Integration of models of various types of aquifers for water quality management in the transboundary area of the Soča/Isonzo river basin (Slovenia/Italy)

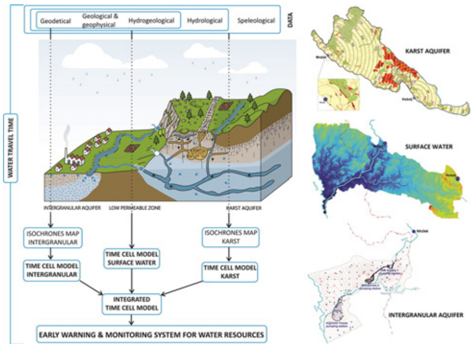
Goran Vižintin [a], Nataša Ravbar [b,c,*], Jože Janež [d], Eva Koren [a], Naško Janež [d], Luca Zini [e], Francesco Treu [e], Metka Petrič [b,c]

[a] *University of Ljubljana, Faculty of Natural Science and Engineering, Aškerčeva 12, SI-1000 Ljubljana, Slovenia*
[b] *Karst Research Institute ZRC SAZU, Titov trg 2, SI-6230 Postojna, Slovenia*
[c] *University of Nova Gorica, UNESCO Chair on Karst Education, Glavni trg 8, SI-5271 Vipava, Slovenia*
[d] *Geologija d.o.o., Prešernova 2, SI-6250 Idrija, Slovenia*
[e] *University of Trieste, Department of Mathematics and Geosciences, Via Weiss 2, IT-34127 Trieste, Italy*

HIGHLIGHTS

- An integrated system of hydrological and hydrogeological models has been created.
- The system couples different porous media with complex water flow regimes.
- The system is based on water travel time between surface and water source.
- The study provides a scientific basis for an early-warning and monitoring system.
- The system is applicable in transboundary water resources management.

GRAPHICAL ABSTRACT



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ABSTRACT

Due to intrinsic characteristics of aquifers groundwater frequently passes between various types of aquifers without hindrance. The complex connection of underground water paths enables flow regardless of administrative boundaries. This can cause problems in water resources management. Numerical modelling is an important tool for the understanding, interpretation and management of aquifers. Useful and reliable methods of numerical modelling differ with regard to the type of aquifer, but their connections in a single hydrodynamic model are rare. The purpose of this study was to connect different models into an integrated system that enables determination of water travel time from the point of contamination to water sources. The worst-case scenario is considered. The system was applied in the Soča/Isonzo basin, a transboundary river in Slovenia and Italy, where there is a complex contact of karst and intergranular aquifers and surface flows over bedrock with low permeability. Time cell models were first elaborated separately for individual hydrogeological units. These were the result of numerical hydrological modelling (intergranular aquifer and surface flow) or complex GIS analysis taking into account the vulnerability map and tracer tests results (karst aquifer). The obtained cellular models present the basis of a contamination early-warning system, since it allows an estimation when contaminants can be expected to appear, and in which water sources. The system proves that the contaminants spread rapidly through karst aquifers and via surface flows, and more slowly through intergranular aquifers. For this reason, karst water sources are more at risk from one-off contamination incidents, while water sources in intergranular aquifers are more at risk in

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* Corresponding author at: Karst Research Institute ZRC SAZU, Titov trg 2, SI-6230 Postojna, Slovenia.
E-mail address: natasa.ravbar@zrc-sazu.si (N. Ravbar).

cases of long-term contamination. The system that has been developed is the basis for a single system of protection, action and quality monitoring in the areas of complex aquifer systems within or on the borders of administrative units.

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1. Introduction

1.1. Background

Unlike transboundary surface water and river basins, transboundary aquifers are not well known to policymakers. The fact is, the impacts of inadequate actions (for example contamination) spread unhindered across the administrative borders and coordinated transboundary management is necessary. Five aspects of transboundary aquifers are distinguished: scientific-hydrogeological, legal, socio-economic, institutional and environmental analysis (ISARM, 2016). In this article the focus is on the first of these aspects, since in any legal agreements drawn up for the common management of transboundary resources, the initial stage must be the correct identification of the flow and movement of water within the aquifer (Comair et al., 2013).

For this purpose, various research methods are used. In the past decades numerical modelling has made great progress in hydrogeology and become a part of everyday basic or applied research. Because aquifers differ in terms of the morphology of the pores or spaces in the rock, certain types of aquifers require specific modelling approaches. Models of groundwater flow in intergranular aquifers are based on equivalent porous media (EPM) and Darcy flow equations (Darcy, 1856). They are becoming increasingly useful and reliable tools when it comes to addressing the principal challenges involved in planning and deciding on water resources management (e.g. Barthel et al., 2005; Vižintin et al., 2009; Xu et al., 2012).

In recent years various modelling techniques to simulate the functioning of karst aquifers have been developed that may be classified under two main basic principles: lumped parameter models (global models) and distributive models (Kovács and Sauter, 2007). The first imply the mathematical analysis of spring discharge time series that are believed to reflect the overall (global) hydrogeological response of karst aquifers (e.g. Kurtulus and Razack, 2010; Butscher and Huggenberger, 2008). Such approach is very limited in assessing the spatial distribution of the water flow and mass transport. The second are used for quantitative spatial simulation of groundwater flow fields (e.g. Ghasemizadeh et al., 2012; Hartmann et al., 2014). As they require detailed information on aquifer geometry, hydraulic parameter fields and recharge conditions, their performance is usually poor due to the lack of adequate data and significant uncertainty in subsurface geometry.

The modelling techniques described above are usually used exclusively for application in individual media and studies that connect models of water flow between different types of aquifer in an integrated manner are very rare. Polomčić et al. (2013) used a mixed hydrodynamic model in a regional study of a karst aquifer which is fed by overlying alluvial aquifer. The MODFLOW-2000 code was applied to combine both aquifer types in one model with several layers. This was possible because of a known position of the alluvial aquifer above the karst aquifer and well-known structures of the two systems.

The idea of integrated modelling was thoroughly researched in several projects developing the water management tools for river basins with complex geological and hydrogeological characteristics. One such example is the Upper Danube catchment, which is characterized by various types of aquifers, including karst. The MODFLOW was used for a construction of the Danubia Groundwater Model. A lot of effort was put in setting up the appropriate conceptual model, namely in the adequate definition of the model layers geometry and boundary conditions. However, only a coarse discretization for a general overview in large areas was possible and the results were lacking the spatial and temporal details of local simulations. It was concluded that such models should only be used to address long term, regional problems and that an application to local, short-term period questions is not possible (Barthel et al., 2005).

The present study addresses the following issues highlighted above: i) modelling of complex aquifer systems and ii) joint management of transboundary aquifer systems. It focuses on the area of the basin of the transboundary river Soča/Isonzo, which connects the karst aquifer of the Trnovo-Banjšice plateau in Slovenia and the alluvial aquifer with intergranular porosity of the Isonzo plain in Italy and Slovenia. Both aquifers store significant quantities of groundwater that is used to supply drinking water in the border regions: karst springs from this aquifer supply around 90,000 people in both countries, and the alluvial aquifer a total of 350,000 inhabitants in Italy (Zini et al., 2013). Any contamination in the area in question and the resulting deterioration in the quality of the water sources could therefore affect a large number of people. For this reason, timely and coordinated action is necessary. Both aquifers also supply the Soča/Isonzo, which drains into the Adriatic Sea, and therefore contamination in the catchment area of the river would also represent potential contamination of the sea in the shallow Gulf of Trieste.

