GEOLOGIJA 59/1, 85-98, Ljubljana 2016
http://dx.doi.org/10.5474/geologija.2016.006

Groundwater under strong influence of surface water – case study from Črneče (Northern Slovenia)

Podzemna voda pod močnim vplivom površinske vode – primer Črneč v severni Sloveniji

Mihael BRENČIČ[1,2] & Teja KERŠMANC[1]

[1]Department of Geology, Faculty of Natural Sciences and Engineering, University of Ljubljana, Aškerčeva cesta 12, SI–1000 Ljubljana, Slovenia; mihael.brencic@ntf.uni-lj.si
[2]Geological Survey of Slovenia, Dimičeva ulica 14, SI–1000 Ljubljana, Slovenia

Prejeto / Received 22. 6. 2016; Sprejeto / Accepted 12. 7. 2016; Objavljeno na spletu / Published online 11. 8. 2016

Key words: groundwater level maps, groundwater flow direction, hyporeic zone, floods, Drava River
Ključne besede: karte gladin podzemne vode, smer toka podzemne vode, obrežno območje, poplave, reka Drava

Abstract

The article presents an analysis of the nine-year long data set of groundwater levels measurements in the influence area of the Drava River in Črneče in the southern Koroška (Carinthia – N Slovenia). Statistical analysis of the groundwater levels fluctuations, flow rates and stages of the Drava River were performed. It is followed by analysis of the interrelation between the groundwater level observations and mutual comparison between the groundwater level and river stages. Particular emphasis is placed on the analysis of the impact of extreme flood event on 05.11.2012 on groundwater levels, which caused catastrophic flooding throughout the whole Slovenian part of the Drava River Valley. With the help of groundwater level maps it is illustrated that in the hyporeic zone of the river intensive change in the distribution of groundwater flow field is undergoing. We are dealing with both the inflow of river water in the aquifer, as the outflow of groundwater into the river, and sometimes with the flow of groundwater which is parallel to the river bank.

Izvleček

V članku prikazujemo analizo devetletnega niza podatkov meritev gladin podzemne vode na vplivnem območju reke Drave pri Črnečah na Koroškem. Podana je statistična analiza nihanja gladin podzemne vode, pretokov in pretočnih višin reke Drave. Sledi analiza medsebojnega odnosa med opazovanji podzemne vode na posameznih mestih, ter medsebojna primerjava gladin podzemne vode in pretočnih višin reke. Poseben poudarek je dan na analizi vpliva ekstremnega poplavnega dogodka dne 05.11.2012, ko je Drava poplavila po celotni dolini. S pomočjo analize kart gladin podzemne vode je prikazano, da se v obrežnem pasu reke dogajajo intenzivne spremembe njene dinamike. Opraviti imamo tako z vtokom rečne vode v vodonosnik, kot z iztokom podzemne vode v reko, ter s tokom podzemne vode, ki je vzporeden rečnemu bregu.

Introduction

Groundwater and surface waters are strongly related and very often representing boundary conditions to each other; whether groundwater is seeping into the surface stream or surface water infiltrates into the aquifer. Particularly interesting is the transition zone between both, usually referred as a bank or hyporeic zone. This zone represents important groundwater storage as well as having very important ecological role. Interactions between the groundwater and the surface water are very often studied and scientific literature about the topic is very extensive. It is a well investigated problem with the application of various methods (Kalbus et al., 2006). Results and conclusions of these studies are thoroughly summarised in various review papers (Sophocleus, 2002; Hayashi & Rosenbery, 2002).

In Slovenia, looking from regional prospective, relation between surface water and groundwater is very important. Several bigger water supply systems taping water from the aquifers are depending on the infiltrated surface water. At the same time several rivers are substantially recharged through the base flow originating from groundwater. However, in spite of the great importance of interaction between alluvial aquifers and surface waters, not many results are published. Aquifer of Ljubljansko polje is recharged through the infiltration of Sava River (Breznik, 1969; Bračič Železnik et al., 2005); the phenomena was studied by water balance methods (Andjelov et al., 2005), tracer experiments (Auersperger et al., 2005) and stable isotopes (Urbanc & Jamnik, 1998). Well known is also interaction between groundwater and surface water on Sorško polje where a phenomenon was studied by classical hydogeological methods (Žlebnik, 1975) as well as with geochemistry and stable isotopes (Urbanc & Jamnik, 2008). Infiltration of Iška River into the alluvial aquifer of Ljubljansko Barje was studied by Breznik (1975), interaction between Mura River and groundwater in the low land of Pomurje is also important (Globevnik & Mikoš, 2009) and relation between groundwater and surface water and their influence on the hydrogeological conditions in Velenje Coal Mine were thoroughly studied as well (Kanduč et al., 2010; 2014).

One of the biggest surface water courses in Slovenia is the Drava River with specific hydrological regime due to the late season melting of snow and ice in its headwaters area. Second largest Slovenian city Maribor in large part depends on the drinking water supply under the strong influence of the Drava River. To the best of the authors' knowledge the only published study in the scientific literature dealing with surface water and groundwater interaction under the influence of the Drava River in Slovenian part is a paper written by Žlebnik (1965).

In the paper as a case study relation between surface water and groundwater is represented for the area near Črneče in the northern part of Slovenia. Data of groundwater level for the analysis are coming from operational groundwater monitoring for Črneče municipal landfill which is positioned very close to the right bank of the Drava River. Groundwater level observations were performed according to the requirements enacted in Slovenian "Rules on the operational monitoring of underground water pollution" (Official Gazette RS, No. 49/2006) and are in their starting point not intended to be applicable for the observing relations between the Drava River and groundwater on its right bank. Groundwater level observations started in March 2007 with the approximate frequency of two measurements per month. At the time of paper preparation nine years of consecutive observations are available. Observations offer opportunity to study relation between groundwater in highly permeable unconfined alluvial aquifer and surface water.

For the Črneče site in the paper are presented: 1) results of groundwater level monitoring, 2) groundwater level frequency analysis, 3) representative groundwater level maps, 4) relation between river level and groundwater level, 5) relation between groundwater level and catastrophic flood event, and finally 6) interpretation and conclusions.

General settings

Geographical position

Investigated area is located in the northern Slovenia in the Drava River Valley 3 km west of the city Dravograd (Fig. 1). The groundwater monitoring network used in the study is positioned around the municipality landfill Črneče standing on the western rim of Črneško polje (Črneče field) near the village of Črneče on the right bank of the Drava River. Access to the area is through the regional road Dravograd – Libeliče.

Geomorphologicaly the Črneče site is positioned in the transition area between the flooding plain of the Drava River in the north and high river terrace in the south. Flooding plain surface is positioned at approximately 341 m a.s.l. which in this part is relatively narrow and up to 50 m wide. Flatter part of the river terrace is positioned between 366 and 372 m a.s.l. and its rim extends in the approximate direction of east-west parallel to the river. Landfill is positioned in the former gravel pit (Fig.1) where sand and gravel material was excavated from the terrace sediments (Fig. 2). Surface area of the landfill is 11,280 m². On the south hill Črneška gora (Črneče Mountain) is present which rises up to 1,061 m a.s.l. On the western edge of the landfill is small creek flowing in the direction from south to the north into the Drava River (Fig. 1). Exact discharge of the creek was not measured, but according to its recharge area mean discharges are in the order of 50 l/s. Surrounding area of the landfill is covered by the mixed forest. Wider area is mainly covered with the agricultural fields.

