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Identification of Groundwater Level Decline in the Zagreb and Samobor-Zaprešić Aquifers since the Sixties of the Twentieth Century

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Review scientific paper

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Abstract

This study examines historically measured groundwater levels on observation wells of the Zagreb and Samobor-Zaprešić aquifers since the 70-ies of the 20th century until today. The analysis also entails older groundwater level maps dating from the 60-ies of the previous century, which offer additional insight into the historical groundwater levels. The analysis of the existing groundwater levels and historical groundwater levels has identified changes of those levels in certain areas of the aquifer, special reference being taken to developments which, with time, led to the deceleration of negative trends of groundwater levels in certain parts of the aquifer. The most significant such developments in the past 50 or so years are the construction of the weir of the Zagreb cogeneration plant (TE-TO) in the Sava River and the occurrence of hydrologically above-average favourable years like 2013/2014, which have been separately analysed. The analysis has found that today's groundwater levels in the Zagreb and Samobor-Zaprešić aquifers are generally lower by approximately 3 to 6 m in comparison with the historical levels from the 60-ies of the last century.

Keywords:
historical groundwater levels, groundwater time series, head difference maps, Zagreb and Samobor-Zaprešić aquifer

1. Introduction

Groundwater is an important freshwater resource used for irrigation, industrial needs, and public water supply in many countries of the world, therefore, the same is true for the Republic of Croatia, where 90% of the needs for public water supply is satisfied by groundwater exploitation. Aquifer discharge, which occurs faster than natural restoration, leads to the lowering of groundwater levels and a decrease of the total groundwater reserves. Lower groundwater levels and a decrease in groundwater reserves can lead to difficulties in water supply and endanger ecosystems dependent on groundwater. Efficient and sustainable groundwater management requires good knowledge of aquifer discharge and recharge systems, as well as of the trends of groundwater levels. Time series of groundwater levels are the main source of information on the influence of hydrologic and anthropogenic factors on the groundwater systems. According to the Water Management Strategy (Croatian Official Gazette No. 91/08), which is a long-term planning document of state policy on water management, groundwater of the Zagreb and Samobor-Zaprešić aquifers, analysed in this study, are defined as strategic groundwater reserves of Croatia, on which the current and future water supply of the City of Zagreb and Zagrebačka County is based. Therefore, recognising the trends of groundwater levels in those aquifers is of utmost importance.

Considering the importance of groundwater, numerous authors have examined the main causes of groundwater level decline. **Chaudhuri et al. (2014)** have published a study of groundwater level decline in Texas, USA, and they have found that the main cause for the negative trends of groundwater levels is agriculture, i.e. irrigation. In Western India, it has been shown that groundwater levels are dependent on topography and the presence of surface waters **(Machiwal et al., 2011)** while the analysis of groundwater level decline conducted by **Panda et al. (2012)** has led to the conclusion that the main reasons for lowering the water table are an increase in temperatures and frequent drought periods. In the vicinity of Beijing, the main cause of groundwater level decline is increased exploitation **(Zhou et al., 2016)**; the same results have been obtained in Northern China **(Li et al., 2014)**. Many studies have shown that the use of spatial and statistical methods can result in important data on trends of changes in groundwater levels, as well as on factors influencing them **(Chaudhuri et al., 2014; Machiwal et al., 2011, Zhou et al., 2016, Li et al., 2014; Healy et al., 2007; Burn et al., 2004; Chen et al., 2004; Konikow, 2013; Wellman, 2015; Eshtawi et al., 2016)**. The examination of the Zagreb

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and Samobor-Zaprešić aquifers commenced in the mid-twentieth century, so that in IGI studies (1966/1967), **Miletić and Borčić (1966**) and **Borčić et al. (1968)** consider the dependence of the water level of the Sava River and groundwater levels in the Zagreb alluvial aquifer. The causes of changes in water levels of the Sava River and groundwater levels have also been analysed by **Bonacci and Trninić (1986)**. Subsequent research is to a great extent documented in the project "Groundwater recording and management in the Republic of Croatia" (Croatian abbr. EGPV), which was realised in cooperation with the company Hrvatske vode (Croatian Waters, the legal entity for water management in Croatia) and the Faculty of Mining, Geology and Petroleum Engineering. Similarly, in their study, **Bačani et al. (1999)** consider the contribution of the Sava River to the restoration of groundwater reserves by the application of water balance analysis. **Bačani and Miletić (2004)** have predicted groundwater levels by application of average recession coefficients obtained by the linear regression method. Based on data collected in the framework of the EGPV project, **Bačani and Posavec (2009)** have analysed the constant groundwater reserves in the preceding period of 30 years while they have analysed the restorable reserves in the period from 1997 to 2007. The analyses have shown that, on average, groundwater levels declined by 1-2 meters every 10 years, and the main causes of continuous decline of groundwater levels in the Zagreb and Samobor-Zaprešić aquifers are to be found in the lowering of the river bed of the Sava River, the construction of levees for protection from flooding which disabled occasional flooding of the hinterland and infiltration of water from flooded areas into the aquifer, as well as groundwater exploitation for the needs of public water supply of households and industry.

In the framework of this study, the general decline of medium groundwater levels has been considered, based on available level measurements, which started to be observed more significantly in the 70-ies of the last century. A groundwater level difference map has been created comparing the current groundwater levels and groundwater levels documented in the 70-ies of the last century, with the main aim of identification of the decline of groundwater levels in certain parts of the aquifer. Furthermore, older measurements of groundwater levels in certain locations have been considered, which – although, considering spatial frequency, they are insufficient for spatial analysis, i.e. the creation of head contour maps, they still offer insight into groundwater levels documented even before the 70-ies of the twentieth century. The analysis has also included older groundwater level maps dating from the 60-ies of the past century, which offer additional insight into the historically measured groundwater levels. Considering the engineering interventions in the Sava River in the form of construction of the weir of the Zagreb cogeneration plant TE-TO (**Biondić, 1995**), as well as the occurrence of hydrologically above-average favourable years such as 2013/2014, the author has also analysed the developments which have temporarily slowed down the negative trends of groundwater levels, but haven't halted them.

