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Assessment of aquifer intrinsic vulnerability by the SINTACS method

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ABSTRACT

Application of the SINTACS method for assessment of the intrinsic vulnerability of an aquifer is demonstrated in the catchment areas of the Jadro and Žrnovnica springs. Both springs provide drinking water, supplying the population of Split and the surrounding settlements. Rapid economic expansion in the catchment area, accompanied with an increasing trend in the quantity of a number of contaminants in the spring water, prompted comprehensive investigations in order to finalise the Water Management Study of the Jadro and Žrnovnica springs. Results of the Study were analysed by GIS tools and employed as input data for production of the groundwater vulnerability map of the Jadro and Žrnovnica catchment areas. In addition to the standard method of defining the C factor which, in this case, is represented by the values of C(a), a modification is also introduced which takes into account analysis of sinkhole density.

Keywords: groundwater, intrinsic vulnerability, SINTACS, karst, GIS, Jadro and Žrnovnica

1. INTRODUCTION

Groundwater is the main source of potable water in many parts of the world including the Republic of Croatia, where approximately half of the country's territory is covered by karstified carbonate rocks, and the so-called Dinaric type of karst. This is why the utmost caution must be paid explicitly to groundwater protection in karst aquifers. Karstified carbonate rocks are typically covered by a thin, irregularly distributed, soil layer, and are intersected by a multitude of interconnected fractures facilitating the rapid infiltration of surface water. Groundwater flows through the conduits and fissures with high velocity and with a relatively short retention time, allowing the quick and far-reaching spread of potential contamination from the surface. This is why karst aquifer systems are thought to be extremely vulnerable and easily threatened to various extents by each and every human activity.

The concept of vulnerability is based on the premise that the physical properties of the environment offer a certain degree of protection to the groundwater with respect to human influence and ingress of contamination into the subsurface. Vulnerability is a relative, unquantifiable, and non-dimensional property that may be either intrinsic or specific (VRBA & ZAPOROZEC, 1994). Intrinsic groundwater vulnerability takes into account the geologic, hydrologic and hydrogeologic properties of the area regardless of the characteristics of the pollutant, or the mode of contamination (ZWAHLEN, 2004).

One of the first methods to assess the vulnerability of groundwater which is adjusted for the hydrogeologic, climatic, and social conditions of the Mediterranean region was the SINTACS method (CIVITA & DE MAIO, 2000). Assessment of vulnerability using this method is based on the evaluation of seven key parameters vital for defining the pollution retention capacity, description of vertical flow to the water table and horizontal flow within the saturated zone which include: depth to groundwater, effective infiltration, attenuation capacity in the unsaturated zone, attenuation capacity in the soil/sediment cover, hydrogeologic properties of the aquifer, hydraulic conductivity range of the aquifer and the hydrological role of the topographic slope. Results of the vulnerability analysis are presented in the form of groundwater vulnerability maps. These maps are utilized pri-

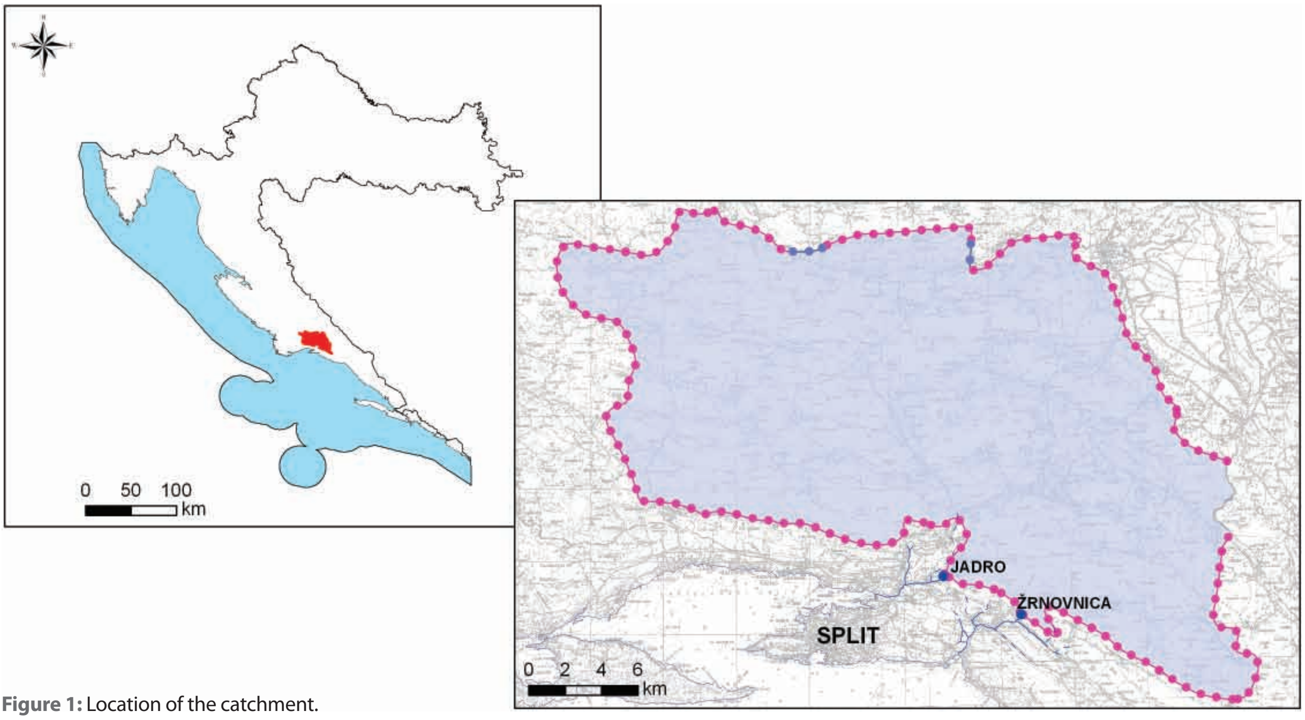

Figure 1: Location of the catchment.

marily for groundwater management and protection in the particular area and as an irreplaceable background for decision making in management and land use.