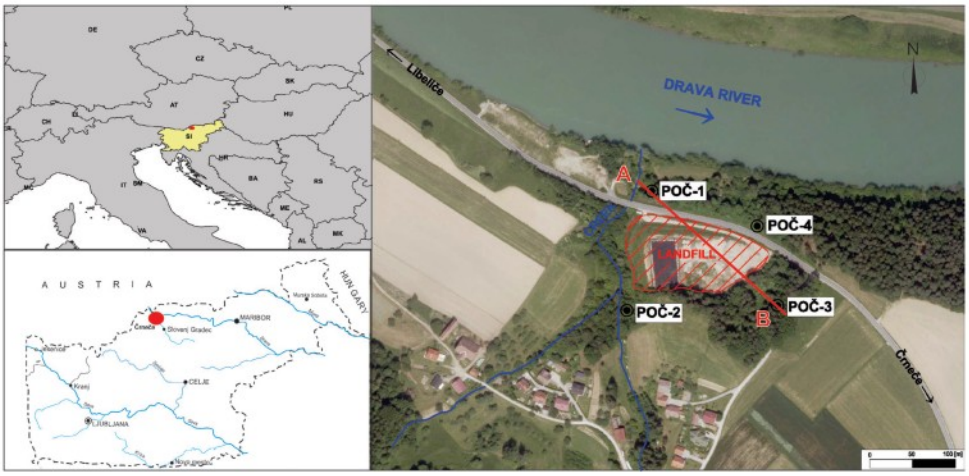


Fig. 1. Geographical position of the study site Črneče (AB – position of hydrogeological profile).

Geology of the area

Geology of the area is represented with two geological units. The bedrock consists of metamorphic rocks of Palaeozoic age above which Quaternary sediments are deposited (Fig. 2). Boreholes around the landfill reveal that in the bedrock micashist is present. According to general geologic map it consists of biotite, muscovite, quartz and plagioclase, in some parts biotite is altered by chloritisation process. It is also possible that fine to medium grained muscovite – biotite gneiss is present in the bedrock (Mioč, 1978; 1983). Bedrock surface is positioned in the interval between 332.50 and 333.00 m a.s.l. Only at the south-western corner bedrock surface is slightly higher at approximately 334.5 m a.s.l.

Basic geological map of the wider area defines four terraces (Mioč, 1978: 1983; Mioč & Žnidarčič, 1978: 1983). At the Črneče site only two terraces can be discerned; lower terrace near the Drava River and higher terrace south of the landfill. Quaternary sediments are predominantly coarse grained with some pebbles with the diameter larger than 20 cm. Sediments are poorly sorted with larger grains dispersed inside of the fine grains of sand and even sandy clay sediment. Grains consist of metamorphic and magmatic rocks with some grains of carbonate rocks. The thickness of the quaternary sediments depends on the position according to the terrace. In the western part of the investigated area the thickness of the Quaternary sediments is 11.5 m (observation borehole POČ-1, Fig. 2) but in the eastern part where surface starts to rise toward the south the depth is 27 m (observation borehole POČ-4). At the top of the terrace the thickness of Quaternary sediments is 36 m.

Groundwater monitoring network

In the groundwater monitoring network four observation boreholes are present. They are positioned in slightly deformed parallelogram around the landfill (Fig. 1) forming the inside area of 32,340 m^2. Boreholes POČ-1 and POČ-4 are positioned in the flooding plain near the Drava River. Borehole POČ-2 is positioned in the small creek valley and borehole POČ-3 is positioned on the top of the terrace.

Boreholes were made in 2005 by air-rotary drilling. They are constructed as standing open pipes equipped with PVC-U DN 100 casing used for drinking water. Filter perforation is 1 mm and no gravel pack was constructed. All boreholes were drilled 2 m deep into the bedrock where settlement tank was constructed. Observation borehole's heads are equipped with the standard type head produced by OTT Company. After completion all boreholes were cleaned with air-lift until clean water flowed out from the borehole. Boreholes are regularly cleaned by the air-lift with the frequency once per two or three years. Other technical details of observation boreholes are given in the Table 1.

Table 1. Construction data of the observation boreholes at Črneče site.

Observation borehole	Perpendicular distance from the river [m]	Altitude of observation borehole head [m a.s.l.]	Depth [m]	Interval of filters [m]
POČ-1	39	344.12	13.5	5.5 – 11.5
POČ-2	183	352.44	20.0	10.0 – 18.0
POČ-3	142	368.00	38.0	24.0 – 36.0
POČ-4	55	359.89	29.0	21.0 – 27.0

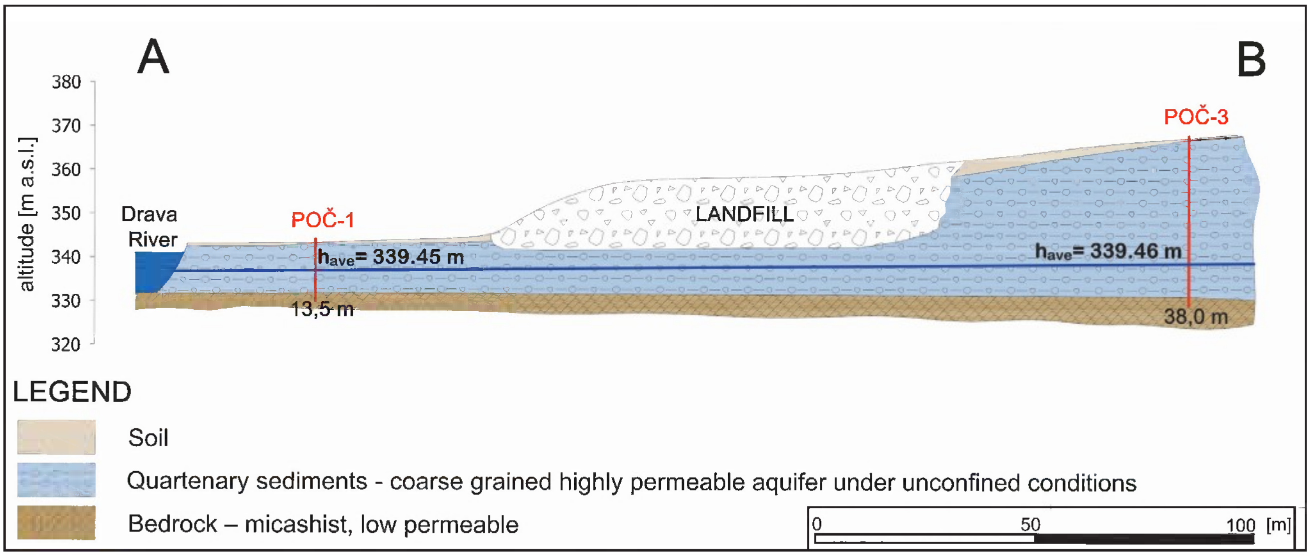


Fig. 2. Hydogeological profile (for the position see Fig. 1).

Data sets

Following data sets are available for the analysis; groundwater level observations at the Črneče landfill site, discharge level and discharge data at gauging station Črneče on the Drava River and discharge level measurements at Dravograd hydropower plant. Available data sets differ among each other in the number of available data. Not all direct comparisons between different sets can be made. Differences in the data sets are the consequence of data availability for the analysis and conditions under which gauging stations were operated in the past.

Groundwater level measurements at the landfill site Črneče started on 21.03.2007. Available data set of groundwater level measurements spans until the end of the year 2015 (last measuring date 21.12.2015). Measurements are performed with the manual groundwater dipper by the staff of Municipality Supply Company of Dravograd on nearly regular frequency of two weeks. On observation boreholes POČ-1 and POČ-2 data set consist of 210 measurements and on observation boreholes POČ-3 and POČ-4 data set consists of 208 measurements.

Environmental Agency of Slovenia - ARSO is managing discharge gauging station Črneče on the Drava River (LON 14.98870865°; LAT 46.59820803°) which is positioned on the right bank of the river in the air distance of 540 m from the landfill observation borehole POČ-1. Zero level of the gauging station (z_0) is defined at 333.765 m a.s.l. Contributing area of the gauging station is represented by the surface of 12,057 km^2 and it is positioned at the change of 432.48 km from the confluence with the Danube River. Station started operation in year 2007; however, data are only partially available (ARSO, 2016b). The gauging station Črneče is specific because it is positioned in the damming area of the hydropower plant Dravograd which is in the downstream direction in the distance of 3,750 m; consequently at some times backward flow in the river bed is present influencing the accuracy of the calculated discharges.