2. Study area

The research area is located in North-western Croatia, in the lowlands of the Sava River, and it extends from the Slovenian border on the northwest to Rugvice on the east, and stretches from Marijagorička hills and the southern slopes of Medvednica on the north to the north-eastern slopes of Samoborsko gorje and Vukomeričke Gorice on the south (see **Figure 1**). The Samobor-Zaprešić aquifer is about 15 km long with an average width of approximately 5 km while the Zagreb aquifer is about 30 km long and 10-15 km wide. The Zagreb and Samobor-Zaprešić aquifers are built of Middle and Late Pleistocene and Holocene sediments. The genesis, spatial position, lithologic structure, and dimensions of both aquifers are the result of paleogeographic, climatic and tectonic processes, which were predominant during Quaternary. During the Middle and Late Pleistocene, the research area was covered with lakes and swamps while the surrounding hillocky and mountainous area was the mainland subject to intense erosion and denudation. The eroded material floated into streams and sedimented in lakes and swamps **(Velić and Saftić, 1991)**. The tectonic movements at the end of Pleistocene and the beginning of Holocene led to faulting and terrain lowering, and that is how the transport of big amounts of large clastic material from the Alps started **(Velić and Durn, 1993, Velić et al., 1999)**. Depending on the potency of a water flow, at the same time as the material was being transported, an erosion and relocation of the already sedimented material in the Sava River was taking place. The result of such conditions is a distinct aquifer heterogeneity and anisotropy, as well as uneven deposit thickness. The Zagreb and Samobor-Zaprešić aquifers are of the unconfined type, and their upper boundary consists of a water table in contact with the Sava River. The Sava River bed is cut into alluvial deposits, which are predominantly represented by gravel and represent the main aquifer layer. Aquifer recharge is to the greatest extent realised by infiltration from the Sava River, and to a lesser degree by rainwater infiltration and inflow across aquifer boundaries **(Nakić, et al., 2013)**. During high water levels, the Sava River recharges the aquifer while during medium and low water levels on some parts of the water flow, aquifer discharge takes place, adversely affecting groundwater levels **(Posavec and Škudar, 2016; Posavec et al., 2017)**. Groundwater recharge/discharge from the Sava River depends to the greatest extent on the river flow and flow rate, i.e. the flux and associated water levels as well as ground water levels, whose difference governs hydraulic gradients, the duration of high/low water levels in the river, and temperature affecting the hydraulic conductivity of deposits on the bottom of

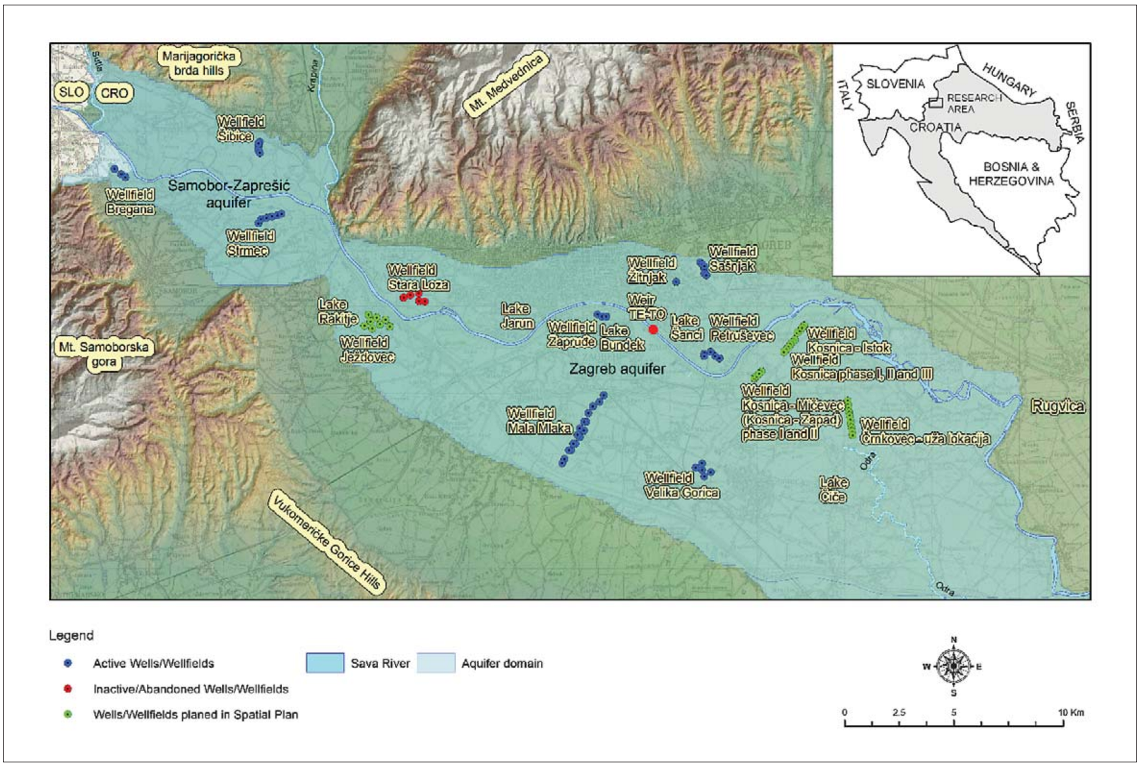

Figure 1: Research area

the river, in the Sava River bed, and in the aquifer layer, i.e. on groundwater level and aquifer properties **(Posavec, 2006)**.

