Assessing groundwater vulnerability by SINTACS method in the Lower Savinja Valley, Slovenia

Ocenjevanje ranljivosti podzemne vode z metodo SINTACS v Spodnji Savinjski dolini, Slovenija

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Abstract: Three alluvial groundwater bodies in Slovenia have been assessed as a groundwater body with poor chemical status, mainly due to high concentrations of nitrate and other pollutants from intensive agricultural land use. In more than half of the national monitoring sampling sites in groundwater bodies, the annual average concentrations exceed 50 mg/l nitrate. In spite of the limitation in fertilisation, there is no evidence of a significant decreasing trend in nitrate concentrations in groundwater. The EU Water Framework Directive (WFD) requires further characterization of those groundwater bodies which have been identified as being at risk in order to establish a more precise assessment of the significance of such risk. The Lower Savinja Valley shallow alluvial aquifer with poor groundwater chemical status has been selected as a test case for such further characterization. This article discusses the issues of groundwater vulnerability assessment by the SINTACS method and sensitivity analysis of the model parameters. The result of the research offers a new basis for planning of detailed monitoring and protection measures, as well as good orientation for further methodological investigation.

Izvleček: V Sloveniji je bilo predvsem zaradi vsebnosti nitratov in drugih onesnaževal iz intenzivne kmetijske pridelave na treh aluvijalnih podzemnih vodnih telesih ocenjeno slabo kemijsko stanje. Na več kot polovici vzorčnih mest državnega monitoringa povprečne letne vsebnosti nitrata presegajo 50 mg/l. Nitrati kljub omejitvam

Scientific paper

pri gnojenju na nobenem vodnem telesu nimajo značilnega trenda zniževanja. Evropska vodna direktiva (WFD) zahteva podrobnejšo karakterizacijo vseh vodnih teles, za katera je bilo ugotovljeno tveganje za nedoseganje zastavljenih okoljskih ciljev. Za omenjena telesa podzemne vode naj bi izdelali bolj podrobno oceno značilnosti oz. pomembnosti tega tveganja. Za testni primer podrobnejše karakterizacije telesa podzemne vode s tveganjem je bil izbran plitvi aluvijalni vodonosnik Spodnje Savinjske doline s slabim kemijskim stanjem podzemne vode. Članek obravnava rezultate ocene ranljivosti podzemne vode z metodo SINTACS in rezultate analize občutljivosti modelnih parametrov. Rezultati raziskave nudijo novo podlago za načrtovanje programa podrobnejšega monitoringa in programa zaščitnih ukrepov, kakor tudi novo usmeritev nadaljnim metodološkim raziskavam.

Key words: groundwater, vulnerability, contamination, SINTACS, sensitivity analysis

Ključne besede: podzemna voda, ranljivost, kontaminacija, SINTACS, analiza občutljivosti

Introduction

Three out of twentyone Slovenian groundwater bodies have been identified as a groundwater body at risk in the first national groundwater chemical status assessment (Krajnc et al., 2005). The central part of the smallest Slovenian groundwater body - Savinja Valley - has been selected as a test case for further characterization according to the WFD (Directive 2000/60/EC, 2000), (Figure 1). It is about a 100 square kilometer-wide shallow alluvial aquifer system with about 5 percent of the total groundwater volume of all Slovenian alluvial aquifers. An important part of the regional water demand of the Savinja Valley is satisfied by pumping groundwater from the sandy gravel aquifers of the plain, where, even a decade ago, conflicts of interest occurred among the local population. The region of the Lower Savinja Valley is primarily renowned as the "valley of hops" with intensive agricultural activities and urbanization (Figure 2).

National groundwater level monitoring as well as groundwater quality monitoring in the Lower Savinja Valley have been permanently performed by the Environmental Agency of the Republic of Slovenia since 1955 and 1990 respectively. Activities in the last decade have been initiated to complete the conceptual model of the aquifer and initial characterization of the groundwater body. Studies included a review of the results of the previous hydrogeological investigations in the area, additional hydrogeological field mapping and water balance analysis (Uhan, 1996; Prestor et al., 2005).