At the time of paper preparation two sets of data were available for the gauging station Črneče. One set of data originates from the web hydrological archive of surface waters (ARSO, 2016b); there only average daily discharges for the period 01.01.2012 to 31.12.2012 and daily average stage data from 01.01.2014 to 31.12.2014 are available. Second set of data, not available on the web page, was obtained directly from ARSO. In this set average daily discharge data for the years 2011 to 2013 are available and therefore for analysis complete data set of average daily discharges for the period from 01.01.2011 to 31.12.2014 can be used. In this data set 968 daily data are available with the data gap between 01.01.2013 to 08.05.2013. In the data set available directly from ARSO are also daily (average) stage data. They are available for the period from 10.04.2009 to 31.08.2014, altogether 1,612 data. In the record two data gaps are present; first from 27.12.2009 to 04.06.2010 and second from 05.11.2012 to 09.05.2013; the latter is the consequence of catastrophic flood event which destroyed gauging station. After the reconstruction of the gauging station zero gauging level (z_0) has changed to 333.46 m a.s.l. This happens to represent step change in the time series of stage data causing none-homogeneity of data. Additionally other step change was detected in the data between 31.12.2011 and 01.01.2012. All step changes were manually corrected to the levels similar at stable hydrological regime before the catastrophic flood event. Such manual homogenisation procedure is justified with further analyses where only relative reactions of groundwater to changes in river regime were observed.

Gauging station HE Dravograd is operated by the hydropower plant Dravograd and discharges are transferred to the data base of ARSO where they are available on the web hydrological archive of surface waters (ARSO, 2016c). The gauging station (LON 15.02349159°; LAT 46.58695904°) is positioned on the dam of the hydropower plant. Zero level of the gauging station is not defined. Catchment area of the gauging station is represented by the surface of 12,071 km^2 and it is positioned at the change of 428.82 km from the confluence with the Danube. Station started with the operation in year 1952; however discharge data are available from 01.01.1965 until 31.12.2014; altogether 18,259 data. Year 1967 was removed from our analysis due to spurious data.

Methods

Only simple methods were used for analyses. Descriptive statistics, duration curves, indicator diagrams and kriging procedures are briefly described as follows.

Descriptive statistics were calculated for analysed data sets. First quartile value is assigned with the index 25 (e.g. for groundwater level h_{25}, for the discharges Q_{25}) and third quartile with the index 75. Interquartile range IQR is defined as a difference between third and first quartile.

Duration curves are based on the ranking of values from the lowest (i=1) to the highest (i=N). Relative frequency F in % of certain observation is defined as F = 100/(N+1) where N is total number of observations. Duration represents share of total observation period with the groundwater level lower than certain value.

Groundwater level indicator diagram is represented as a scatter plot where in each axis data from one of the neighbouring observation boreholes are plotted.

Groundwater level maps were drawn with the help of kriging procedure implemented in the software Surfer 10 (GoldenSoft Inc., 2011). Results of the kriging procedure were transferred into AutoCAD MAP 3D (Auto Desk, 2014) where manually corrected surface was generated whenever it was necessary due to artificial shapes in groundwater generated by the kriging procedure.

Results and interpretation

Drava River discharges

Reliable estimates of the Drava River discharges can be made at the gauging station HE Dravograd. Exception are minimum discharges which are difficult to estimate reliably. From the data analysis follow that two periods in the record are present; first from 1965 to 1995 and second from 1995 to 2014 (Fig. 3). Such behaviour indicates strong none-homogeneity in data series. For the period 1965 to 1995 minimum monthly discharge of 71.0 m^3/s was measured on 06.02.1972; this is also minimum value for the minimum average daily discharge. For this period average minimum monthly discharge was 184.5 m^3/s. After 1995 the appearances of minimum monthly discharges changed, sharp drop in the behaviour of minimum discharges is present (Fig. 3). Until the end of the observation period 0 m^3/s discharges are reported 112 times, before that period no reports are available on zero discharges; among 228 records available during this second period zero discharges represent a share of 49 %. For the period 1995 to 2014 average minimum monthly discharge is 38.0 m^3/s and minimum average daily discharge calculated from averaged daily discharges was 58.9 m^3/s. Two possible explanations for such change in the behaviour of minimum monthly discharges are possible. First, it indicates that that discharge over the dam of hydropower plant was not present and that there was no flow in the river above the dam, therefore stage of the river was also stable. Another possibility for such behaviour is change in the gauging profile or the discharge measuring method, however this is highly unlikely.

Average daily discharge for the period 1965 – 2014 is 260 m^3/s with Q_{25} of 158 m^3/s and Q_{75} of 322 m^3/s. For the period of 1965 to 1995 average discharge is 264.1 m^3/s and for the period 1995 to 2014 average discharge is 254.3 m^3/s. Absolute record value for the maximum discharges is 2,570 m^3/s measured on 05.11.2012 when catastrophic flood happened. This discharge is much larger compared to the discharge of 1,961 m^3/s recorded on 20.08.1966. Catastrophic event of November 2012 must be regarded as separate and exceptional event discussed further in more details. If we do not consider catastrophic event of 2012 the average maximum monthly discharge in the period 1965 – 2014 is 509 m^3/s.

