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The quantitative status of groundwater in alluvial aquifers in norther Croatia

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ABSTRACT

The quantity and spatial distribution of groundwater in Croatia is determined by geological composition, climate and hydrological conditions and the hydrogeological characteristics of individual areas. Northern Croatia is part of the southern margin of the Pannonian basin and is dominated by the spacious lowlands of the Sava and Drava rivers, where aquifers of intergranular porosity of Pleistocene and Holocene ages were formed. The lithological composition of the aquifers is dominated by gravel and sand in the western parts of the Drava and Sava basins. Sandy aquifers are prevalent in the central and eastern parts. Groundwater accumulated in these aquifers is the basis of the water supply in northern Croatia, which is the reason why monitoring of its status, both quantitative and qualitative is exceptionally important. Data obtained by long-term monitoring of groundwater levels facilitated assessment of the quantitative status of groundwater. To determine the causes of changes in the hydrodynamic conditions of the aquifers, results of long-term monitoring of precipitation and stages of the Drava and Sava rivers were also used. Linear regression was used to analyse changes in groundwater levels, the Drava and Sava river stages and precipitation quantities. The results generally show that there is a negative groundwater level trend over almost the entire area of the Drava and Sava alluvial aquifer. This is a consequence of deepening of the Drava and Sava river beds and lowering of their stages, together with a decreasing trend of total annual precipitation.

Keywords: monitoring, groundwater level trend, stages of the Drava and Sava rivers, precipitation

1. INTRODUCTION

The EU Water Framework Directive (WFD, 2000/60/EC) stipulates determination of the quantitative status of groundwater, the basic indicator of which is groundwater levels. According to the Directive, good quantitative status is assigned to groundwater bodies or groups of groundwater bodies where, despite long-term water abstraction in an area, there is no lowering of groundwater levels. Groundwater exploitation does not disturb the sustainability of terrestrial and aquatic ecosystems depending on groundwater, while enabling a long-term water supply to the population (Fig. 1). Therefore, renewable groundwater resources within one or more groundwater bodies contain groundwater which can be exploited (available groundwater resources) for different purposes (water supply, irrigation), as well as the groundwater resources necessary for sustainability of ecosystems (groundwater inviolable flow). Good quantitative status is assigned to such a groundwater body within which the groundwater abstraction quantity is less than or equal to the resources available for exploitation.

The good quantitative status of groundwater is strongly related to the assessment of safe yield - the term that has been

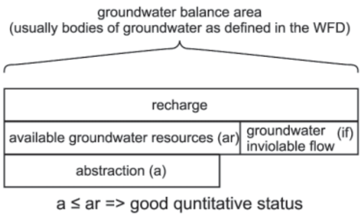

Figure 1: Good quantitative status of groundwater according to the understanding of Water Framework Directive (according to REJMAN, 2007).

used in hydrogeological practice for years. It can be assessed for an aquifer or part of an aquifer at different scales, i.e. for abstraction sites, particular groundwater bodies or entire basins. In literature published in English, there are several synonyms used in connection with sustainable groundwater management, e.g. safe yield, sustainable yield and renewable yield. Although many professionals use them readily, there is still ambiguity regarding their exact meaning and what they actually represent (ALLEY & LEAKE, 2004; KALF & WOOLLEY, 2005). While this provides an ongoing discussion, it is important to understand that safe yield not only takes into account mass balance assessment, but also other constraints e.g. ecological, socio-economic and groundwater quality requirements.

Alluvial aquifers in northern Croatia are the primary source of water supply in this area, so knowledge of their quantitative status is important, both to this region and for the Republic of Croatia as a whole. These aquifers are recharged by infiltration of precipitation and water from surface flows. Within the investigation, trend analyses of groundwater levels, the Sava and Drava river water levels, and precipitation quantities were carried out by linear regression. Finally, groundwater exploitation quantities were compared to figures for renewable groundwater resources. The primary objective of this study was to assess the quantitative status of groundwater pursuant to the requirements of the EU Water Framework Directive.

2. GEOLOGICAL AND HYDROGEOLOGICAL SETTING

The spatial distribution and lithological composition of the Quaternary alluvial aquifers in the Drava and Sava lowland is significantly different (Fig. 2).

The Drava Quaternary aquifer gradually deepens from the west towards the east. In the Drava basin, sediments were mainly transported by the Drava River, although the influence of transport from the northern and southern areas cannot be neglected. Due to the ever-decreasing longitudinal fall of the Drava from the west to the east, the average size of sedimentary gravel and sand particles also gradually decreases in this direction. In the western part of the Drava basin, sand was deposited with gravel. In the central part, there is both lateral and vertical separation in the deposits of gravel and sand, while from Virovitica downstream, medium to fine-grained uniform sand dominates the aquifer. Distinct sand layers are also located within gravel layers in the western area, indicating occasional energy decreases in the water flow. However, the full lithological cross section of the Drava aquifer generally shows an even distribution of unconsolidated sediments, from the largest particle sizes in the west to the smallest in the easternmost parts of the basin (URUMOVIĆ et al., 1994).

The lateral extent of the Quaternary aquifer in the Sava basin is significantly less developed than in the Drava basin (Fig. 2). There are numerous local lowered and elevated tectonic structures along the Sava River basin with the resulting local increase or decrease in aquifer thickness. In the western part of the Sava basin, the aquifer mostly consists of gravel with sand. Downstream of Sisak, there is marked heterogeneity in the Quaternary deposits largely corresponding to the asymmetry of the Sava basin. Here, the Sava's right tributaries (the Una, Vrbas, Ukrina and Bosna rivers) play an important role, both in terms of the size of discharge and the process of sedimentation of coarse-grained clastic sediment. In Croatia, the gravelly-sandy sediment of the Sava's right tributaries belongs to the distal fan deposits which have been deposited by these rivers. The majority of the gravelly deposits of the Vrbas, Ukrina and Bosna rivers are located in Bosnia-Herzegovina. Between these gravelly-sandy fan deposits and the faults which separate the Sava basin from Moslavačka Gora Mountain and the Slavonian range, the Quaternary alluvial aquifer is poorly developed (Fig. 2). In this area, there are deep subartesian and artesian aquifers of Pliocene and Early Pleistocene age.

Alluvial aquifers in northern Croatia are mostly covered with semi-permeable silty-clayey deposits (aquitard). In the westernmost parts of both lowlands, aquitard thickness is generally low (< 1m) and in many places there is no cover at all or only soil is present. Further downstream, the thickness generally increases attaining up to 50−70 m in the easternmost parts (Fig. 3).

Groundwater levels in alluvial aquifers in northern Croatia have been monitored for a long period of time. National monitoring and data collection is carried out by the State Meteorological and Hydrological Service. In addition, groundwater levels are also monitored in the catchments areas of public water supply abstraction sites. The monitoring network includes many piezometers installed for different purposes mostly between 1950 and 1990. In the Drava aquifer area, most piezometers are located in the western areas and were installed for purpose of design and monitoring of hydropower plant operation (Fig. 3). Downstream of Virovitica, monitoring of groundwater levels is generally carried out by relatively shallow piezometers, which tap more permeable deposits within the aquitard, as observed by MILETIĆ et al. (1971).

In the alluvial aquifer in the Sava river valley, more comprehensive monitoring of groundwater levels is only carried out in the greater Zagreb area, and even here, the piezometer network was mostly developed for the planned hydropower plants. However, there is also a groundwater level monitoring network in the Zagreb area developed in the catchment areas of the major pumping sites. The majority of piezom-

