Groundwater Recharge Assessment Using Multi Component Analysis: Case Study at the NW Edge of the Varaždin Alluvial Aquifer, Croatia

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Abstract: Exploring the interaction between precipitation, surface water, and groundwater has been a key subject of many studies dealing with water quality management. The Varaždin aquifer is an example of an area where high nitrate content in groundwater raised public concern, so it is important to understand the aquifer recharge for proper management and preservation of groundwater quality. The NW part of the Varaždin aquifer has been selected for study area, as precipitation, Drava River, accumulation lake, and groundwater interact in this area. In this study, groundwater and surface water levels, water temperature, water isotopes (^{2}H and ^{18}O), and chloride (Cl^-) were monitored in precipitation, surface water, and groundwater during the four-year period to estimate groundwater recharge. Head contour maps were constructed based on the groundwater and surface water levels. The results show that aquifer is recharged from both Drava River and accumulation lake for all hydrological conditions–low, mean, and high groundwater levels. The monitoring results of water temperature, chloride content, and stable water isotopes were used as tracers, i.e. as an input to the mixing model for estimation of the contribution ratio from each recharge source. The calculation of mixing proportions showed that surface water is a key mechanism of groundwater recharge in the study area, with a contribution ratio ranging from 55% to 100% depending on the proximity of the observation well to surface water.

Keywords: groundwater recharge; surface water–groundwater interaction; stable water isotopes; mixing model; Varaždin alluvial aquifer

1. Introduction

Groundwater is a vital part of the hydrological cycle, as billions of people use groundwater for drinking worldwide. Therefore, accurate estimation of groundwater recharge is extremely important for proper management of groundwater systems [1]. Groundwater recharge can be diffuse (from atmospheric precipitation that occurs quite uniformly over large areas) or focused (from surface water bodies such as streams, lakes, lagoons) [2,3]. Various methods are used to estimate the groundwater recharge, such as direct measurements of water level fluctuations, water budget methods, empirical relations, tracer techniques, and numerical modeling [4,5]. The application of multiple methods reduces the uncertainty of individual methods and improves the reliability of the overall recharge assessment.

The Varaždin aquifer is a paramount source of drinking water for approximately 170,000 residents of the Varaždin County in NW Croatia. The aquifer is recognized as a part of strategic groundwater reserves in Croatia due to quality and quantity of groundwater. To ensure sustainable use of groundwater for the entire county, it is very important to define recharge that renews groundwater reserves. Furthermore, management of water resources has to observe Varaždin aquifer as an integrated system with constant interactions between precipitation, surface water, groundwater, and human influence, such as pollution, pumping, technical interventions in the environment, etc. Previous research of the Varaždin

aquifer have been conducted to explore groundwater recharge using different methodology, e.g., water level measurements to indicate flow direction and recharge/discharge zones [6], stable water isotope analyses to study the interaction between precipitation, surface water and groundwater [7], statistical methods and flow duration curves to examine hydraulic connection between surface water and groundwater [8]. However, the recharge of the Varaždin aquifer from both diffuse and focused sources has not been quantified yet.

The main aim of the paper was to identify the key mechanism of groundwater recharge on the NW edge of the Varaždin aquifer, using natural tracers in mixing model. Hydrochemistry and environmental isotopes have been widely employed as effective tracers to define the sources of groundwater recharge [9–12]. Scanlon et al. [2] recognize heat, water isotopes (^{2}H and ^{18}O), and chloride (Cl^-) as commonly applied tracers in their paper about appropriate techniques to quantify groundwater recharge. Water temperature has been frequently used as a natural tracer to study surface water and groundwater interactions [13–15]. Chloride is a conservative tracer, which is often used to estimate groundwater recharge [16–18]. Application of stable water isotopes has become the common technique in investigating hydrological processes [19–21], because they undergo measurable and systematic fractionations within the water cycle. For the purpose of this study, groundwater levels and these natural tracers were monitored during the four-year period within the study area. Groundwater and surface water level measurements were used for qualitative characterization, i.e., to define the recharge direction at the surface water-groundwater boundary for different hydrological conditions. The monitoring results of water temperature, chloride content, and stable water isotopes were used for quantitative characterization of recharge, as an input to the mixing model to determine the contribution ratio from each recharge source (end-members).