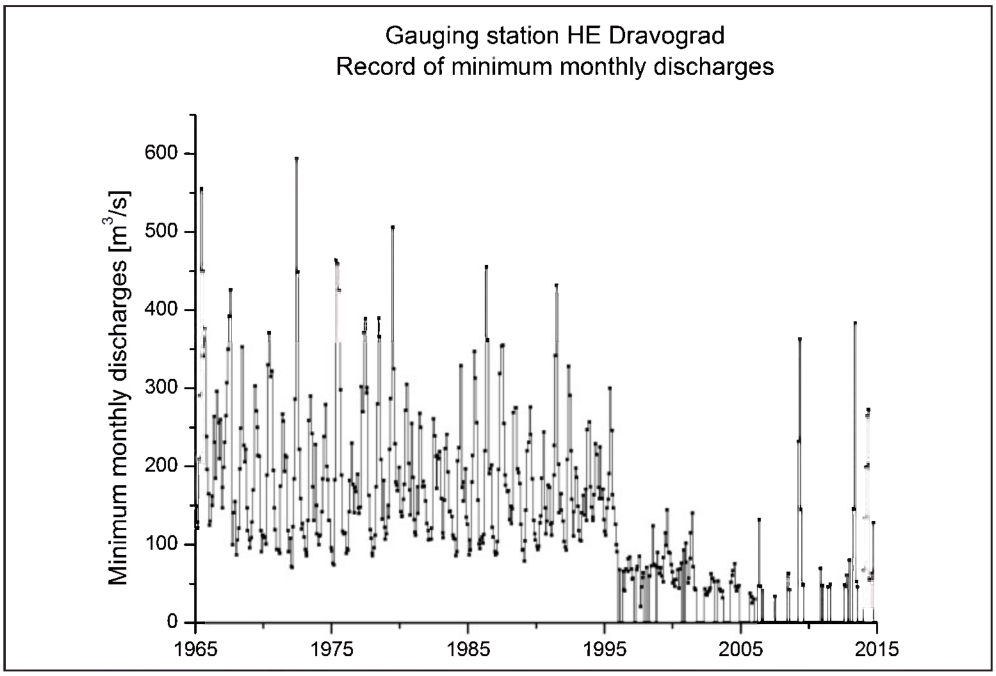


Fig. 3. Minimum monthly discharges at gauging station HE Dravograd

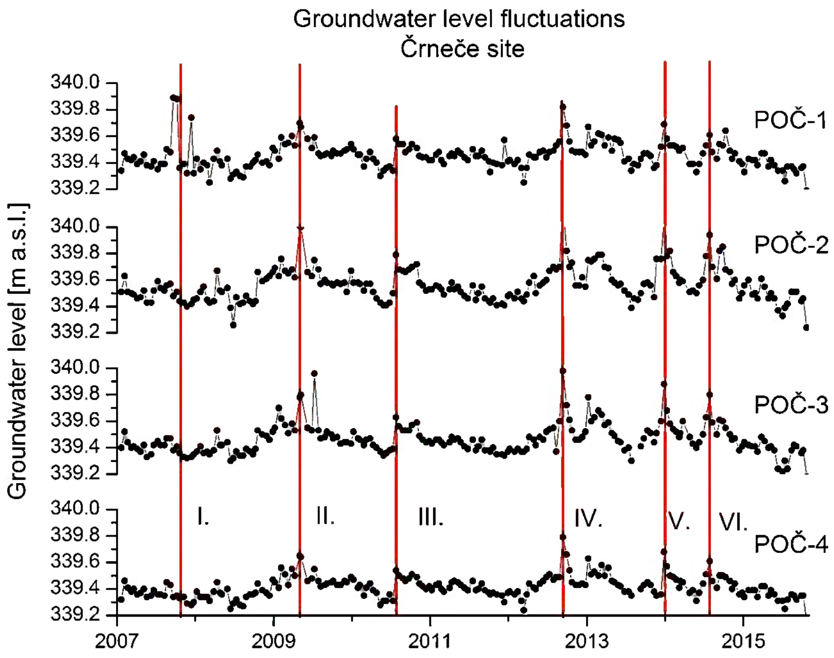


Fig. 4. Groundwater level fluctuations at Črneče site marked with significant hydrological events.

At Črneče gauging station in the period between 2011 – 2013 average daily discharge was 277.9 m^3/s, for the same period at gauging station HE Dravograd average daily discharge was 272.0 m^3/s. Comparing both gauging stations relative difference represents 0.9 % which from the accuracy point of view is negligible.

Groundwater level fluctuations

Descriptive statistics of groundwater fluctuation for the period from 2007 to the end of 2015 are given in the Table 2 and graphically time series are represented in Fig. 4. From the comparison of median and average values it follows that distribution of groundwater levels is symmetrical because values are nearly identical. Ranges are showing that amplitude of the groundwater fluctuation is rather small; the largest fluctuation is observed at the observation borehole POČ-2 which is positioned near small creek flowing to the Drava River, the smallest fluctuations are observed for the observation boreholes POČ-1 and POČ-4 which are in close vicinity of the river. Calculations of first quartile values h_{25} and third quartile values h_{75} are showing the interquartile range IQR is very small, the largest is again for the observation borehole POČ-2, but for the POČ-1 and POČ-4 observation boreholes fluctuations are also very small. This means that during the majority of the observation period 50 % of all the time, groundwater is very stable and fluctuates only for several centimetres.

Table 2. Descriptive statistics of groundwater level fluctuations

Descriptive statistics [m]	Observation boreholes			
	POČ-1	POČ-2	POČ-3	POČ-4
min	339.19	339.24	339.18	339.16
h_{25}	339.39	339.47	339.39	339.36
median	339.45	339.55	339.45	339.41
average	339.45	339.57	339.46	339.41
h_{75}	339.50	339.63	339.52	339.46
max	339.89	340.20	339.98	339.79
range	0.70	0.96	0.80	0.63
IQR	0.11	0.16	0.13	0.10

Several significant hydrological events with relatively fast rise of groundwater level can be detected from the Fig. 4 where six events are marked with vertical lines. Some of these events can not be detected in all observation boreholes. Event I. from November 2007 can be detected only in the observation borehole POČ-1. In the entire observation period for this borehole it is the highest detected groundwater level of 339.89 m a.s.l. Event II. was detected in June 2009 and event III. was detected in September 2010. The most important event detected in all observation boreholes is marked as IV. and is concomitant to catastrophic flood of November 2012. Unfortunately the measurement had been taken four days after the maximum flood stage when groundwater level was already in the declining stage. Exact flood related peak at maximum is not known. The event V. was detected in February 2014 and event VI. at the end of the year 2014.

Stable groundwater levels can be also illustrated with the duration curve. In the Fig. 5 only the duration curve for observation borehole POČ-1 is illustrated because other observation boreholes are showing similar behaviour. The

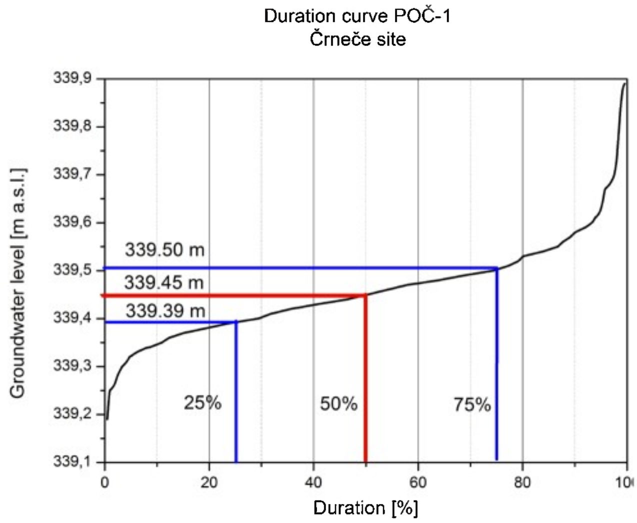


Fig. 5. Duration curve of groundwater level for observation borehole POČ-1

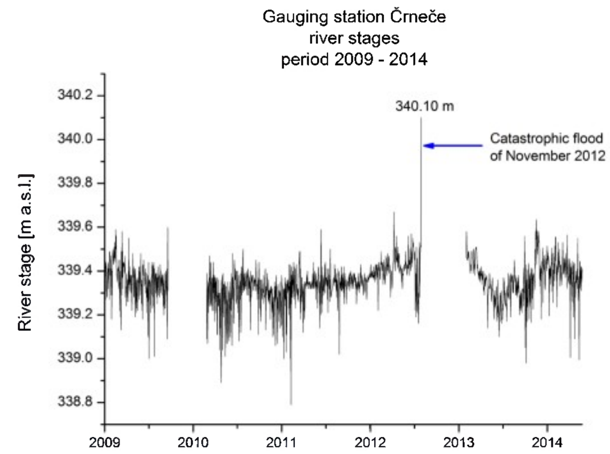


Fig. 6. River stages at Črneče gauging station

duration curve has a profound S shape illustrating that events at both extremes are very rare; low and high values are appearing only occasionally.

River stages fluctuations

Fluctuations of river stages at the gauging station Črneče for the period from 10.04.2009 to 31.08.2014 are illustrated on the Fig. 6. Maximum stage of 340.10 m a.s.l. was recorded on 05.11.2012 as a consequence of the catastrophic flood. After this event station was not in the operation until May 2013. Minimum stage of 338.79 m a.s.l. was recorded on 18.05.2011. Total difference between maximum and minimum stage is only 1.21 m. In the rest of the diagram rather fast fluctuations, short drops or short rises can be observed. Such behaviour is illustration of the river level damming at hydropower plant Dravograd, showing that stage is relatively constant and at the same time changes in the stage are fast. Amplitudes of fluctuations are changing rather fast but usually they are not exceeding 0.4 m.

Groundwater level indicator diagrams

For detection of groundwater level dynamics four groundwater level indicator diagrams were drawn on the Fig. 7; three diagrams are representing comparison with the groundwater levels in the borehole POČ-1 and the fourth represents comparison between groundwater levels between observation boreholes POČ-4 and POČ-3. In all diagrams line 1:1 is drawn.

In the Fig. 7A comparison between POČ- 1 and POČ-2 is represented. Borehole POČ-1 is positioned near the Drava River and observation borehole POČ-2 is positioned in the creek valley near the rim of the upper terrace. In the diagram nearly all data points are positioned above the line 1:1 indicating that groundwater level in the borehole POČ-2 in majority of cases is higher than in the borehole POČ-1, therefore it can be interpreted as an observation borehole which is positioned in upstream position. Only some small number of points are positioned below the 1:1 line indicating that groundwater levels at those observation times in borehole POČ-1 were higher. According to the position of this borehole such high groundwater levels can be only the consequence of the Drava River higher stages. Some data points in the upper part of the diagram are showing that in the observation borehole POČ-2 groundwater is much higher than in the borehole POČ-1 which is the consequence of the relatively fast inflow of the groundwater from the background of the borehole POČ-2 and also infiltration of the creek water into the aquifer.