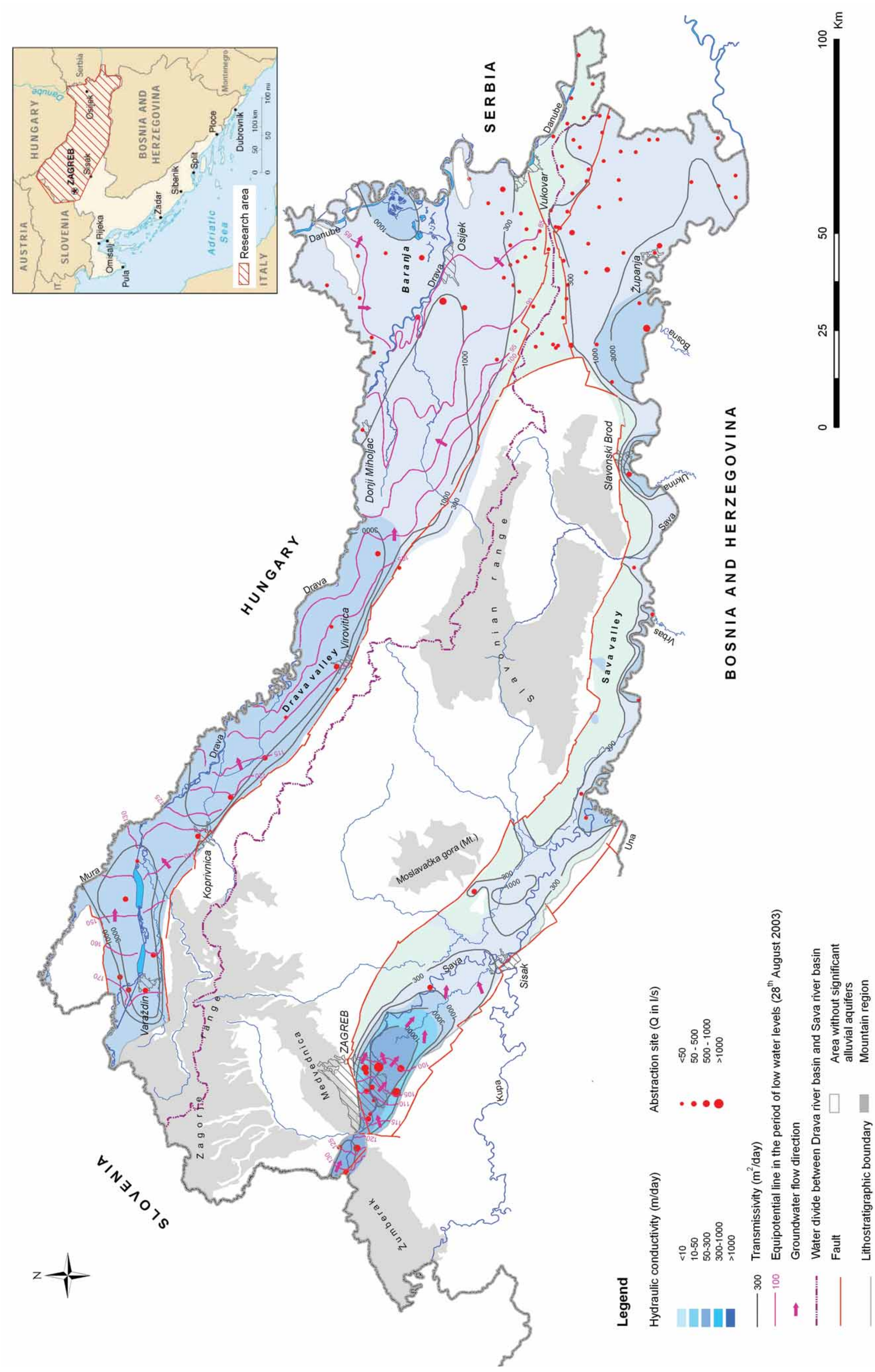

Figure 2: Hydrogeological parameters of the main alluvial aquifers in northern Croatia and general groundwater flow direction.

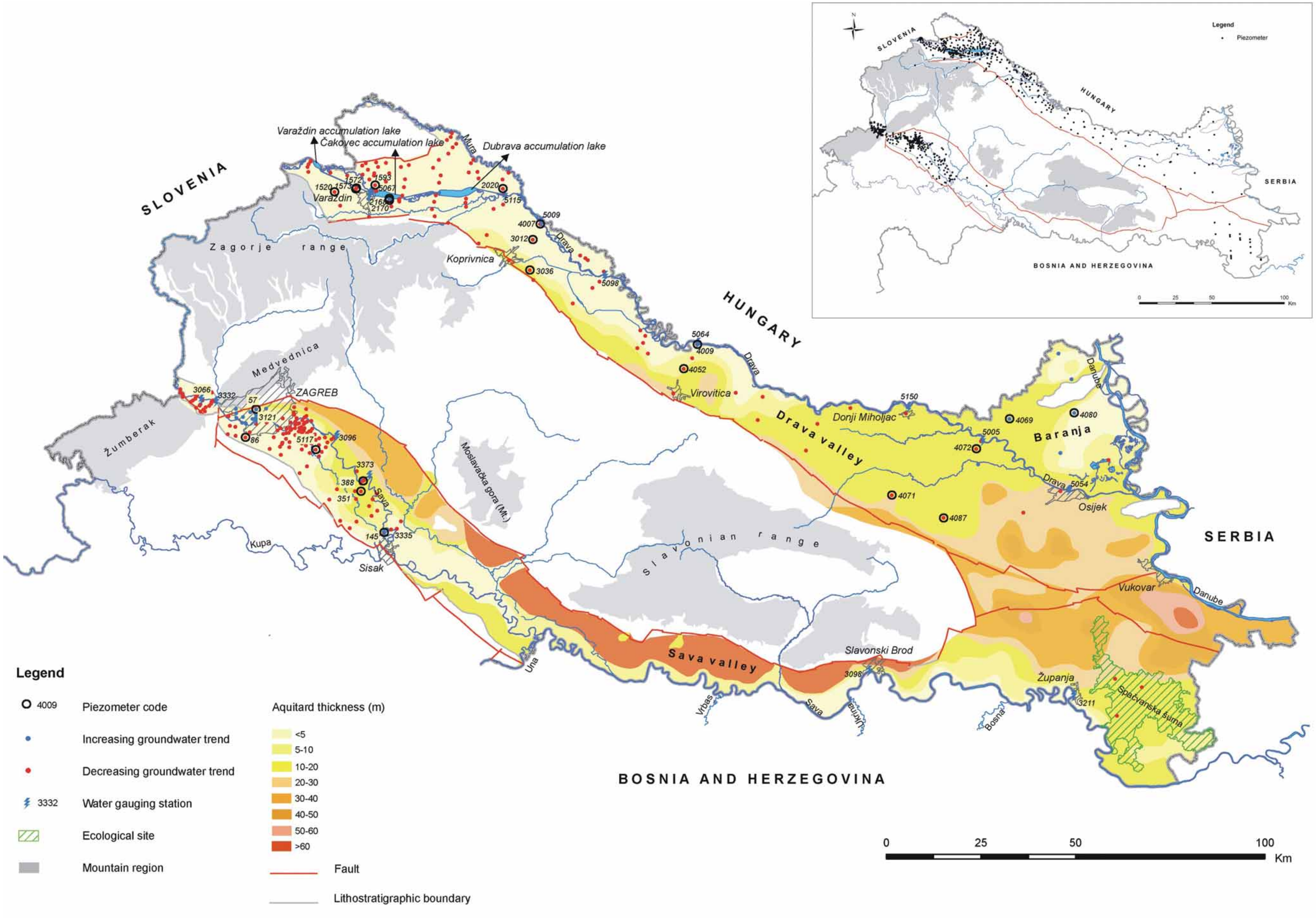

Figure 3: Monitoring network for groundwater and surface water levels and thickness of aquitard in northern Croatia.

eters are relatively shallow and tap the unconfined aquifer. In the eastern part of the Zagreb area, a somewhat larger number of piezometers have been drilled with the aim of monitoring groundwater levels along the depth of the aquifer system. Between Zagreb and Sisak, the piezometer network in the main aquifer is very sparse. In contrast, a larger number of piezometers were installed to monitor groundwater levels in the aquitard above the aquifer. Downstream of Sisak, the piezometer network is virtually non-existent; monitoring of groundwater levels is carried out only at the existing abstraction sites of public water supply. In the area of Spačvanska šuma (Spačva forest) in eastern Croatia, there are several shallow piezometers at which groundwater levels are also monitored in the aquitard and aquifer. In total, the State Meteorological and Hydrological Service monitors about 430 piezometers in the Drava river basin and about 440 in the Sava river basin.

The general direction of groundwater flow is shown in Figure 2. In the Drava lowland, there is dominant groundwater drainage into the Drava River. Recharge from surface water bodies is related to the accumulation lakes built for hydropower plants along the Drava River and, during floods, to the inundation area of the Drava and Danube. In the westernmost part of the Sava lowland, the alluvial aquifer is recharged by infiltration from the Sava River, which is further enhanced due to intense groundwater abstraction at the Zagreb abstraction sites. In the stretch from Zagreb to Sisak, on the right Sava bank, the aquifer is recharged from the Sava River during high stage periods, whereas the river itself drains groundwater during low-stage periods.

3. DATA AND METHODS

The assessment of quantitative groundwater status was carried out by analysing a time series of groundwater levels, stages of nearby rivers and precipitation quantities. The following data were included.

1. Time series of groundwater levels data from 1997–2007 (11 years inclusive). The locations of piezometers were selected so that profiles were formed approximately perpendicular to the water gauging stations on the Drava and Sava rivers (Fig. 3). These data were in some places also supplemented by a time series of groundwater level data for different periods (1987–2001 on the left Drava river bank upstream of the gauging station 5115, 1995–2005 in the Varaždin area and 1988-2003 in the Zagreb area). In Baranja, monitoring was not carried out during and after the Homeland War and was only established in mid-2001. Data analysis showed that the groundwater level trend in Baranja from 2002 to 2007 was the opposite of the one in the period from 1997 to 2007 on all piezometers analyzed in the upstream area of the Drava basin i.e. that in that period there was an increasing trend in groundwater levels. In order to determine the reason for these differences, time series of data were analyzed for the periods from 1997 to 2007, 1997 to 2001 and 2002 to 2007 on piezometers located outside Baranja. The same was also undertaken for the gauging stations (5009, 5150, 5054) (Fig. 3) on the Drava river and for precipitation quantities at the Varaždin, Virovitica and Osijek meteorological stations.
2. The time series of stage data on the Drava and Sava rivers for the period 1997–2007 (11 years): at 8 water gauging stations on the Drava river (5067, 5115, 5009, 5098, 5064, 5150, 5005 and 5054) and 7 water gauging stations on the Sava River (3066, 3332, 3096, 3373, 3335, 3098, 3211) (Fig 3). At the beginning of the 1990's, a river dam was built near the TE-TO thermal power plant on the Sava River at Zagreb. In order to identify the impact of the river dam on the groundwater levels, water levels at the gauging station 3121 (Fig. 3) are shown for the period from 1978 to 2008.
3. Time series of precipitation data at 4 main meteorological stations (Varaždin, Osijek, Zagreb – Pleso airport, Sisak) and 1 rainfall gauging station (Virovitica) for the period 1997 – 2008 (12 years) and for the period 1978 – 2008 (30 years).
4. Abstraction rates of groundwater at individual abstraction sites (based on issued concessions) (CROATIAN WATERS, 2007).
5. Estimated renewable groundwater resources (GEREŠ, 1998; MAYER, 1996; URUMOVIĆ et al., 1994; BRKIĆ & MAYER, 2005).
6. Hydrogeological characteristics of the aquifers (aquifer geometry, aquifer type – unconfined, confined, semi-confined, hydrogeological parameters, groundwater flow direction) deposited in the Drava and Sava basins.