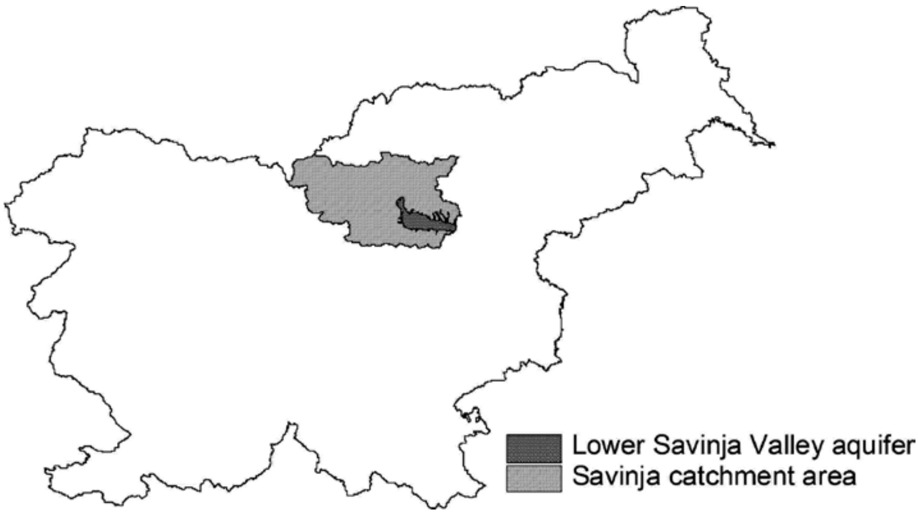

Figure 1. Position of the Lower Savinja Valley aquifer and their part of the Savinja river watershed
Slika 1. Vodonosnik Spodnje Savinjske doline in njeno prispevno hidrološko območje Savinje

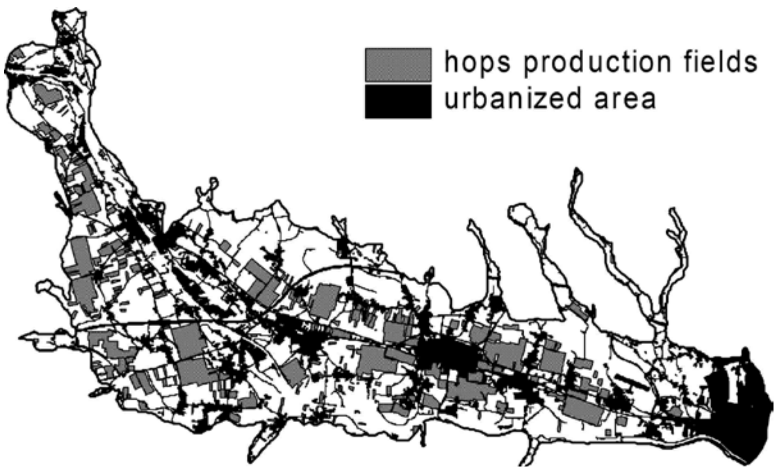

Figure 2. The hops production fields and urbanized areas in the Lower Savinja Valley
Slika 2. Hmeljišča in urbanizirana območja Spodnje Savinjske doline

In order to meet the requirements of the Water Framework Directive, the Lower Savinja Valley groundwater quality and quantity status assessment were made in the year 2005 (Andjelov et al., 2006; Krajnc et al., 2007). Good quantitative but poor chemical statuses were assessed. The reason for the bad chemical status of the groundwater was found in high nitrate and pesticide concentrations, with an average 55.17 mg/l and maximum 143.02 mg/l for nitrates and an average 0.49 μg/l and maximum 2.63 μg/l for the sum of pesticides.

Following the first chemical status assessment results in 2005, further characterization has started with detailed groundwater vulnerability assessment using the Geographical Information System. We utilised the parametric method to assess intrinsic groundwater vulnerability and single-parameter sensitivity analysis. The purpose of the research was to improve knowledge about the natural protection ability of the unsaturated zone and about the pressure impacts, originating especially from diffuse pollution sources, in order to improve planning of protection measures.

Methodology

Groundwater vulnerability represents the intrinsic geological and hydrogeological characteristics of the aquifer. Its concept has been widely used in assessing the likely impact of pollution pressures during the groundwater characterization process and in the regional groundwater protection strategy. The SINTACS scheme of aquifer pollution vulnerability mapping was established for hydrogeological, climatic and impacts settings, typical for the Mediterranean countries (Civita, 1990). This assessment procedure incorporates seven parameters, relevant for the contaminant attenuation and vertical flow capacity (Table 1). In the vulnerability assessment procedure, the Savinja Valley area was discretised with a regular mesh grid of 100×100 m. The grid square cell structure of the SINTACS input data has been designed in order to use several weight strings. The weight strings have been prepared in order to satisfactorily describe the effective hydrogeological and impacting situation as set up by the sum of data. The present release of SINTACS presents five weight strings for normal impact, relevant impact, drainage from the surface network, deep karstified terrain and fissured terrain. For each of the 7.887 grid squares, element normalized SINTACS index was calculated and differently vulnerable areas were assessed using SINTACS R5 parametric methods (Civita & De Maio, 2000).