2. Study Area

The study area is located in the Drava River valley, on the NW edge of the Varaždin alluvial aquifer in NW Croatia (Figure 1). In this part of the aquifer, groundwater is in contact with surface water: Drava River and accumulation lake Varaždin. The SW part of the study area is considered impermeable due to contact with Haloze hills.

The Drava (ger. Drau, hung. Dráva) river spring is located in the Eastern Alps between Dobbiaco (Toblach) and San Candido (Innichen) in Italy. The Drava drainage system follows largely the Periadriatic fault zone from Italy into Austria and from the confluence with the Lavant River, the Drava River follows the dextral Lavanttal fault for about 15 km before exiting this prominent valley again to enter the narrow gorge between the Pohorje and the Koralpe [22], after which the Drava finally enters the flat Pannonian Basin by the Maribor town. From there it flows southeastward through Slovenia. Then it passes through Croatia and the southern Hungarian border and joins the Danube River near the town of Osijek. Our study area is located at the Drava River entrance into Croatia that means that inflow comes from upstream catchment areas in Italy, Austria and Slovenia that are presented in Table 1.

Table 1. Basin area per country upstream from Croatia.

Country	Basin Area (km^2)	Basin Area (%)
Italy	345	2.24
Austria	11,774	76.47
Slovenia	3277	21.28
Total	15,396	100.00

The biggest catchment area upstream of Slovenian/Croatian border falls within Austria (76.47%) that means that Austrian precipitation has the biggest influence on Drava's discharge regime. Average yearly precipitation of Austrian federal state Carinthia was 1198 mm for period 1981–2010 and in its capital town Klagenfurt was 963 mm for period 1831–2017 [23]. The Drava River has a typical fluvial-glacial water regime according to

its topography and climatic zones–it is characterized by low flows in winter in January and February and high flows in the second half of spring and at the beginning of summer (May, June and July) due to the melting of snow and ice and the highest annual quantity of precipitation. Its other high point is attained in November, when it is filled by autumn rainfall from the wide Alpine hinterland.
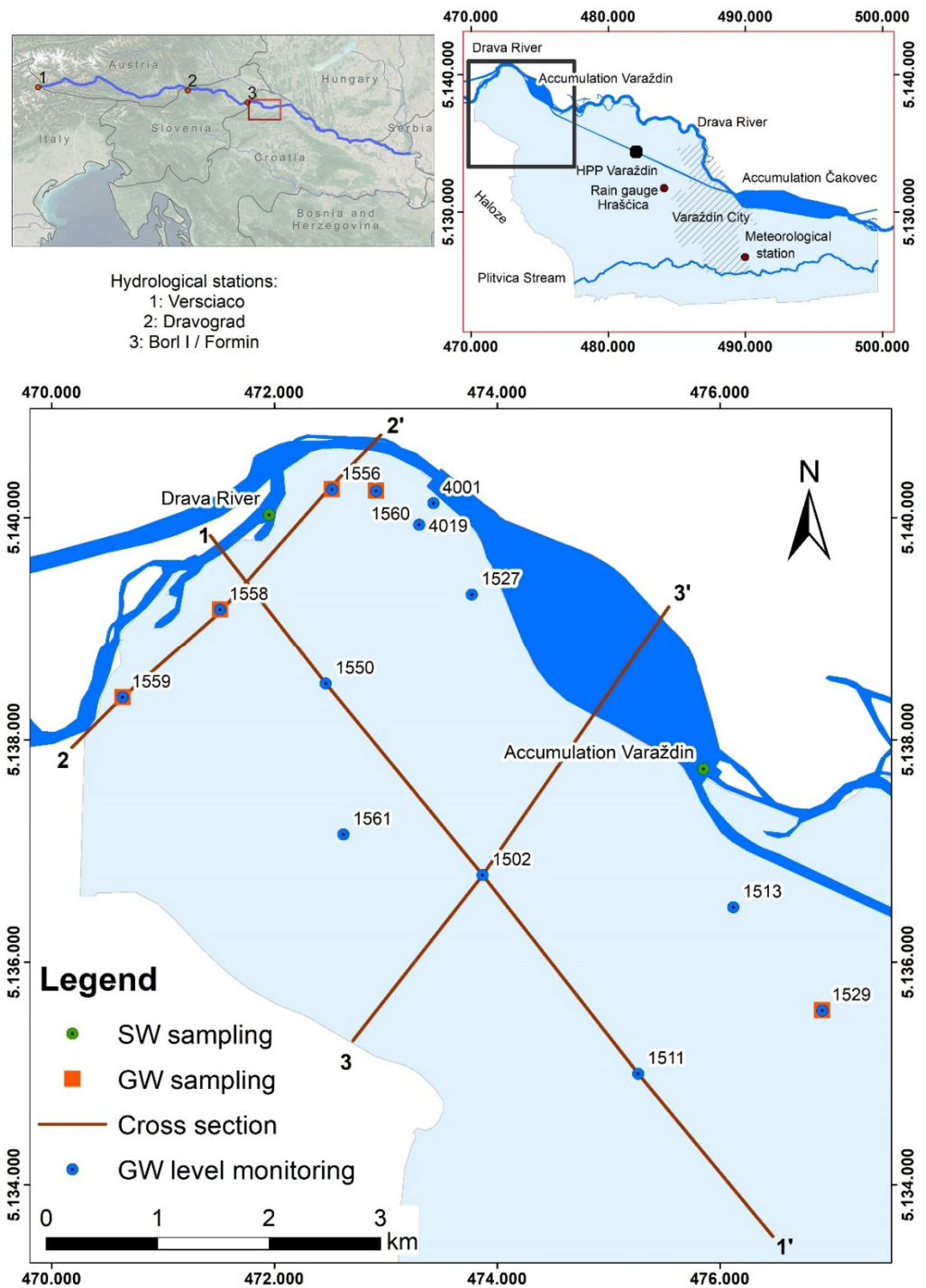