The hydrographs for 23 piezometers are comprehensively presented in the paper. Table 1 shows the four main characteristics of these piezometers: (1) depth interval of the screen in m, (2) tapped layer, (3) type of aquifer, and (4) approximate distance from the Drava or Sava rivers or hydropower plant drainage canal in m. The type of aquifer in some cases varies between unconfined and semi-confined, depending upon the water regime and the position of a water table.

The data quality was checked by visual inspection of the hydrograph at each considered piezometer and also during construction of a head equipotential map. Data anomalous to the regional scheme of groundwater flow, as a result of measurement errors or storage data errors, were neglected. Linear regression analyses were undertaken on the time series of the groundwater levels, river stages and precipitation data. This is frequently used when it is necessary to define the nature of a connection between two or more variables. Two procedures were applied: correlation and trend analysis. In the case of correlation analyses, the Pearson's correlation coefficient value is critical for determination of linear connection strength. If the connection between the variables is functional, i.e. full, the Pearson's correlation coefficient would be 1. In all other cases, it would range from 0 to 1. If the linear connection is strong, it is closer to 1, while in the case of the weak connection it is closer to 0.

Analysis of the determined trends of groundwater levels, water levels of the Drava and Sava rivers and precipita-

Table 1: The basic characteristics of piezometers chosen for presentation.

River basin	Piezometer	Depth interval of the screen (m)	Tapped layer	Type of aquifer	Approximately distance from the rivers Drava or Sava, or hydropower plant drainage canal (m)
Drava and Danube	2168	4-8	aquifer	unconfined	1050
	2170	4-8	aquifer	unconfined	2000
	1572	5.5-9.5	aquifer	unconfined	170
	1573	5.5-9.5	aquifer	unconfined	420
	1520	5.5-9.5	aquifer	unconfined	6000
	1593	5.5-9.5	aquifer	unconfined	2200
	2020	3.5-4.5	aquifer	unconfined	1700
	4007	9-15	aquifer	unconfined/semiconfined	450
	3012	3-5	aquifer	unconfined/semiconfined	5000
	3036	6-10	aquifer	unconfined/semiconfined	13000
	4009	6.5-12.5	aquifer	unconfined/semiconfined	200
	4052	21-29	aquifer	semiconfined	7500
	4071	76-86	aquifer	semiconfined	24000
	4072	42-54, 78-90, 114-126	aquifer	semiconfined	2800
	4087	8-10	aquitard		23500
	4069	50-56, 80-86	aquifer	semiconfined	9000
	4080	8-12	aquifer	semiconfined	18000
Sava	57	8-12.5	aquifer	unconfined	2800
	86	2-8	aquifer	unconfined	3200
	5117	65-70	aquifer	unconfined/semiconfined	4600
	388	7-9	aquitard		550
	351	11.5-15.5	aquifer	semiconfined	2200
	145	10-14	aquifer	semiconfined	500

tion quantities, as well as existing groundwater exploitation quantities and estimated renewable resources, allowed definition of the quantitative status of groundwater in the alluvial aquifers in the Drava and Sava basins.

4. RESULTS AND DISCUSSION

4.1. Hydrodynamic conditions of the Drava aquifer

Analysis of groundwater levels in the Drava aquifer shows an observable lowering trend in nearly all analyzed locations (Fig. 3). Piezometers in areas immediately surrounding the accumulation lakes for the hydropower plants along the Drava River in the wider Varaždin area (Fig. 4) are the only exceptions. Here, groundwater levels are dominantly under the influence of the lakes. Since the drainage canals surrounding the accumulation lakes have only a local influence, the accumulation lakes recharge the aquifer in the immediate surroundings, preventing or reducing the general trend of a lowering of groundwater levels. Groundwater levels are also steady in the influence area of the drainage canal stretching from the Varaždin power plant to the discharge point (Fig. 5). Apart from the visual impression, the stability of groundwater levels is also indicated by the low values of regression coefficients (Figs. 4 & 5). Far from the accumulation lakes and drainage canal their impact on groundwater dynamics is weakened (LARVA, 2008). The annual amplitudes of groundwater levels are more marked, and their negative trend is also evident (Fig. 6).

Downstream of the Varaždin area, a general trend of lowering groundwater levels from 1997 to 2007 is observed (Fig. 3). Figures 7–9. present a time series of groundwater levels at piezometers 1593, 2020, 3012, 3036, 4052, 4071, 4072, 4069 and 4080. Between 1997 and 2007, two opposite trends have been observed on most analysed piezometers – a negative groundwater level trend is observed from 1997 to 2001 and a positive one from 2002 to 2007 (Figs. 7b, 8b and 9).

At piezometers 4071 and 4072, which tap a deeper interval of the aquifer, lowering of groundwater levels was observed in both monitoring periods (Fig. 9). The lowering of levels was more marked at piezometer 4071 than at pie-

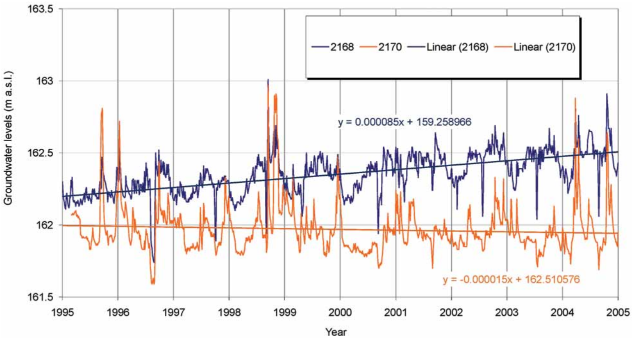

Figure 4: Groundwater levels at piezometers 2168 and 2170 located in the vicinity of the right bank of the Varaždin accumulation lake with linear trend lines for 1995–2005.

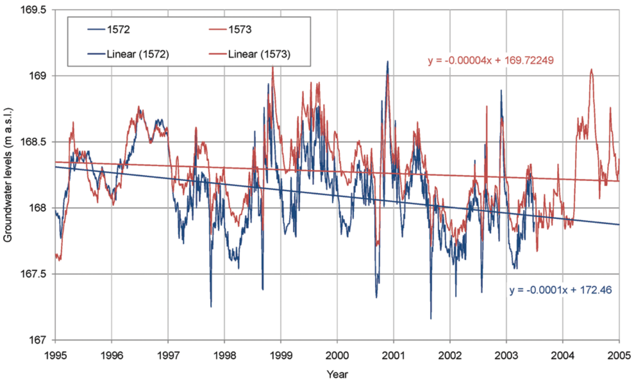

Figure 5: Groundwater levels at piezometers 1572 and 1573 located in the vicinity of the right bank of the drainage canal from the Varaždin hydropower plant to the restitution with linear trend lines for 1995–2005.

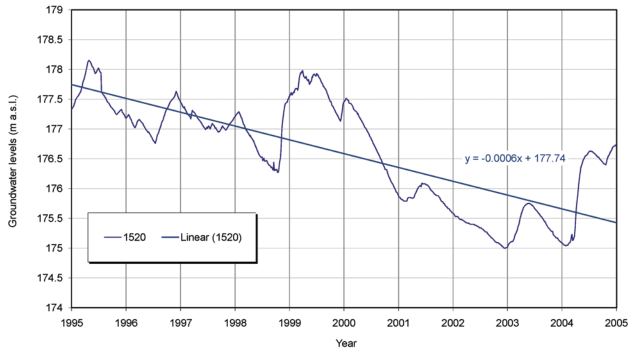

Figure 6: Groundwater levels trend at piezometer 1520 located in the central part of the Varaždin aquifer, far from the Drava River, with linear trend line for 1995–2005.

zometer 4072. The latter piezometer taps the shallower part of the aquifer system and is located closer to the Drava river, so the groundwater level here is under a stronger influence of the river. On the right bank of the Drava, but far from the river (Table 1), groundwater levels, even at shallower piezometers (4087), had a lowering trend (Fig. 10). Groundwater levels here are more influenced by precipitation.

All water gauging stations downstream of the hydropower plants and accumulation lakes show a trend of lowering of Drava water levels. The Drava stage in the greater Varaždin area is affected by the operation of the Varaždin,

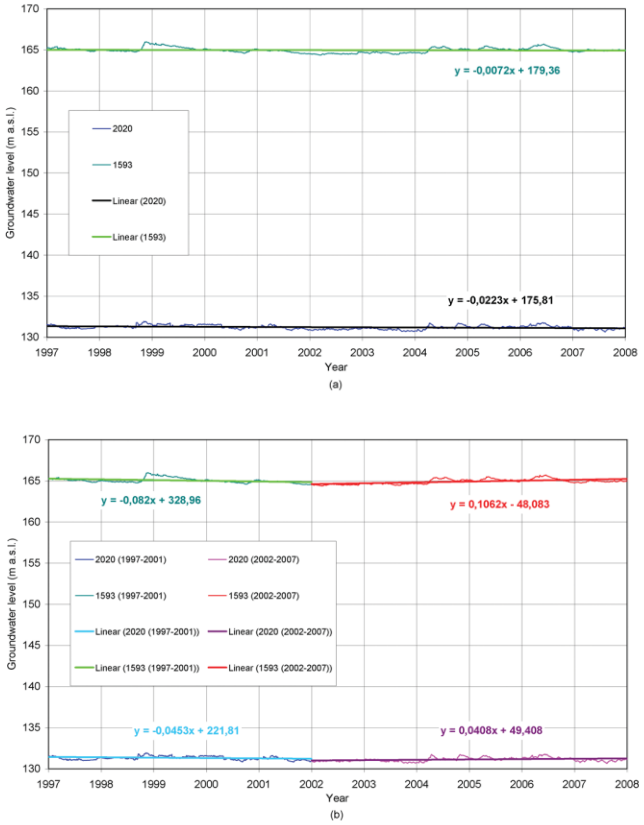

Figure 7: Groundwater levels at piezometers 1593 and 2020 with linear trend lines for (a) 1997–2007 and for (b) 1997–2001 and 2002–2007.

