwater tables (Majandang and Sarapirome, 2013). Kirlas et al. (2022) performed groundwater vulnerability mapping in the Nea Moudania aquifer in Greece with seven distinct GIS-based methodologies. The vadose zone and topography were identified as the most influential characteristics on the groundwater vulnerability index, whereas hydraulic conductivity was deemed the least useful parameter. Eftekhari and Akbari (2020) delineated various index zones in their groundwater vulnerability assessment employing the SINTACS-LU model in the Birjand plain, located in the South Khorasan region, Iran. The model demonstrated a suitable association with nitrate concentration as a measure of groundwater contamination. Slimani et al. (2023) employed three distinct GIS-supported methodologies (GOD, DRASTIC, and SINTACS) in their investigation of groundwater pollution vulnerability in the Ouargla region of Algeria. The DRASTIC and SINTACS methodologies have been identified as better and more appropriate for the region, with groundwater depth being the most influential parameter on the index value. Primastuti and Kusratmoko (2018) delineated contamination-sensitive zones within the aquifer utilizing the SINTACS and SINTACS-Lu methodologies in Taman Rahayu. A 70% correlation with nitrate concentrations was established using the SINTACS method, whereas an 80% correlation was found with the SINTACS-Lu approach. Utami (2019) performed a vulnerability index analysis with a modified SINTACS model that incorporated land use parameters in the Opak Hılır basin. There were significant correlations found between the amount of nitrate and the adjusted SINTACS vulnerability index values (Primastuti and Kusratmoko, 2018; Utami, 2019). Analysis of prior research indicates that the SINTACS approach is appropriate for evaluating groundwater vulnerability. The revised SINTACS approach has a superior correlation value compared to the original SINTACS method. The revised SINTACS approach is deemed more suitable as it incorporates additional land characteristics.

This study employed the widely recognized SINTACS and modified SINTACS methodologies to assess groundwater vulnerability in the alluvial aquifer and the overlying karstic limestone aquifer for BÇB. Hydrological scenarios were constructed based on the region's land use, lithological, and hydrological attributes. Furthermore, no groundwater risk assessment has been conducted yet in the research area, which exhibits karstic features.

2. Materials and Methods

2.1. Study area description

The BÇB is situated in the western Mediterranean area of southwestern Turkey, namely within Burdur province, in a region characterized by karstic and tectonic formations known as the Lakes Region (Figure 1). It is moreover a subsidiary basin of the Lake Burdur basin. The research region is situated between latitudes N 37º 35.5' and N 37º 44' and longitudes E 30º 19.5' and E 30º 29', encompassing an area of 132 km². The height of the region varies from 1075 to 1925 meters.

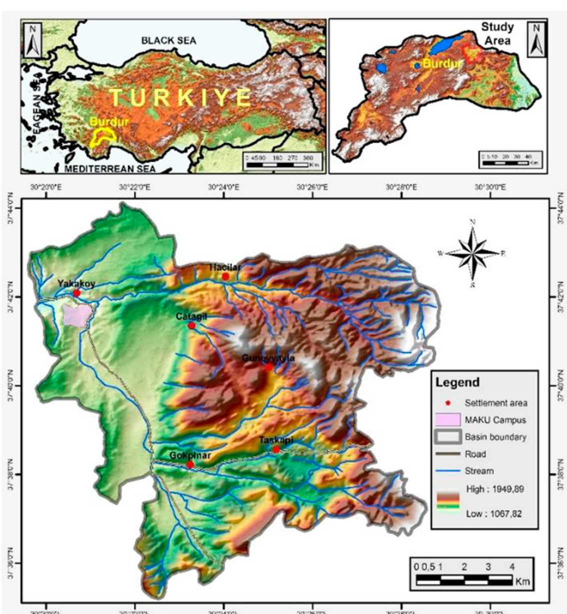

Figure 1. Location map of BÇB

2.2. Geology

The geological formations in the research region comprise Mesozoic-aged limestones near the base. The limestones at the base constitute the karst aquifer, with groundwater flowing southward from this aquifer into the Mediterranean Sea (Davraz et al., 2009). Superimposed over the limestones are the ophiolitic complex, Palaeogene-aged sandstone, mudstone, siltstone, and claystone, followed by Neogene-aged conglomerate, sandstone, claystone, and siltstone, along with Neogene-aged travertine, culminating in Quaternary-aged alluvium composed of unconsolidated blocks, gravel, sand, and silt.