Results and discussion

Deep to the groundwater (SINTACS parameter S)

Groundwater is not deep under the surface in the Lower Savinja Valley. For the processing of the results of groundwater level measurements from fourteen measurement stations, a weighted moving average method has been used. In the period 1986-2005, the groundwater level was the highest in the north-central part (0.69 metre) and deepest in the central part of the valley (7.25 metre). The average depth to the groundwater at the majority (71.66 %) of the 100×100 metre grid cells amounts

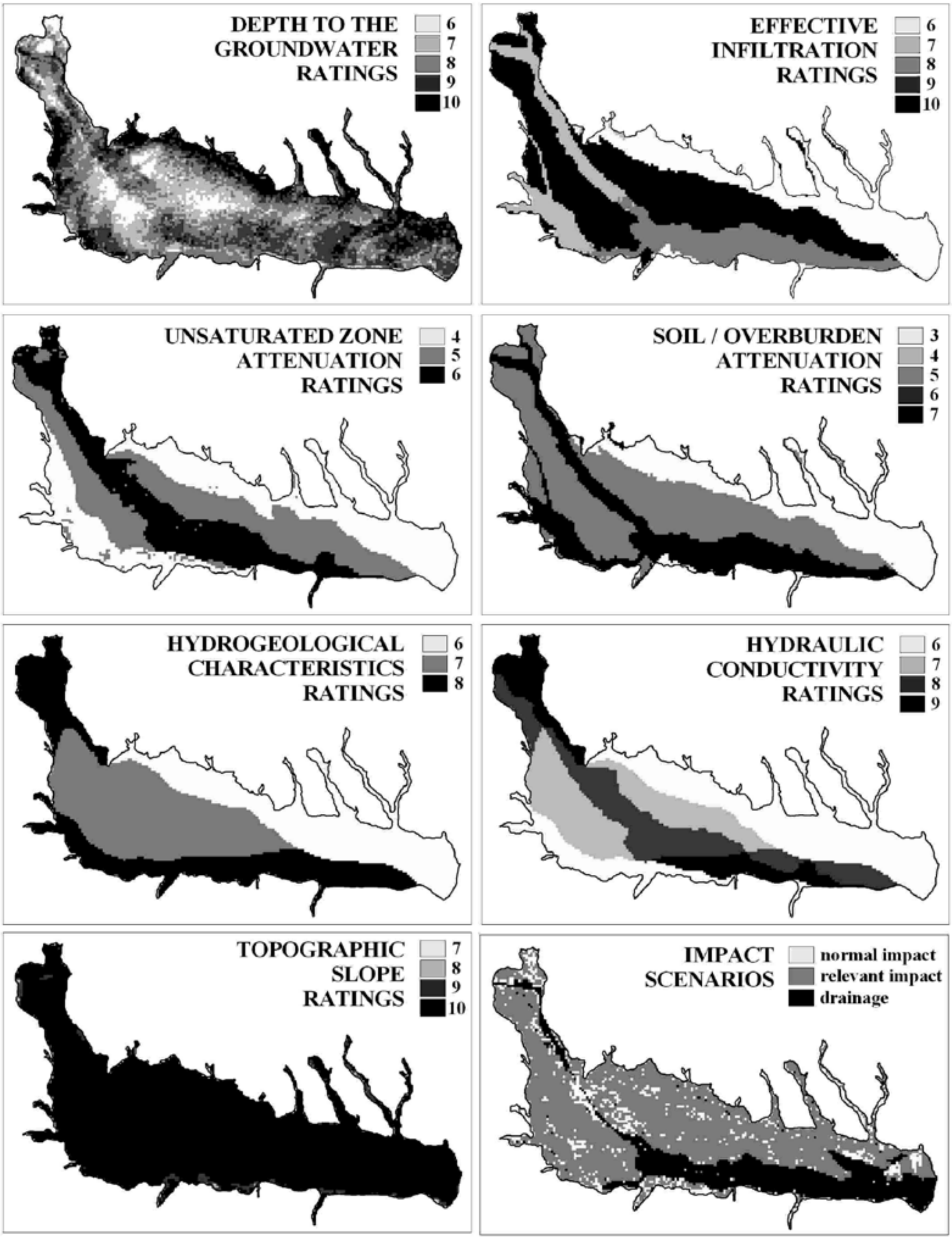

Figure 3. Parametric maps of SINTACS groundwater vulnerability model for the Lower Savinja Valley aquifer