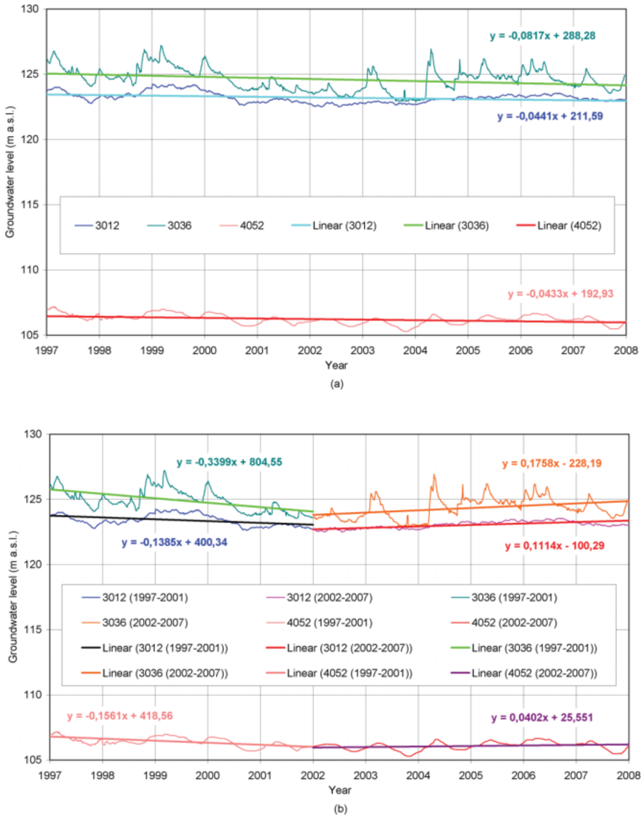

Figure 8: Groundwater levels at piezometers 3012, 3036 and 4052 with linear trend lines for (a) 1997–2007 and for (b) 1997–2001 and 2002–2007.

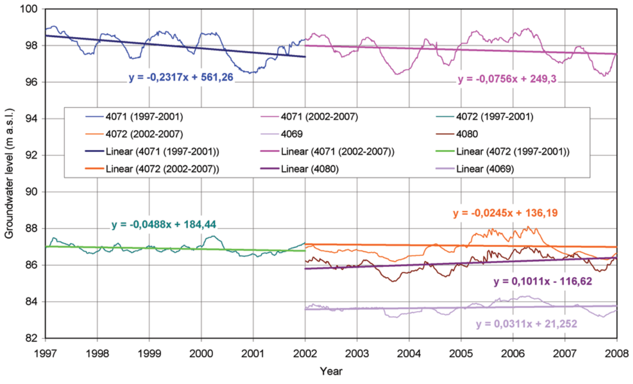

Figure 9: Groundwater levels at piezometers 4071, 4072, 4069 and 4080 with linear trend lines for 1997–2007 and 2002–2007.

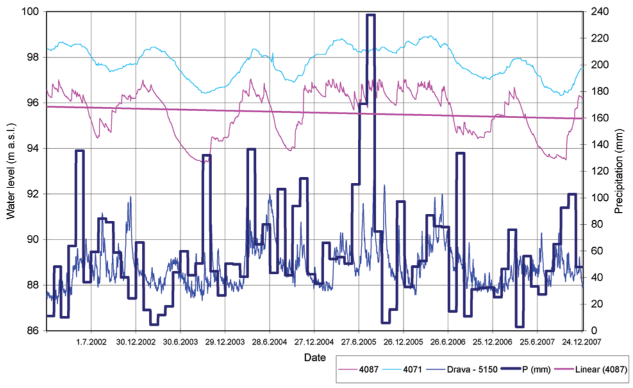

Figure 10: Groundwater levels at piezometers 4071 and 4087, Drava water levels at gauging station 5150 and monthly precipitation at the Osijek meteorological station.

Čakovec and Dubrava hydropower plants. The water levels in the old Drava river channel depend on the water quantities discharged from the accumulation lakes, which, in turn, depends on the water discharged into the lake and on the volume of the lake reservoir. Water levels in the accumulation lakes generally vary within 1 m. Downstream of the hydropower plants, the Drava water levels had a negative trend throughout the entire monitoring period 1997 – 2007 (Fig. 11a). However, considering the observed periods separately, the trend was in both cases positive (Fig. 11b).

This difference is the consequence of the factors which influence the Drava hydrograph. For shorter time intervals, water levels are predominantly influenced by climate conditions in the analyzed time interval. For mean annual precipitation in the period from 1997 to 2001, there was an increasing trend in the Osijek area, but a decreasing one in the areas of Varaždin and Virovitica. From 2002 to 2007, there was a registered increase in precipitation (Fig. 12) at all observed meteorological stations. The trend of precipitation increase which was registered in the northwestern part of Croatia (Varaždin) in the period from 2002 to 2007 can also be expected in the upstream stretches of the Drava River beyond the Croatian borders, which eventually results in increased water levels of the Drava in Croatia. In the same period, low water levels also showed an increasing trend (Fig. 13). This was due to the fact that in the periods of expected low water levels during winter (January and February) and summer (August, September), precipitation was higher than the 1997–2007 mean. Alternatively, the increasing trend of Drava water levels from 1997 to 2001 can probably be attributed to the snow melt in the Drava river basin outside Croatian borders although decreased precipitation quantities were registered in north western Croatia.

However, the Drava water levels observed throughout the period from 1997 to 2007 showed a trend of decrease. It is a consequence of morphological changes in the Drava river bed (river bed erosion) caused by the construction of hydropower plants, regulation of the river and its tributaries, construction of hundreds of kilometres of levees for flood protection as well as exploitation of gravel from the river bed (BIONDIĆ, 1999; BONACCI & OSKORUŠ, 2010). The morphological changes in the Drava river bed are a relatively slow, long process, which is observed when long time series of the suspended sediment yield are analyzed. These changes are even more marked when the hydrological and sediment regime for the Drava is analyzed over several recent decades (BONACCI & OSKORUŠ, 2010).

It can be concluded from the aforementioned analyses, that the trend of decreased groundwater levels recorded on the piezometers in the period from 1997 to 2001 is a consequence of decreased precipitation in the same time interval. From 2002 – 2007, there were observed trends of increased

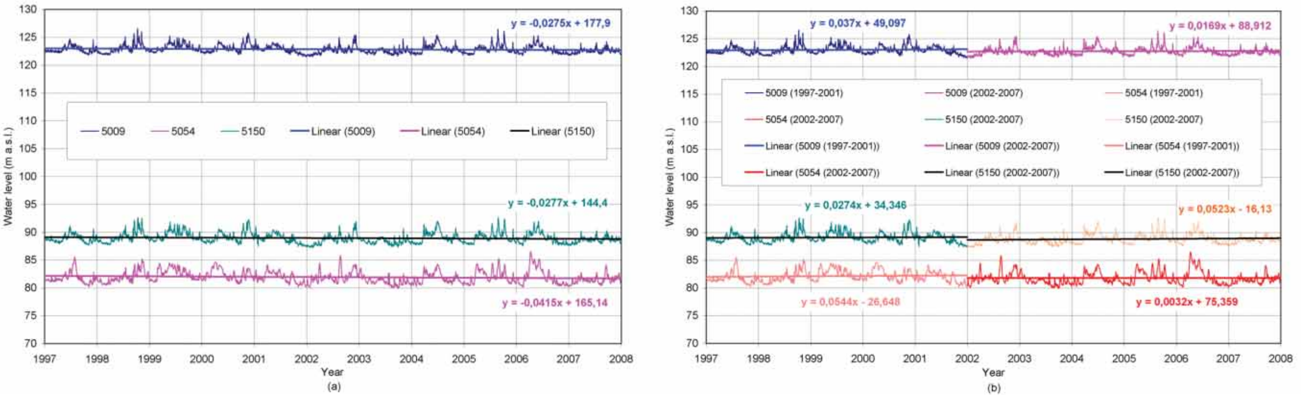

Figure 11: Drava water levels at the water gauging stations 5009, 5150 and 5054 with linear trend lines for (a) 1997–2007 and for (b) 1997–2001 and 2002–2007.