2.3. Hydrogeology

The primary geological formations facilitating groundwater transfer in BÇB are Quaternary alluvium and limestone deposits. Additional units that contain groundwater, based on their hydrogeological properties, include Plioquaternary-aged travertine, lacustrine sediments, conglomerate, and sandstone. Cretaceous-aged limestone, constituting the foundation of the research region, outcrops across an expanse of 32.81 km² (25%) inside the basin, while Dutdere limestones outcrop over 12.89 km² (10%). Alluvium, a unit exhibiting aquifer properties, emerges over an area of 33.74 km² (26%). Units exhibiting aquifer characteristics, covering 61% of the total basin area, heighten the susceptibility of groundwater to contamination. Fractures, fissures, and karstic formations in limestone facilitate the infiltration of precipitation into groundwater. This situation is corroborated by the presence of lakes in the Insuyu Cave, composed of karstic limestone, which are replenished by rainwater descending from the cave ceiling. The Triassic allochthonous Dutdere limestone, the other karstic unit, was influenced by tectonic movements. Dutdere limestone possesses the characteristic of an aquifer comprising minor karstic voids formed along fractures and fissures. In terms of thickness and distribution, Cretaceous limestone possesses superior potential for groundwater compared to Dutdere limestone. Furthermore, the Dutdere limestone, situated atop the impermeable Ophiolitic complex, emanates from multiple sources along this interface. A confined aquifer with lateral recharge can be seen in travertine from the Plioquaternary period and lacustrine sediments from the Pliocene period (Taşdelen, 2018). The geological and hydrogeological characteristics of the region render groundwater susceptible to many contamination sources. The primary cause of pollution originates from agriculture, attributable to the extensive application of synthetic fertilizers and pesticides in the basin's agricultural practices. Alongside the rising utilization of groundwater in the research area, Burdur Province has increasingly sourced drinking water from boreholes in recent years. Consequently, the water level in the subterranean lakes of the karstic Insuyu cave within the basin has progressively diminished, leading to the desiccation of the lakes. Two problems jeopardizing the groundwater in the research area are the unregulated extraction of groundwater and the potential for agricultural contamination. This circumstance jeopardizes all operations reliant on groundwater inside the basin. The significance of groundwater vulnerability assessments is recognized in light of groundwater utilization and pollution sources within the basin.

2.4. Methodology

The methodology used in the groundwater vulnerability assessment for the BÇB is shown in Figure 2.

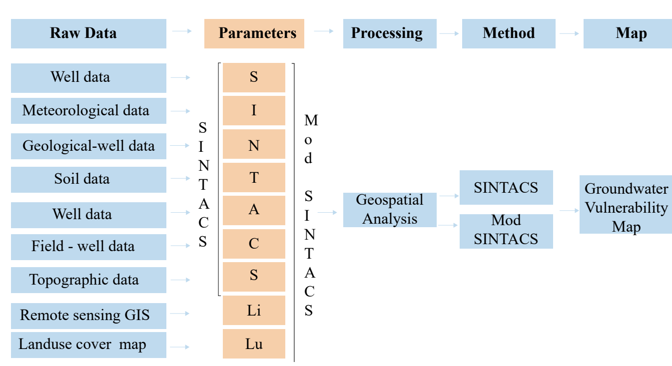

Figure 2. Methodology framework applied in this study

The SINTACS approach is regarded as the Italian equivalent of the DRASTIC method, a prominent aquifer vulnerability assessment technique globally, tailored to Mediterranean conditions. Upon digitizing the SINTACS parameters in ArcGIS software, the Inverse Distance Weighted (IDW) interpolation method was employed to generate parameter maps in raster format with 25x25 m cells. The IDW approach relies on the notion of allocating point data to spatial raster data inside a grid network composed of designated cells (Soyaslan, 2020).

2.5. The SINTACS method

The SINTACS approach was initially formulated by Civita in 1990, 1993, and 1994, and then refined by Civita and De Maio in 1997 for evaluating and delineating groundwater sensitivity in aquifer systems. The SINTACS approach employs a weighted aggregation of seven distinct characteristics to evaluate groundwater sensitivity. The parameters that confer the SINTACS method its designation and are utilized in groundwater sensitivity index computations are as follows (Civita and De Maio, 2004):

- S_1 : Depth to water (**S**oggiacenza),
- I : Infiltration (**I**nfiltrazione),
- N : Effect on the auto-depuration of the unsaturated zone (**N**onsaturo),
- T: Typology of the cover (**T**ipologia della copertura),
- A : Hydrogeologic characteristics of aquifer (**A**quifero),
- C: Hydraulic conductivity (**C**onducibilita),
- S_2: Slope (Superficie topografica)

The SINTACS parameters are fundamental elements necessary for evaluating the susceptibility of a groundwater aquifer to contamination. Moreover, the tectonic, hydrogeological, and land use attributes of the study area may influence the employment of supplementary parameters. The methodology was amended by including lineament (Li) and land use (Lu) parameters, owing to the tectonic features of the research region adjacent to active fault lines and prevailing land use characteristics.