3. Data and methods

In this study, measured groundwater levels were analysed in 803 observation wells in the area of the Zagreb and Samobor-Zaprešić aquifers since the 70-ies of the twentieth century. The measurements were conducted by the Meteorological and Hydrological Service of the Republic of Croatia (Croatian abbr. DHMZ), as well as the companies Vodoopskrba i odvodnja d.o.o. and Zaprešić d.o.o. The measurements of the Sava River water levels were also analysed by the DHMZ at 13 gauging stations from the border with the Republic of Slovenia to Dubrovčak, used to create the head contour maps together with measurements of groundwater levels. The data on groundwater levels, the Sava River water levels, coordinates of observation wells and gauging stations on the Sava River have been gathered from the database of the project Groundwater recording and management in the Republic of Croatia (Croatian abbr. EGPV).

Head contour maps have been created for medium water levels of the 70-ies of the past century on the day of May 22nd, 1975, and for medium water levels in the year 2015, which was an average hydrologic year, on the day of May 6th, 2015. Furthermore, a map of their head differences was created identifying the changes of groundwater levels in the area of the Zagreb and Samobor-Zaprešić aquifers. For the creation of head contour maps and head difference maps, i.e. for the spatial interpolation of measured values of groundwater levels and the interpolation of calculated values of differences in groundwater levels, a standard interpolation algorithm *Natural Neighbour* was used.

The analysis also entails older groundwater level maps **(Miletić and Borčić, 1966)** dating from the 60-ies of the last century. High water level maps on the day of December 13th, 1965 and low water level maps on the day of November 4th, 1965 offered additional insights into the historically measured groundwater levels.

In addition, time series of groundwater levels were analysed, i.e. hydrographs of characteristic observation wells in the area of active wellfields and in the vicinity of the weir of the Zagreb cogeneration plant TE-TO. The analyses of time series of groundwater levels have offered insight into trends of groundwater levels and significant developments, which have, in time, led to changes in general trends in certain parts of the aquifers. Prediction trends of groundwater levels, which would have been observed had it not been for the construction of the weir of the Zagreb cogeneration plant TE-TO in the Sava River, were also analysed as well as the occurrence of hydrologically above-average favourable years, such as 2013/2014.

4. Results

The head contour map of medium water levels on the day of May 22nd, 1975 offers insight into medium