The idea was to prepare a single Slovenian-Italian transboundary response system in cases of hazards posed to drinking water sources from technological risks and natural disasters which could be used by the Civil Protection Services of the two countries. As its scientific-hydrogeological basis an integrated system of models has been developed that takes into account the characteristics of karst and intergranular aquifers, and the surface flow which connects the two aquifers. It enables a uniform determination of the time it takes water to flow from the point of contamination to at-risk water abstraction points in the areas of complex aquifer systems. In the case of pollution, the model can be used for a first assessment of the endangered water abstraction points and the time when contaminants can first be expected to appear there. Based on this, a detailed monitoring of the water quality and corresponding protection measures can be initiated in due time.

1.2. Differences in the hydrological behaviour of different types of aquifers

Alluvial aquifers with intergranular porosity are naturally fed and recharged through precipitation (rain, melting snow), and also indirectly through underground flow from rivers and lakes, and sometimes even the sea. Groundwater moves gravitationally through the pores between the grains towards the impermeable base of the aquifer or follows the incline of its surface. The velocity of the movement of water through the aquifer depends on the structure of the aquifer and the slope of the aquifer layers and usually reaches a rate of between a few metres and a few tens of metres a day (De Marsily, 1986). They can be described using the representative elementary volume (REV) method and this homogeneity allows the use of numerical models of water flow and mass transport.

Karst aquifers are characterized by a heterogeneous structure with three types of porosity: micropores in the bedrock, small fissures or fractures and larger fissures and conduits. The consequence of this is great variability of water flow through karst systems. As a result, the hydrological functioning of karst systems reflects a duality of recharge, flow and storage, and discharge (Kiraly, 1998): a) diffuse infiltration of precipitation on the karst surface (autogenic recharge) and concentrated inflow via sinking streams into karst conduits (allogenic recharge); b) low flow velocities in less permeable zones of the aquifer and rapid flow in karst conduits (even up to several hundred m/h); c) great variability of flow rates of springs. Because of these characteristics, karst aquifers cannot be described using the REV method (Bakalowicz, 2005; Neuman, 2005). It is extremely difficult to define the characteristics of karst aquifers on the basis of available data in the form necessary for the elaboration of numerical hydrological models that would allow realistic simulations of natural conditions (Quinlan et al., 1996; Quinn et al., 2006; Kovács et al., 2005; Hartmann et al., 2013).

2. Study area

The study area is divided, in terms of its hydrogeological structure, into a karst aquifer (Trnovo-Banjšice plateau) and an intergranular aquifer (alluvium of the Isonzo plain). Between them is an area of very low permeability (the Brda/Collio hill region and the Vipava Valley), in which a surface drainage network is developed. The hydrological connection between these units is represented by the river Soča/Isonzo and its tributaries (Fig. 1).

The Trnovo-Banjšice plateau rises above the Soča/Isonzo Valley (0–100 m a.s.l.) at elevations of between 800 and 1500 m a.s.l. The plateau is built of carbonate sedimentary rocks of Early Triassic, Jurassic and Cretaceous age. Limestones predominate, in places passing into dolomites. Within the system of overthrust and underthrust structural units, Eocene flysch is found in the bedrock of the carbonate massif. Mesozoic carbonate rocks build the central part of the karst aquifer, while the flysch represents a lateral and basal impermeable hydrogeological barrier. Karst groundwater is located at great depth and flows out onto the surface at the lowest points of the impermeable margin in several karst springs, which even in dry periods give a total flow of around 2 m^3/s. Several tracer tests carried out in this area evidenced the overlapping of the recharge areas of individual springs (Kranjc, 1997). The biggest of them is the Mrzlek spring (flows of between 0.5 and 50 m^3/s), which represents the main outflow of karst water into the Soča/Isonzo. An important inflow of karst water into the Soča/Isonzo (via its tributary the Vipava/Vipacco) is also represented by the Hubelj spring, with flows ranging from 0.18 to 49 m^3/s. A 3-D model constructed on the basis of geological data and results of tracer tests evidenced a divergent region between the systems of Mrzlek and Hubelj springs (Turk et al., 2013). In this area, the perched groundwater body is expected to overflow to the east towards the Hubelj spring and to the west towards the Mrzlek spring.

The Isonzo plain is created by alluvial sediments deposited by the Soča/Isonzo and its tributaries in the Quaternary period. In the upper part of the Isonzo plain, which is presented on Fig. 1, well-permeable coarse-grained sediments build an intergranular aquifer with high yield that is recharged by precipitation and seepage from the Soča/Isonzo. In the lower part of the plain, to the south of the area presented on Fig. 1, the phreatic aquifer joins with a multi layered aquifer system characterized by alternating gravel-sand and clay-silt deposits. The boundary between the two represents the so-called springs line, along which part of the groundwater comes to the surface as a result of the decrease in permeability with a discharge of about 16 m^3/s. Approximately 1550 pumping wells are located throughout the area of alluvial sediments. The total quantity of pumped water is almost 2 m^3/s (Zini et al., 2011). This study is focused on the main water sources (IRIS Gorizia 1 and 2, and ACEGAS Trieste pumping station).

The alluvial aquifer is limited to the north and east by the flysch areas of Brda/Collio and the Vipava Valley, to the west by the gravelly bed of the river Torre, and to the south-east by the limestone slopes of the plateau of the Classical Karst Region. A surface drainage network that discharges into the Soča/Isonzo is developed on flysch. Part of the groundwater also seeps from the alluvium of the Isonzo plain into the karst aquifer of the Classical Karst Region with an estimated discharge of about 10 m^3/s (Zini et al., 2015).

In climatic terms the study area lies at the transition between the Mediterranean (Isonzo plain), continental and Alpine climate zones (Trnovo-Banjšice plateau). While the plain receives annual precipitation of between 1000 and 2000 mm, the plateau acts as a climatic barrier and receives between 2000 and 3000 mm a year (Pristov, 1997).

The complex system which is the focus of this study is schematically presented in Fig. 2. The karst aquifer is an important reservoir of