In the diagram of Fig. 7B comparison between observation boreholes POČ-1 and POČ-3 is shown. Observation borehole POČ-3 is positioned on the top of the terrace. Data points in majority are positioned around 1:1 line indicating that groundwater level relation between boreholes is changing; sometimes groundwater level in the borehole POČ-1 is higher than in the borehole POČ-3 and reverse. Some data points are positioned out of the line 1:1; those well below the line 1:1 are indicating flooding water intruding from the Drava River and those above the line 1:1 are indicating water coming from the southern hinterland of the terrace.

In the diagram of Fig. 7C relations between groundwater levels in the observation boreholes POČ-1 and POČ-4 are shown. Both boreholes are positioned bellow the terrace and are very close to the Drava River. Therefore, it is interesting that nearly all the data points are positioned below line 1:1 showing groundwater levels in POČ-4 are slightly lower than in the POČ-

1 which indicates that the later is positioned in the upstream position. Again in the lower right part of the diagram some data points are indicating direct influence of the Drava River on observation borehole POČ-1 but at the same time this influence is not detected in the borehole POČ-4.

On the diagram of Fig. 7D comparison between observation boreholes POČ-4 and POČ-3 is shown. Both boreholes are forming profile which is perpendicular to the Drava River. Nearly all data points are positioned above the line 1:1 indicating that in majority nearly all observations in observation borehole POČ-3 are higher than in the observation borehole POČ-4 showing POČ-3 is in the upstream direction. Only few observation data are positioned bellow the line 1:1. They are measured at relatively low water conditions indicating when groundwater level in the aquifer is at very low level river water penetrate much further in the aquifer.

Relation between groundwater level and river stage

For the comparison between the Drava River stages and groundwater level observation borehole POČ-1 was chosen (Fig. 8). POČ-1 observation borehole is taken because it is the closest observation borehole to the river. Reported the Drava River stages from the ARSO data base (ARSO, 2016b) were slightly shifted for 0.1 m higher to have direct comparison between groundwater level and stages. The shift was estimated on the comparison between average levels and stages. In the diagram with vertical lines are indicated important hydrological events (see Fig. 4).

From the diagram in Fig. 8 follows that groundwater levels and stage levels are related. But relation between groundwater levels and river stages is not straightforward; there is no direct correlation which indicates that groundwater level in the borehole POČ-1 is the only consequence of

Groundwater level indicator diagrams

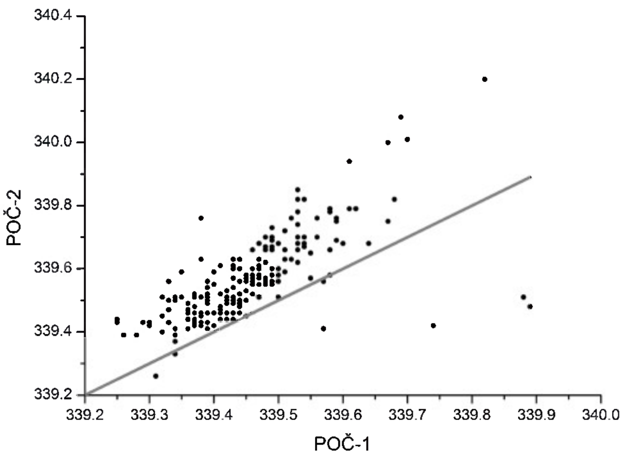


Fig. 7A. Relation between observations in boreholes POČ-1 and POČ-2.

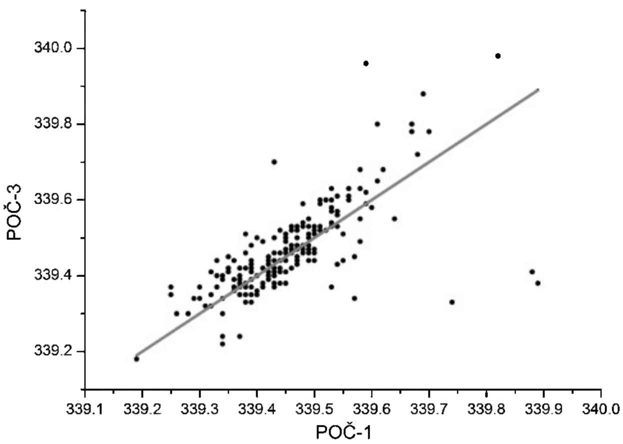


Fig. 7B. Relation between observations in boreholes POČ-1 and POČ-3.

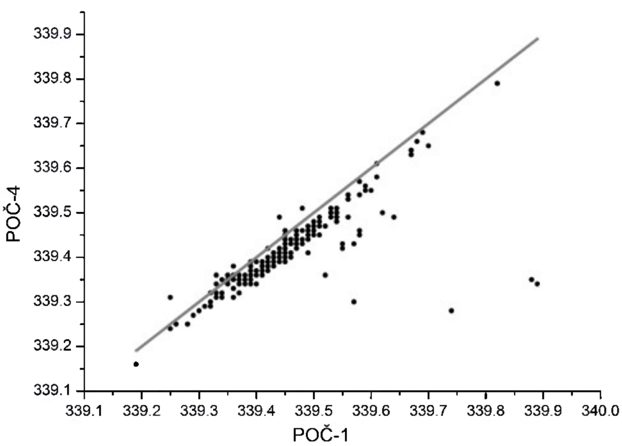


Fig. 7C. Relation between observations in boreholes POČ-1 and POČ-4.

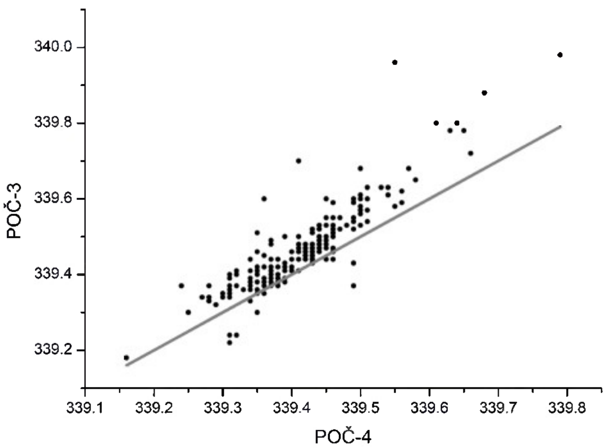


Fig. 7D. Relation between observations in boreholes POČ-4 and POČ-3.

the Drava River stages and fluctuation. There is indication that sometimes the Drava River stage is higher than groundwater level and reverse and there is practically no direct equilibrium with the same levels and stages. Lowering of the stages in the river causes lowering in the groundwater level and rising stages in the river is causing rising in the groundwater levels. Diagram also indicates that changes in the groundwater levels in the aquifer are slower than in the changes of the river stages; influences of the river are damped. Changes in the river stages in the sense of lowering and rising are too fast to be reflected fully in the groundwater levels. Groundwater level in the borehole POČ-1 is also influenced also by the inflow from the south. Among detected hydrological events (see also Fig. 4) all events are caused by higher river stages. For the event V. river stage data are not available.