Table 2 presents the ranges and ratings of SINTACS parameters. The rating values fluctuate from 1 to 10, contingent upon the subclasses of the parameter. The parameter exhibiting the greatest risk and significance regarding groundwater contamination is allocated a rating of 10, whereas the parameter of least significance is assigned a rating of 1. The SINTACS parameters are categorized into subclasses based on their influence on the potential for groundwater pollution.

Despite utilizing identical parameters, the SINTACS and DRASTIC procedures assign divergent ratings to the parameters employed in the SINTACS approach. The primary distinction between the SINTACS and DRASTIC approaches is that the SINTACS method offers five distinct groundwater vulnerability scenarios. Normal impact, severe impact, substantial drainage from a surficial network, fissured aquifers, and karstified aquifers are some of the situations that have been studied (Civita and De Maio, 1997; Civita and De Maio, 2004; Kirlas et al., 2022; Slimani et al., 2023; Von Hoyer and Söfner, 1998; Civita 10). The ratings (r) for each parameter range from 1 to 10, whereas the weights (w) range from 1 to 5 (Kirlas et al., 2022). The variable weights allocated to the parameters based on the scenarios are presented in Table 3.

Table 2. Ranges and ratings of SINTACS parameters (Civita and De Maio, 1997)

SINTACS parameters	Range	Rating	SINTACS parameters	Range	Rating
S_1 (m)	0–1	10		Peat	7.5-8
	1–4	9		Sandy	8-8.5
	4–6	8		Clean sand	9-9.5
	6–8	7		Clean gravel	9.5-10
	8–10	6		Thin or absent	10
	10–20	5	A	Coarse alluvial deposits	8-9
	>20	4		Karstifed limestone	9-10
I (mm)	<50	1		Fractured limestone	6-9
	50–60	2		Fissured dolomite	4-7
	60–75	3		Medium fne alluvial deposits	6-8
	75–100	4		Sand complex	7-9
	100–125	5		Sandstone, conglomerate	4-9
	125–150	6		Turbiditic sequences	5-8
	150–175	7		Fissured volcanic rocks	8-10
	175–250	8		Marl, clay stone	1-3
	250–325	9		Clay, silt, peat	1-3
N	Coarse alluvial deposits	6-9		Pyro-clastic rock	4-8
	Karstifed limestone	8-10		Fissured metamorphic rocks	2-5
	Fractured limestone	4-8	C (m/day)	<0.1 1	1
	Fissured dolomite	2-5		0.1–0.43	2
	Medium fne alluvial deposits	3-6		0.43–0.86	4
	Sand complex	4-7		0.86–4.32	5
	Sandstone, conglomerate	5-8		4.32–8.64	6
	Turbiditic sequences	2-5		8.64–43.2	7
	Fissured volcanic rocks	5-10		43.2–86.4	8
	Marl, clay stone	1-3		86.4–432	9
	Clay, silt, peat	1-2		432–864	10
	Pyro-clastic rock	2-5	S_2 (%)	0–2	10
	Fissured metamorphic rocks	2-6		3–4	9
T	Clay	1-1.5		5–6	8
	Silty-clay	1.5-2		7–9	7
	Clay loam	2-3		10–12	6
	Silty clay loam	3-4		13–15	5
	Silt loam	3.5-4		16–18	4
	Loam	4-5		19–21	3
	Sandy clay loam	4.5-5		22–25	2
	Sandy loam	5.5-6		>26	1
	Sandy clay	6.3-7			

Table 3. Weighted scenarios in the SINTACS method (Civita and De Maio, 1997)

Weighting Scenarions	S	I	N	T	A	C	S
Normal impact	5	4	5	3	3	3	3
Severe impact	5	5	4	5	3	2	2
Drainage from surficial network	4	4	4	2	5	5	2
Karstic impact	2	5	1	3	5	5	5
Fissuring impact	3	3	3	4	4	5	4