The area selected for assessment of intrinsic aquifer vulnerability by the SINTACS method encompasses the catchment areas of the Jadro and Žrnovnica springs (Fig. 1) located in the wider hinterland of the city of Split. Split is the largest city in Dalmatia and the second largest in Croatia with more than 180,000 people living in the town and its suburbs. It is also the second largest Croatian port and the third largest in the Mediterranean, based on passenger transport figures. The popularity of Split as a tourist destination is constantly increasing (www.split.hr). Based on the results of earlier investigations, the waters from the Jadro and Žrnovnica springs are perceived as being of great importance with regard to the water supply needs of the local population, as well as being increasingly vulnerable due to economic growth. The catchment area is mostly composed of permeable carbonate rocks which significantly complicate protection of the water reserves. Construction of business zones within the catchment, the absence of wastewater systems in the expanding settlements, and construction of roads adversely affect the active protection of groundwater, causing possible degradation. Since the groundwater reserves in the catchment are of invaluable natural and economic worth for the city of Split and its surrounding area, efficient protection is a mandatory requirement given the simultaneous economic development of the entire region.

The SINTACS model of intrinsic vulnerability assessment has previously been tested throughout Italy (CIVITA & DE MAIO, 2000); CORNIELLO et al., 2004; POLEMIO et al., 2009), in selected parts of Slovenia (JANŽA & PRESTOR, 2002; MALI & JANŽA, 2005; UHAN et al., 2008) and Spain (LONGO et al., 2001), regarding the aquifers with intergranular and karst and fissured porosity.

2. AREA OF INVESTIGATION

The Jadro and Žrnovnica springs are located in the foothills of the Mosor and Kozjak Mts. in the contact zone between the Splitska Zagora carbonate sedimentary rocks of good permeability and the coastal flysch belt. Jadro is situated at an altitude of 35 m a.s.l., while Žrnovnica lies at the altitude of 90 m a.s.l. According to the available hydrological data, the minimum discharge of the Jadro spring ranges between 3.60 m^3/s (August 1995) and 3.90 m^3/s (September 1997, August and September 2003). It is at its lowest in the dry period, mostly in August and September, when the mean monthly discharge may decrease to only 4.0m^3/s (August 1995, and September 2003). During the dry period water abstraction from the Jadro spring often exceeds the permissible 2.0 m^3/s, rising up to 2.9 m^3/s, KAPELJ et al. (2006)[1].

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[1] KAPELJ, S., KAPELJ, J., BIONDIĆ, R., BIONDIĆ, B., KOVAČ, I., TUŠAR, B., PRELOGOVIĆ, E., MARJANAC, T., ANDRIĆ, M., KOVAČIĆ, D., STRELEC, S. & GAZDEK, M. (2006): Studija upravljanja vodama sliva Jadra i Žrnovnice – Prva faza studijsko istraživačkih radova [*Water management study of the Jadro and Žrnovnica springs recharge area, first phase* – in Croatian].− EVV: 1/2005. Hrvatske vode, Split, 147 p.