Slika 3. Karte parametrov SINTACS modela ranljivosti podzemne vode vodonosnika Spodnje Savinjske doline

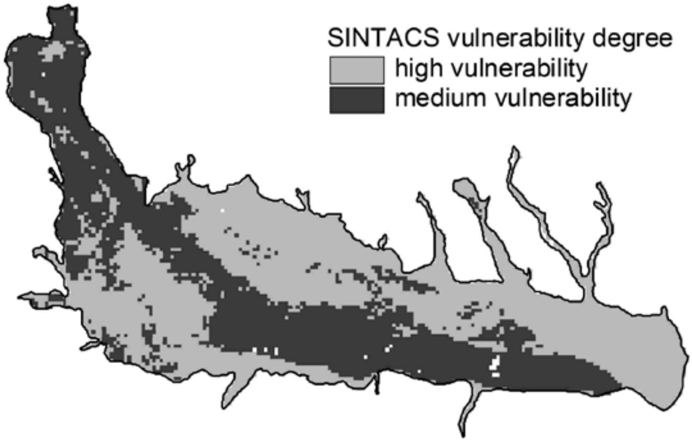

Figure 4. Distribution of the groundwater vulnerability index in the Lower Savinja Valley
Slika 4. Prostorska razporeditev indeksa ranljivosti podzemne vode v Spodnji Savinjski dolini

Table 1. Main characteristics of SINTACS parameters in the Lower Savinja Valley aquifer
Tabela 1. Osnovne značilnosti parametrov SINTACS v Spodnji Savinjski dolini

SINTACS Parameter	**Characteristics**
Depth to the groundwater table	average 3.9 m
Effective infiltration	average annual precipitation 1233 mm, average annual air temperature 9 °C
Unsaturated zone attenuation capacity	mainly holocene alluvial sandy gravel with clay component
Soil/overburden attenuation capacity	eutric cambisol, eutric fluvisol, eutric gleysol
Hydrogeological characteristics of the aquifer	unconfined aquifer, max. thickness of gravel, sand and clay sediments is 28 m, average 8 m
Coefficient of hydraulic conductivity	holocene: $1.1 \cdot 10^{-3} \div 1.1 \cdot 10^{-2}$ m/s, pleistocene: $2.0 \cdot 10^{-5} \div 2.0 \cdot 10^{-4}$ m/s
Topographic slope	average 0.8 %

to less than 4.5 metre, which corresponds to the ratings 8, 9 and 10 with the highest vulnerability rate. The majority (31.63 %) of the grid cells is to be found in the range of 2.5 and 4.5 metres.

Effective infiltration action (SINTACS parameter I)

For the calculation of the effective infiltration out of precipitation and evapotranspiration data, we used the hydrogeological inverse balance method (Civita et al., 1999), while taking the hydrogeological characteristics of the aquifer or soil texture characteristics into consideration. We estimated the interdependence of the following factors on the Lower Savinja Valley study area: (1) yearly average precipitation and corrected yearly average air temperature for the period 1986-2005 and (2) average elevation of the nearest gauging stations. We calculated the evapotranspiration and the effective precipitation of each of the 100×100 grid cells, using the numerical model CALCO INFILTRAZIONE (Civita and De Maio, 2000) after Turc (1954), and got the effective infiltration through estimating the potential infiltration coeficient. The effective infiltration in the period 1986-2005 ranged between 121 mm and 387 mm. The most frequently represented ratings are rating 10, ranging between 235 and 316 mm (47.76 %), and rating 6, ranging between 111 and 136 mm of effective infiltration (25.03 %).

Unsaturated zone attenuation capacity (SINTACS parameter N)

The unsaturated zone of the Lower Savinja Valley aquifer consists mostly of holocen sandy gravel with clay component at the marginal parts of the aquifer. We attributed the N rating between 4 and 6 to the litotypes on the basis of litotypes vs. N ratings diagram (Civita and De Maio, 2000). The pleistocene sediments with the assumed rating of N=3 can also be found at the lower part of the unsaturated zone of the central west-central part of the aquifer. For the areas, where the unsaturated zone is consist of holocene and pleistocene litotypes, we calculated the weighted mean that refers to the thickness. The unsaturated zone with rating N=4 represents 39.20 % of the 100×100 grid cells and is therefore prevalent at the area of the Lower Savinja Valley, followed by the unsaturated zone with a rating N=5 (34.53 %) and the unsaturated zone with a rating N=6 (26.27 %).