The SINTACS method's framework was designed to accommodate varied weight sets assigned to factors based on differing hydrogeological and impact scenarios. This study developed hydrogeological scenarios based on land use, landforms, and the hydrogeological structure of the region (Mastrocicco et al., 2017; Civita, 1990; Civita, 1993). Given the hydrogeological attributes of the study area, standard and karstic impact scenarios derived from SINTACS weighting sequences were employed (Civita and De Maio, 2004). Regions subjected to standard impact are those where agriculture, plant protection agents, fertilizer, and irrigation are employed. These regions typically encompass areas with gentle gradients where alluvial aquifers and other geological formations are exposed. Regions subjected to karstic influence are characterized by undulating, sloped topography containing limestones with karstic dissolution cavities. These regions encompass desolate, uncultivated land or places devoid of agriculture, save for indigenous flora. Agricultural practices, irrigation, and fertilization are not conducted in these regions.Each criterion map for each variable was created as a GIS data layer in raster format with grid dimensions of 25 x 25 meters. The SINTACS vulnerability index (IV) was computed for each grid element utilizing the subsequent equation (Equation 1):

$$\text{SINTACS } I_v = (S_{1r}S_{1w}) + (I_rI_w) + (N_rN_w) + (T_rT_w) + (A_rA_w) + (C_rC_w) + (S_{2r}S_{2w}) \quad (1)$$

In Equation 1, the subscript r denotes the rating of the seven parameters, while v represents their weights. The groundwater vulnerability index spans from 26 to 260, with the vulnerability index classifications and their respective ranges detailed in Table 4. To facilitate comparison and interpretation of the results, these data were standardized to a range of 0 to 100. This normalization is categorized into six vulnerability classes: 0-24 very low (VL), >24-40 low (L), >40-55 moderate (M), >55-65 high (H), >65-80 very high (VH), and >80-100 extremely high (EH) (Majandang and Sarapirome, 2013).

Table 4. Vulnerability index rating classes for the SINTACS method (Civita and De Maio, 1997)

Vulnerability classes	Ranges
Very low	26-80
Low	80-105
Medium	105-140
High	140-186
Very high	186-210
Extremely high	210-260

2.6. The modified SINTACS method

The new SINTACS method was made by adding linearity and land use features to the existing framework, which had seven factors. This was done even though the original SINTACS method already had standard and karst effect scenarios. The vulnerability index value (Imv) for the modified SINTACS method is computed as outlined in Equation 2.

$$\text{Modified SINTACS } I_{mv} = (S_{1r}S_{1w}) + (I_rI_w) + (N_rN_w) + (T_rT_w) + (A_rA_w) + (C_rC_w) + (S_{2r}S_{2w}) + (Li_rLi_w) + (Lu_rLu_w) \quad (2)$$

The r values in the sub-index of the modified SINTACS vulnerability index (Imv) equation represent the ratings of the parameters; the w values denote the weights; and the final two parameters are lineament (Li) and land use (Lu). Consequently, the SINTACS vulnerability index (IV) has seven parameters, but the modified SINTACS (Imv) incorporates nine parameters, including the additional Li and Lu parameters. This feature enables the enhanced SINTACS approach to depict additional hydrogeological properties. Consequently, it facilitates a more precise transfer of the field to the model environment. This also applies to the vulnerability parameters of databases and SINTACS.

Groundwater depth (S1)

The S1 parameter value of the SINTACS technique is derived from groundwater depth. As the depth of groundwater from the surface increases, the rating of the S1 parameter, which ranges from 10 to 1, diminishes. Groundwater depth numbers represent the distance to the groundwater surface as measured in boreholes within the study region. The locations and groundwater levels of the surveyed wells were integrated into the GIS environment, resulting in the creation of a database. A digital terrain model (DTM) was generated utilizing the groundwater depth data from the database. Linear interpolation, a conventional technique, was employed in the development of the Digital Terrain Model (DTM), resulting in a raster-based regional technical map created at a scale of 1:100,000. The RECLASS command within the GIS environment classified the groundwater depth map based on the range values of the SINTACS approach. A grid of points associated with the groundwater depth parameter was generated. The groundwater was categorized into six classes based on depth and awarded rating values from 4 to 10 (Figure 3a).

Infiltration (I)

The effective infiltration action parameter is determined from the effective rainfall and surface hydrogeological parameters by a numerical model applied to grid cells. Seven distinct homogenous regions were delineated based on the average rainfall-to-elevation ratio. According to the established grid cells of the study area, the subsequent statistics were automatically computed for each cell: specific rainfall, adjusted temperature, specific evapotranspiration, specific infiltration charge, and specific surface runoff. Following the computation of the infiltration value for each grid cell, it was visualized and classed in RASTER format (Figure 3b).