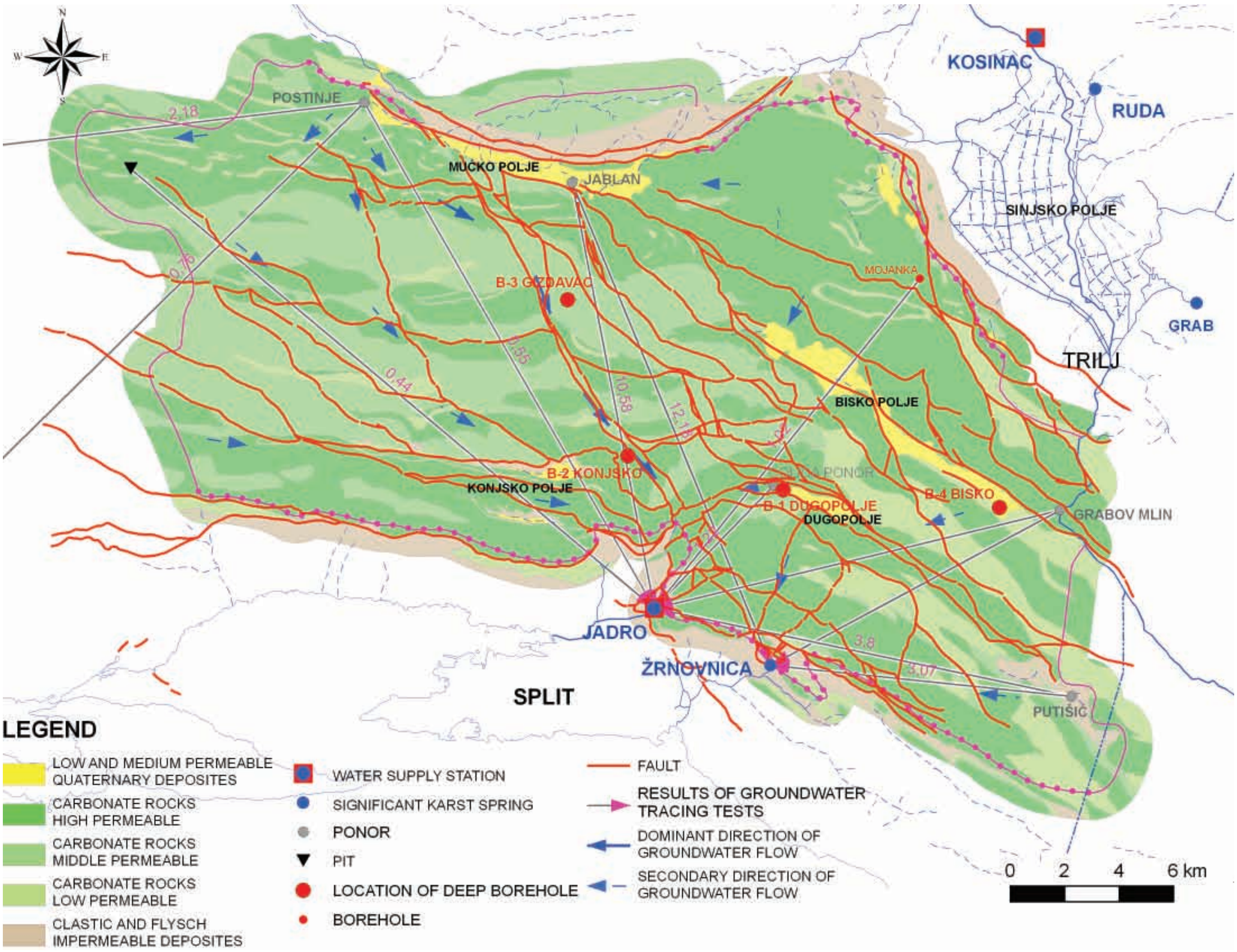

Figure 2: Hydrogeologic map of the study area.

Žrnovnica joins several smaller springs upwelling in the broader area. The minimum measured discharge of this spring area is up to 250 l/s (September 9th 1993) while the maximum discharge is up to 19.1m^3/s (December 18th 2004). The Jadro spring is used for the water supply of Split, surrounding settlements and the towns of Solin, Kaštela and Trogir. Žrnovnica is used for the water supply of the village of Žrnovnica and irrigation of agricultural areas.

According to the data available from the earlier hydrogeological research, the catchment area of the Jadro and Žrnovnica springs varied between 300 and 500 km^2 depending on the authors (BONACCI, 1978)[2] and (FRITZ et al., 1988)[3]. This particularly relates to the definition of the eastern and western watersheds, since the northern and southern borders of the catchment are much easier to determine, being the contact with impermeable sediment functioning as a complete hydrogeological barrier. According to more recent research, (since 2000), and especially on the grounds of groundwater tracing tests results, the eastern and western watersheds have been redefined, since the influence of the contiguous catchments and significant contribution of contiguous rivers (Krka River from the west and Cetina river from the east) have been determined. This is substantiated by the fact that the Žrnovnica, in natural conditions, was an intermittent spring, which dried up in times of drought, but after construction of dams on the Cetina River for HE Đale, has become a permanent spring.

The catchment area is predominantly composed of carbonate rocks, limestone and dolomite, and flysch sediments, while other rocks occur more rarely. Four main categories

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[2] BONACCI, O. (1978): Hidrogeološka studija Žrnovnice.− [*Hydrogeological study of Žrnovnica* − in Croatian].– Unpubl. Report. Arhiva Građevinskog instituta, Split.

[3] FRITZ, F., PAVLIČIĆ, A., RENIĆ, A. & KAPELJ, J. (1988): Izvori Jadro i Žrnovnica. Dio hidrogeoloških istražnih radova potrebnih za prijedlog zona sanitarne zaštite [*Jadro and Žrnovnica springs. Part of the hydrogeological investigation works required for the proposal of sanitary protection zones* – in Croatian].− Unpubl. Report. Arhiva HGI 140/88, Zagreb.

of rocks are distinguished according to their permeability on the hydrogeological map of the catchment area (Fig. 2): permeable rocks – includes Permian, Mesozoic and partly Eocene carbonate rocks (dark green), moderately permeable rocks – this group includes dolomitic limestones and dolomites of Cenomanian and platey limestones of Turonian age (medium green), poorly permeable rocks – this group comprises Permian argillaceous limestones, Anisian dolomite, clastic rocks and breccia, marly limestones and calcareous marls of Palaeocene age (light green), and impermeable rocks – the clastic deposits of the Lower Triassic and Eocene flysch (brown). In addition, a subgroup of sedimentary rocks of alternating properties has also been identified. These sediments originated by aerial weathering of the parent rocks or deluvial processes on the slope material. They contain silty-clayey materials with various limestone rock fragments. Local cultivable areas contain a substantial amount of sand. The latter can be found in karst poljes, river valleys and in local depressions in general. In the interpretation of the Basic Hydrogeological Map of the Croatian Republic (Split and Primošten Sheets), FRITZ & KAPELJ (1998) provided a detailed description of the hydrogeological characteristics of the rocks observed in this area.