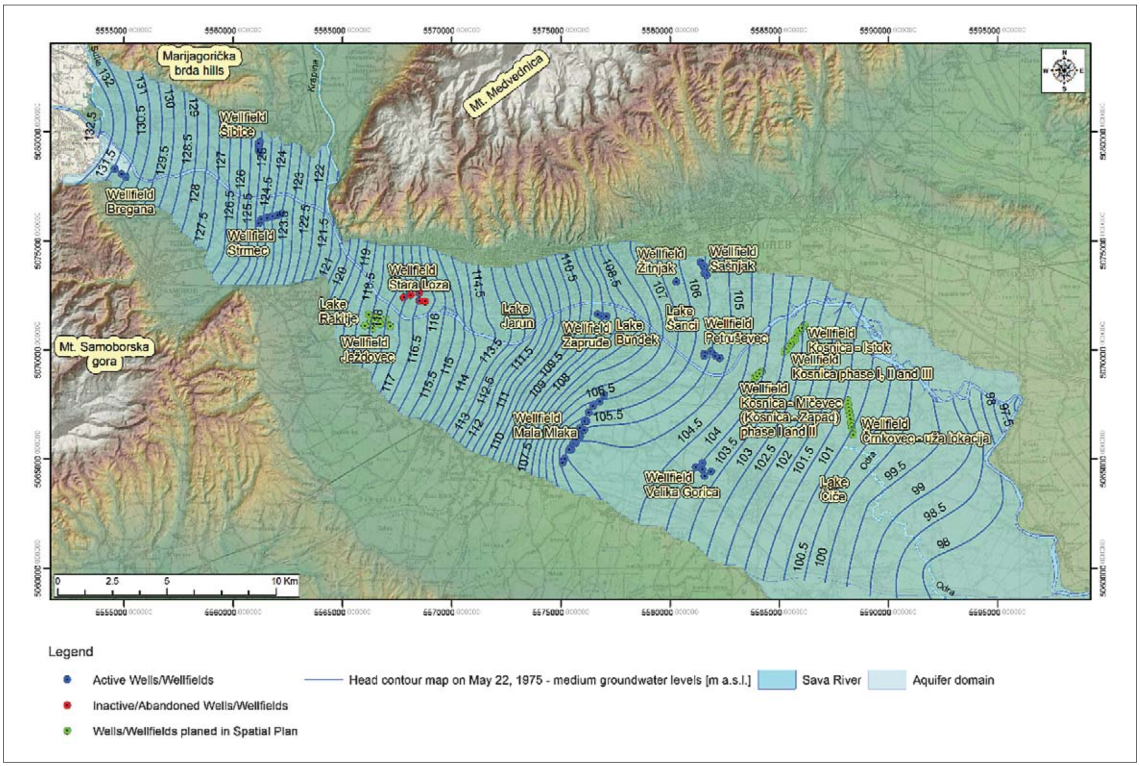

Figure 2: Head contour map of medium ground water levels in 1970's

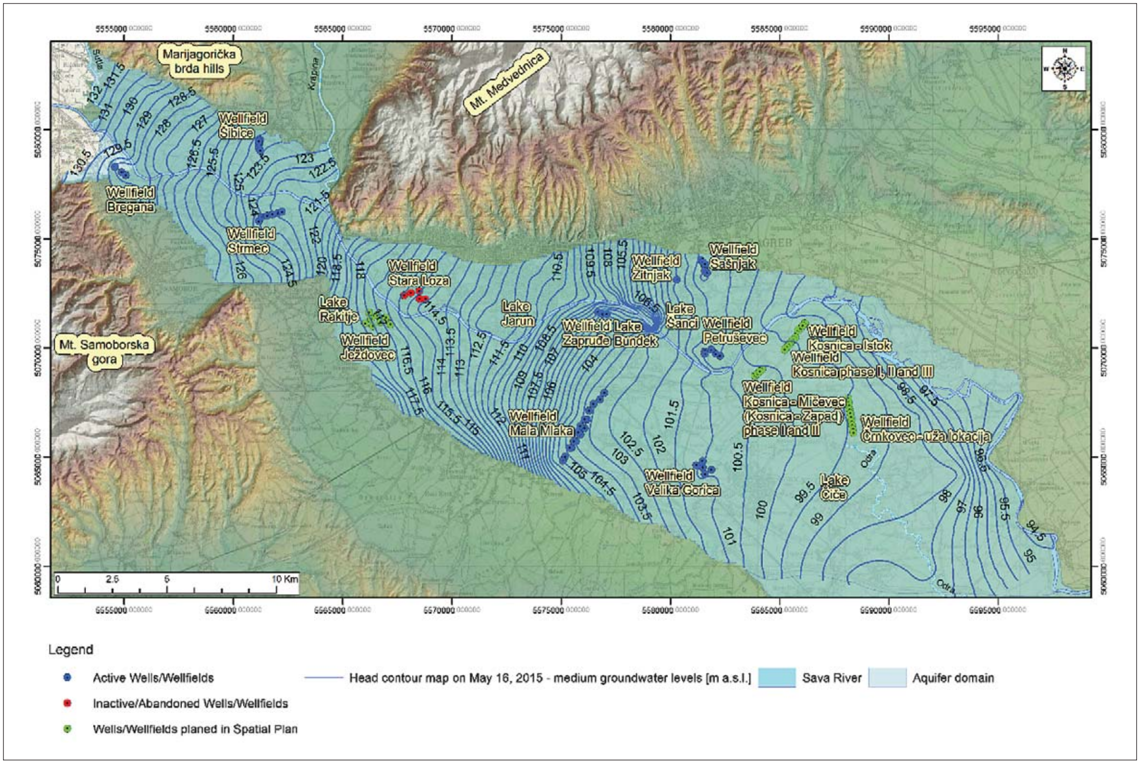

Figure 3: Head contour map of medium ground water levels in year 2015

groundwater levels of the 70-ies of the last century, which amounted to approximately 132.5 m a.s.l. in the western and 121 m a.s.l. in the eastern parts of the Samobor-Zaprešić aquifer (see **Figure 2**). As for the wellfields used for public water supply, the medium groundwater level amounted to approximately 131 m a.s.l. in the area of the Bregana wellfield, approximately 125 m a.s.l. in the area of the Šibice wellfield, and approximately 124 m a.s.l. in the area of the Strmec wellfield. As far as the Zagreb aquifer is concerned, the me-

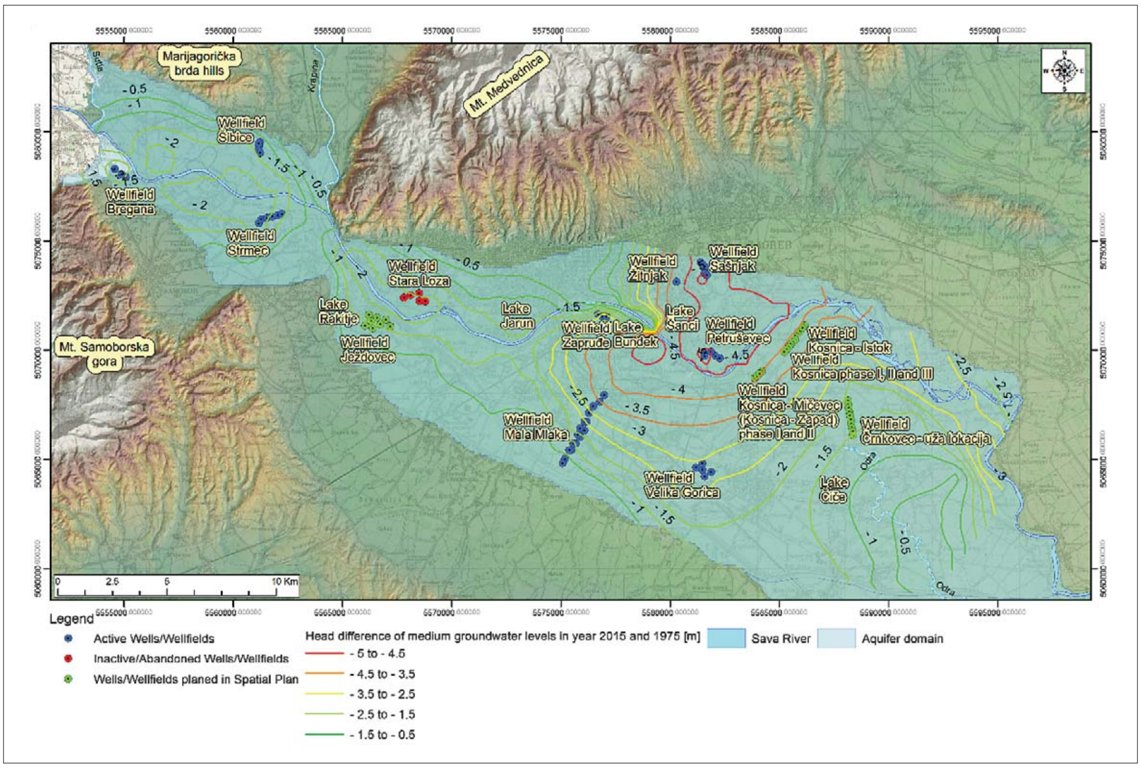

Figure 4: Head difference map of ground water level decline from the middle of the twentieth century until year 2015