Effects of the unsaturated zone (N)

The N parameter, sometimes referred to as unsaturated zone attenuation capacity, was determined by the analysis of well data and stratigraphic studies in the research area. The hydrogeological attributes of the region's geological formations, including texture, mineral composition, grain size, discontinuities, and karstification, were utilized in the specification of the SINTACS N parameter. The data were verified and standardized to ensure precise zoning of the hydrogeological information. The previously established points for unsaturated thickness were allocated to these homogeneous regions. The data associated with parameter N for these sites was classified, and a RASTER map was generated at a scale of 1:100,000. The GIS system generated thematic maps and additional parameters (Figure 3c).

Typology of the Cover (T)

The European Environment Agency (EEA) provided the land cover use classification that led to the establishment of the SINTACS T parameter, also known as soil/overburden attenuation capacity. The land cover utilization data generated by the EEA via computer-assisted visual interpretation of satellite imagery was created as part of the CORINE (Coordination of Information on the Environment) project. The CORINE database and local soil maps were analyzed, resulting in the pedological zoning of the entire basin, accompanied by hydrogeological data (Figure 3d).

Hydrogeological properties of the aquifer (A)

The SINTACS A parameter, encompassing the hydrogeological attributes of the aquifer, delineates the processes occurring beneath the contaminant's piezometric level. This process encompasses all interactions between the hydrogeological properties of the lithology constituting the aquifer environment and the pollutant. The approaches utilized for the SINTACS A parameter were identical to those employed for the N parameter. The hydrogeological features map of the aquifer was correlated with the SINTACS locations utilizing the same computation methods. The grid within the GIS framework was implemented across the entire region in accordance with the hydrogeological features map of the aquifer (Figure 3e).