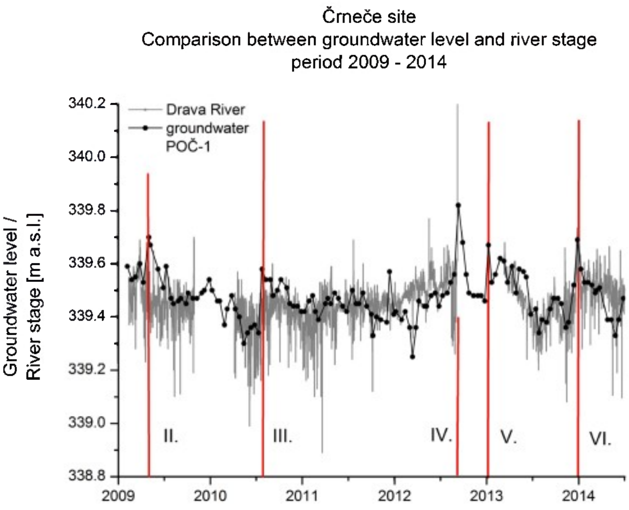


Fig. 8. Comparison between groundwater level in observation borehole POČ-1 and river stages at gauging station Črneče.

Catastrophic flood event in November 2012

During the observation period in November 2012 an exceptional flood event occurred. On 05.11.2012 discharge record values at Dravograd were reached. High flood wave caused damage of the gauging station Črneče which stopped working. According to the data set for gauging station HE Dravograd available at hydrological archive (ARSO, 2016c) record discharge was 2570 m^3/s but later analyses reveal somehow different estimates. According to Kobold (2013) and Kobold and co-workers (2013) discharges were higher than 2,600 m^3/s, Anzeljc & Kobold (2013) estimated discharge at gauging station Črneče on 2,669 m^3/s. Estimated return period was around 100 years. Such discharge was the consequence of the heavy rainfall from 04.11.2012 and 05.11.2012 falling on the snow which started to thaw. The discharges at gauging station started to rise fast in the morning at 3 a.m 05.11.2012 and reached their peak between 12 and 15 p.m. of the same day. Record discharge caused severe flooding in the down-stream direction along the valley and several settlements were severely damaged. High flood peak and sharp discharge rises were the consequence of improper emptying of the hydropower plant reservoirs in the upstream direction in Austria (Anzeljc & Kobold, 2013). By analysis it was also estimated how the discharges will behave if there will be no intervention with fast emptying of reservoirs behind the dams in Austria. Discharge will be in the interval between 1,790 and 1,980 m^3/s with the return period of around 20 years and the peak arrival to the site between 14 and 21 a.m. on 05.11.2012. (Anzeljc & Kobold, 2013).

Detailed diagram of the November 2012 event is illustrated in the Fig. 9. Due to the malfunction of the gauging station it is not known if the area around observation boreholes POČ-1 and POČ- 4 during the event was flooded. Unfortunately, groundwater level measurements were performed only 4 days after the flood peak and the exact level of groundwater during the flooding is not known. From the diagram (Fig. 9) follows that flood influenced groundwater levels but these influences quickly fade out. High groundwater levels probably last only few days after flood event.

We suppose that groundwater monitoring data from November 2012 until January 2015 are representing drainage of the aquifer. At the same time we conceptually assume that aquifer is linear reservoir where the draining curve can be described by the exponential equation. If we extrapolate this curve groundwater level at the peak of the flood

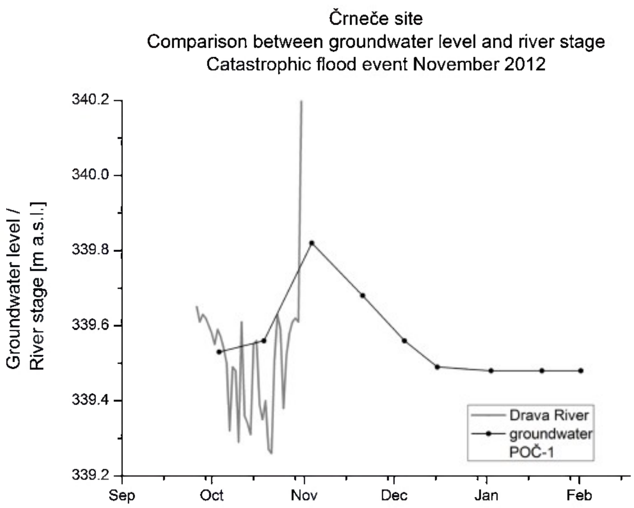
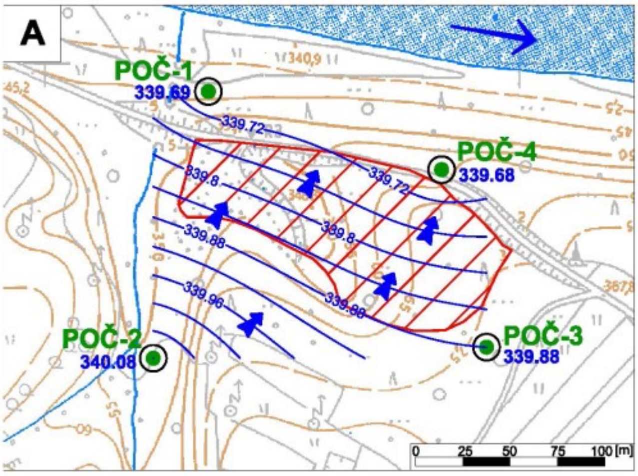


Fig. 9. Comparison between groundwater level in observation borehole POČ-1 and river stages at gauging station Črneče during flood event in November 2012.

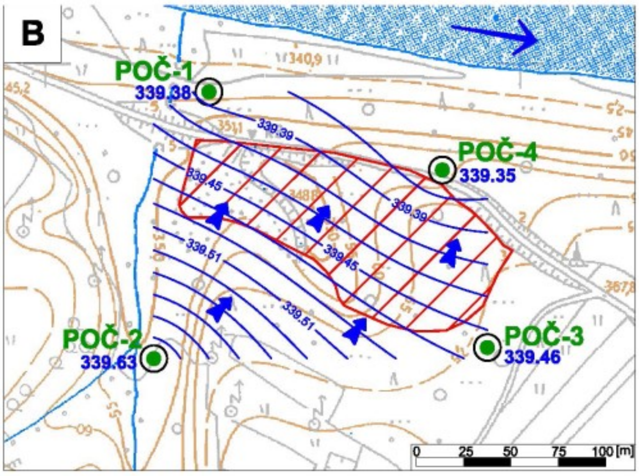
event can be estimated. The value obtained with extrapolation is 339.85 m a.s.l. which is surprisingly low. We can question extrapolation procedure but it somehow shows that if the flood event was relatively short it has no profound influences on the groundwater levels; the flood has influence on the groundwater but consequent rise of groundwater level was not substantial.

Groundwater level maps

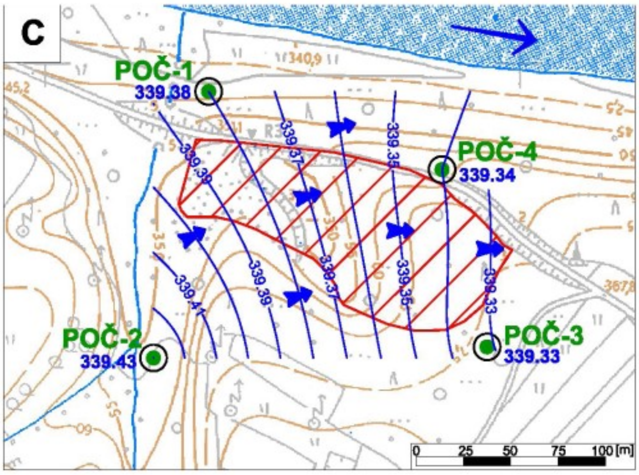
Based on the groundwater level observation it is possible to reconstruct the groundwater level maps. In spite of the fact that groundwater fluctuation in the observation boreholes is not exceeding 1.0 m dynamics of groundwater is diverse and several realisations of groundwater surface were detected.