dium groundwater level on the day of May 22nd, 1975 amounted to approximately 121 m a.s.l. in its western and 98 m a.s.l. in its eastern parts. Looking at wellfields used for public water supply, the maps show the medium groundwater level of approximately 109.5 m a.s.l. in the area of the Zapruđe wellfield, approximately 106 m a.s.l. in the area of the Mala Mlaka wellfield, approximately 105.5 m a.s.l. in the area of the Sašnjak and Petruševec wellfields, and approximately 104 m a.s.l. in the area of the Velika Gorica wellfield. The general groundwater flowing direction for medium water levels was from the northwest to southeast, but the influence of exploitation that leads to the changes in local direction of flow and forming of cones of depression is to be observed in the area of the Mala Mlaka wellfield.

However, the head contour map of medium groundwater levels on the day of May 16th, 2015 offers insight into more recent medium groundwater levels, which amounted to approximately 132 m a.s.l. and 119 m a.s.l. in the western and eastern parts of the Samobor-Zaprešić aquifer, respectively (see **Figure 3**). As far as the wellfields used for public water supply are concerned, the medium groundwater level amounted to approximately 128.5 m a.s.l. in the area of the Bregana wellfield, approximately 123.5 m a.s.l. in the area of the Šibice wellfield, and approximately 122.5 m a.s.l. in the area of the Strmec wellfield. As far as the Zagreb aquifer is concerned, the medium groundwater level on the day of May 16th, 2015 amounted to approximately 119 m a.s.l. and 95 m a.s.l. in its western and in its eastern parts, respectively. Looking at wellfields used for public water supply, the medium groundwater level amounted to approximately 106.5 m a.s.l. in the area of the Zapruđe wellfield, approximately 104 m a.s.l. in the area of the Mala Mlaka wellfield, approximately 100.5 m a.s.l. in the area of the Sašnjak and Petruševec wellfields, and approximately 101 m a.s.l. in the area of the Velika Gorica wellfield. The general groundwater flow direction was also from the northwest to the southeast, but the influence of exploitation that leads to the changes in local direction of flow and creation of cones of depression is now also to be observed in the area of all active wellfields, as well as in the part of the aquifer upstream from the weir of the Zagreb cogeneration plant TE-TO.

By subtracting the head contours of medium groundwater levels on the day of May 16th, 2015 from the head contours of medium groundwater levels on the day of May 22nd, 1975, head difference map was obtained, which offered insight into the decline of groundwater levels in certain parts of the Zagreb and Samobor-Zaprešić aquifers since the middle of 70-ies of the last century (see **Figure 4**). Groundwater levels in the area of the Samobor-Zaprešić aquifer has generally been decreased by approximately 2 m while the decline in the area of the Zagreb aquifer differs in its western, central, and eastern parts. The decline in the area of the western part of the Zagreb aquifer amounts generally to approximately 1-2 m, in the central part to approximately 2-5 m, and in the eastern part to approximately 1-3 m. The decline is expressed at the most in the area of wellfields downstream from the weir of the Zagreb cogeneration plant TE-TO, namely, in the area of the Petruševec and

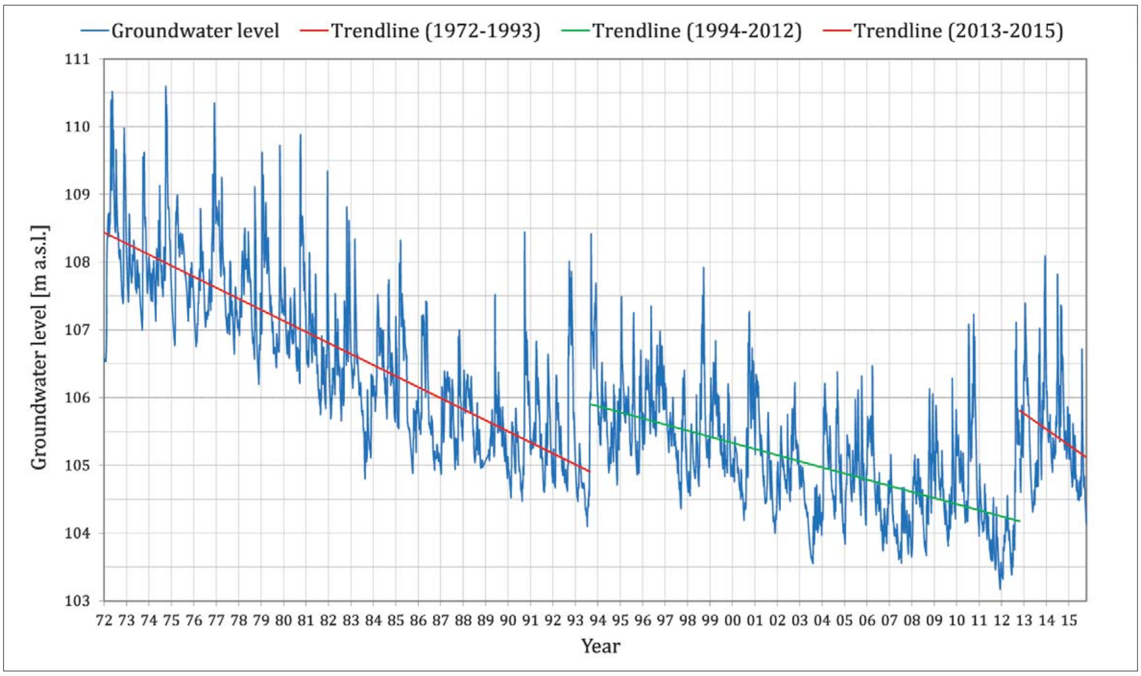

Figure 5: Negative trend of groundwater levels – observation well 107 located upstream from weir TE-TO, right bank of the Sava River