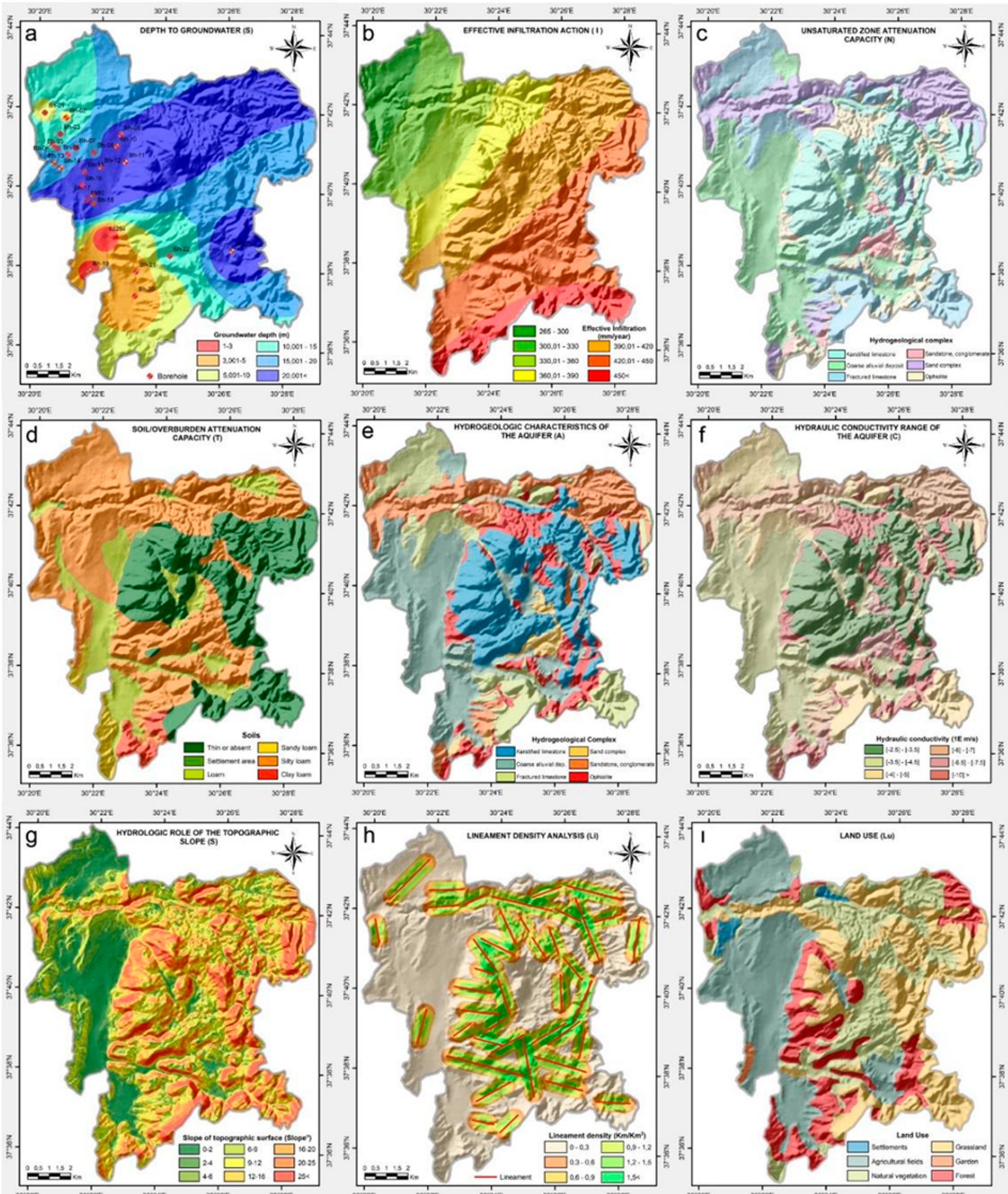

Figure 3. Thematic maps of the study area

Hydraulic conductivity (C)

The hydraulic conductivity or hydraulic conductivity range of the aquifer, as described in the SINTACS C parameter, was found by looking at well test data, drilling logs, and well stratigraphy. In regions with inadequate data, the variation in the C parameter points of the aquifer was acknowledged. The hydraulic conductivity map was generated with particular discharge data and conductivity values derived from slug and recovery tests. The C parameter diminishes to -10 in ophiolitic lithologies characterized by low permeability, -2.5 in karstic limestones, and -3.5 in alluvial aquifers. In accordance with the SINTACS points, the C parameter was classed, and a raster map at a scale of 1:100,000 was generated within the GIS environment (Figure 3f).

Slope (S2)

The second S2 parameter of the SINTACS acronym, representing the hydrologic function of the topographic slope, was derived using the Regional DTM within the GIS framework, featuring slope classifications from 0 to 28%. The slope (S2) parameter was classed based on SINTACS points, and a raster map was generated at a scale of 1:100,000. A height grid was generated from DTM within a GIS framework, and a grid depicting the topographic surface slope was produced using SLOPE housing. The classification of slope categories was established by analyzing the distribution of % slope ranges to be mapped and the constraints of the SINTACS approach (Figure 3g).

Lineaments (Li)

The approach was enhanced by using lineament data in the groundwater vulnerability index computations, in addition to the SINTACS parameters. Lineaments (Li) parameter: A total of 38 lineaments were identified through the analysis of LANDSAT satellite pictures inside a GIS framework. Fault lines, fracture lines, formation boundaries, and other discontinuities influencing water movement were considered in the identification of lineaments. Lineaments have formed due to the basin's location in a tectonically active area. It makes sense to include the lineaments parameter in the SINTACS model because it helps water move (Figure 3h).

Land use (Lu)

The second parameter land use (Lu), incorporated into the SINTACS parameters, was revised for the research region by considering field studies and land use data, resulting in the production of a thematic map using the updated information. The land use parameter is categorized into six classes: settlement, agricultural field, natural vegetation, grassland, garden, and forest. The rigorous farming practices in the study region necessitate the application of pesticides and fertilizers. Adding the land use parameter to the SINTACS model is very important for making it more accurate and sensitive, since farming in the basin has a negative effect on groundwater sensitivity (Figure 3i).

3. Results and discussion

3.1. Map of groundwater vulnerability

The SINTACS vulnerability index map (Figure 4) was derived from seven hydrogeological parameters, whereas the modified SINTACS vulnerability index map (Figure 5) was derived from nine hydrogeological parameters. The parameters employed in these maps were computed with ArcGIS software and GIS analytical techniques. The SINTACS vulnerability index values are categorized into six distinct classes, ranging from 26 to 260.The risk zones characterized by elevated groundwater sensitivity within the basin are situated in regions designated for residential use, where the slope is minimal (0-2%), loam soils are conducive to agriculture, and the groundwater depth is relatively shallow. Furthermore, groundwater sensitivity is observed to rise, particularly at locations with diminished groundwater levels where agricultural activities and boreholes are situated.