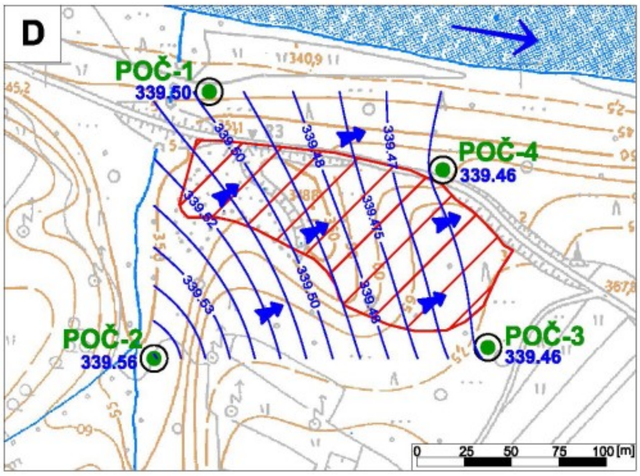
Groundwater level map of the typical high level conditions - 24.02.2014



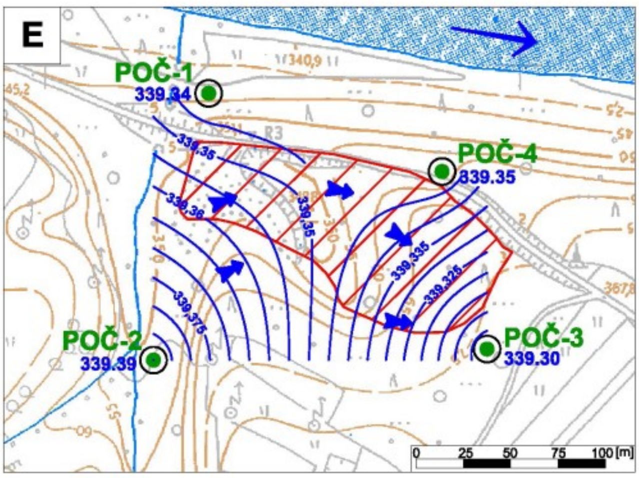
Groundwater level map of the typical low level conditions - 09.02.2009



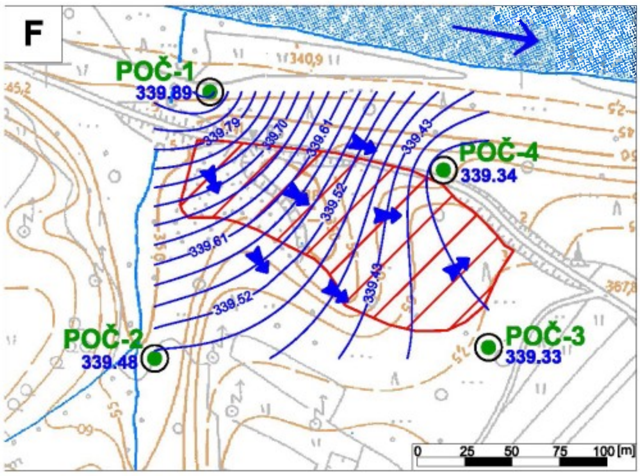
Groundwater level map as a result of water infiltration from the creek and river at high stage 19.07.2007



Groundwater level map as a result of water infiltration from the creek and low river stage 16.09.2011



Groundwater level map as a result of water infiltration from the creek and river when creek is at low water conditions 25.09.2013



Groundwater level map of the strong river influence - 19.11.2007

Fig. 10. Groundwater level maps at different hydrological conditions.

For the understanding of the groundwater surface shape at the Črneče site it is important to recognise boundary conditions. In the northern part the Drava River is present and small creek flowing from the south to the river represents western boundary. Due to the altitude which rises to the south and terrace sediments, it is expected that from there gravity induced recharge is present. To the east boundary is open and some hundreds meters away possible boundaries are not known to us. Typical and the most interesting reconstructed situations are represented on the Figs. 10 A – F.

In Figs. 10A and 10B most frequent situations of groundwater level are present. In the Fig. 10A situation at high groundwater level conditions is present and in Fig. 10B at low water conditions. In both cases groundwater is flowing from the south to the north recharging the Drava River. From the boundary conditions in the west of the map it is evident that water from the creek is infiltrating into the aquifer stabilising groundwater level at that part. At higher groundwater level (Fig. 10A) hydraulic gradient is slightly higher (2.7×10^{-3}) comparing to lower groundwater level represented in the Fig. 10B (1.7×10^{-3}).

Situations represented in Figs. 10C and 10D are showing conditions where groundwater level is at the same time under the influence of water infiltrating from the creek and water infiltrating from the Drava River. Groundwater flow direction is deflected more to the east direction comparing to predominant flow directions shown previously on Figs 10A and 10B. The deflection from this direction depends on the intrusion of water from the Drava River; if the river is at higher stage more water is flowing into the aquifer from the riverbed, and if river stage is lower less water is infiltrating from the riverbed. At the situation on Fig. 10C there is more influence from the Drava River than in the case represented on the Fig. 10D.

Last two situations shown on Figs. 10E and 10F are very rare, they happened only few times. In the Fig. 10E situation is represented where strong groundwater flow parallel to the bank of the Drava River is present. Groundwater is flowing transversally from observation borehole POČ-1 towards POČ-3 and at the same time infiltration of surface water from the creek is present.

Last situation presented in the Fig. 10F is also very rare. It represents sudden intrusion of river water into the aquifer. In observation borehole POČ-1 groundwater is rather high and in other boreholes low and consequently from northwest corner river water is dispersing into the aquifer. These data are indicating that river infiltrates into the aquifer and flows in the direction NW-SE from observation borehole POČ-1 to POČ-4 and POČ-3. Such behaviour of groundwater flow was detected also with the indicator diagram on Fig. 7D. No data are available about the presence of water in the creek at the time of map 10F, but the creek was probably dry or at very low water conditions and no infiltration was present from its bed allowing river to intrude further into the aquifer.

Interpretation of groundwater dynamics

Groundwater flow field in the aquifer on the right bank of the Drava River at the Črneče site is the consequence of the interrelation between infiltrating water from the river and inflow of groundwater from the southern hinterland. Three main flow directions are present; first is inflow from the Drava River, second is infiltration of water from the creek and third is inflow of groundwater from the south. Groundwater level maps are showing that infiltration from the creek bed is influencing groundwater level on the west. If stage of the river is low than groundwater flow direction is parallel to the creek bed and it has direction from the south to the north. If stage of the river water is higher, than groundwater on the northern part, near the bank, falls under the influence of the river which intrudes into the aquifer. Inflow of the river water into the aquifer is dependant on the relative position between the river stage and groundwater level. If this difference is small than infiltrating river water pushes groundwater incoming from the south to the east direction and groundwater infiltrating river water is flowing parallel to the river bank. If the river stage becomes much higher water from the river is infiltrating further into the aquifer.

The Drava River is damming the groundwater and this is, together with relatively high permeability of the aquifer and its unconfined conditions, the main cause why relatively low groundwater hydraulic gradients are present at all events. In spite of the low hydraulic gradients, strong changes in the groundwater flow directions are present and changes are such that nearly all directions of flow are possible. Predominant groundwater flow is from the south to the north; very often groundwater flow parallel to the river bank from west to east direction is present. Sometimes on rare occasions fast intrusion of river water into the aquifer happens and in this case water from the river penetrates farer into the aquifer, first flowing from north to south and later from northwest to southeast.

Conclusions

Detailed study of the groundwater level fluctuations near the bank of the Drava River shows that in spite of the fact that high resolution data of groundwater level and river stages are not available, many important characteristics of groundwater fluctuation in the bank zone can be discerned. Groundwater flow in the area under the influence of the river must be observed and interpreted in three dimensions. We have illustrated that groundwater flow is changing due to the conditions not only in the river but also in the recharge area outside of the river influences. On the combination of all conditions at the aquifer boundaries depends what groundwater surface will form and to which direction groundwater will flow.

In the future Črneče site can represent useful polygon for further research on the interrelation and interdependencies between surface water and groundwater. As we have shown groundwater flow in the influence area on the rivers' bank must be observed from the spatial and three dimensional points of view. It remains open how equipotential lines inside of the aquifer are distributed under the river stage and groundwater inflow changing conditions. This can be solved only with the help of three dimensional numerical models. Understanding of the processes can be also improved by the introduction of continuous measurements of groundwater level fluctuations as well as river stages fluctuations gaining more detailed information on changes. Further insights can also be possible with the help of geochemical studies. Available data based on the chemical status of groundwater and sampling of stable isotopes during different hydrological events can be very helpful.