Figure 1. Geographical position of the study area with locations of observation wells used for groundwater level monitoring and sampling sites for surface water and groundwater. The transects 1–1′, 2–2′, and 3–3′ correspond to the representative hydrogeological cross-sections shown in Figure 2.

Table 2 shows the mean inflows of the Drava River into the countries through which it flows. Drava's average inflow from Italy into Austria was 3.13 m^3/s (Amministrazione Provincia Bolzano/Südtiroler Landesverwaltung, personal communication, 14 October 2021), while its outflow into Slovenia at Dravograd hydrological station raised to 244 m^3/s [24]. The Drava River brought around 289 m^3/s into Croatia at the hydrological stations Borl I and Formin [25,26]. Such data shows that the biggest discharge contribution was observed in Austrian territory that is in accordance with the biggest Austrian areal catchment part. Along its path, it has a number of tributaries with their sources in the high Alps at Hoche Tauern, i.e., *Isel*, with its source beneath Grossvenediger (3674 m a.s.l.) joining Drava near Lienz, and *Möll* with its source near Heiligenblutt below Großglockner (3798 m a.s.l.) [27]. According to Bermanec et al. [28] the region of Hoche Tauern is considered to be the source of gold found in fluvial sediments of river Drava from Maribor in Slovenia downstream. This is also the proof of runoff origin from the Hoche Tauern mountains parts that are still under glaciers. River regime is heavily disturbed due to numerous hydroelectric power plants along its way, causing reduced sediment transport and decrease of river discharge, which consequently affect the natural groundwater recharge both in Slovenia and Croatia.

Table 2. Drava's mean inflows from the upstream countries during 1991–2010 period.

Location	Border IT/AUT	Border AUT/SI	Border SI/HR
Hydrological station (country)	Versciaco/Vierschach (IT)	Dravograd (SI)	Borl I + Formin, Drava total (SI)
Av. discharge (m^3/s)	3.13	244	289

The old Drava riverbed in the study area was altered during the 1970s due to the construction of the hydroelectric power plant Varaždin (HPP Varaždin) and its main facilities: accumulation lake, embankment and concrete dam, intake channel, engine room, and derivation channel. Today, Drava River flows into accumulation lake from which it continues either as the Drava River watercourse in the north, or through an intake channel for electricity production in engine room of the HPP. On the NW aquifer boundary, Drava River is cut into the aquifer, directly connecting surface water with groundwater. The accumulation lake is built with embankments and side ditches. It is 3.5 km long, has an area of 2.85 km^2, and a total volume of about 8 hm^3 at an average flow. The lake water level usually varies between 190 and 191 m a.s.l. The embankments of the lake are lined with 9 cm thick asphalt-concrete lining on the water sides to ensure water tightness. Side drainage ditches were constructed along the embankment to collect leaked water from the lake.