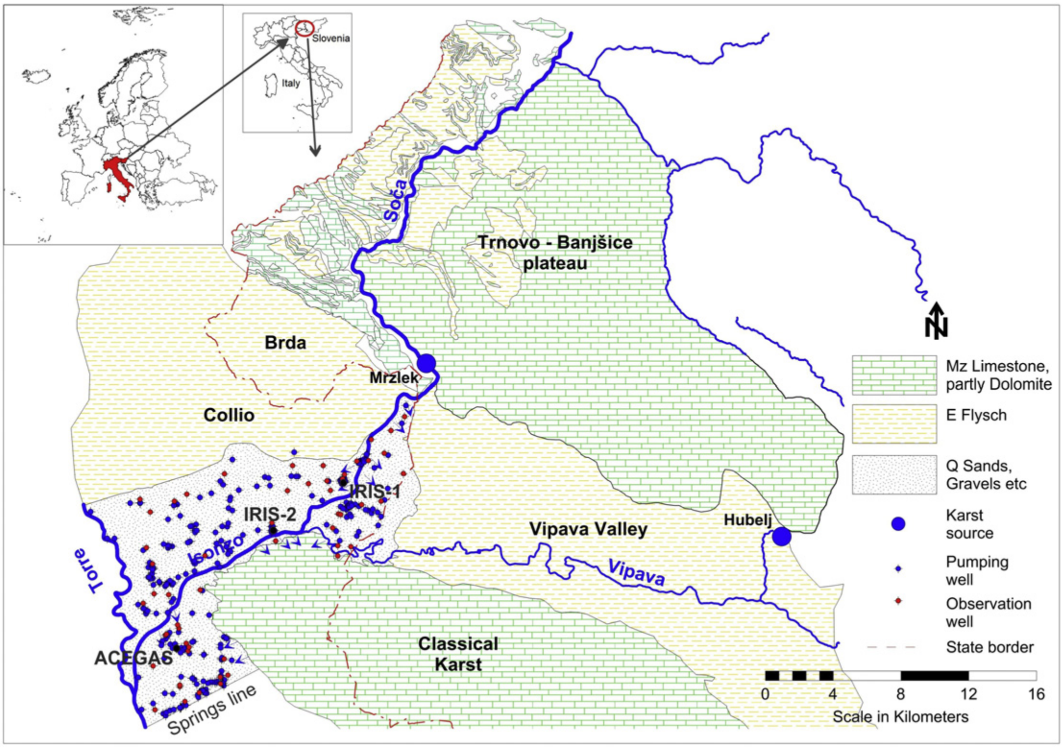

Fig. 1. Geological map of the study area with different types of aquifers and drinking water sources (Map based on Zini et al., 2011 and GeoZS, 2013).

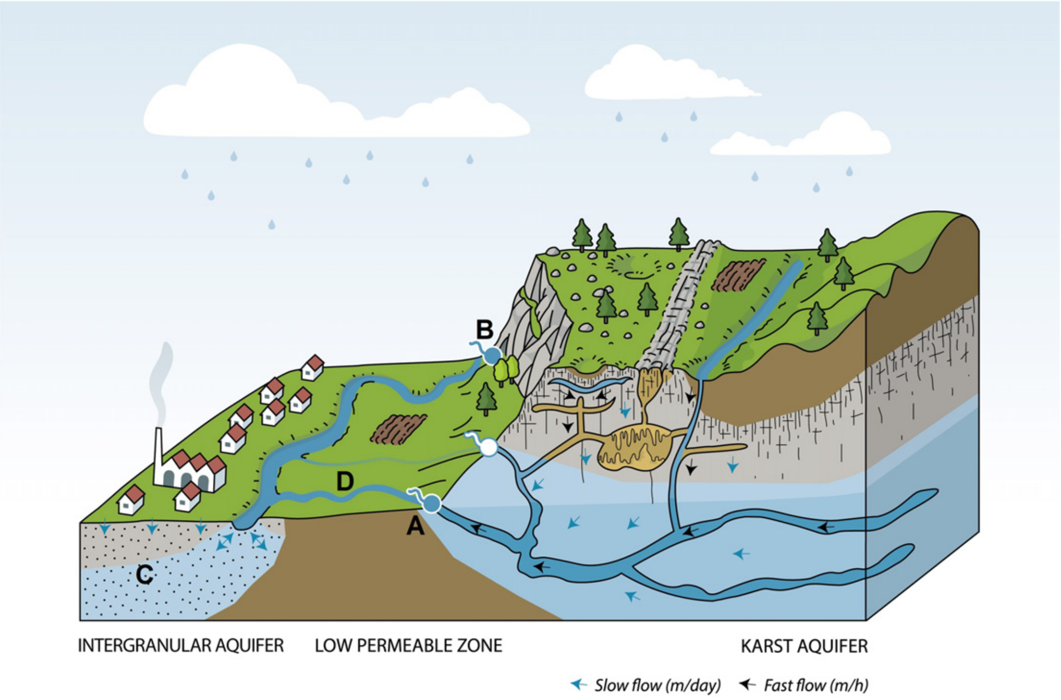

Fig. 2. A schematic presentation of major differences of water flow in intergranular and karst aquifers resembling hydrogeological settings of the study area (modified after Ravbar and Šebela, 2015).

groundwater that is recharged autogenically by precipitation and allogenically by sinking streams. Groundwater comes to the surface in large karst springs when it comes into contact with rocks with very low permeability and drains into the river either directly (B on Fig. 2 resembles the Mrzlek spring) or via surface flows (A on Fig. 2 resembles the Hubelj spring and D the Vipava/Vipacco River). The river flows over alluvial sediments (C resembles the Isonzo plain) and, depending on hydrological and hydrogeological conditions, recharges or drains them. The alluvial sediments represent an intergranular aquifer with a free groundwater surface (unconfined aquifer), which likewise stores significant quantities of water. The level of groundwater is maintained with the help of good infiltration of precipitation, which percolates into the aquifer, and from the rivers that flow across the area in question.

3. Methods and modelling

3.1. Design of an integrated system of models of various types of aquifers

A system of separate models of individual hydrogeological units connected in a single system of modelling tools was created (Fig. 3). The basic concept is built on an estimate of the time it would take water to flow from the point of contamination to at-risk water abstraction points. Within this system, the shortest possible times or worst-case scenarios from the point of view of the spread of contamination are defined. In order to use this approach, it was first necessary to define the directions and velocities of water flow. In this phase the individual hydrogeological units were dealt with separately using different approaches.

The karst aquifer was modelled using the KARSYS approach developed at the Swiss Institute for Speleology and Karst Studies (Jeannin et al., 2013). In the context of the Slovenian-Swiss research project “Swiss contribution” a 3D geological model was created first on the basis of geological maps and cross-sections in Geomodeller® software. Then, with the inclusion of all existing hydrogeological data (e.g. the position and characteristics of springs, water caves and ponors, the results of tracer tests with natural and artificial tracers) a 3D hydrogeological model was created in Cinema 4D® software (Turk et al., 2013 and references therein). This enabled a definition of underground water bodies, determination of the direction of groundwater flow and an outline of the boundaries of the recharge areas of the karst water sources.

For estimating the velocity of water flow the results of previous tracer tests were used. Because the identified velocities are dependent on the method and location of the injection of tracer and hydrological conditions at the time of the tests, these factors need to be taken into account when analysing and interpreting them (Geyer et al., 2007; Gabrovšek and Dreybrodt, 2011). The most suitable way to estimate the characteristics of injection sites with regard to factors affecting the flow from surface to springs (meteorological, geological, geomorphological, speleological, hydrogeological and pedological factors and the vegetation characteristics of the area) is to use one of the existing methods of vulnerability mapping. The authors of this study have had most positive experiences with the so-called Slovene Approach.

As part of a comprehensive groundwater protection strategy (Zwahlen, 2004), the Slovene Approach is a precise, physically based methodology that syntheses the information on flow and transport processes. Available data on several parameters significantly influencing the path of the water or a potential contaminant from the surface through the aquifer to the abstraction point is used. Each parameter is classified into defined categories or discrete intervals, which reflects the relative degree of vulnerability to contamination. Vulnerability indexes are classified into three vulnerability categories. Detail conceptual instructions and guidelines are provided in Ravbar and Goldscheider (2007).