A variety of different karst phenomena can be found in the catchment area. Distinct terrain fracturing paved the way for the intense karstification of carbonate rocks. No perennial flows are formed on the carbonate bedrock meaning all rainfall sinks underground over a short time interval. In parts of the catchment where clastic rocks are present, there are intermittent surface water flows which quickly converge on single sinkholes occurring in the karst poljes and therefore enter into the zones of horizontal circulation of groundwater KAPELJ et al. (2008)[4].

3. SINTACS METHOD

The SINTACS method of vulnerability assessment is based on evaluation of the following parameters (CIVITA & DE MAIO, 2000):

- depth to groundwater,
- impact of effective infiltration,
- capacity of attenuation in the unsaturated zone,
- capacity of attenuation in the soil/sediment cover,
- hydrogeologic properties of the aquifer,
- hydraulic conductivity range of the aquifer,
- hydrological role of the terrain slope.

Parameters of the SINTACS model are converted using the suggested diagrams, tables, ranges and computation into S, I, N, T, A, C and S parameters, each in the range of values between 1 and 10, where the higher value denotes greater aquifer vulnerability.

a. Parameter S – depth to groundwater

Depth to groundwater represents the distance from the surface to groundwater level or for a confined aquifer, the thickness of sediments overlying the aquifer. It is important for vulnerability assessment because it influences the filtration time of contaminated fluid. According to the model assessment rating, a greater depth means a less vulnerable aquifer.

b. Parameter I – impact of effective infiltration

Effective infiltration represents the amount of water which reaches the aquifer from the surface. It is important for vulnerability assessment, due to its role in the infiltration of pollution from the surface and dilution of contaminants during transport through the unsaturated and saturated zones. Calculation of the parameter values is based on precipitation (P) and evapotranspiration (Et) (a series of at least 20 mean annual precipitation and mean annual air temperature results) combined with surface hydrogeological conditions, as contained in the potential infiltration index (χ – theta) (eq.1).

$$I = (P - Et) \cdot \chi \quad (1)$$

c. Parameter N – attenuation capacity in the unsaturated zone

The unsaturated zone is important for vulnerability assessment because it represents protection of the aquifer against the contaminated fluid. Physical and chemical processes operate within the unsaturated zone diluting the contamination. In as much as the unsaturated zone contains beds with different lithological and hydrogeological characteristics in vertical distribution; relating a value to the zone thickness is calculated as the sum of the products between depth and weight of each separate bed divided by the total thickness of the unsaturated zone.

d. Parameter T – attenuation capacity of the soil/sediment cover

Soil and sediment cover function very efficiently in slowing or retaining the contaminated flow through the hydrogeologic system and thus assume a very important role in vulnerability assessment. Soil is often represented as an environment suitable for the accumulation and transformation of matter. It is therefore necessary to study two groups of parameters: first, those affecting the physical characteristics (grain size, texture, porosity, hydraulic conductivity…), and secondly the parameters that affect absorption ability (pH, cation exchange capacity (CEC), organic matter content and amount of clay). Since the data needed for assessment of parameter T are commonly unavailable and restricted to granu-

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[4] KAPELJ, S., KAPELJ, J., MARJANAC, T., PRELOGOVIĆ, E., CVETKO-TEŠOVIĆ, B., BIONDIĆ, B., IVANKOVIĆ, T., JUKIĆ, D. & DENIĆ-JUKIĆ, V. (2008): Studija upravljanja vodama sliva Jadra i Žrnovnice – Druga faza studijsko istraživačkih radova [Water *management study of the Jadro and Žrnovnica springs recharge area, second phase* – in Croatian].– EVV:9/2007. Hrvatske vode, Split, 122 p.

lometric composition and texture, rating diagrams refer particularly to these soil characteristics.

e. Parameter A – hydrogeologic properties of the aquifer

For assessing groundwater vulnerability, hydrogeologic properties of the aquifer are related to the processes within the saturated zone. Those processes are: molecular and kinematic dispersion, dilution, sorption, and chemical reactions between bedrock and contaminants. Hydrogeologic investigations collate all the available information on lithology, structure, fracturing and karstification of the saturated zone, offering a single database necessary to assess all facets of aquifer vulnerability. Based on the available data, and using default ranges in the rating diagrams, the user may choose a satisfactory value for each cell within the aquifer.

f. Parameter C – hydraulic conductivity range of the aquifer

Hydraulic conductivity is defined as the ability of an aquifer to transmit the water inside the saturated medium, or from the viewpoint of vulnerability assessment, mobility of contamination the density and viscosity of which are equal to that of water. Assessment and zoning of this parameter is extremely difficult, especially if there are no available data from field research. Assessment diagrams needed for allocation of parameter C values are related to the coefficient of conductivity (K).