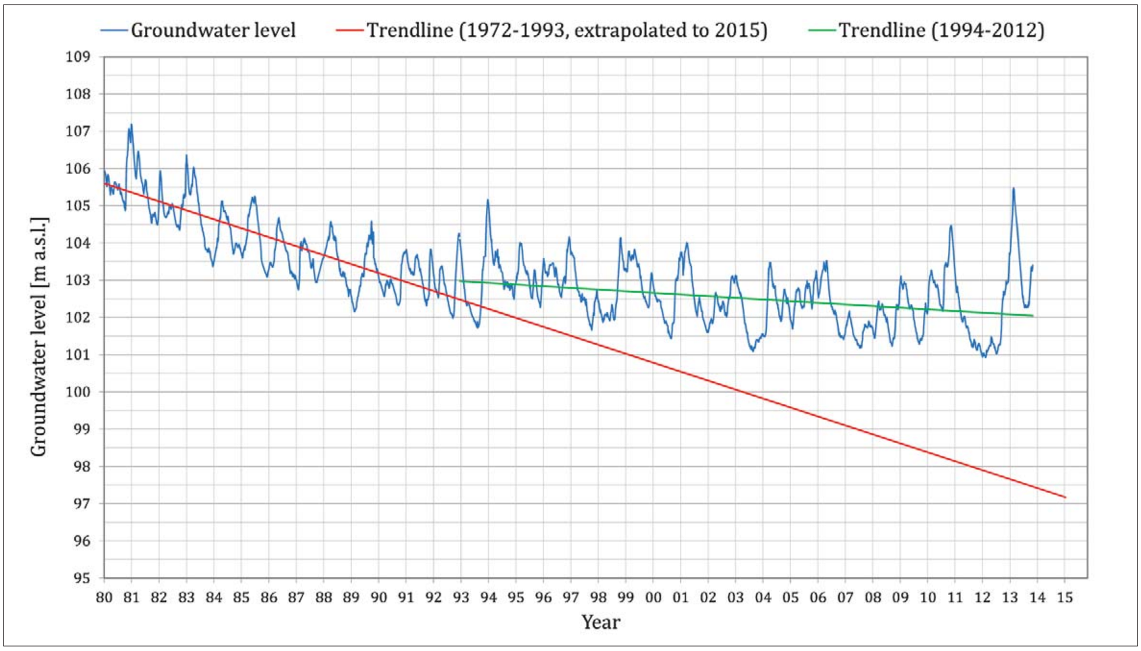

Figure 6: Negative trend of groundwater levels – observation well 283 located on the area of wellfield Mala Mlaka

Sašnjak wellfields (approximately 4-5 m), and in the area of the central and northern parts of the Mala Mlaka wellfield (approximately 3 m).

The analysis of groundwater level map from the year 1965 for the area of the Zagreb aquifer **(Miletić and Borčić, 1966)** shows even more significant differences. Thus, the medium groundwater levels in the area of the Mala Mlaka wellfield amounted to approximately 108.5 m a.s.l., which differs by approximately 5 m from the medium groundwater levels for the year 2015. An even more significant difference has been observed in the area of the Petruševec wellfield, as well as in the area of the Sašnjak wellfield, where the difference is approximately 6.5 m.

Significant differences in the decline of groundwater levels in the central and western parts of the Zagreb aquifer (see **Figure 4**) have come about, to the greatest degree, as a result of the construction of the weir of the Zagreb cogeneration plant TE-TO in the Sava River and of the groundwater exploitation in the area of the most

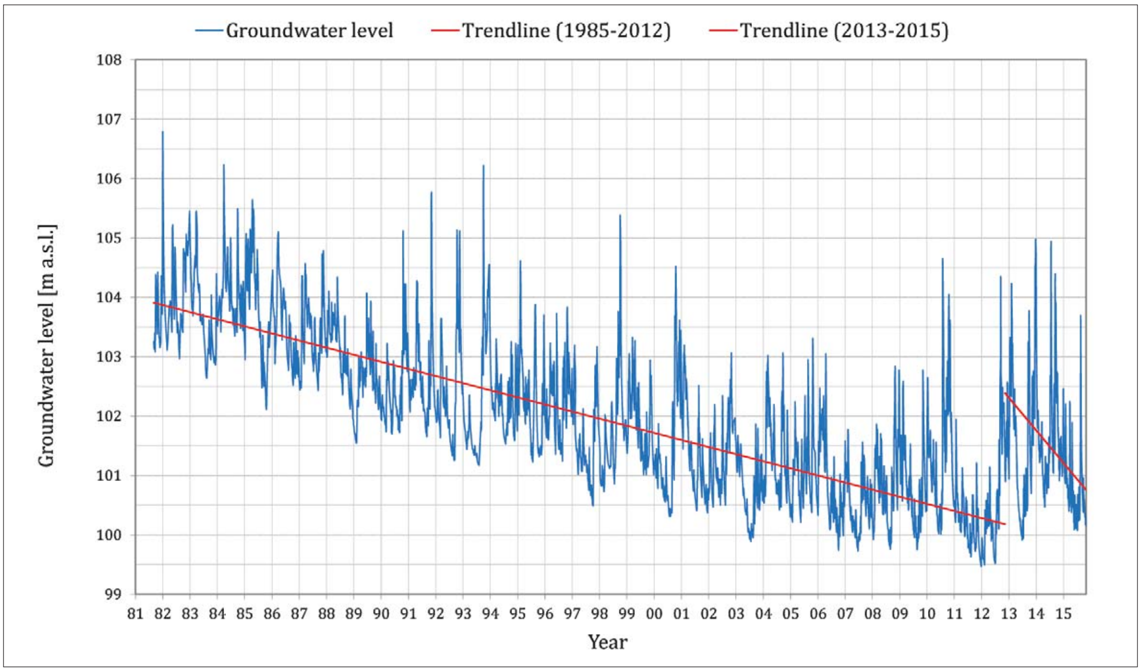

Figure 7: Negative trend of groundwater levels – observation well 631 located on the area of wellfield Petruševec