With the help of ArcGIS 10.1 software the vulnerability classes were determined in the described way, ranging from areas of high vulnerability, from which a contaminant can reach a spring rapidly and in undiluted form, to areas of low vulnerability, from which the contaminant takes longer to reach the springs and can also degrade en route. In all the tracer tests carried out, the identified flow velocities must therefore be analysed appropriately with regard to the identified level of vulnerability of the injection sites and with regard to precipitation and hydrological conditions during the tests themselves. On this basis, maximum apparent flow velocities (with regard to the time of the tracer appearance and the air distance to the water source) were determined for each vulnerability class.

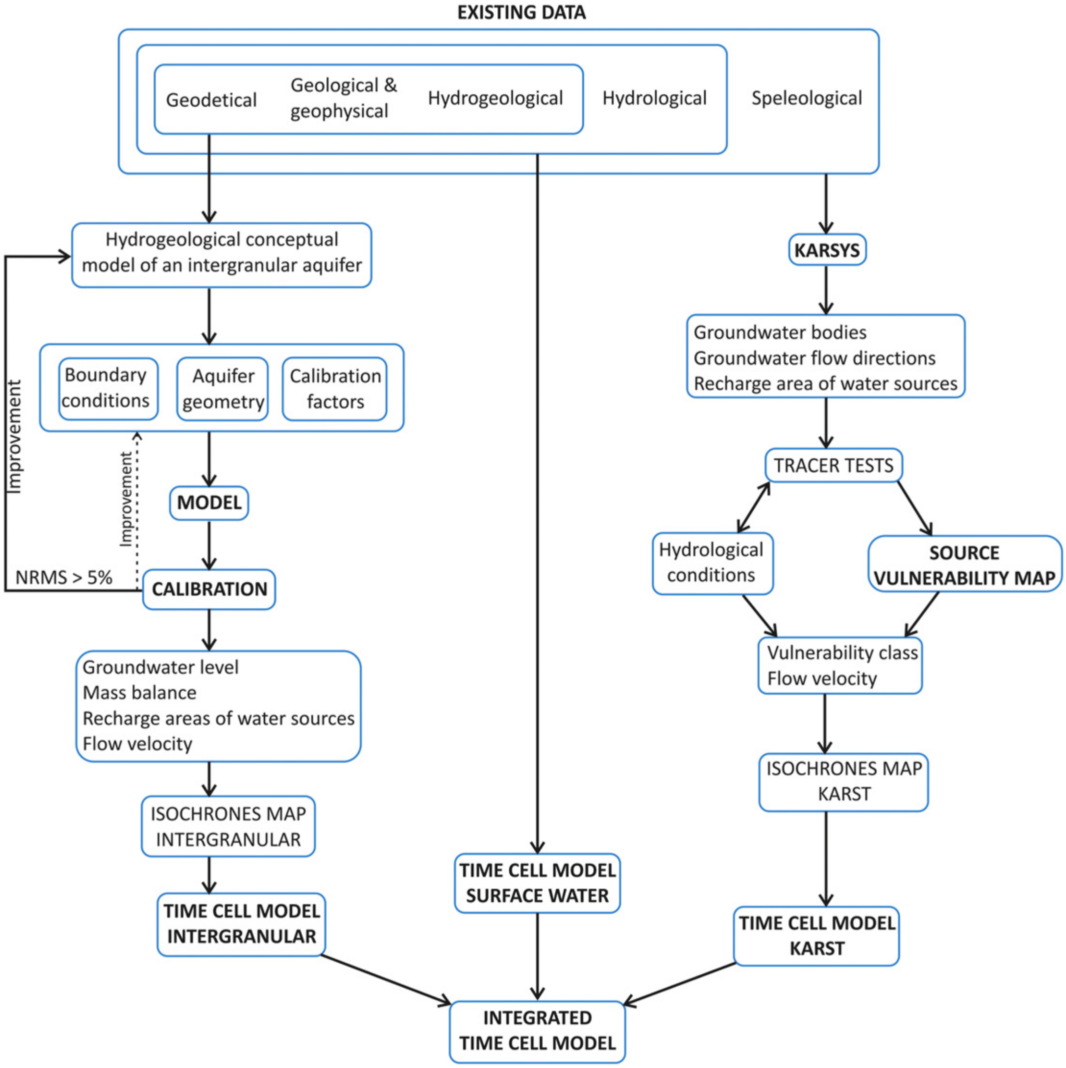

Fig. 3. Design of an integrated system of models of aquifers with various porosity.

The next step was a creation of an isochrone map which enables an estimation what water sources and when would be affected in the case of contamination in a specific location. Isochrones were calculated with the help of QGIS 2.0 software separately for the recharge area of each karst spring. Time of water flow from individual points to the source was calculated based on the distance to the spring and maximum apparent flow velocity of the vulnerability class of this point. For this calculation a script in the Python 2.7.5 programming language was created (App. A). Based on the raster map the isochrones were drawn.

Building of a model of the intergranular aquifer in alluvium was done using the FeFlow 7.0 program (DHI WASY, 2015), which uses the finite element method (FEM) to solve the differential partial equation of flow and transport. This version of the program allows the creation of multi-layered models that have the same mesh density across all layers. Successful modelling with FeFlow requires good knowledge of the aquifer geometry from the outset, since although later corrections are possible, these can lead to numerical instability, lower accuracy and longer calculation times.

The model was calibrated with the help of the PEST tool. The hydraulic conductivity values K_{xx}, K_{yy} and K_{zz} are not tied during the calibration procedure. The model was run several hundred times for the necessary calibration. In cases where the improvement did not achieve the condition NRMS < 5%, the hydrodynamic boundaries of the model in the north (gradient boundary and partial surface recharge) were also changed in the model (Table 1).

The PEST program works by taking into account zones within which it can change the hydraulic conductivity and recharge values determined by the builder of the model. Because of the more continuous transitions between individual zones, evenly distributed points were selected instead of these zones. Forty pilot points were determined in each model layer Q, for which PEST, with the help of Tikhonov regularisation, optimised the value of hydraulic conductivity with simultaneous interpolation of conductivity in the intervening space. The values of the points were both upwardly and downwardly limited.

Table 1
List of parameters included in the intergranular and surface hydrology models.

Model	Parameter	Determination	Method	Limits
Intergranular	K_{xx}	Calibration	PEST	Yes
	K_{yy}	Calibration	PEST	Yes
	K_{zz}	Calibration	PEST	Yes
	S_y	Calibration	PEST	Yes
	Dirichlet boundary	Measured	Heads	No
	Neumann boundary	Calibration	Manual	Yes
	Cauchy boundary	Calibration	Manual	Yes
	Well	Measured	Heads	No
	Infiltration	Measured	Lysimeter	No
Surface hydrology	Hydraulic radius	Measured	GIS	Yes
	Slope	Measured	GIS	No
	Manning coefficient	Measured	GIS	No

The results of modelling the intergranular aquifer are calibrated hydraulic conductivities and groundwater levels, while with the help of the particle tracking method the areas of influence of individual water sources and the time-dependence of travel times of conservative particles towards these water sources (flow velocity) are also defined. On this basis, isochrones are defined for an individual water source which represent the travel time of particles from a selected point to individual water sources (pumping stations) in the area of the intergranular aquifer.