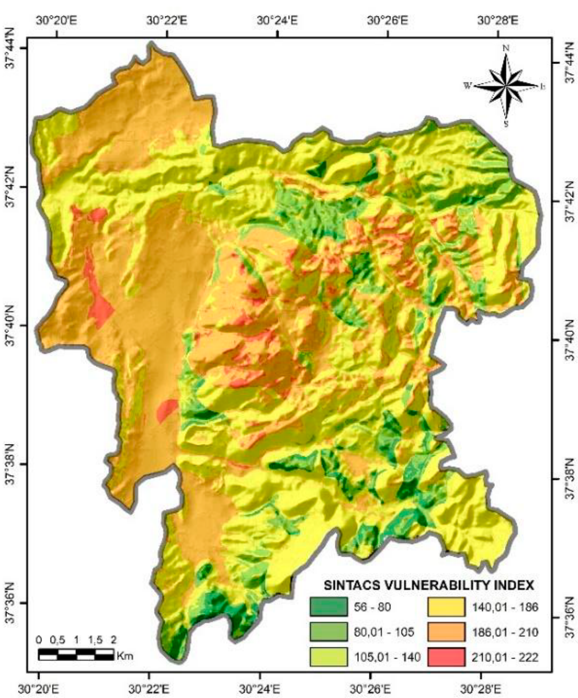

Figure 4. SINTACS Vulnerability index map

The primary distinction between the map generated by the modified SINTACS method and the map produced by the SINTACS method is the elevation of the risk level. Augmenting the parameter count and using lineament density alongside land use factors have proven helpful in this context. In very elevated areas, the influence of lineament density is minimal, whereas the impact of land use is significant. The agricultural regions along the north-south axis in the western part of the research area are deemed more hazardous.

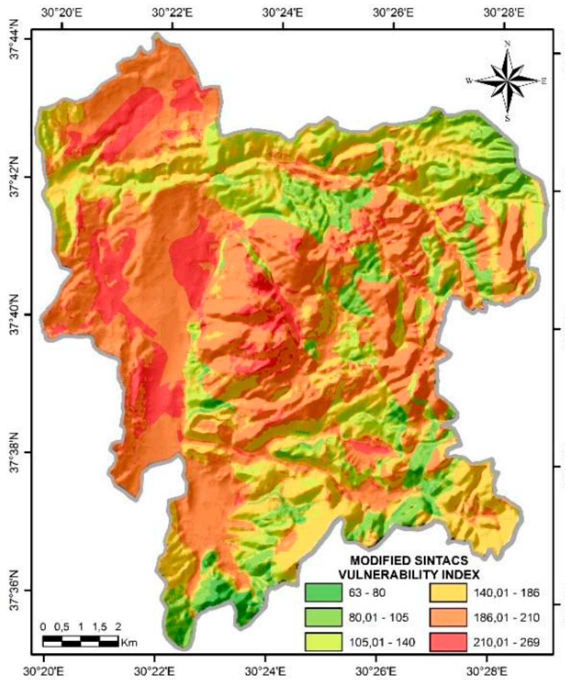

Figure 5. Modified SINTACS Vulnerability index map

This scenario underscores the necessity of incorporating the land use variable in the assessments of groundwater vulnerability. Furthermore, it was ascertained that regions devoid of settlements and agricultural zones with elevated topography exhibit reduced risk of groundwater susceptibility. Furthermore, the low-slope alluvial regions in the western part of the research area present greater risk compared to the high-slope rocky regions in the east. The SINTACS vulnerability index, based on established ratings and weightings, spans from 56 to 222, whereas the modified SINTACS vulnerability index runs from 63 to 269 (Figure 6).

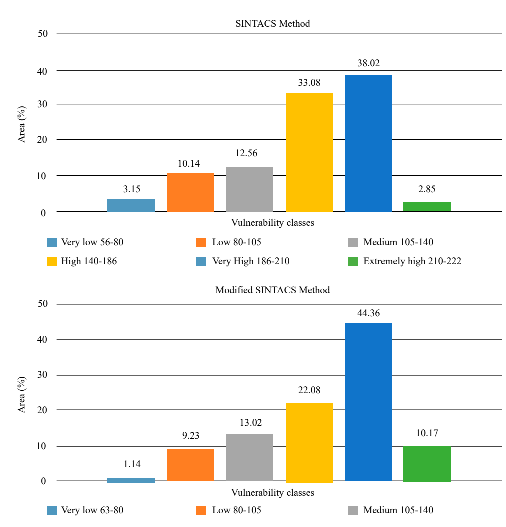

Figure 6. Area percentage results of SINTACS and modified SINTACS methods

The area percentage values fluctuate based on the data distribution among the border values. The augmentation of index values on the revised map is attributable to the incorporation of lineament density and land use variables in the computations. The updated SINTACS index values have a more uniform distribution than the original SINTACS values. In the SINTACS approach, the maximum value is attributed to a very high class at 38.22%, while the minimum value is assigned to an extremely high class at 2.85%. In the revised SINTACS technique, the highest value is attributed to the very high class at 44.36%, while the lowest value is associated with the very low class at 1.14%.