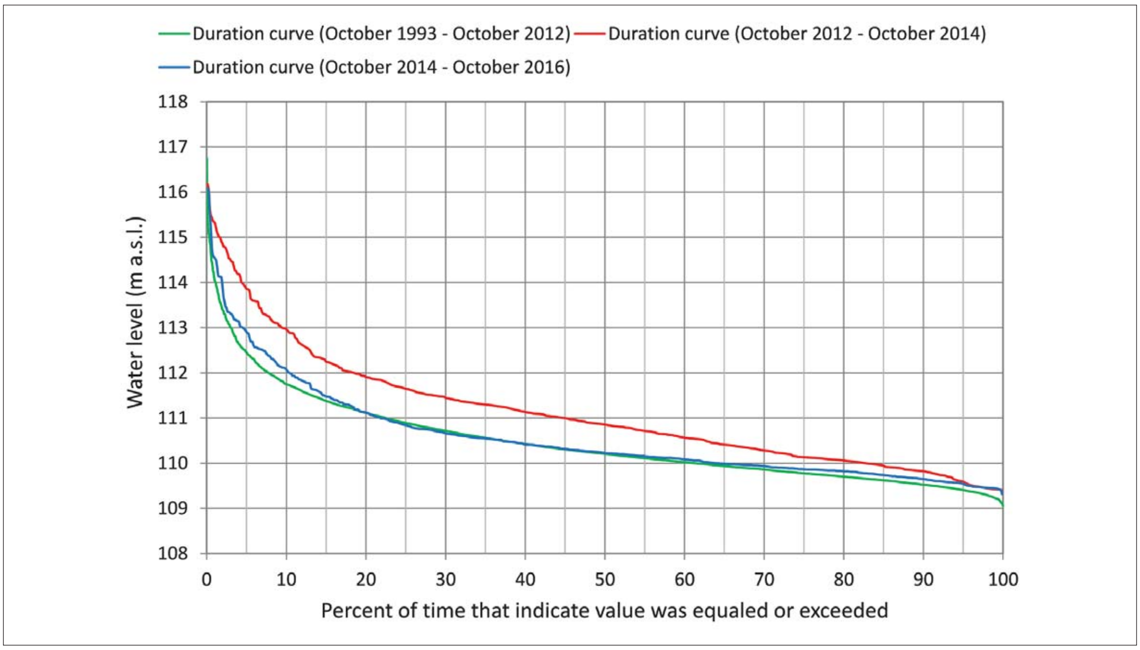

Figure 8: Duration curves of the river Sava water level – gauging station Zagreb

important wellfields of the City of Zagreb, namely, the Mala Mlaka and Petruševec wellfields. Thus, the construction of the weir of the Zagreb cogeneration plant TE-TO has slowed down the negative trend of the decline of groundwater levels in the western part of the Zagreb aquifer, i.e. in the area of the aquifer upstream from the weir, due to the stalling of further erosion of the Sava River bed and its deepening. On **Figure 5**, we can observe a hydrograph of the observation well 107 located on the right bank of the Sava River, immediately upstream from the weir of the Zagreb cogeneration plant TE-TO. After the last weir repair in the year 1993, groundwater levels upstream from the weir have somewhat risen, but, in time, the negative trend continued, however, it has been somewhat slowed down. Slowing down of the negative trend upstream from the weir of the Zagreb cogeneration plant TE-TO influenced the Mala Mlaka wellfield significantly. Namely, groundwater levels in the area of the Mala Mlaka wellfield would be approximately 5 m lower today had the weir of the Zagreb cogeneration plant TE-TO not slowed down the negative trend of groundwater levels (see **Figure 6**).

The analysis of time series of groundwater levels shows that the influence on the total difference between the decline of groundwater levels in the 60-ies of the twentieth century and today's levels – apart from the erosion of the Sava River bed and its consequential deepening – is also a result of the weir of the Zagreb cogeneration plant TE-TO and hydrologically favourable periods, which also influence the trends of groundwater levels. Namely, during high water levels of the Sava River – which are a result of intense rainfall in the upstream part of the Sava River basin – primarily in the Republic of Slovenia, significant recharge of the aquifer and a rise of groundwater levels occur. E.g. the analysis of hydrographs of the observation well 107 (see **Figure 5**) and the observation well 631 located in the area of the Petruševec wellfield (see **Figure 7**) shows that the hydrologically favourable period of the years 2013/2014 significantly slowed down the negative trend of groundwater levels although – after that period – the negative trend continued. Namely, the influence of such an exceptionally hydrologically favourable period, which has – to a certain degree – risen groundwater levels, has been observed on all observation wells of the Zagreb and Samobor-Zaprešić aquifers. The analysis of time series of groundwater levels shows that since the 60-ies of the last century, there was no such exceptionally hydrologically favourable period for two subsequent years. Thus, if we analyse water levels of the Sava River at the Zagreb gauging station located in the vicinity of Jadranski most, we can observe that the water levels that lasted 60% and less are higher by 0.5-1.5 m than those documented in the periods from 1993 to 2012 and from 2014 to 2016 (see **Figure 8**). Such a long duration of high water levels of the Sava River have led to a significant recharge of the aquifer and to a general rise of groundwater levels. However, the analysis of the period following the year 2014 shows that water levels of the Sava River are, once again, in accordance with the average groundwater levels (see **Figure 8**), which led to the discharge of the aquifer. The negative trend of groundwater levels continued at a somewhat faster pace considering higher hydraulic gradients, which are a consequence of higher groundwater levels resulting from a more intense recharge of the aquifer in hydrologically extremely favourable years 2013/2014.