The karst aquifer and the intergranular aquifer are connected to each other by the times taken for water to pass over less permeable rocks, which mainly takes place via surface waters. Modelling tools must therefore also include the manner of flow of surface flows over the area of very low permeability and determine a time connection between the water in karst springs, surface water courses, surface runoff and the intergranular aquifer. The time cell model of surface flow is created on the basis of geomorphological, hydrogeological and pedological factors and the vegetation characteristics of the area through the use of the Manning's equation (Manning et al., 1890; Table 1). The Manning's equation is an empiric type of formula used for estimating the average velocity of the liquid in closed and open channels. Empiric part of Manning's equation is presented with Gauckler–Manning coefficient. The coefficient is mostly dependent from the relief shape, type of vegetation, roughness of terrain (and indirectly the pedological properties). The information has been analysed with prior raster GIS work of the available data. After these analyses the area has been divided into classes and assigned the appropriate pre-defined value (Chow, 1959).

The isochrone maps for the karst aquifer and the intergranular aquifer are also transferred by rasterisation into time cell models of individual water sources in the area of the two aquifers. The missing values in the areas between the isochrones are filled in with the help of geostatistical interpolation known as kriging. Unlike the so-called vector maps, where lines connect points with equal times, cellular models must know the time in each cell of the model.

Finally, the cellular models for individual water sources in the karst aquifer and the intergranular aquifer and for the connection between them via surface flow are combined in an integrated time cell model which allows assessment of the travel time of water from the point of contamination to a selected karst or alluvial water source.

3.2. Application to the study area

The following data from existing databases were used to create individual models: geological maps and cross-sections (GeoZS, 2013; Zini et al., 2011), data from 127 boreholes (Zini et al., 2011), topographic maps, DEM (GURS, 2013; Zini et al., 2011), a pedological map (Grčman et al., 2015; Zini et al., 2011), land use data (MKGP, 2013; Zini et al., 2011), meteorological and hydrological data (ARSO, 2013; Zini et al., 2011), speleological data (Cave Registry, 2012). The results of 33 tracer tests using artificial tracers (Habič, 1982; Kranjc, 1997; Veselič and Čenčur Curk, 2001; Bricelj and Čenčur Curk, 2005) were used to define the characteristics of groundwater flow for the vulnerability assessment and determine apparent flow velocity in the karst aquifer.

4. Results and discussion

4.1. Hydrogeological model of the karst aquifer

Using the KARSYS method, the underground water bodies within the karst aquifer of the Trnovo-Banjšice plateau were defined and the directions of groundwater flow determined. The Mrzlek and Hubelj karst springs were included in subsequent processing. Both springs are used to supply drinking water and also directly or indirectly recharge the Soča/Isonzo and thus also the intergranular aquifer of the Isonzo plain. The size of their catchments was determined (Turk et al., 2013). These catchments overlap in one part, which means that contamination in that part of the aquifer can appear in both springs.

The vulnerability mapping identified the most vulnerable areas (R1) in the heart of the plateau, where there are bare karst areas and areas in the immediate catchment area of sinking streams. Moderately vulnerable areas (R2) include areas of carbonate rocks covered by a thin soil layer, while the least vulnerable areas (R3) are areas of carbonate rocks covered by thicker soil layers and sediments, and non-karst areas. Analysis of the results of tracer tests took into account precipitation and hydrological conditions at the time of testing. The model was in fact set up for conditions in which any contamination can spread most quickly. For the karst aquifer, these are conditions of a high water level with frequent precipitation, in which fractures in the vadose zone are hydraulically connected and there is rapid transport of solutes through the vadose and phreatic zones towards karst springs. The flow velocities identified by tracer tests were therefore adapted to the delay in the appearance of precipitation and the flood pulse following injection in such a way as to estimate the highest possible velocities under conditions most favourable for water flow and solute transport (Table 2). Through comparison of the results obtained, and taking into account the vulnerability class of the injection points, a maximum apparent velocity of groundwater flow towards a spring was determined for each of the three vulnerability classes: for the most vulnerable area 95 m/h, for the moderately vulnerable area 60 m/h and for the least vulnerable area 10 m/h. Taking into account these velocities and the distance from both karst water sources, an isochrone map was drawn up within their catchment area which shows the distribution of travel times of water from a selected point on the map to an individual water source (Fig. 4). The time distances between the isochrones are 6 h for the most vulnerable, 24 h for the moderately vulnerable, and 48 h for the least vulnerable areas. The map also takes into account the special characteristic of karst aquifers whereby water and contaminants can flow towards both springs from a given point inside the common recharge area.

From the most vulnerable areas which are closer to the water sources, contaminants can appear in the Mrzlek and Hubelj springs within a single day. From more distant areas they can appear in less than a week. Flow from less vulnerable areas is typically slower and several months can pass before the appearance of contaminants in the water sources.

4.2. Hydrogeological model of the intergranular aquifer

A significant element affecting the behaviour of the model of the intergranular aquifer of the Isonzo plain is the river Soča/Isonzo (which drains or recharges the aquifer). For an illustration of its tributary the Torre, an appropriate quantitative inflow over the Neumann boundary was added during the calibration procedure. The influence of the other smaller rivers was neglected. A single value for effective precipitation (1500 mm/a) was assumed for the entire model and then a logical value for effective infiltration was determined on the basis of the existing data. Wells with relevant pumping quantities and piezometers were inserted in the modelling area and used to help calibrate the model.

A single-layer stationary flow model was chosen to illustrate flow. The model was calibrated to the situation in August 2013, when the level of groundwater was low. The selection of this period is connected to the choice of the most favourable conditions for the spread of contaminants. In this period the groundwater level was relatively low while the level of the Soča/Isonzo was relatively high, which means favourable conditions for aquifer recharge from the river. The external boundaries of the model are the Classical Karst (SE boundary), the river Torre (W boundary), the Brda/Collio hill region and the Vipava Valley (N and NE boundary), and the springs line (S boundary).

Using parameter optimization software PEST, hydraulic conductivities (K) for all three directions were calibrated (Fig. 5). Infiltrations rates, Darcy flows on the northern borders of the groundwater model, with the exceptions of the Cauchy boundary conditions expressed with transfer function, were used as fixed parameters knowing them from

Table 2
Results of the selected tracer test in the recharge areas of the Mrzlek and Hubelj springs (D-air distance from the injection point to the spring, t_1-time from injection to the first detection of tracer, t_p-time t_1 adapted to the delay in the appearance of precipitation and the flood pulse following injection, v_m-apparent flow velocity calculated as D/t_p). The highest values of v_m (marked in bold) were used for the assessment of the maximum apparent velocity of groundwater flow in individual vulnerability classes R (R1, R2, R3).

Date	Injection point	R	D (km)	t_1 (h)	t_p (h)	v_m (m/h)	Reference
16/4/94	Shaft	**R1**	19.6	206	206	**95**	Kranjc (1997)
28/10/82	Sinking stream	R1	6.5	300	70	93	Kranjc (1997)
14/10/93	Shaft	R1	19.6	216	216	91	Kranjc (1997)
1/8/95	Shaft	R1	19.6	894	350	56	Kranjc (1997)
1/8/95	Surface, fissure	**R2**	10.4	721	172	**60**	Kranjc (1997)
12/9/80	Distant catchment of a sinking stream	R2	13.0	672	288	45	Habič (1982)
14/10/93	Doline, thick soil cover	**R3**	0.9	87	87	**10**	Kranjc (1997)
1/8/95	Doline, thick soil cover	R3	0.9	608	128	7	Kranjc (1997)

previous works (Zini et al., 2011, 2013; Treu et al., 2017). To have overparametrization problem under control, ranges of limit values for parametrization parameters (K ranging between one and 1200 m/day) were established. These values were mostly coming from single pumping test (Zini et al., 2011). In addition, the lower limit of the NRMS values was set to stay below 5% (current value is 2.403%).