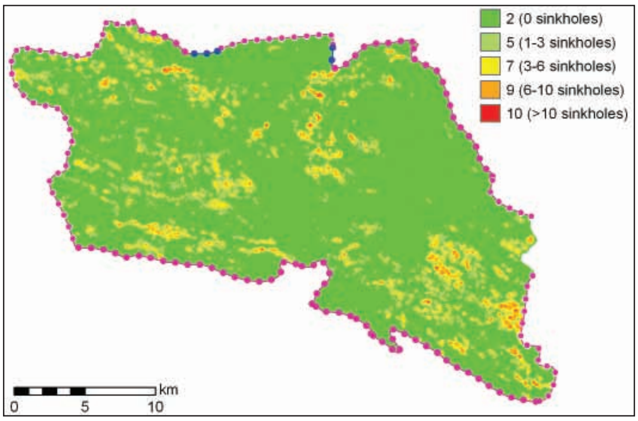

Figure 3: The map of sinkhole density.

Nevertheless, the density of sinkholes is used as an additional indicator of groundwater transmission in this case. Sinkholes are one of the key elements indicating the intensity of karstification of carbonate sedimentary rocks. They were digitized as points from topographic maps M 1:25000 (10312 individual objects were singled out). After analyzing the density of sinkholes as the number of sinkholes in a 250x250 m area, the spatial distribution of sinkholes was calculated yielding the map of sinkhole density containing 5 density classes (Fig. 3).

g. Parameter S – hydrological role of the terrain slope

Terrain slope is a very important factor in vulnerability assessment because it defines the surface runoff as a part of precipitation, and thus determines the areas in which there is a greater possibility for contaminants to infiltrate from the surface into the aquifer. Greater values of the S parameter are allocated to gentler slopes or the flattened parts of the terrain due to the reduced possibility for contamination spread (dissemination) due to gravity. Besides, the terrain slope can be an indicator of the soil type and thus indirectly determines the capacity of the hydrogeologic system to retain contamination.

4. DEFINING THE SINTACS PARAMETERS FOR THE JADRO AND ŽRNOVNICA CATCHMENTS

Data collected in the Jadro and Žrnovnica catchment basins were treated by GIS using ESRI ArcGis software. Data were saved in the database from which the layers were generated in vector and raster form, (hydrogeologic units, digital elevation model, depth to groundwater, geomorphologic objects, precipitation). These were later processed separately and supplemented by a spatial overlay with the necessary attributes and finally classified for each of the seven given parameters – S, I, N, T, A, C, S. According to numeric values of the individual parameters, the vector layers were converted into the raster grid format, with a cell resolution of 25 m for each separate parameter (Fig. 4). The final result was obtained by mapping algebra (raster calculator in extension of Spatial analyst) using the combination of grids. This was the map of intrinsic aquifer vulnerability in the catchment area of Jadro and Žrnovica.

Parameter S – Depths to groundwater for most of the Jadro and Žrnovica catchment areas were estimated at more than 100 m except for that measured at Dugopolje (40 m), and assumed in the Bisko polje (70 m). Adequate values were added to the vectorized polygons in these poljes according to rating diagrams of the S factor of 2 and 1.3. For the remaining area extending to the border of the Jadro-Žrnovnica catchment, where the depth to groundwater exceeds 100 m, a value of 1 was assigned to the S parameter.

Parameter I – Effective infiltration in the catchment area is computed according to the precipitation and evapotranspiration data in ZANINOVIĆ et al. (2008) which combined with parameters for particular lithologic units yielded the specific values based on the rating diagrams of the I factor. The values of 4.5 have been assigned for permeable carbonate rocks; 3 for low permeable rocks (flysch), and 6.8 for Quaternary cover sediments to the polygons defined on the hydrogeological map.

Parameter N – The attenuation capacity in the unsaturated zone is calculated for Quaternary terrains covered with soil and for other areas without the soil cover. It is defined according to the rating diagram and added to the lithology, explicitly to the permeability value of the specific area. For those parts of the terrain covered with Quaternary sediments,