5. Conclusions

The decline of groundwater levels can cause numerous ecologic and economic problems, which can adversely affect the aquifer and public water supply, as well as efficient water management, in general. Therefore, it is important to understand the factors affecting it.

Firstly, the decline of groundwater levels leads to a decrease of the total aquifer reserves. Furthermore, the decline of groundwater levels can adversely affect the public water supply in many ways. If groundwater level declines below the screen top in wells, the capacity of the wells decreases. Moreover, if it declines below the well pump intake, it is necessary to lower the pump if such a possibility exists, which leads to increased financial costs, i.e. increased electricity consumption for water abstraction. In some cases, it is also necessary to drill new wells or to build new wellfields, which also requires significant financial investments. Furthermore, the decline of groundwater levels causes increased endangerment of groundwater dependent ecosystems.

The analysis of historical groundwater levels has shown that since the 70-ies of the past century in the area of the Samobor-Zaprešić aquifer, groundwater levels have generally declined by approximately 2 m while their decline in the area of the Zagreb aquifer amounted to approximately 1-2 m in its western part, approximately 2-5 m in its central part, and approximately 1-3 m in the eastern part of the aquifer. The most significant decline has been observed downstream from the weir of the Zagreb cogeneration plant TE-TO, more specifically, in the area of the Petruševec and Sašnjak wellfields and in the central and northern parts of the Mala Mlaka wellfield, where it amounted to 4-5 m and approximately 3 m, respectively. Analysis of the groundwater level map from the year 1965 for the area of the Zagreb aquifer has shown that these differences are even more significant and amount to approximately 5 m and 6.5 m in the area of the Mala Mlaka wellfield and the Petruševec and Sašnjak wellfields, respectively.

The decline of groundwater levels would have been even more significant had the weir of the Zagreb cogeneration plant TE-TO in the Sava River not been constructed. Namely, the weir of the Zagreb cogeneration plant TE-TO has, to a certain extent, slowed down the negative trend of the decline of groundwater levels in the western part of the Zagreb aquifer, thus halting the further erosion and deepening of the Sava River bed. Slowing down of the negative trend also influenced the Mala Mlaka wellfield to a great degree, in the area of which groundwater levels would be lower by approximately 5 m today had the weir of the Zagreb cogeneration plant TE-TO not been constructed.

The total difference in the decline of groundwater levels between the 60-ies of the past century and today – apart from erosion of the Sava River bed and its deepening, as well as the weir of the Zagreb cogeneration plant TE-TO – has also been influenced by an increase in pumping rates of the wellfields. Namely, in the eighties of the past century when pronounced exploitation began, the pumping rate amounted to some 3 m^3/s. The pumping rate was increased constantly in the following years and in the late nineties amounted to some 5 m^3/s. In following years, the pumping rate stabilized and started to decrease slowly to some 4 m^3/s, which is more or less the present state pumping rate. Furthermore, the decline of groundwater levels has also been significantly influenced by hydrologically favourable periods, which affect the slowing down of negative trends of the decline of groundwater levels. Thus, the hydrologically favourable period of the years 2013/2014, during which high water levels of the Sava River of above-average duration had been observed, slowed down to a certain degree the negative trend of groundwater levels. Namely, the water levels that lasted 60% or less were higher by 05.-1.5 m than the average ones, which led to a significant recharge of the aquifer and a general rise of groundwater levels. However, the negative trend of groundwater levels continued again after the year 2014.

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SAŽETAK

Identifikacija sniženja razine podzemne vode na području zagrebačkoga i samoborsko-zaprešićkoga vodonosnika od šezdesetih godina prošloga stoljeća

U radu su analizirane povijesne izmjerene razine podzemne vode u piezometrima zagrebačkoga i samoborsko-zaprešićkoga vodonosnika od sedamdesetih godina prošloga stoljeća do danas. U analizu su uključene i starije karte razina podzemne vode koje datiraju iz šezdesetih godina prošloga stoljeća, a koje daju dodatan uvid u povijesno stanje razina podzemne vode. Analizom postojećega stanja i povijesnih razina podzemne vode identificirane su promjene razina na pojedinim dijelovima vodonosnika, s posebnim osvrtom na događaje koji su tijekom vremena doveli do usporavanja negativnoga trenda razina podzemne vode na pojedinim dijelovima vodonosnika. Najvažniji takvi događaji u posljednjih pedesetak godina jesu izgradnja praga TE-TO u rijeci Savi kod termoelektrane toplane Zagreb te pojave hidrološki natprosječno povoljnih godina kao što su bile 2013./2014., a na koje je dan poseban osvrt. Analizom je utvrđeno da su razine podzemne vode zagrebačkoga i samoborsko-zaprešićkoga vodonosnika danas općenito niže za oko 3 do 6 m u odnosu na povijesno stanje razina iz šezdesetih godina prošloga stoljeća.

Ključne riječi:
povijesne razine podzemne vode, vremenski nizovi razina podzemne vode, karte razlika razina podzemne vode, zagrebački i samoborsko-zaprešićki vodonosnik

Authors' contribution

Mate Vujević (Dipl.ing.geol.) – Author Mate Vujević gathered and processed the data, processed the figures and wrote one part of the text. **Kristijan Posavec** (Professor, PhD) – Co-author Kristijan Posavec organized the data and wrote one part of the text.