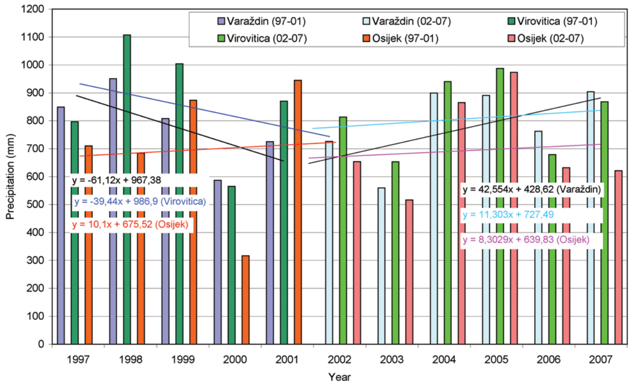

Figure 12: Total annual precipitation at the Varaždin, Virovitica and Osijek meteorological stations with linear trend lines for 1997–2001 and 2002–2007.

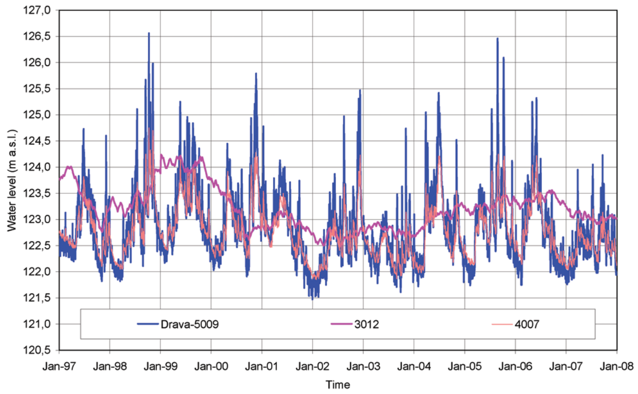

Figure 15: Drava water levels at gauging station 5009, piezometer 4007 (about 450 m from the river) and piezometer 3012 (about 5 km from the river).

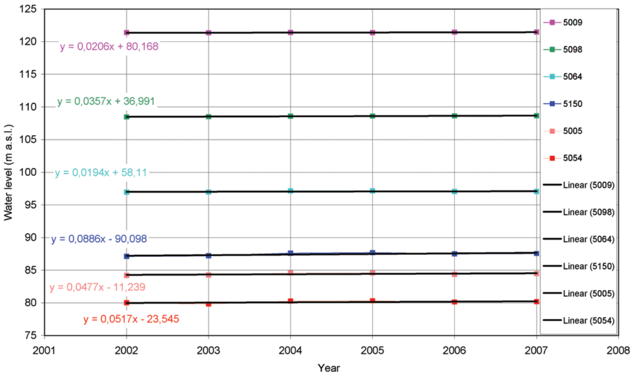

Figure 13: Minimum annual stages of the Drava river at the water gauging stations 5009, 5098, 5064, 5150, 5005 and 5054 with linear trend lines for the period from 2002 to 2007.

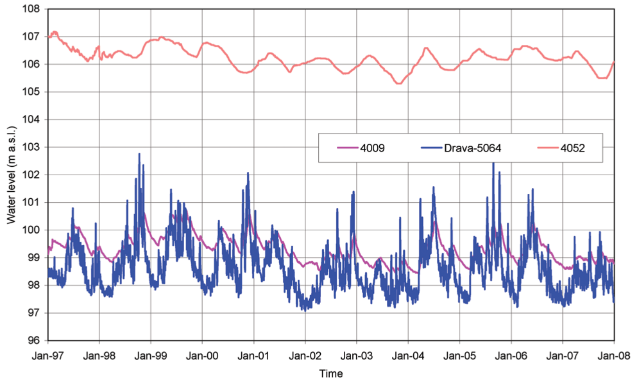

Figure 16: Drava water levels at gauging station 5064, piezometer 4009 (about 200 m from the Drava) and piezometer 4052 (about 7.5 km from the Drava).

precipitation and increased Drava water levels. It can, therefore, be concluded that over shorter time periods the trend of increased groundwater levels is predominantly influenced by precipitation. In a longer time period, however, the trend of decreased groundwater levels is influenced by the trend of decreased Drava water levels, as observed in the period from 1997 to 2007.

Downstream of the constructed hydropower plants, groundwater does not have a strong connection to the changes of the Drava river stages, with the exception of the direct proximity of the river. The strongest connection was observed between the water level at the water gauging station 5009 and piezometer 4007 (correlation coefficient of 0.93), (Fig. 14a), and also between the water level at the water gauging station 5064 and the piezometer 4009 (correlation coefficient of 0.7). At about 1.5 km from the Drava, the correlation coefficient is about 0.3, and far from the river generally about 0.2 (Fig. 14b).

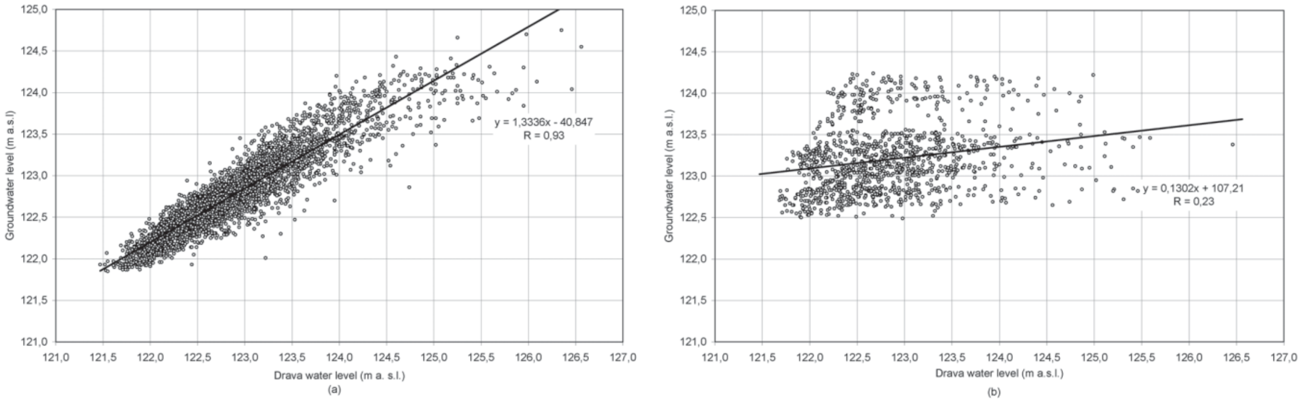

Figure 14: Correlation coefficients between Drava River stage at (a) the water gauging stations 5009 and piezometer 4007 and at (b) the water gauging stations 5009 and piezometer 3012.

In the area of the Drava lowland, groundwater drainage into the Drava River is dominant, and the aquifer is recharged through infiltration of precipitation estimated at about 30 % of mean annual precipitation in the western part and about 10 % of mean annual precipitation in the eastern part of the Drava valley (URUMOVIĆ et al., 1994). Only at high water levels, is the aquifer in the area approximately between the water gauging station 5009 (Fig. 15) and the water gauging station 5064 (Fig. 16) recharged from the Drava river. Although the groundwater level trend is similar to the Drava water level trend, far from the Drava there is frequently no observable reaction of groundwater levels to high water levels in the Drava River. Any increase in groundwater levels in this area of the Drava aquifer is predominantly influenced by precipitation.

Total annual precipitation in the Varaždin area ranges from 600 to 1000 mm (Figs. 17a and 17b). The lowest precipitation quantities were registered in 2000 and 2003. In the 30-year period, the mean annual precipitation was 825 mm, and in the monitoring period 1997 – 2008 it was 782 mm. In the easternmost area of the Drava basin, total annual precipitation ranges from 300 to 950 mm (Figs. 17a and 17b). As with the western part, the lowest precipitation quantities were registered in 2000 and 2003. In the 30-year period, the mean annual precipitation was 666 mm (excluded 1991 and 1992, when it was not monitored), and in the monitoring period 1997– 2008 it was 702 mm. In this latter period, the trend of decreased precipitation was recorded.

Mean monthly precipitation at the meteorological station Varaždin from 1978 – 2008 was generally higher than the mean monthly precipitation for the period 1997 – 2008 (Fig. 18), with the exception of the means for July and September, which were slightly higher in the period 1997 – 2008. In the same months, the deviation from the mean was also higher. The deviation from the mean annual precipitation was also higher in the period 1997 – 2008 in comparison with the period from 1978 to 2008.

In the eastern part of the Drava basin, the distribution of precipitation differs from that in the western part. The mean precipitation values were nearly identical in the first half of both observed periods (Fig. 19). In contrast, in the second half of the year, they were higher in the period 1997 – 2008 than those in the 30-year period. In this period, the mean precipitation quantity in July and August was 15–20 % higher than that for the 30-year period. In the summer months, deviation from the mean was also higher. The deviation from the mean annual precipitation was also higher in this period in comparison with the period from 1978 to 2008.

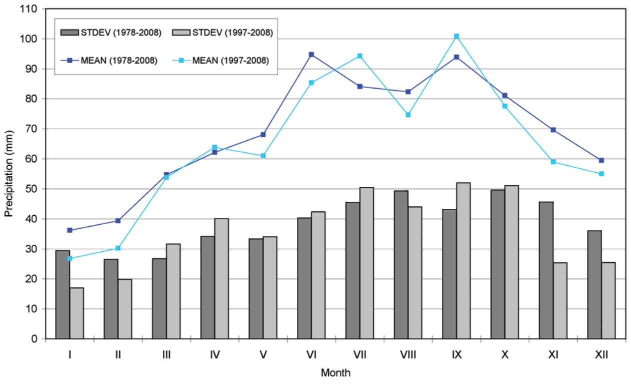

Figure 18: Mean values and standard deviations of monthly precipitation at the Varaždin meteorological station.