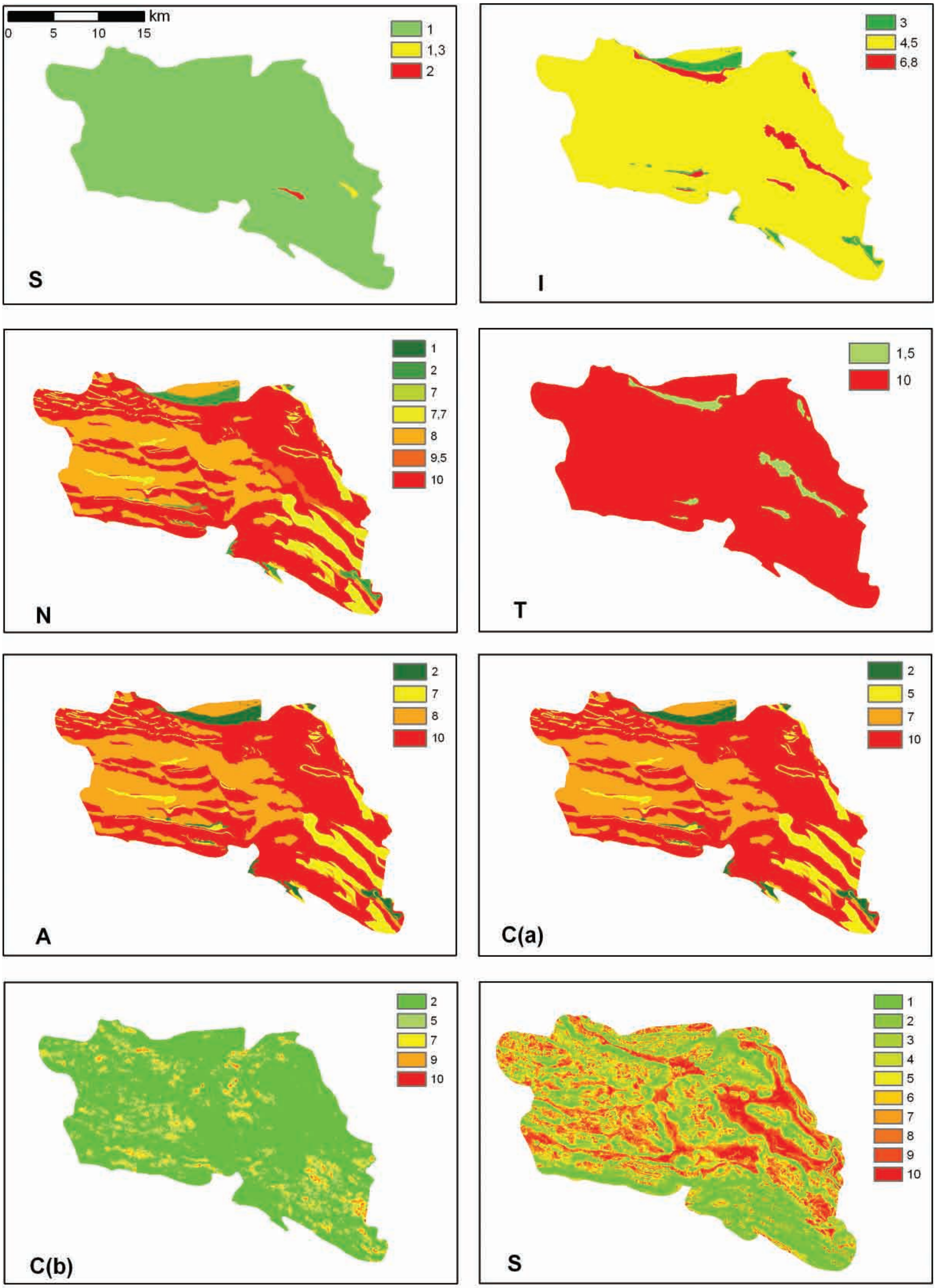

Figure 4: Layer display representing specific parameters.

the following values were calculated: Dugopolje – 7.7, Bisko Polje – 8.0, Dicmo and Konjsko– 9.0, Blaca – 9.5, and Muć 10.0. High values of parameter N on the karst poljes, where silty-clayey materials should provide better aquifer protection, can be interpreted as being due to thin surface sediments, beneath which very permeable and thicker carbonate rocks occur. Permeable carbonate rocks are rated as 10.0, moderately permeable as 8.0, poorly permeable as 7.0, low permeable flysch areas as 2.0, and low permeable areas with igneous rock as 1.0.

Parameter T – the rates of soil and sediment cover capacities is rated for the Quaternary sediments in the karst poljes as 1.5, while for the rest of the catchment area with almost no cover whatsoever as 10.0.

Parameter A – hydrogeologic features of the aquifer depend on the hydrogeologic properties of the related rocks by which they are represented. For Quaternary areas and karst poljes the factors are assessed according to the bedrock. Permeable rocks are ascribed the value of 10, moderately permeable as 8, poorly permeable 7, and those of low permeability as 2. Polygons are converted into grids with cells assuming the values of parameter A.

Parameter C – hydraulic conductivity of the aquifer was rated using three methods. The default, according to the SINTACS method is defined using the hydrogeological properties of the rocks with assigned C factor values scanned from the rating diagram. Permeable rocks are rated 10, moderately permeable are rated 7, poorly permeable 5, and those of low permeability as 2. The value of 10 is given to the area covered with Quaternary sediments, because they are relatively thin and very permeable carbonate rocks lie beneath them. According to the C factor values the polygons were converted into a C(a) grid with cells having the afore-mentioned values.

In the second case, parallel to the default rating method of the C factor, which is hereby represented by a C(a) value, a modification is introduced taking sinkhole density into account. Spatial analysis of the sinkhole density in an area 250x250 m, resulted in the definition of 5 classes with assigned values of the C factor (Fig. 3): a density of >10 sinkholes is rated 10, 6–10 sinkholes is 9, 3–6 sinkholes is 7, 1–3 sinkholes is 5, and 0 sinkholes is 2. The C(b) grid is then created with C factor values determined according to the sinkhole density. Using spatial overlaying of the C(a) and C(b) layers, a new raster is generated applying the higher value of C(a) or C(b) for each grid cell as a final value of the C parameter. Here, the role of the C(b) parameter was to additionally increase the vulnerability of the investigated area on the account of high sinkhole density which, for the C(a) factor, is obtained solely on the grounds of the rock properties.

In the third case, the C parameter value is obtained by a different combination of C(a) and C(b) factors. The values in the C(a) and C(b) raster cells are the same as in the previous cases, but in the final version of the modified SINTACS R5 method for C grid, the raster used is calculated as (C(a) + C(b))/2.

Parameter S – Terrain slope in the form of a grid and with cell values according to the slope percent (%) is created by the Surface analysis based on the digital slope relief at 25m resolution. Slopes are classified in 10 groups with ranges of: 0–2, 2–4, 4–6, 6–9, 9–12, 12–15, 15–18, 18–21, 21–25 and >25 %. Grid is reclassified and dependent on slope assigned with values 10, 9, 8, 7, 6, 5, 4, 3, 2 and 1, the values of S parameter. The cell values 10 for the slope 0–2, 9 for the slope 2–4, 8 for 4–6, etc.