Soil/overburden attenuation capacity (SINTACS parameter T)

The significant water movement and pollutant retaining processes are dependent on textural characteristics of the soil, where the clay component is of special importance. There are three significant pedocartographical units prevalent in the Lower Savinja Valley: eutric fluvisol, evtric cambisol and evtric gleysol. Representation of all the other pedosystematical units is strongly inferior. The value of parameter T, read out of the soil textures vs. ratings T diagram (Civita and De Maio, 2000), is defined on the basis of nine pedological profiles in the Lower Savinja Valley. There are three types of soil prevalent in these profiles: light to medium-heavy eutric fluvisol (T=7), medium-heavy eutric soil (T=5) and medium-heavy to heavy evtric gleysol (T=3). There are 100×100 m grid cells with the rating T=5 prevalent (47.76 %) in the Lower Savinja Valley, followed by grid cells with a rating of T=7 (27.21 %) and T=3 (25.03 %).

Hydrogeological characteristics of the aquifer (SINTACS parameter A)

We compared the hydrogeological structure of the studied area (KÄSS et al., 1976; UHAN, 1996) with the results of statistical analysis of the groundwaterlevel national monitoring hydrograms (UHAN, 1997). Two highly separable factors with more than 92 % explained variance of groundwater level were founded through principle component analysis. The interpretation of the second factor is prevailingly bound to the lower terrace aquifer with high permeability. By that the coincidence of factor scores with water levels and flows of the Savinja River was discovered. Hydrogeological conditions along the bed of the river *Savinja* between *Breg pri Polzeli* and the confluence with *Bolska* allow the influent flow of the *Savinja* river. In the riverbed of *Bolska* and *Savinja* the exfluent flow, supplemented with groundwater springs at the area of *Kaplja vas* and *Vrbje*, was registered from the conflence with *Bolska*. The statistical analyses of the principal components of the groundwaterlevel national monitoring hydrograms support the spatial interpretation especially of those hydrogeological elements, linked with the spatial distribution of the holocene sediments or hydraulic relation of the groundwater and surface water. We attributed values of parameter A between 6 and 8 to the hydrogeological homogene units upon the recommendation of CIVITA and DE MAIO (2000). We attributed the following areas with the following values of parameter A: (1) lower terrace area with holocene coarse-grained sediments and less clay and silt fractions and a more dynamic hydrogeological regime – value 8, (2) the area of upper terrace with pleistocen – value 7 and (3) the area of the highest terrace with more compacted pliocen sediments with more clay component – value 6. These litotypes are in the Lower Savinja Valley and are mainly equally distributed, with a slight prevalence of the rating 7, which represents the occurrence of the holocene sediment.

Hydraulic conductivity range of the aquifer (SINTACS parameter C)

The estimate of the hydraulic conductivity range of the holocene part of the the Lower Savinja Valley, based on pumping tests, is between $1.1\cdot10^{-3}$ and $1.1\cdot10^{-2}$ m/s, whereas the hydraulic conductivity range of the pleistocene part of the aquifer is estimated at between $2.0\cdot10^{-5}$ m/s and $2.0\cdot10^{-4}$ m/s. The conductivity coefficient of $1.2\cdot10^{-2}$ m/s was defined using the tracer test east of *Arja vas*. The pumping test gave similar results ($0.65\cdot10^{-2}$ m/s), while the granulometric analyses of particular sedimentological heterogenic samples from the exploration hole resulted in the conductivity coefficient ranging between $6.5\cdot10^{-5}$ m/s and $2.3\cdot10^{-2}$ m/s (KÄSS et al., 1976). The hydraulic conductivity range of the pliocene sediments is due to the clay components and sediment compaction even lower than that of the pleistocene sediments. The hydraulic conductivity range of the holocene part of the Lower Savinja Valley is with the SINTACS value of C=9 (13.28 % of the cells) relatively high and lowers itself at areas of holocene sedimentation and even moreso at the marginal parts of the sedimentation basin or at the areas of pliocen sedimentation. Most of the area has the value of C=6 (41.28 %), followed by C=7 (23.47 %) and C=8 (21,86 %).