The alluvial aquifer consists of Quaternary sediments, which were deposited during the Pleistocene and Holocene [29]. The aquifer matrix is mainly gravel and sand, with variable portions of fine-grained particles [30,31]. The hydrochemical type of groundwater is mainly CaMg–HCO_3, as a consequence of dissolution of carbonate and weathering of silicate minerals that build aquifer sediments [32]. The aquifer thickens from less than 5 m at the NW part to about 15 m in the SE part of the study area (Figure 2). Hydrogeologically, the aquifer is unconfined. The general groundwater flow direction is from NW to SE [6]. The covering layer exists sporadically, so the gravel and sand are often present on the surface of the terrain. The bottom of the aquifer in the study area consists mainly of impermeable marl.
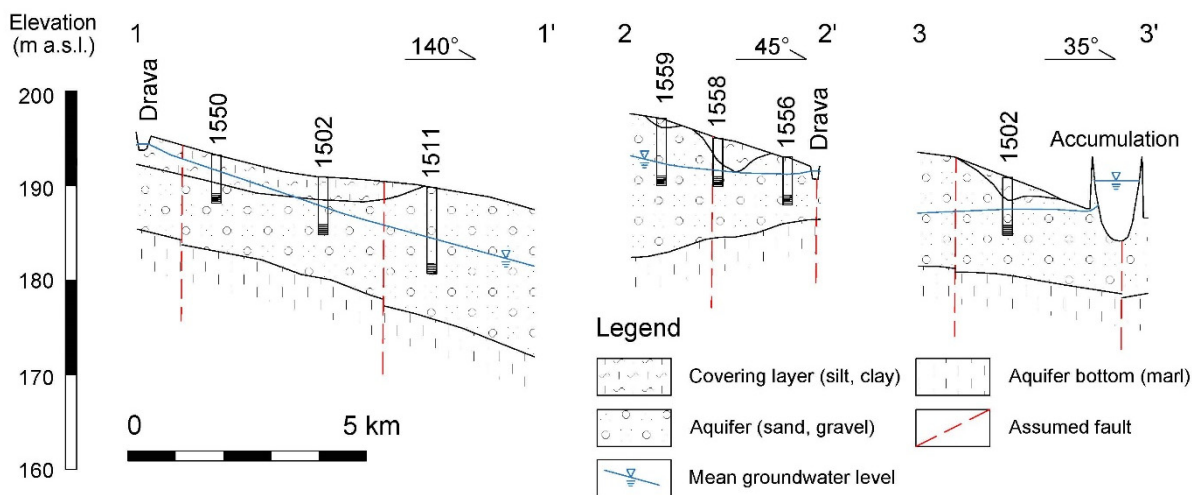
Figure 2. Schematic hydrogeological cross-sections across the NW edge of the Varaždin aquifer representing mean groundwater levels.