Acknowledgement

Municipality Supply Company of Dravograd (Javno komunalno podjetje Dravograd d.o.o.) is greatly acknowledged for allowing us to use their data. Hermina Ivanuša Šket from National Laboratory for Health Environment and Food from Maribor is acknowledged for the long and fruitful cooperation on the monitoring projects. Dr. Mira Kobold and staff of the Department for hydrological analyses and prognoses, ARSO (Sektor za analize in prognoze površinskih voda, ARSO) are acknowledged for making data of Črneče and HE Dravograd gauging stations available. The paper is part of the activities guided under the research program "Groundwater and geochemistry" (P1-0020) of Geological Survey of Slovenia financially supported by Slovenian Research Agency. The paper has been prepared by the senior author during his stay supported by CEEPUS scholarship in summer 2016 at Department of Applied Geology, Eötvös Loránd University, Budapest (HU).

References

Andjelov, M., Bat, M., Frantar, P., Mikulič, Z., Savič, V. & Uhan, J. 2005: Pregled elementov vodne bilance = Overview of water balance elements – in Slovenian. In: Rejec Brancelj, I., Smrekar, A. & Kladnik, D. (eds.): Podtalnica Ljubljanskega polja, 27–38.

Anzeljc, V. & Kobold, M. 2013: Hidrološka analiza poplavnega dogodka na Dravi 5.11.2012 = Hydrological analysis of the Drava flood event on 5.11.2012 – in Slovenian. In: Juvan, S. (ed.): 24. Mišičev vodarski dan, 12–23, http://mvd20.com/LETO2013/R2.pdf.

Auersperger, P., Čenčur Curk, B., Jamnik, B., Janža, M., Kus, J., Prestor, J. & Urbanc, J. 2005: Dinamika podzemne vode = Grounwater dynamics – in Slovenian. In: Rejec Brancelj, I., Smrekar, A., Kladnik, D. (eds.): Podtalnica Ljubljanskega polja: 39–61.

ARSO, 2016a: Spisek vodomernih postaj (List of gauging stations – in Slovenian). www.arso.gov.si/vode/podatki/arhiv/spisek_postaj.xls (last access 10.06.2016).

ARSO, 2016b: Gauging station Črneče. http://vode.arso.gov.si/hidarhiv/pov_arhiv_tab.php?p_vodotok=Drava&p_postaja=2005 (last access 10.06.2016).

ARSO, 2016c: Gauging station HE Dravograd. http://vode.arso.gov.si/hidarhiv/pov_arhiv_tab.php?p_vodotok=Drava&p_postaja=2010 (last access 10.06.2016).

Auto Desk, 2014: AutoCAD MAP 3D. Relase 14. California.

Bračič Železnik, B., Pintar, M. & Urbanc, J. 2005: Naravne razmere vodonosnika = Natural conditions in the aquifer – in Slovenian. In: Rejec Brancelj, I., Smrekar, A. & Kladnik, D. (eds.): Podtalnica Ljubljanskega polja: 13–26.

Breznik, M. 1969: Podtalnica Ljubljanskega polja in možnosti njenega povečenega izkoriščanja = Ground water of the Ljubljana polje and possibilites of increasing its exploration – in Slovenian. Geologija, 12: 165–184.

Breznik, M. 1975: Podtalnica Iškega vršaja = The groundwater of the alluvial fan of Iška River – in Slovenian. Geologija, 18: 289–309.

GoldenSoft Inc. 2011: Surfer. Relase 10. Colorado.

Globevnik, L. & Mikoš, M. 2009: Boundary conditions of morphodynamic processes in the Mura River in Slovenia. Catena, 79/3: 265–276, doi:10.1016/j.catena.2009.06.008.

Hayashi, M. & Rosenberry, D.O. 2002: Efect of groundwater exchange on the hydrology and ecology of surface water. Ground Water, 40/3: 309–316, doi:10.1111/j.1745-6584.2002.tb02659.x.

Kalbus, E., Reinstorf, F. & Schirmer, M. 2006: Measuring methods for groundwater-surface water interactions: a review. Hydrol. Earth Syst. Sci., 10: 873–887, doi:10.5194/hessd-3-1809-2006.

Kanduč, T., Jamnikar, S. & Mcintosh, J. 2010: Geochemical characteristics of surface waters and groundwaters in the Velenje

Basin. Geologija, 53/1: 37–46, doi:10.5474/geologija.2010.003.

Kanduč, T., Grassa, F., Mcintosh, J., Stibilj, V., Ulrich-Supovec, M., Supovec, I. & Jamnikar, S. 2014: A geochemical and stable isotope investigation of groundwater/surface-water interactions in the Velenje Basin, Slovenia. Hydrogeol. J., 22/4: 971–984, doi:10.1007/s10040-014-1103-7.

Kobold, M. 2013: Poplave konec oktobra in v začetku novembra 2012 = Floods at the end of October and begining of November 2012 – in Slovenian. Ujma, 27: 44–51.

Kobold, M., Polajnar, J., Pogačnik, N., Petan, S., Lalić, B., Šupek, M., Strojan, I. & Jeromel, M. 2013: Poplave v oktobru in povodenj v novembru 2012 = Floods in October and catastrophic flood in November 2012 – in Slovenian. In: Juvan, S. (ed.): 24. Mišičev vodarski dan: 1-11. http://www.mvd20.com/LETO2013/R1.pdf.

Mioč, P. 1978: Osnovna geološka karta SFRJ 1:100.000 L 33-55. Tolmač lista Slovenj Gradec = Basic geological map of SFRY 1:100.000 L 33-55; guide book of sheet Slovenj Gradec – in Slovenian. Zvezni geološki zavod, Beograd.

Mioč, P. 1983: Osnovna geološka karta L 33-54. Tolmač lista Ravne na Koroškem = Basic geological map of SFRY 1:100.000 L 33-54; guide book of sheet Ravne na Koroškem – in Slovenian. Zvezni geološki zavod, Beograd: 68 p.

Mioč, P. & Žnidarčič, M. 1978: Osnovna geološka karta SFRJ 1:100.000 L 33-55 (list Slovenj Gradec) = Basic geological map of SFRY 1:100.000 L 33-55; sheet Slovenj Gradec – in Slovenian. Zvezni geološki zavod, Beograd: 74 p.

Mioč, P. & Žnidarčič, M. 1983: Osnovna geološka karta 1:100.000 L 33-54 (list Ravne na Koroškem) = Basic geological map of SFRY 1:100.000 L 33-55; sheet Ravne na Koroškem– in Slovenian. Zvezni geološki zavod, Beograd.

Sophocleous, M. 2002: Interactions between groundwater and surface water: the state of the science. Hydrogeol. J., 10/2: 348–348, doi:10.1007/s10040-002-0204-x.

Urbanc, J., & Jamnik, B. 1998: Izotopske raziskave podzemne vode Ljubljanskega polja = Isotope investigations of groundwater from Ljubljansko polje (Slovenia). Geologija, 41: 355–364, doi:10.5474/geologija.1998.018.

Urbanc, J. & Jamnik, B. 2008: Hidrokemijske in izotopske raziskave podzemne vode na Sorškem polju = Hydrochemical and isotope groundwater investigations in Sorško polje – in Slovenian. Geologija, 51/1: 71–76, doi:10.5474/geologija.2008.008.

Žlebnik, L. 1965: Hidrogeološki problemi v zvezi z epigenetsko dolino Drave v Mariboru = Hydrogeologic problems connected with epigenetic valley of the Drava River at Maribor town – in Slovenian. Geologija, 8: 320–328.

Žlebnik, L. 1975: Hidrogeološke razmere na Sorškem polju = Hydrogeologic features of the Sora filed – in Slovenian. Geologija, 18: 259–288.