Table 2. Scenarios and weights for SINTACS parameters (Civita and De Maio, 2000)
Tabela 2. Scenariji in uteži za parametre SINTACS (Civita and De Maio, 2000)

Parameters	**S**	**I**	**N**	**T**	**A**	**C**	**X**
normal impact scenario	5	4	5	3	3	3	3
relevant impact scenario	5	5	4	5	3	2	2
drainage from surficial network scenario	4	4	4	2	5	5	2

Hydrological role of the topographic slope (SINTACS parameter X)

The Lower Savinja Valley is a flat surface aquifer with unexpressive topographic slopes. There is a 99-metre difference between the highest elevation on the west and the lowest elevation on the east, but the slope of the surface of the valley is gradual. Morphological particularities are declivities between individual terraces, sometimes as high as 10 metres. The prevalent slope inclination is based on a digital elevation model analysis 0.5°, which in relation to the slope inclination and value of parameter X corresponds with the rating 10.

Impact scenarios and weight strings

We adjusted the groundwater vulnerability model to the hydrogeological conditions and impact scenarios of the discussed area and accepted first three impact scenarios (Civita and De Maio, 2000). We used the normal impact scenario or relevant impact scenario and drainage from the river network scenario for the shallow aquifer of the Lower Savinja Valley. As far as the first two scenarios are concerned, the stress has been layed especially upon the intensive agriculural use of land, irrigation and urbanisation. The third scenario was attributed to the influent flow of the Savinja River and its affluents, to wetlands and to flooded areas. The predominant part of the Lower Savinja Valley is heavily anthropogenicly loaded (75.0 %), while the rest of the aquifer area is moderately loaded (4.2 %) or distinctive possibilities of surface drainage into the aquifer exist (20.8 %).

Elaboration of the vulnerability map

The assessment of the seven SINTACS parameters and three selected scenario enables the calculation of groundwater vulnerability SINTACS index $I_{SINTACS}$, which for the particular 100×100 m grid cell represents a sum of ratings and weights for all seven SINTACS parameters:

$$I_{SINTACS} = \sum_{j=1}^{7} P_j \cdot W_j$$

where $I_{SINTACS}$ is the vulnerability index and P_j and W_j are the ratings and the weights respectively of the grid cell *i*.

The SINTACS index ranging between 139 and 215 with the average of 183 has been calculated for 7.887 100×100 m grid cells at the area of Lower Savinja Valley. The Lower Savinja Valley is in SINTACS estimation placed in 4th and 5th groundwater vulnerability class. At the northeast and southwest of the aquifer (56.5 %) a 4th vulnerabilty class is prevalent, while in the northwestern and central area (43.2 %), especially in the narrower area of *Savinja* river and lower terrace, the vulnerability increases (Figure 4).

Sensitivity analysis

The selection of ratings and weights that have to be assigned to the seven parameters for the SINTACS index calculation is unavoidably subjective. We applied the single-parameter sensitivity analysis, which evaluates the influence of each parameter on the groundwater vulnerability map. The analysis used for the Lower Savinja Valley SINTACS groundwater vulnerability map was based on the theory developed by LODWICK et al. (1990) and effectivly used by NAPOLITANO and FABBRI (1996).

For each grid square element we calculate the effective weight W_p (in %) using the following formula:

$$W_p = \left(\frac{P_r \cdot P_w}{I_{SINTACS}} \right) \cdot 100$$

where P_r and P_w are the ratings and the weights respectively of the layer *P* assigned to the subarea *i*, and $I_{SINTACS}$ is the vulnerability index.

The highest sensitivity to the output of the model was found at the depth to the groundwater (S) and effective infiltration action (I), while lower sensitivity was found at hydrogeological characteristics of the aquifer (A) and soil/overburden attenuation capacity (T). The lowest sensitivity of the model was found at the unsaturated zone attenuation capacity (N), the hydraulic conductivity range of the aquifer (C) and hydrological role of the topographic slope (X), (Table 3).

Conclusions

In the Lower Savinja Valley aquifer case study an attempt has been made to assess the groundwater vulnerability and single-parameter sensitivity analysis. The first groundwater vulnerability assessment of this case study area using the SINTACS parametric method allows us to distinguish from two classes with different vulnerability degrees. The first zone of medium vulnerability is characterised mainly by the lower terrace with shallow groundwater, high surface/groundwater interaction and a thin protective soil layer. The second zone of medium vulnerability is characterised mainly by the upper terraces with deeper groundwater and thick soil layer

Table 3. Average sensitivity weights (in %) of SINTACS parameters in the Lower Savinja Valley aquifer
Tabela 3. Povprečne uteži občutljivosti (v %) za parametre SINTACS v Spodnji Savinjski dolini

Parameters	W_S	W_I	W_N	W_T	W_A	W_C	W_X
Average actual weights	21,54	21,22	10,96	11,18	13,19	10,93	10,99