According to the Köppen–Geiger classification system of climate types, the study area belongs to the Cfb group or warm-temperate climate [33]. Meteorological parameters (air temperature and precipitation) presented here are from the main meteorological station, located in the vicinity of the Varaždin City (Figure 1). According to the data from the last climate normal period (1981–2010), mean annual air temperature and precipitation were 10.6 °C and 832 mm, respectively [7]. On average, the coldest and driest month was January, the warmest month was July, while maximum precipitation fell in September (Figure 3). Precipitation mostly originates from the Atlantic air masses, with influence of the Mediterranean air masses during the colder season [7]. Modeling results indicate that the mean annual precipitation is distributed as 34% groundwater recharge, 21% surface runoff, and 45% actual evapotranspiration [6].
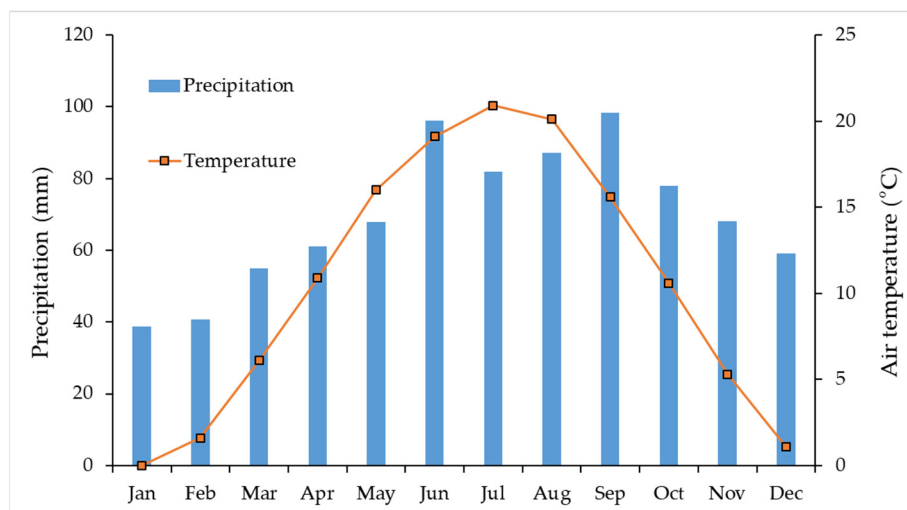

Figure 3. Mean monthly precipitation and air temperature in Varaždin area in the 1981–2010 period.

3. Data and Methods

3.1. Water Sampling and Laboratory Analyses

Water sampling campaigns were carried out for four years on a monthly basis (June 2017–June 2021) for chemical and isotope analyses. Groundwater samples were collected from five observation wells (Figure 1), which are in the groundwater level monitoring network of Croatian Meteorological and Hydrological Service (DHMZ). Observation wells selection criteria were convenient access to the well and the possibility of groundwater

abstraction. Selected wells are situated quite close to the surface water: the distance from the Drava River to the wells 1556, 1558, 1559, and 1560 is roughly between 200 and 400 m, while the furthest well 1529 is about 6.7 km away from the Drava River, and about 2.5 km away from the accumulation lake, measured in the groundwater flow direction (Table 3).

Table 3. Observation wells coordinates, depths, and distance to the surface waters.

Observation Well	Latitude (° N)	Longitude (° E)	Elevation (m a.s.l.)	Well Depth (m)	Distance from the Surface Water (m)
1556	46.401421	16.14261	193.03	5.6	393 (Drava River)
1558	46.391673	16.129586	193.97	5.0	387 (Drava River)
1559	46.384482	16.118252	196.77	7.0	193 (Drava River)
1560	46.401302	16.147773	192.30	5.0	345 (Drava River)
1529	46.359419	16.200068	187.32	8.0	6672 (Drava River) 2519 (accumm. lake)

The wells are small in diameter (one inch), perforated at the bottom, and relatively shallow-between 5 and 7 m in the vicinity of the Drava River (Figure 2, cross section 2–2′), with maximum depth of 8 m in the well 1529 downstream. Prior to sampling, about three volumes of groundwater from each well were pumped out to provide a representative sample from the aquifer. The surface water sampling was conducted on two locations: Drava River and accumulation lake Varaždin (Figure 1). Water temperature (T) was measured in situ using a WTW multi-probe. Monthly composite precipitation was sampled in the Hrašćica village using standard rain gauge. Samples were poured into a 50 mL (groundwater and surface waters) and 1 L (precipitation) HDPE plastic bottles with a tight-fitting cap. All samples were preserved in the portable refrigerator and measured in the laboratory immediately upon returning from the field. Chemical and isotope analyses were conducted in the Hydrochemical Laboratory of the Croatian Geological Survey. All samples were filtered through 0.45 μm sterile syringe filters (Chromafil Xtra PET-45/25) before analyses to remove impurities. Chloride content (Cl^-) was measured on Ion Chromatographer Dionex ICS 6000, while stable isotope ratio ($\delta^{18}O$) was analysed using Picarro L2130-i Isotope Analyzer [34]. The isotope ratios are expressed in standard δ-notation (‰) relative to the international measurement standard, VSMOW2 [35,36]. Measurement precision was ± 0.3 ‰ for $\delta^{18}O$ and ± 1 ‰ for δ^2H.