5. RESULTS

The Jadro and Žrnovnica catchment areas belong to the typical karst of the Outer Dinarides (KAPELJ et al., 2009)[5] and the SINTACS method introduces for these areas the weighted factors for each of the component grids of a specific parameter. The result is the sum of grids enlarged by the weighted parameters. The weighted parameters applied in karst areas for the SINTACS parameters are as follows: S -2; I-5; N-1; T-3; A-5; C-5 and S-5 (CIVITA & DE MAIO, 2000).

Based both on the grids of the SINTACS method and the weighted parameters, the grids were created with indices of intrinsic vulnerability. The vulnerability index I_v is classified as ranges giving the degree of intrinsic vulnerability, as represented in Table 1.

Table 1: Classes of intrinsic vulnerability.

VULNERABILITY INDEX (I_V)	DEGREE OF INTRINSIC VULNERABILITY
26–80	very low
80–105	low
105–140	medium
140–186	high
186–210	very high
210–260	extreme

Three variations of the SINTACS method were used in order to calculate the degree of aquifer vulnerability in the Jadro and Žrnovnica catchment areas. In the first case, the default value from the diagram was used for the C parameter

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[5] KAPELJ, S., KAPELJ, J., DOGANČIĆ, D., LOBOREC, J., IVANKOVIĆ, T., CVETKO-TEŠOVIĆ, B. & MILANOVIĆ, D. (2009): Studija upravljanja vodama sliva Jadra i Žrnovnice – Treća faza studijsko istraživačkih radova [*Water management study of the Jadro and Žrnovnica springs recharge area, third phase* – in Croatian].− EVV:21/2008. Hrvatske vode, Split, 59 p.

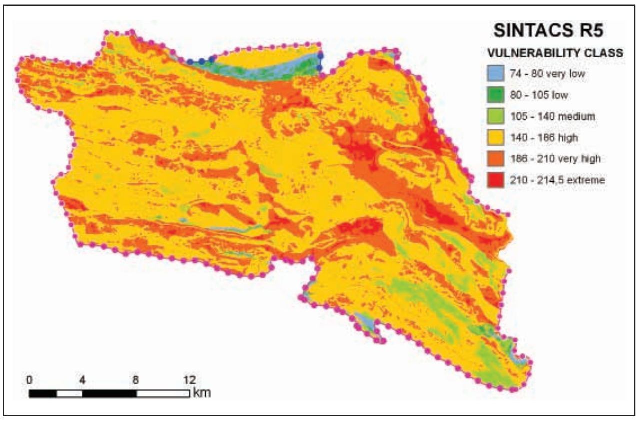

Figure 5: Map of intrinsic aquifer vulnerability according to the standard SINTACS method and weighted factors for karst.

(eq.2). In the second case the C parameter was computed after the modified method which includes the influence of sinkhole density. The higher value in combination C(a) or C(b) was then used as a final result (eq.3). Finally, in the third case the C factor was calculated according to the formula: (C(a)+C(b))/2 (eq.4). Results of the computation were displayed in the form of vulnerability maps.

Calculation of the aquifer vulnerability indices by the standard SINTACS method produced the weighted factors for karst:

$$\mathbf{I_V(SINTACS\ R5) = S{*}2+I{*}5+N{*}1+T{*}3+A{*}5+C{*}5+S{*}5} \quad (2)$$

Calculation of the aquifer vulnerability index according to the modified SINTACS method (including sinkhole density) and weighted factors for karst gives:

$$\mathbf{I_V(SINTACS\ 1.modification) = S{*}2+I{*}5+N{*}1+T{*}3+A{*}5+(Ca\ or\ Cb){*}5+S{*}5} \quad (3)$$

Calculation of the aquifer vulnerability index according to the modified SINTACS method (including sinkhole density) and weighted factors for karst equals:

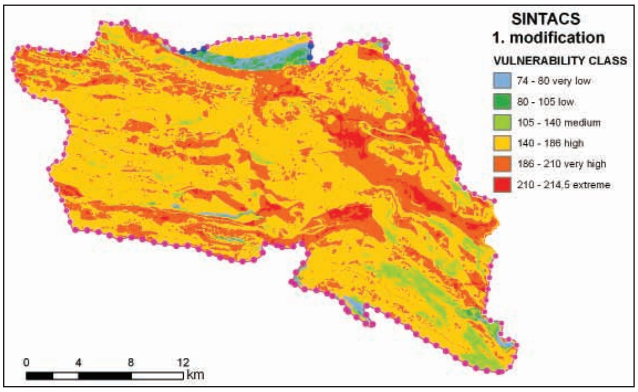

Figure 6: Map of intrinsic aquifer vulnerability according to the modified SINTACS method (including sinkhole density) and weighted factors for karst (1. Modification).