The results of modelling of the intergranular aquifer are calibrated hydraulic conductivities and groundwater levels in the upper part of the Isonzo plain. On this basis, areas of influence and the time-dependence of travel times of conservative particles towards water pumping stations were determined with the help of the particle tracking method for the three most important water sources in the alluvium. A map was drawn up of isochrones representing the travel time of particles to an individual water source (Fig. 6A).

The results of the model for August 2013 indicate a good correspondence between observed and simulated groundwater levels at the reference points (piezometers), since the error value is within the permitted interval (Fig. 6B). The values of the calibrated parameters (hydraulic conductivity) in the PEST program are also realistic or in line with expectations (Zini et al., 2011, 2013; Treu et al., 2017; Fig. 5). The values of water inflows and outflows at the external boundaries of the model (Neumann boundary) are largely consistent with results known to date. With the help of a Cauchy boundary, inserted into the area of the river Soča/Isonzo, the simulation of the model allows us to describe the reciprocal relationship of the aquifer and the river. The results show that the Soča/Isonzo loses around 1/5 of its water during its passage over the upper Isonzo plain. In its upper and middle sections, the Soča/Isonzo mainly recharges the aquifer, while in its lower section it drains it. The losses of the Soča/Isonzo thus obtained correspond to the findings of earlier studies (Mosetti, 1989; Zini et al., 2013).

Flow seepage velocities of groundwater through the intergranular aquifer are low (aprox. 0.1 to 10 m/day), which means that the times necessary for any contaminant to reach pumping stations (wells) from more distant areas are very long and are measured in months or years.

4.3. Hydrological model of surface flow

A model of surface runoff was created on the basis of knowledge of the relief, slope, soils, vegetation, roughness of terrain and river channels. The basis for the elaboration of the model was Manning's equation. The

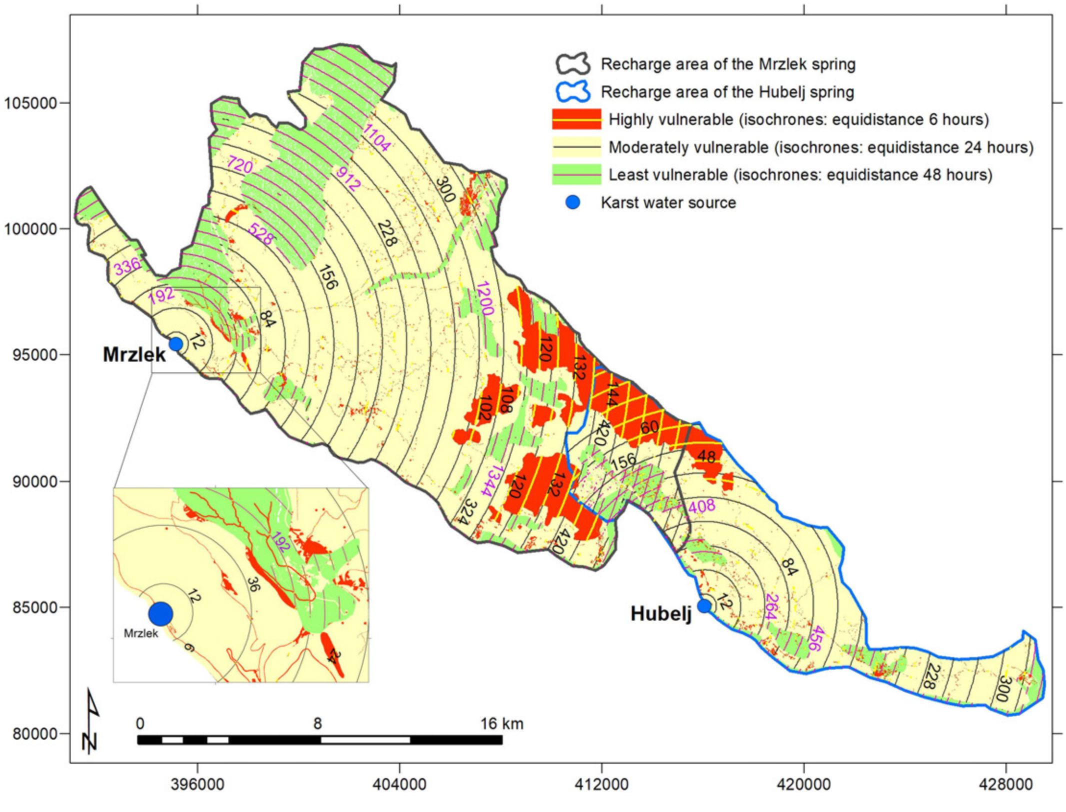

Fig. 4. Isochrone map for the karst water sources with areas of different vulnerability.