3.2. Qualitative Analysis of Recharge

The recharge direction between surface water and groundwater in the study area was described by constructing map of hydraulic head contour lines for different hydrological conditions–low, mean, and high groundwater levels. Data on groundwater levels and surface water levels for the study period (June 2017–June 2021) were previewed and used to construct the head contour lines with 0.5 m contour interval. The groundwater level data sets for 13 observation wells in the study area (Figure 1) were provided by DHMZ. A review of the data shows that groundwater levels are measured every 3–4 days. The difference between low and high groundwater levels within individual wells ranged from 0.91 m in well 4019 to 2.20 m in well 1558. The daily measurements of water level of the accumulation lake Varaždin are provided by Croatian National Power Company (HEP). Drava River water levels on the NW boundary of the aquifer were calculated by linear interpolation method between two hydrological stations with measurements of water level: accumulation lake Varaždin and hydrological station Borl I [25], which is situated on the Drava River in Slovenia outside the study area. The water level data for all monitoring stations were analyzed in detail in Microsoft Excel to select the representative hydrological conditions of low, mean, and high groundwater levels. The selected dates were 20 July 2017 (low), 11 July 2019 (mean), and 21 November 2019 (high groundwater levels). The water levels on selected dates were used as an input data for construction of head contour maps in Surfer software, using Kriging interpolation method.

3.3. Mixing Calculations

The calculations of mixing ratios (proportions) were performed using conservative tracers (Cl^- concentrations and $\delta^{18}O$) based on mass balance calculations, which have been widely used [37–39] to determine proportions of two end-members in the sample (studied water). In this study, the aim was to calculate mixing proportions of surface waters (Drava River and accumulation lake) and precipitation in groundwater using PHREEQC software [40]. The calculation was done by using these two equations:

$$f_{SW} = \frac{Cl^-_{sample} - Cl^-_{prec}}{Cl^-_{sw} - Cl^-_{prec}} \tag{1}$$

$$f_{SW} = \frac{\delta^{18}O_{sample} - \delta^{18}O_{prec}}{\delta^{18}O_{sw} - \delta^{18}O_{prec}} \tag{2}$$

where f_{SW} represents the fraction (between 0 and 1) of surface water estimated in a groundwater sample of mixed origin, with the remainder assumed to comprise groundwater of meteoric origin. The Cl^-_{sample} and $\delta^{18}O_{sample}$ represent concentrations in groundwater of the observation wells, Cl^-_{sw} and $\delta^{18}O_{sw}$ represent concentrations in surface water, and Cl^-_{prec} and $\delta^{18}O_{prec}$ represent concentrations in precipitation. Since the water from the lake is isotopically and chemically identical to the river water, only Drava River was used as surface water input in calculations. In addition, a modification was applied in relation to [38], and instead of average values, monthly values of Cl^- and $\delta^{18}O$ in surface water were used. The average rainfall Cl^- concentration of 1.4 mg/L and the $\delta^{18}O$ value of Varaždin weighted rainfall of −8.8 ‰ [7] were used for the precipitation input to the mixing model. In addition, the water temperature was used as a tracer to determine how changes in surface water affect the groundwater, i.e., the temperature time delay in observation well in response to changes in surface water temperature.

4. Results and Discussion

4.1. Temperature, Chloride, and Stable Water Isotopes

The mean, minimum and maximum values of measured water temperature and analyzed chloride, $\delta^{18}O$ and δ^2H in the groundwater and surface water samples collected from June 2017 to June 2021 are presented in Table 4.

All observed parameters show similar values for both surface waters, as it is essentially the same water flowing from the Drava River into the accumulation lake Varaždin. Measured temperature of the Drava River and accumulation lake show typical seasonal variations characteristic of surface waters, with temperatures between 0.5 °C in the colder months and 26.6 °C in the warmer months. The chloride concentrations ranged from 0.5 to 36.7 mg/L which are generally controlled by flushing of the surface in catchment area during rainy seasons and flood events.