The distribution of precipitation throughout the year has also altered which has had a significant influence on groundwater recharge and consequently on groundwater levels. Lower quantities of precipitation have been recorded in the spring and autumn months, while in the summer months there is a trend of increased precipitation. From the prospect of groundwater renewal, increased precipitation during the summer months has a small effect due to evapotranspiration, surface runoff and rebuilding up of soil water budget. Such observations are in accordance with the results of the quantitative precipitation analyses for 1901 to 2000 (Ministry of Environmental Protection, Physical Planning and Construction, 2006). The overall annual precipitation trend shows a decrease during the 20th century in the whole of Croatia. This decrease is more pronounced in eastern Croatia (at the meteorological station Osijek 13%) than in north western Croatia (at the meteorological station Zagreb-Grič 3%). The annual distribution of precipitation shows a significant decrease in spring precipitation (Osijek 41 %/100 years, Zagreb-Grič 11 %/100 years) and autumn precipitation (Osijek 30 %/100 years , Zagreb-Grič 14 %/100 years).

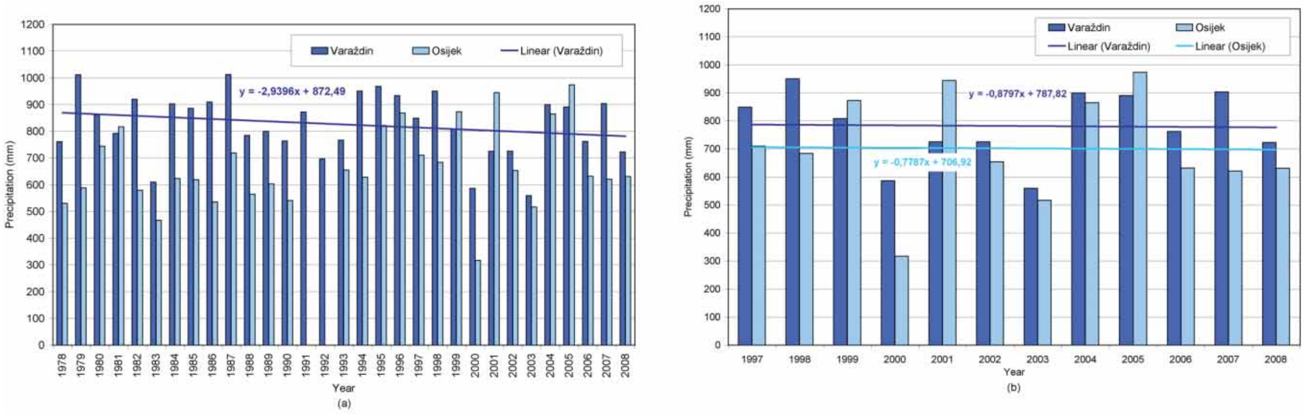

Figure 17: Total annual precipitation at the meteorological stations Varaždin and Osijek with linear trend lines for (a) 1978–2008 and (b) 1997–2008.

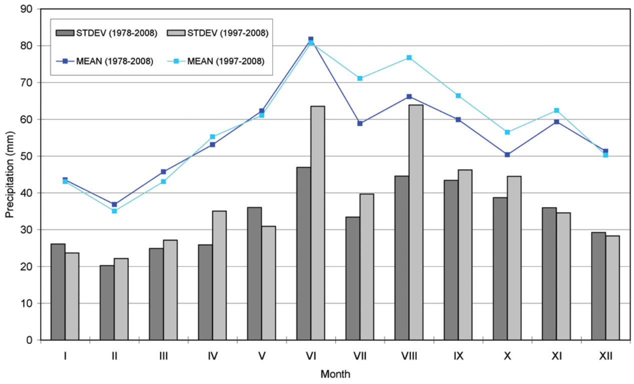

Figure 19: Mean values and standard deviations of monthly precipitation at the Osijek meteorological station (without data for 1991 and 1992).

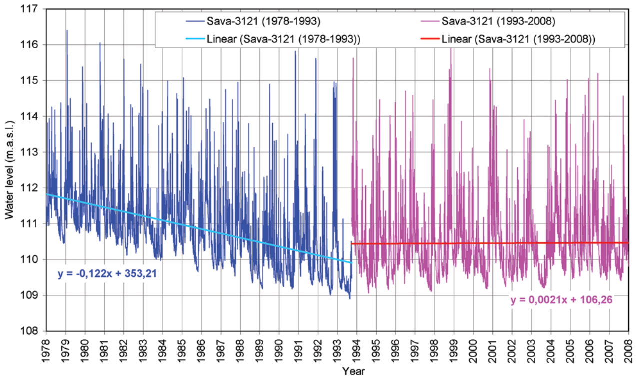

Figure 20: Sava water levels at water gauging station 3121 with linear trend lines for the period 1978–1993 and 1994–2007.

4.2. Hydrodynamic conditions of the Sava aquifer

In the Sava aquifer, monitoring of groundwater levels is carried out at several hundred piezometers in the area from the state border with the Republic of Slovenia to Sisak. Downstream of Sisak, the piezometer network is virtually non-existent, and monitoring of groundwater levels is carried out only at the existing abstraction sites of public water supply and in the area of Spačvanska šuma (Spačva forest) in eastern Croatia.

The trend of lowering groundwater levels in the Zagreb area has been observed over a longer period (TRNINIĆ & BOŠNJAK, 2008). It appeared as a consequence of the deepening of the Sava river bed, and thus the lowering of its water levels, even though the exploitation of large quantities of groundwater for the public water supply of the City of Zagreb cannot be neglected as a factor. Erosion of the Sava, as well as of the Drava river bed, is caused by significant morphological changes brought about by the regulation of the river and its tributaries, construction of hundreds of kilometres of levees for flood protection and exploitation of gravel from the river bed. In this manner, sediment transfer ceased, which started the process of river bed deepening. Interestingly, a detailed analysis of the time series for minimum, mean and maximum annual discharges of the Sava at Zagreb in the period 1926 – 2006 identified a significant trend of decreased discharge, which indeed indicates a reduction in water quantity (TRNINIĆ & BOŠNJAK, 2008), with anthropological and climate impacts stated as the causes.

At the beginning of the 1990s, the trend of decreasing Sava river water levels was stopped by the river dam near thermal power plant TE-TO Zagreb (Fig. 20). This also stopped the trend of decreasing groundwater levels in the small area upstream of the power plant (Fig. 3). This is particularly marked on the left river bank where, among other factors, there is no significant groundwater exploitation.

In the remaining Zagreb area, the trend of decreased groundwater levels was observed on almost all piezometers and in all parts of the aquifer system (Fig. 3). Figure 21 presents a time series of groundwater levels at piezometers 86, 57 and 5117. Piezometer 86 is located upstream of the abstraction site for public water supply and piezometer 57 is located upstream of the power plant on the left river bank (Fig. 3). In contrast, piezometer 5117 is located in the eastern part of Zagreb where there is no significant groundwater exploitation.

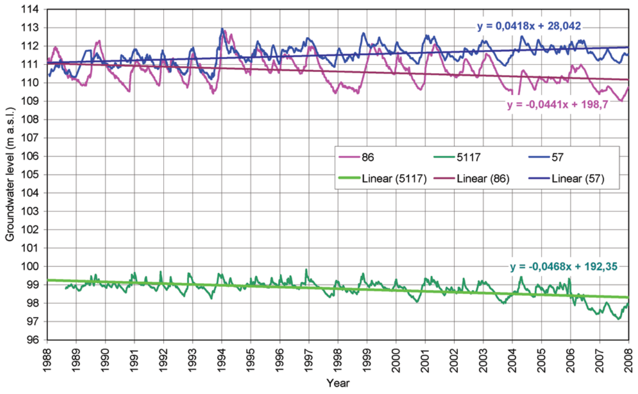

Figure 21: Groundwater levels at piezometer 57 upstream of the multi-purpose reservoir of the TE-TO on the Sava left bank, and piezometers 86 and 5117 on the Sava right bank with linear trend lines for the period 1988–2007.

Lowering of groundwater levels in the Zagreb area is also related to the large abstracted water quantities at the abstraction sites, i.e. aquifer over-abstraction (BAČANI & POSAVEC, 2008; 2009). It is undeniable that abstraction of large quantities of water impact on the lowering of groundwater levels; however, they are not the main reason for it. Total abstracted quantities at the abstraction sites in Zagreb in the period 1988 – 2008 changed depending on consumer demand. In the period 1988 – 1993 they equalled about 120 million m^3/year, in the period 1993 – 2000 there was a slight increase in the abstracted quantities whereas since 2000 there has been an evident trend of their decrease (Fig. 22). The reason for the decrease in abstracted quantities is attributed to decreased industrial consumption and to the fact that, even though the number of individual consumers has increased, there is a slight decrease in consumption per capita (KOČO & ILIČIĆ, 2009).

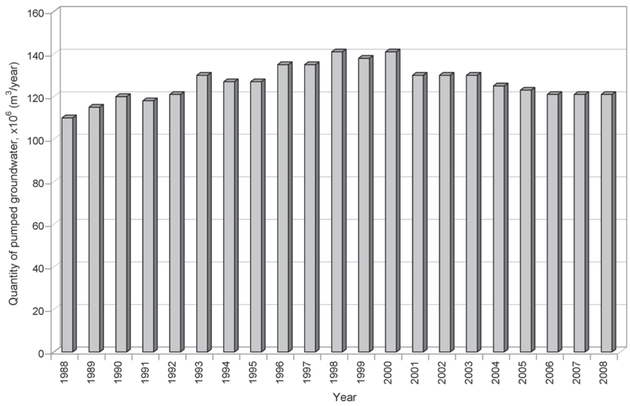

Figure 22: Total abstracted quantity at the abstraction sites in Zagreb for 1988–2008 (according to KOČO & ILIČIĆ, 2009).