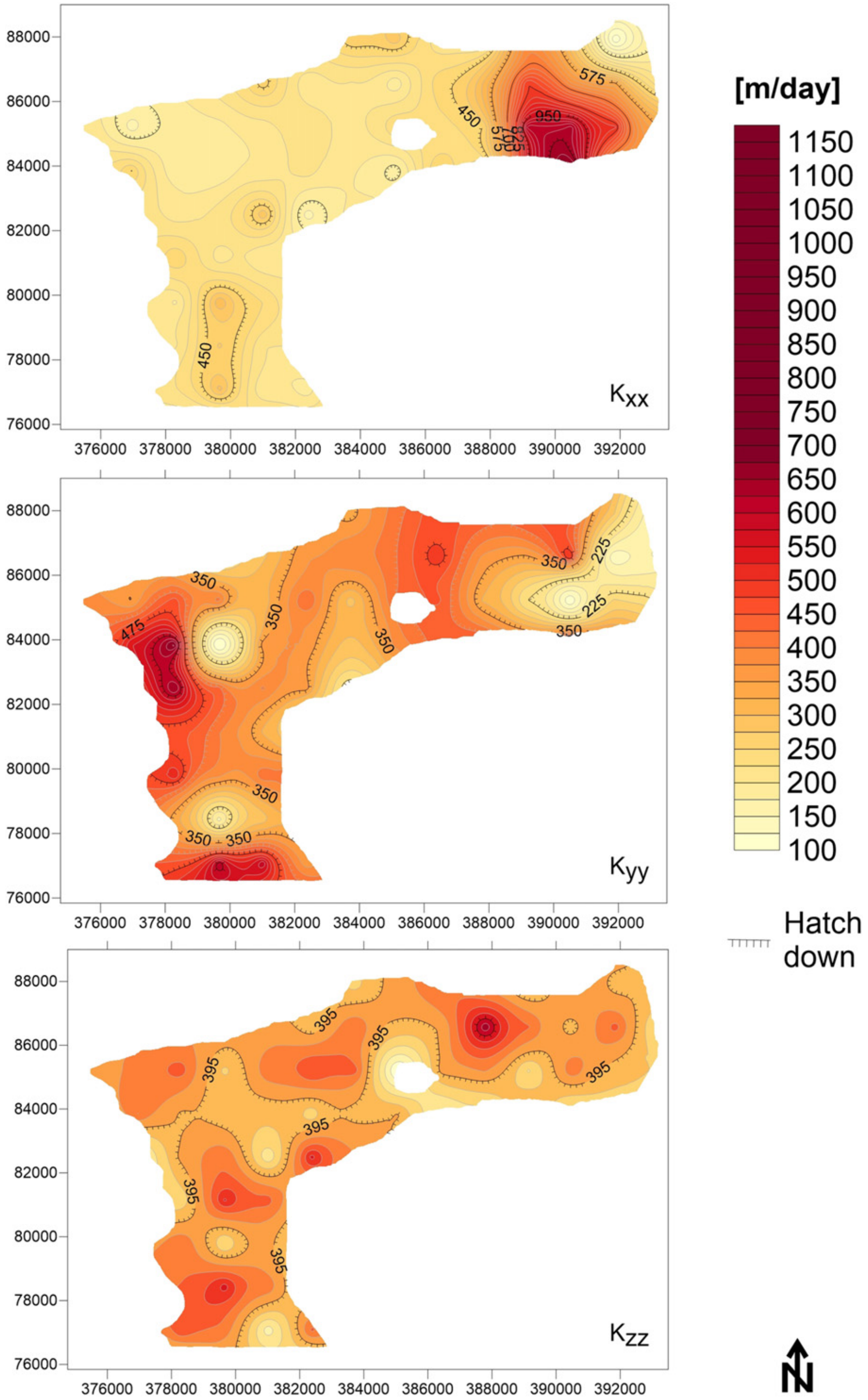

Fig. 5. The hydraulic conductivity values as a result of the model calibration.

map shows the travel times of water from any point of the cell model to the confluence of the Soča/Isonzo and the Torre (Fig. 7). Times for the inflow of water from springs to the areas of influence of alluvial water sources can be very short and are usually between 2 and 6 h.

4.4. Integrated system of models

The completion of modelling and the calculation of isochrones was followed by GIS raster analysis, within which cellular models were used to determine the arrival times of a water particle at individual water sources within the area of both aquifers. Through the use of various methods, several cellular models were developed (two for the Mrzlek and Hubelj springs in the karst section, three for selected water sources – pumping stations – in the alluvium and one for surface flow over rocks with very low permeability in the intermediate area). The information was then combined into an integrated time cell model which allows an estimate of the travel time of a water particle from a given point in the catchment area to a selected karst or alluvial water source. Due to large differences in the velocity of flow in individual hydrological units and overlapping of isochrones of individual water abstraction points their presentation on a single map is practically impossible.

The main inflow from karst springs into the intergranular aquifer is via the rivers Soča/Isonzo and Vipava/Vipacco. Flow times via these two surface flows therefore represent the connection between the

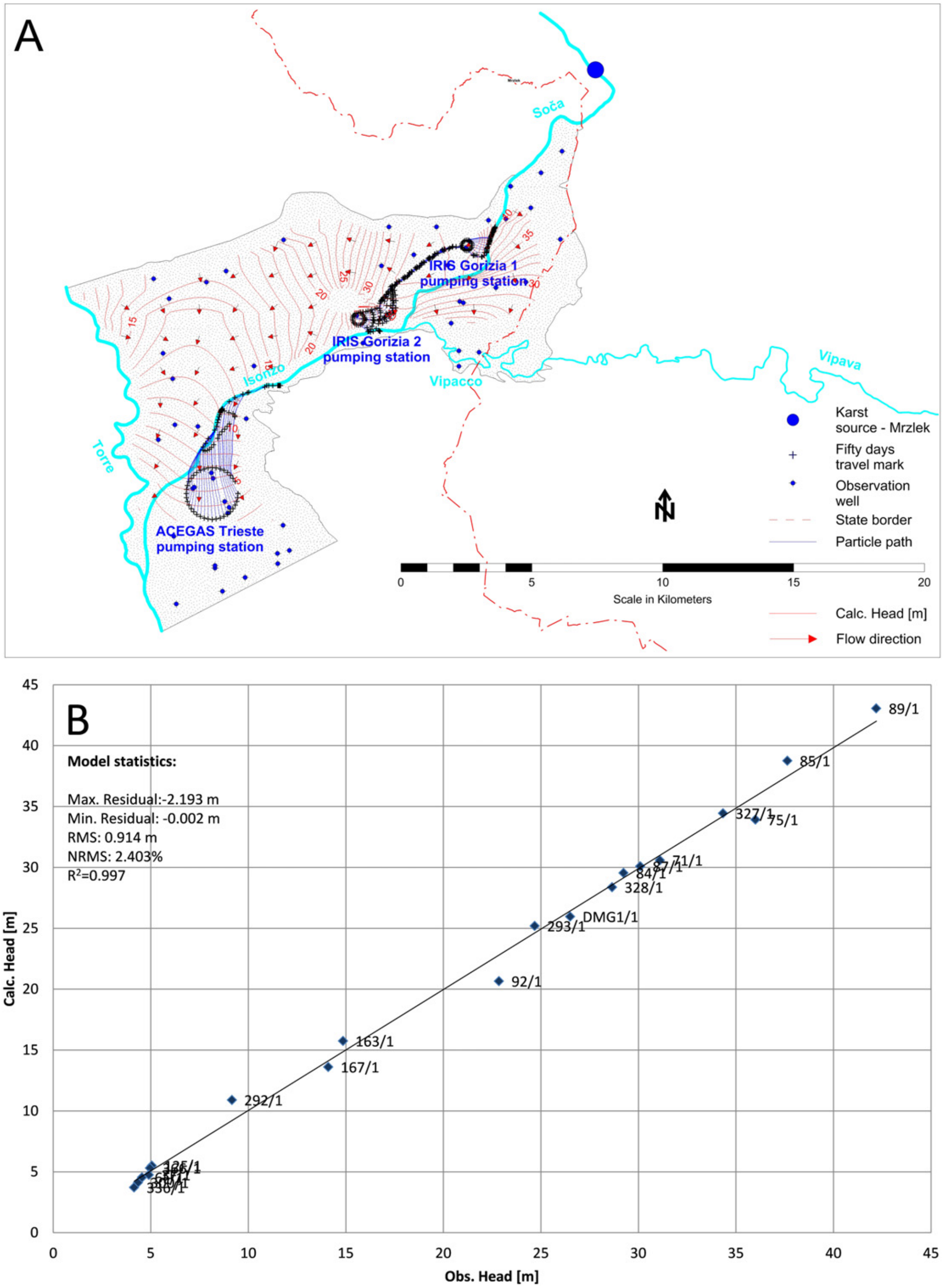

Fig. 6. Results of the intergranular aquifer modelling: A) Isochrone map of the main water sources and B) A correlation of the observed vs. calculated heads.

karst springs and areas influenced by the alluvial sources. It follows from the analysis and the expert system that any contaminant on the surface will spread rapidly towards karst springs and onwards via surface flows, while flow through the intergranular aquifer will be significantly slower. In the case of one-off contamination events, karst water sources are therefore most at risk. Owing to the good permeability, contaminants infiltrate underground practically immediately and remediation through removal of contaminants at the incident site is not possible.