3.2. Uncertainties and limitations of the SINTACS model

The SINTACS model assesses groundwater pollution sensitivity by integrating GIS and AHP methodologies. The SINTACS model incorporates the geological, hydrogeological, climatic, morphological, and hydrological attributes of the region, although it excludes the types and characteristics of pollution. This technique requires revision and adaptation for various water sources and pollutant types. While the parameters in the model are calibrated to more accurately reflect the environment, no study is performed concerning the nature of the pollution. The sources of underground water pollution and their dispersion processes occur in distinctly various manners. Consequently, the emphasis has not been placed on the extent and dissemination of agricultural-origin contaminants, including chemical fertilizers and pesticides, in the groundwater of our research area. This scenario pertains to all techniques employed in groundwater sensitivity analysis.

The primary advantage of the SINTACS method over other sensitivity analysis techniques is its utilization of parameters that represent a substantially greater number of settings. Furthermore, it is capable of executing weighing across five distinct scenarios that are unavailable in alternative methods. Given the karstic features of my study location, the "karstic impact" scenario has been employed.

3.3. Groundwater Management Strategy

Previous research and groundwater level observations indicate that the groundwater flow in the BÇB area is directed southward, toward the Mediterranean. The underlying karstic limestones in the research area release groundwater. The groundwater sensitivity analysis showed the most sensitive locations as flatlands characterized by agricultural activity and alluvial lithology. Chemical fertilizers and agricultural pesticides, including herbicides, insecticides, and fungicides, pose a risk of groundwater contamination in agricultural regions. From the standpoint of groundwater management, the application of chemical fertilizers and agricultural pesticides in farming regions must be rigorously regulated. Field investigations measuring groundwater levels revealed several unlawful drilling wells in agricultural regions. Regular measurements of the production quantity and groundwater levels of all boreholes in the basin are essential. Particularly in regions where groundwater flows toward agricultural fields, the quality of groundwater in the drilling wells must be checked. The dissemination of groundwater contamination originating from agricultural regions must be regulated. A comprehensive hydrogeological investigation of the region is required for a project funded by the Burdur Municipality, which obtains its drinking water from the basin. This investigation must clearly define the groundwater quality and groundwater budget. Long-term plans for sustainable groundwater management must be devised within the basin.

4. Conclusions

The SINTACS and modified SINTACS methodologies, utilizing geographic information systems (GIS), were chosen to assess the sensitivity of groundwater in the basin. The SINTACS approach utilized water depth (S1), infiltration (I), unsaturated zone (N), soil (T), hydrogeological features (C), and topographic surface (S2) to assess groundwater sensitivity. In the revised SINTACS approach, lineament density and land use were incorporated alongside these characteristics, and texture parameters were utilized. The index values derived from both approaches were categorized into six subcategories, and themed maps were created.

Both techniques conclude that regions characterized by gentle slopes, agricultural activity, alluvial deposits, and low groundwater levels exhibit heightened vulnerability regarding groundwater sensitivity. The new SINTACS approach concluded that regions designated as very high in groundwater sensitivity have risen. The primary cause for this increase was the land use variable incorporated in the calculation. This underscores the significance of the land use element, absent from conventional calculation methods, in groundwater sensitivity assessments. The outcomes of the SINTACS approach will be applied in all research pertaining to the sustainable utilization, conservation, and administration of groundwater resources in the region. Regions beyond the agricultural areas in the basin are at a diminished risk of groundwater contamination.

The regions engaged in agricultural activities have significant sensitivity. When selecting drilling well sites for potable water, it is imperative to circumvent agricultural regions. Given that the groundwater flow in the region is directed southward, these areas will consequently be influenced by agricultural lands. The SINTACS technique solely accounts for environmental characteristics and neglects the distribution of pollutant types in subterranean and groundwater contexts. In regions with groundwater vulnerability, the subterranean dispersion and proliferation of chemical fertilizers and pesticides, which contribute to pollution, must be meticulously examined. In the basin, particularly in agricultural regions, it is crucial to detect drilling wells established without official authorization and to regulate their output volumes. The groundwater sensitivity map will serve as a foundational resource for agricultural planning and sustainable groundwater methodology research in the BÇB. The findings of this research indicate that the SINTACS model can generate dependable outcomes and will be especially beneficial for strategizing to mitigate the risk of groundwater contamination in vulnerable regions.

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