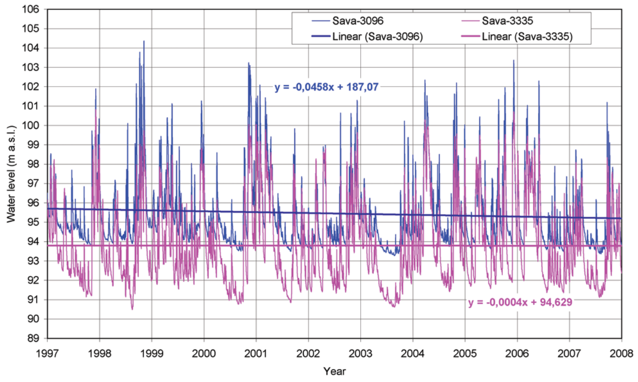

Figure 23: Sava water levels at water gauging stations 3096 and 3335 with linear trend lines for 1997–2007.

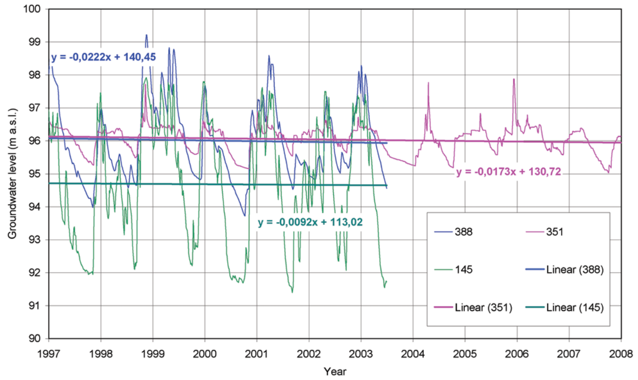

Figure 24: Groundwater levels at piezometers 388, 351 and 145 on the right bank of the Sava river with linear trend lines for 1997–2007.

Although there has been a decrease in the abstracted quantities in the Zagreb area in recent years, the trend of lowering of groundwater levels has not stopped. The same situation is also recorded in the easternmost part of the Zagreb aquifer. A negative groundwater level trend is recorded at nearly all piezometers (Fig. 3), regardless of aquifer depth at which groundwater levels are measured, as was observed at piezometer 5117 (Fig. 21).

Groundwater levels show a strong connection to changes in the Sava water levels in the Zagreb area. A strong connection, described by a correlation coefficient > 0.6, was determined at a distance of about 1 km from the Sava in the western and central parts of the Zagreb area. In the eastern part of the Zagreb area, a strong connection was determined at distances of 2, and even 5 km, from the Sava River (BORČIĆ et al, 1968). Statistical analyses of groundwater levels and the Sava river stages conducted recently show the same results (Bačani et al., 2005)[1]. In the Sisak area, at 320 m from the Sava river, a strong connection was determined, with a correlation coefficient of 0.79 (Larva, 2002). However, where the overlying aquitard is greater than 20 m thick, and the aquifer is not in direct contact with the Sava River, a different situation occurs. About 100 m away from the Sava, the correlation coefficient is 0.42.

The Sava water levels downstream of Zagreb show the same trend (Fig. 23) in line with the trend of negative groundwater levels The water gauging stations which are furthest downstream in Croatia, at Slavonski Brod (station 3098), and Županja (station 3211), show the same negative trend.

Between Zagreb and Sisak, there is also a prevalent negative trend concerning groundwater levels (Figs. 3, 24), although there is no groundwater exploitation in the area.

Total annual precipitation ranges from 700 to 1100 mm in the Zagreb area and from 600 to 1100 mm in the Sisak area (Figs. 25a and 25b). The lowest precipitation was registered in 2003. In the 30-year period, the mean annual precipitation at the Zagreb meteorological station was 934 mm and 932 mm in the monitoring period 1997 – 2008. The time series of total annual precipitation in the period 1978 – 2008 (30 years) in the Zagreb area showed the absence of any meaningful trend. However, analysis of precipitation data in the last 12 years (1997 – 2008) evidently showed a trend of precipitation decrease (Fig. 25b). The same changes have also been observed at the Sisak meteorological station (Fig. 25b).

Between 1997 – 2008 there has also been marked lower precipitation during May and June, as in the Varaždin area, which is slightly higher in the summer months (Figs. 26 and 27). In general, there is an evident trend of increased precipitation during summer months (July, August and even September). At both meteorological stations, the deviation from the mean annual precipitation was higher between 1997 – 2008 compared to the period from 1978 to 2008.

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[1] BAČANI, A., POSAVEC, K., NAKIĆ, Z., PERKOVIĆ, D., MILETIĆ, P., HEINRICH-MILETIĆ, M., PARLOV, J. & BAZIJANEC, M. (2005): Elaborat zaštitnih zona vodocrpilišta grada Zagreba. [Study of protection zones of the City of Zagreb water abstraction sites – in Croatian].− Unpubl. report, Faculty of Mining, Geology and Oil Engineering, University of Zagreb, Zagreb, 374 p.

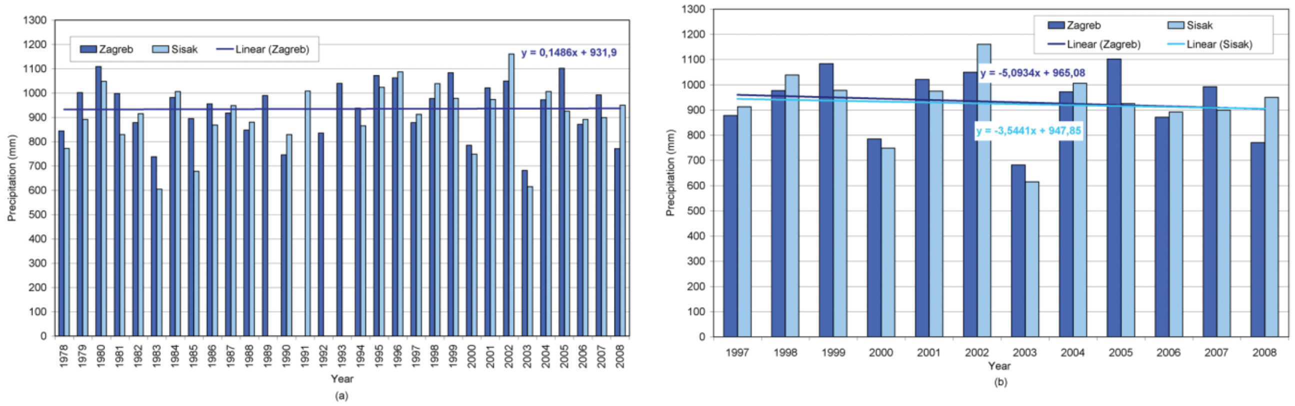

Figure 25: Total annual precipitation at the Zagreb and Sisak meteorological stations with linear trend lines for (a) 1978 2008 and (b) 1997–2008.

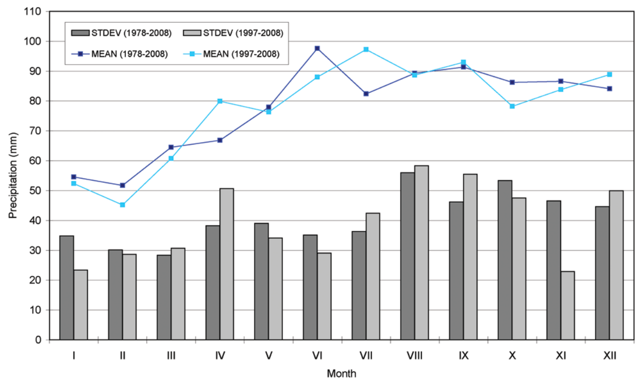

Figure 26: Mean values and standard deviations of monthly precipitation at the Zagreb-Pleso meteorological station.

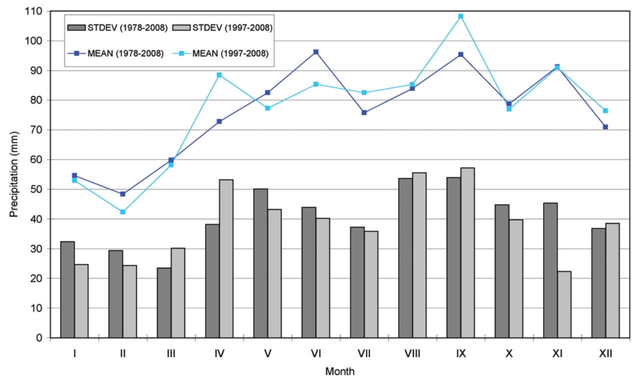

Figure 27: Mean values and standard deviations of monthly precipitation at the Sisak meteorological station.