Each particular contaminant is characterized by its own nature and behaviour, their transport through the underground is highly dependent also on the characteristics of the aquifer. To understand these processes various research methods were developed and tested on different study sites. Very good results of solute transport simulations by numerical modelling were obtained in intergranular aquifers and along the surface flows (e.g. Niu and Phanikumar, 2015; Pirot et al., 2015; Velleux et al., 2008; Weiler and McDonnell, 2004). Significantly less successful were the attempts to model the solute transport in highly heterogeneous karst aquifers. In some cases it was useful to apply the lumped-parameter models, in which the simulations were based on long-term measurements of environmental tracers or on the results of tracing with artificial tracers (Maloszewski et al., 2002; Lauber and Goldscheider, 2014; Hartmann et al., 2016). This study, however, is focused on a special

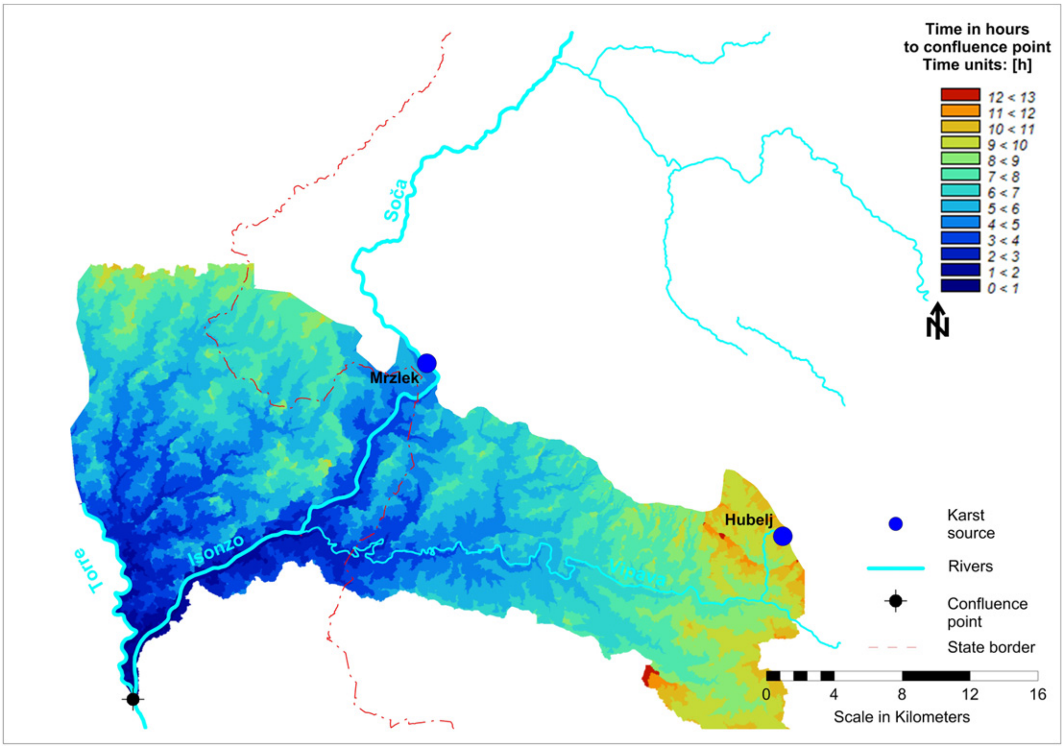

Fig. 7. A surface runoff model of the flysch and alluvial area.

situation of a worst-case scenario when the first possible appearance of the contaminant during the most favourable conditions for the fast transport is considered. In this way the effects deriving from specific contaminant properties such as retardation and degradation are not taken into account. Namely, the areas characterized by immediate infiltration, preferential conduit flows and high flow rates, do not enable significant retention of contaminants. The model enables estimation in which water sources and when contaminants can be expected to appear. Depending on the location of the contamination event this can happen as early as the next day or within a few days (from most vulnerable areas). The time defined by the model indicates the shortest possible time when the monitoring of water quality in at-risk water sources must begin and appropriate measures have to be taken. The monitoring should enable also the control of possible negative impacts of slower transport of contaminants from the least vulnerable areas (e.g. areas with significant protective layer, less permeable zones, etc.) to the source water quality. These observations are in line with some previous studies (e.g., Iqbal and Krothe, 1996; Maloszewski et al., 2002; Kogovšek and Petric, 2004; Butscher and Huggenberger, 2008; Nguyet et al., 2016).

It is also clear from the results of the model that flow through the intergranular aquifer is significantly slower. Therefore, there is more time to take appropriate action. In general, flow in such environments provide a significant contribution to the degradation of microbiological contaminants, since the retention times in the aquifer are usually longer than the lifespan of the contaminants (Harvey and Garabedian, 1991; Fourie and Van Ryneveld, 1995). The alarming findings apply above all to conservative and persistent substances that despite the aquifer's slow dynamics do not or hardly degrade. Moreover, microbiological contamination of the raw water can be treated, while there are less such possibilities to eliminate chemical contamination.

Contamination resulting in a significant deterioration of water quality in the karst water sources (the Mrzlek or the Hubelj) will not have a directly perceptible effect on alluvial water sources. Owing to the slower dynamics of the latter, a bigger threat than the danger of contamination from a one-off incident is the risk of long-term contamination accumulating in their catchment areas and gradually reducing water quality.

5. Conclusions

The joint model presented here enables the uniform treatment of a complex hydrological system. This includes a karst aquifer that feeds karst springs and, via them, water flow over less permeable rocks in the form of surface waters to an alluvial area constituting an intergranular aquifer that is in a dynamic hydraulic connection with the river. For aquifers with various porosity and a combination of groundwater and surface flow, time cell models were first elaborated separately. These were the result of numerical hydrological modelling (the intergranular aquifer and surface flow) or complex GIS analysis taking into account a vulnerability map and the results of tracer tests (the karst aquifer). The cellular models thus obtained enable a connection between the different hydrogeological units in the form of the times needed for a water particle to travel from its point of infiltration to a water source.

The resulting integrated time cell model has multiple applications. It was created as a scientific-hydrogeological basis for the establishment of a single transboundary response system for threats to drinking water sources from technological risks and natural disasters. It is set up in a GIS environment in such a way that even those who are not experts in hydrogeology can quickly and simply obtain first information on threats to drinking water sources in the event of contamination and take them into account when planning immediate action. For any selected location within the area, it is in fact possible to see immediately from the model which water abstraction points are at risk and when contaminants can first be expected to appear. The model is not limited by administrative boundaries between the two neighbouring countries but instead treats the transboundary aquifer system as an integrated whole and enables the planning of a joint response.

The results of the model, which draw attention to the major differences in water flow dynamics in different types of aquifers, also need to be taken into account when developing the basic principles of water quality monitoring. These cannot be the same for karst water sources and alluvial water sources but must rather be adapted to the characteristics of water flow dynamics in the type of aquifer from which these sources are fed. In the case of karst water sources, the very high permeability and rapid flow mean that there is a significant danger of the rapid appearance of contaminants in the case of one-off incidents, while in the case of alluvial water sources there is a danger of long-term accumulation of contaminants and a gradual deterioration of water quality as a result of the slower flow and longer retention times.

The model represents a first attempt at a holistic approach to a complex hydrological system in the area in question and further upgrading and improvements will be possible in the future. As results will be obtained from new field measurements, the quality of input data will improve, which will also improve the quality of the model. In its present form, the model is calibrated for precisely defined hydrological conditions that represent the worst-case scenario from the point of view of the risk of contamination, but it will be possible to upgrade the model so that it also takes into account the impact of changing hydrological conditions.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2017.11.017.

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