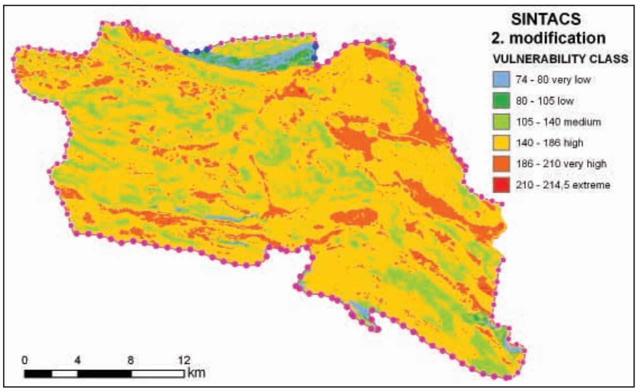

Figure 7: Map of intrinsic aquifer vulnerability according to the modified SINTACS method (including sinkhole density) and weighted factors for karst (2. Modification).

$$\mathbf{I_V(SINTACS\ 2.modification) = S{*}2+I{*}5+N{*}1+T{*}3+A{*}5+((Ca+Cb)/2){*}5+S{*}5} \quad (4)$$

For each map, intrinsic vulnerability was calculated for the part of the catchment occupied by a specific class, and for the part of the total catchment area that it represents. Results are displayed in Table 2.

From the above data it is obvious that sinkhole density affects the assessment of intrinsic aquifer vulnerability in the karst area. It is well known that areas with greater sinkhole density indicate a higher degree of karstification. These areas represent the potential zones of more rapid underground infiltration of water thus indicating greater aquifer vulnerability. For this particular reason, the new factor C(b) was introduced modifying parameter C. In the first modification, the idea was to enhance the C parameter value in those parts which, in accordance with the rock type, do not exhibit high values of the C parameter scanned from the rating diagram, but are characterized by a high number of sinkholes. However, results shown in Table 2 indicate significant overlap of these two conditions. Namely, the maximum C parameter value is already present in the greater proportion of the catchment due to the presence of very permeable karstified carbonate rocks. Thus the lower contribution of the sinkhole density generates a trifling difference between the standard SINTACS R5 and modified SINTACS methods.

In the second modification the C(a) and C(b) factors were combined in a different way. It is precisely because the major part of the catchment is composed of the very permeable limestones exhibiting the maximum value of the C parameter (10) that the idea originated to differentiate these large areas by introduction of the factor of the sinkhole density dependent on density classes. Thus the maximum value of the C parameter is present only in those portions of the catchment where maximum values of C(a) and C(b) factors are overlapping, while elsewhere the value of the C parameter is represented by the arithmetic mean of the C(a) and C(b) parameters. Therefore, in the second modification of the SINTACS method the area of classes of very high and extreme vulnerability decreased, while that of high and medium vulnerability increased (Table 2).

Table 2: The catchment area ratio.

	SINTACS R5		SINTACS – 1.MODIFICATION C=Ca or Cb		SINTACS –2.MODIFICATION C=(Ca+Cb)/2	
CLASS	AREA (km^2)	PART OF THE CATCHMENT AREA (%)	AREA (km^2)	PART OF THE CATCHMENT AREA (%)	AREA (km^2)	PART OF THE CATCHMENT AREA (%)
very low	8.38	1.48	8.59	1.52	8.61	1.52
low	7.55	1.33	7.41	1.31	7.42	1.31
medium	28.34	4.99	27.73	4.89	88.64	15.63
high	352.32	62.14	351.22	61.95	391.14	68.99
very high	149.20	26.32	150.69	26.58	70.43	12.42
extreme	21.18	3.74	21.28	3.75	0.74	0.13

6. CONCLUSION

Application of the SINTACS method in assessment of the intrinsic vulnerability of the aquifer system in the karst areas is presented here, using the example of the Jadro and Žrnovnica catchment. The SINTACS method is based on evaluation of seven parameters describing the geologic, hydrogeologic and hydrologic conditions that directly affect aquifer sensitivity to the influence of human activity leading to contamination of groundwater. The SINTACS method allows a large range of values for assessment of each parameter. Also, it can be applied in every type of aquifer, due to the weighting strings which allow the model to adapt to different hydrogeological conditions. It is therefore extremely important to have good knowledge of the study area when determining the parameter values. This example is used in order to adjust the SINTACS method to the conditions of the Dinaric karst, typified by its exceptional karstification and it's richness of landscape morphologies (sinkholes in particular). This is why certain modifications were introduced into the method itself with the purpose of suggesting an optimal approach to the assessment of vulnerability of the groundwater in the karst, based on comparison of the acquired results.

Based on the calculations (Table 2) where the magnitudes of vulnerable areas are assessed by the standard SINTACS method and by the modified methods, taking into account the sinkhole density (Fig. 6 and Fig. 7), it is possible to draw several conclusions as follows: sinkhole density affects the intrinsic vulnerability of a karst aquifer. Obviously, the sinkhole density increases the permeability of the lithologic members in certain parts of the terrain, and also affects the value of the vulnerability index. The combination of parameter C(a) (obtained using charts of the classical SINTACS method and is dependent on the hydraulic conductivity of the aquifer) and parameter C(b) (obtained through an analysis of sinkhole density), in the expression of the mean (C(a)+C(b))/2, allows extraction of those parts of the catchment that are extremely vulnerable according to both indicators. As a result, those parts of a terrain assigned very high and extreme vulnerability indices, are reduced in area while those with high and medium vulnerability indices are increased. Therefore, the isolated areas showing higher sinkhole density, (a very sensitive indicator of karstification, or rock permeability), indicate the most vulnerable areas that need high protection. However this also raises the possibility of enlarging the exploitative areas in the karst that can be suitable for different uses to those areas having medium, low and very low vulnerability indices.

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