4.3. Renewable groundwater resources in the alluvial aquifers and abstraction rates

Groundwater resources in alluvial aquifers were estimated several times and by several methods. One was based on the estimation of renewable resources as the product of the aquifer surface area and effective infiltration coefficient (URUMOVIĆ et al, 1994). Another calculated renewable sources as either a product of the aquifer surface, difference between maximum and minimum groundwater levels and layer porosity (unconfined aquifer) or a product of aquifer surface, difference between maximum and minimum piezometric pressures and coefficient of aquifer storage (confined aquifer) (MAYER, 1996). The determination of renewable groundwater resources has always been influenced by numerous unknowns due to an insufficient quantity of measured data, thus the larger part of the area was estimated on the basis of analogy with better investigated areas. Usually, two values for renewable groundwater resources in alluvial aquifers are quoted (GEREŠ, 1998), one related to the minimum and the other to the maximum estimate. The differences between those are extremely large, e.g. for the Sava basin, the difference between the minimum and maximum estimates of renewable resources is about 1:6, while for the Drava and Danube basin it is about 1:2 (Table 1). For purposes of the development of the Water Management Strategy in the Republic of Croatia (CROATIAN WATERS, 2009), a new estimate of renewable resources was made (BRKIĆ & MAYER, 2005). The same methodology as in the previous estimates was applied. Renewable resources were determined in quantities closer to the earlier minimum estimates for the aquifer in the Sava valley and are closer to the earlier higher estimated values for the Drava aquifer. Accordingly, in the areas of the Drava and Sava aquifers the renewable groundwater resources were estimated at quantities exceeding 1 billion m^3/year (Table 2).

Based on concessions issued to water companies and industry, about 115 million m^3/year are abstracted from the alluvial aquifer in the Drava basin and about 230 million m^3/year from the aquifer in the Sava basin. Water quantities used for domestic water supply (which is not included in the public water supply system) should be added to these abstracted quantities, as should the quantities used for irrigation. While the data on domestic water supply quantities remain unknown, there is an estimate on water quantities used for irrigation. They range from 15 to 20 × 10^6 m^3/year and also include water loss in irrigation systems (CROATIAN WATERS, 2009). The estimate refers to the whole Croatian territory and, in addition to groundwater quantities, also includes surface water used for irrigation. Although a reliable estimation of groundwater quantities used for irrigation and domestic water supply are still lacking, it could be concluded

Table 2: Estimated renewable groundwater resources in the Drava and Sava alluvial aquifers.

River basin	Renewable groundwater resources (x106 m3/year)				
	GEREŠ (1998)		MAYER (1996)	URUMOVIĆ et al. (1994)	BRKIĆ & MAYER (2005)
	Min. estimation	Max. estimation			
Drava and Danube river basin – alluvial aquifer	499	556	569	1062	810
Sava river basin – alluvial aquifer	1220	7109	1287		1198

that this is still a small proportion of renewable groundwater resources.

When comparing exploited groundwater quantities (based on issued concessions) and estimated renewable groundwater resources, it is evident that only a small proportion of available renewable resources is presently used (15–20%) and that the potential safe yield is much higher. The largest share of abstracted quantities in relation to renewable resources is registered in the Zagreb area, where the Sava river share in the renewal of waters at abstraction sites is about 67% (Bačani et al., 2005)[1]. The limiting factor for groundwater abstraction at the abstraction sites on the right Sava river bank in the Zagreb area is the small thickness of the aquifer. This is particularly marked in the dry, summer months, when, due to low water levels of the Sava and consequent low groundwater levels, the aquifer transmissivity, which regulates the amount of induced recharge of the aquifer from the Sava River, is significantly reduced.

One of the most important questions is whether renewable groundwater resources also mean water quantities that can be permanently exploited? In the past, the volume of recharge to an aquifer was accepted as the maximum quantity of water that could be removed from an aquifer on a sustainable basis (the so-called safe yield) (LEE, 1915; TODD, 1959). Nowadays, according to the EU Water Framework Directive (WFD-2000/60/EC), the sustainable yield of an aquifer must be considerably less than recharge, if adequate amounts of water are to be available to sustain both the quantity and quality of streams, springs, wetlands and other groundwater-dependent ecosystems (SOPHOCLEOUS, 2000). If pumping equals recharge, eventually streams and wetlands may dry up.

Additionally, the practice showed that despite large estimated quantities of renewable groundwater resources at the regional level, there are still difficulties in ensuring sufficient water abstraction quantities at individual locations. Considering the possibility of induced aquifer recharge during groundwater abstraction, the actual abstracted quantities depend on the hydrogeological conditions of an individual location, spatial distribution of an abstraction sites, and position of a well(s) in relation to constant head boundary, groundwater quality and the needs of groundwater-dependent ecosystems. Based on the above, exploitation of groundwater resources should be separately determined for each selected location. For these purposes, mathematical modelling of the groundwater flow is often applied. It represents a powerful management tool that can serve multiple purposes, such as providing a framework for the verification of hydrogeological properties and for defining the quantitative prediction of the responses of aquifer systems to externally applied stress, (e.g. increase in pumping rates). The availability of the input data determines how many of these problems can be solved.

5. CONCLUSIONS

Several conclusions can be drawn from analyses conducted on the time series data of groundwater levels, Drava water levels and precipitation in the Drava river basin. When considering the time series from 1997 to 2007, the trend of decreasing groundwater levels in the aquitard and in the shallower parts of unconfined and semi-confined aquifers is under the predominant influence of decreasing levels of Drava river water. The decrease of the Drava water levels is influenced by morphological changes caused by the construction of hydrotechnical facilities. The morphological changes in the river bed are slow, lengthy processes, the consequences of which are reflected in the gradual decrease in the Drava water levels, and can be observed when analyzing longer time series. However, considerations of shorter time intervals show that the trend of groundwater levels and Drava water levels determined from 1997 to 2001 and from 2002 to 2007 is under the predominant influence of climate conditions in the observed time interval. From 1997 to 2001, there was a trend of decreased groundwater levels as well as a trend of decreased precipitation, while from 2002 to 2007 there was a determined trend of increased mean annual precipitation and increased groundwater levels. In deeper parts of the aquifer, the Drava influence on the groundwater is subdued. Groundwater flow in these areas has a regional character, both according to temporal and spatial criteria. Infiltrated precipitation percolates underground with different retention times that depend on soil humidity, depth of gro-

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[1] BAČANI, A., POSAVEC, K., NAKIĆ, Z., PERKOVIĆ, D., MILETIĆ, P., HEINRICH-MILETIĆ, M., PARLOV, J. & BAZIJANEC, M. (2005): Elaborat zaštitnih zona vodocrpilišta grada Zagreba. [Study of protection zones of the City of Zagreb water abstraction sites – in Croatian].– Unpubl. report, Faculty of Mining, Geology and Oil Engineering, University of Zagreb, Zagreb, 374 p.

undwater levels, hydraulic characteristics of the aquitard, its thickness and on the type of vegetation, as well as on the length between recharge zone and observation point. Due to this retention time, groundwater levels in the deeper parts of the aquifer are not influenced by the relatively short-term trends of precipitation increase, but by a decrease observed over a longer period. Accordingly, the lowering of groundwater levels is a consequence of the mutual impact of a multi-year decrease in the total annual precipitation and a multi-year lowering of the Drava water levels.

In the Sava basin, the situation is somewhat more complex. The trend of lowering of groundwater levels in the Zagreb area is a consequence of the trend of decreased water levels of the Sava River, a decreased total annual precipitation and the exploitation of large quantities of groundwater. The lowering of groundwater levels is also evident downstream of this area, although not as much marked.

A decrease of total annual precipitation from 1997 to 2008 was determined in the entire observed area, and it has an important role in groundwater renewal. Moreover, an altered distribution in precipitation throughout the year has been noticed, which certainly has significant influence on groundwater recharge and consequently on groundwater levels. Lower precipitation was recorded in the spring and autumn months, while in the summer months there is a trend of increased precipitation. From the aspect of groundwater renewal, greater precipitation during the summer months has a small effect due to evapotranspiration, surface runoff, and rebuilding of the soil water budget. According to the EU Water Framework Directive (WFD-2000/60/EC), the assessment of groundwater status and risk is, among other things, based on the water needs of ecosystems depending on groundwater. Based on the guidelines on protection measures in areas of the national ecological network (NATURA 2000), the problem of lowering of groundwater levels is not highlighted; only the need for preservation of the existing state of waters is emphasized in special cases.

Although the lowering of groundwater levels is being recorded, due to relatively large groundwater resources the quantitative status of waters (from the standpoint of the public water supply), in the larger part of the investigated area is presently not endangered, nor will be in the near future. However, the Zagreb area could be categorized as "potentially at risk" due to the relatively large quantities exploited and demands for water as well as evident lowering of groundwater levels. Such a complex situation requires measurement of numerous parameters (water levels, discharges, sediment transfer in the Sava river, groundwater levels, abstracted groundwater quantities, climate changes), their systematic analysis and quantification of anthropological influences.

The present knowledge of groundwater status must be improved by the application of more sophisticated methods that integrate land use, vegetation, climate, and interacting water. In order to achieve the goals, a multidisciplinary approach must be applied which gathers experts from different fields, such as hydrogeology, biology, hydrology, chemistry, etc. Additional improvements of the piezometer network in the areas of the Drava and Sava basins are also necessary. This primarily relates to the area east of Virovitica, on the right bank of the Drava River, where groundwater levels are presently monitored only in the overlying aquitard and also east of Sisak, in the Sava river basin, where presently there is no monitoring of groundwater levels at all. The piezometer network must be designed in a manner to enable measurement of groundwater levels in aquifers exploited at abstraction sites within the public water supply, but also in aquifers abstracted for other uses (irrigation, etc.). Along with the satisfactory monitoring network, mathematical modelling of groundwater flows would enable simulations of different influences on the aquifer system within entire alluvial basins on the regional scale. This would create a basis for the optimal management of this important resource of the Republic of Croatia.

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