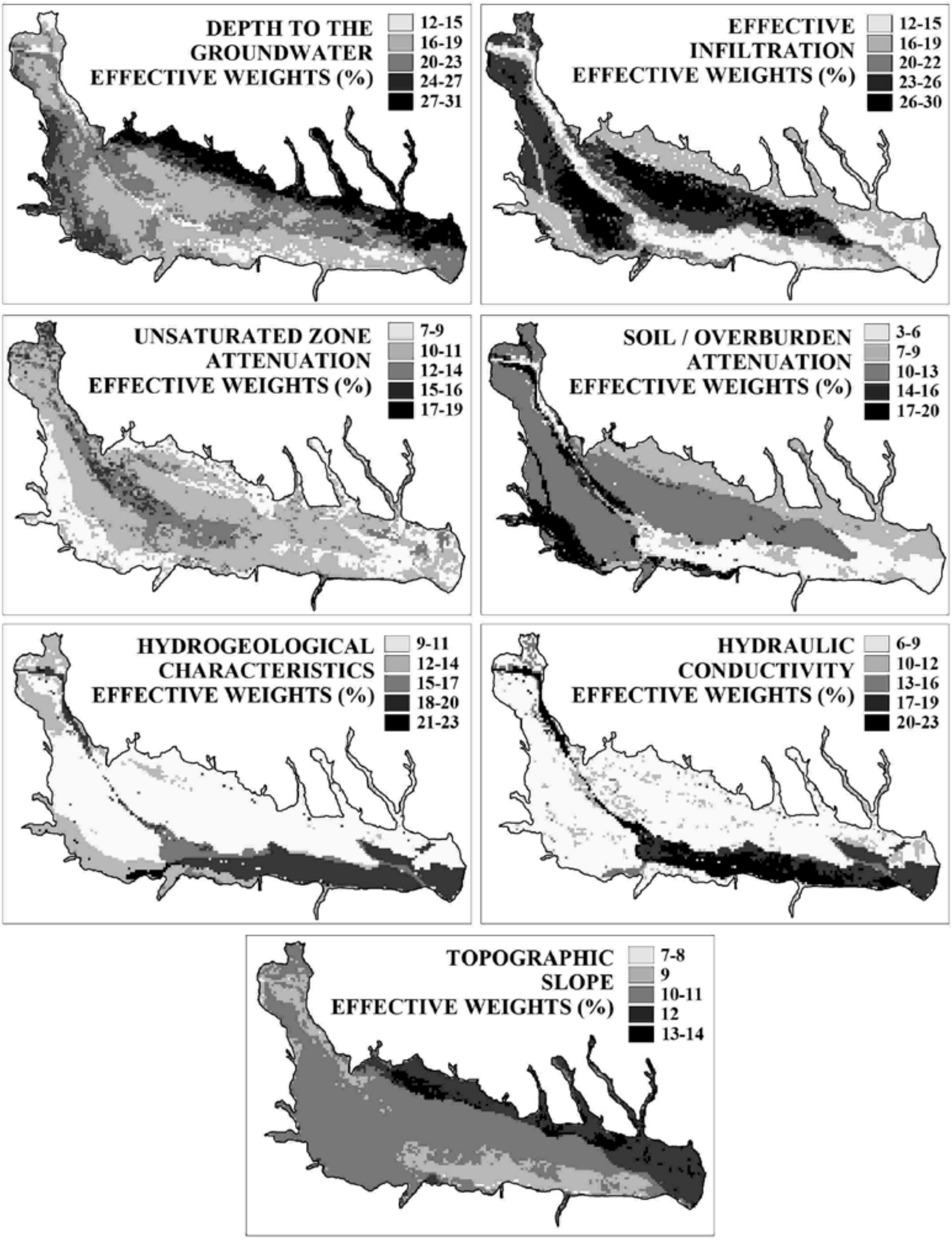

Figure 5. Sensitivity weights maps of SINTACS parameter for the Lower Savinja Valley aquifer

Slika 5. Karte uteži občutljivosti parametrov SINTACS za vodonosnik Spodnje Savinjske doline with increased clay component. 48.9 percent of the hops production fields and 41.4 percent of the urbanised area are situated on the high groundwater vulnerable area of the Lower Savinja Valley aquifer.

The most sensitive parameters in the SINTACS groundwater vulnerability model of the Lower Savinja Valley are depth to the groundwater and effective infiltration action. The results of single-parameter sensitivity analysis enable better understanding of the vulnerability model results, enable consistent evaluation of the analytical result and give a new orientation for further methodological contamination research by using statistical and numerical model results with selected SINTACS groundwater vulnerability parameters.

It is pointed out that detailed vulnerability mapping, including analysis of hydrochemical data, especially nitrate concentration in groundwater, linked to the assessment of pressures and impacts, is a very good basis for establishing detailed monitoring programmes and programmes of measurement to achieve the WFD objectives of good groundwater status for groundwater bodies at risk.

POVZETEK

Ocenjevanje ranljivosti podzemne vode z metodo SINTACS v Spodnji Savinjski dolini, Slovenija

V okviru študijskega primera vodonosnika v Spodnji Savinjski dolini smo ocenjevali ranljivost podzemne vode in analizirali občutljivost parametrov ocenjevalne sheme. Naravno ranljivost podzemne vode smo ocenili po metodologiji SINTACS, analizo občutljivosti pa smo izvedli ločeno po posameznih parametrih ocenjevalne sheme. S tem smo poskusili izboljšati poznavanje prostorske spremenljivosti zaščitnih sposobnosti nezasičene cone z namenom boljšega načrtovanja monitoringa in ukrepov za zaščito podzemne vode v Spodnji Savinjski dolini.

Spodnja Savinjska dolina je ravninski vodonosnik z neizrazito topografijo. Na območju vodonosnika prevladujejo tri pedokartografske enote: obrečna evtrična tla, evtrična rjava tla ter evtrični hipoglej. Nezasičena cona je sestavljena pretežno iz holocenskega peščenega proda z glinasto primesjo na obrobnih delih vodonosnika. Glede na hidrogeološko homogenost izstopa območje spodnje terase z debelozrnatimi prodnimi holocenskimi usedlinami z manj meljaste in glinaste primesi ter z bolj dinamičnim hidrogeološkim režimom, območje srednje terase s prisotnostjo tudi pleistocenskih usedlin ter območje zgornje terase z bolj kompaktnimi in bolj glinastimi holocenskimi usedlinami. Hidravlična prepustnost je ocenjena na podlagi črpalnih poskusov in za holocenske plasti znaša od $1{,}1 \cdot 10^{-3}$ do $1{,}1 \cdot 10^{-2}$ m/s, za pleistocenske plasti pa od $2{,}0 \cdot 10^{-5}$ do $2{,}0 \cdot 10^{-4}$ m/s. Efektiva infiltracija je bila v ocenjevalnem obdobju 1986-2005 med 120 in 390 mm, povprečna globina do podzemne vode pa je bila na pretežnem delu vodonosnika (71,66 %) manjša od 4,5 metre,

Uporabili smo scenarij zmernega ali povečanega antropogenega obremenjevanja ter scenarij dreniranja površinske vode v vodonosnik Spodnje Savinjske doline. Pretežni del Spodnje Savinjske doline je močno antropogeno obremenjen (75,0 %), preostali del območja vodonosnika je zmerno obremenjen (4,2 %) ali pa prevladujejo izrazite možnosti dreniranja površinske vode v vodonosnik (20,8 %).

Ocene sedmih parametrov ocenjevalne sheme po metodi SINTACS in izbranih treh scenarijev je omogočila izračun SINTACS indeksa ranljivosti podzemne vode, ki za posamezno ocenjevalno celico 100×100 metrov predstavlja vsoto vrednosti parametra in uteži za vseh sedem podatkovnih slojev. Za 7.887 celic 100×100 metrov na območju Spodnje Savinjske doline je bil izračunan SINTACS indeks v razponu od 139 do 215 s povprečjem 183. Območje aluvijalnega vodonosnika Spodnje Savinjske doline se po oceni SINTACS uvršča v 4. in 5. razred ranljivosti. V severovzhodnem in jugozahodnem delu vodonosnika prevladuje 4. razred ranljivosti, v severovzhodnem in osrednjem območju pa se ranljivost poveča.

Vpliv posameznih vhodnih parametrov na izhodni rezultat analitičnega modela smo ocenili z analizo občutljivosti posameznih parametrov v modelu ranljivosti. Največjo občutljivost na ranljivost podzemne vode v Spodnji Savinjski dolini ima parameter globine do podzemne vode in parameter efektivne infiltracije, manjša občutljivost pa je bila ugotovljena pri parametru hidrogeoloških lastnosti in lastnosti tal. Najmanjšo občutljivost imajo v tem ocenjevalnem modelu parameter lastnosti nezasičene cone, parameter hidravlične prepustnosti in parameter nagiba površja.

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