The groundwater temperature ranged from 8.7 to 19.8 °C and seasonal variations was observed in monitoring wells closer to the river. Lower temperatures were generally recorded in the colder months, and higher temperatures in the warmer months. The chloride concentrations ranged from 4.1 to 37.3 mg/L (Table 4). Elevated chloride concentrations in groundwater are most commonly associated with application of salt for deicing the roads during the winter months [41,42], but can remain a persistent contaminant throughout the year [43]. However, weathering of minerals that contain chloride can increase the chloride content in groundwater. Concentrations of chloride in all samples did not exceed maximum contaminant level (MCL) of 250 mg/L [44]. Lower mean Cl^- values are associated with wells situated closer to surface waters, while higher mean values are attributed to wells further away from surface waters and/or near the road.

Measured $\delta^{18}O$ values in groundwater samples varied from −11.2 to −8.2 ‰, with average values between −10.1 and −9.5 ‰. Measured $\delta^{18}O$ in surface water samples had slightly more negative values, ranging from −12.1 to −8.1 ‰. Isotopic composition in

groundwater and surface water was compared to two local meteoric water lines: LMWL Klagenfurt [45] that represents climatological conditions upstream of the study area where Drava River springs and from where it is mainly recharged, and LMWL Hrašćica [7] which depicts local climatological conditions in the Varaždin area (Figure 4). The LMWL Hrašćica is slightly below LMWL Klagenfurt. The difference between the two slopes and axis intercept values are 0.3 and 1.6 ‰, respectively. It is observed that measured $\delta^{18}O$ and δ^2H values of surface waters are even above LMWL Klagenfurt, especially in colder parts of the year. This is probably because the major tributaries of the Drava River have catchment areas at altitudes over 3000 m a.s.l. (see Chapter 2: Study Area) which are higher than Klagenfurt station. Consequently, during the colder part of the year, beside altitude effect, the temperature effect is present too, causing more negative values. This feature has been commonly observed in other regions in the world, e.g., in Taiwan [46], where authors concluded that river water mostly originates from the upstream catchment, based on more depleted hydrogen and oxygen isotopes in river in regard to local precipitation. Since observation wells which are close to the river are under the influence of the river, they are isotopically similar. The above insights indicate that the aquifer is recharged by the surface water and precipitation.

Table 4. Statistical values of temperature, chloride and $\delta^{18}O$ in groundwater and surface water.

| Sampling		T (°C)	Cl⁻ (mg/L)	$\delta^{18}O$ (‰)	δ^2H (‰)
	min	9.1	14.1	−11.2	−77.6
1529	max	15.4	37.3	−8.9	−61.0
	mean	12.8	22.4	−9.7	−66.9
	sd	1.5	4.8	0.6	4.1
	min	9.4	5.7	−10.9	−76.0
1556	max	16.0	22.5	−8.6	−58.8
	mean	13.4	9.8	−9.5	−65.4
	sd	1.9	3.7	0.7	5.0
	min	8.7	4.1	−10.0	−70.0
1558	max	16.2	7.1	−9.3	−64.3
	mean	12.8	5.7	−9.7	−66.4
	sd	2.4	1.0	0.2	1.7
	min	15.1	4.5	−10.5	−72.3
1559	max	19.8	11.0	−9.8	−65.8
	mean	17.5	7.1	−10.1	−69.7
	sd	1.6	2.4	0.3	2.3
	min	11.2	11.1	−10.3	−70.1
1560	max	19.8	32.9	−8.2	−56.5
	mean	15.6	19.8	−9.5	−65.6
	sd	2.8	5.9	0.5	3.3
	min	2.5	0.5	−11.6	−80.1
Drava River	max	24.4	36.7	−8.4	−59.9
	mean	13.3	10.1	−10.0	−69.7
	sd	6.8	5.4	0.7	4.8
	min	0.5	0.6	−12.1	−83.6
Accumulation lake	max	26.6	31	−8.1	−57.4
	mean	12.6	7.4	−10.3	−72.1
	sd	6.8	4.5	0.8	5.6
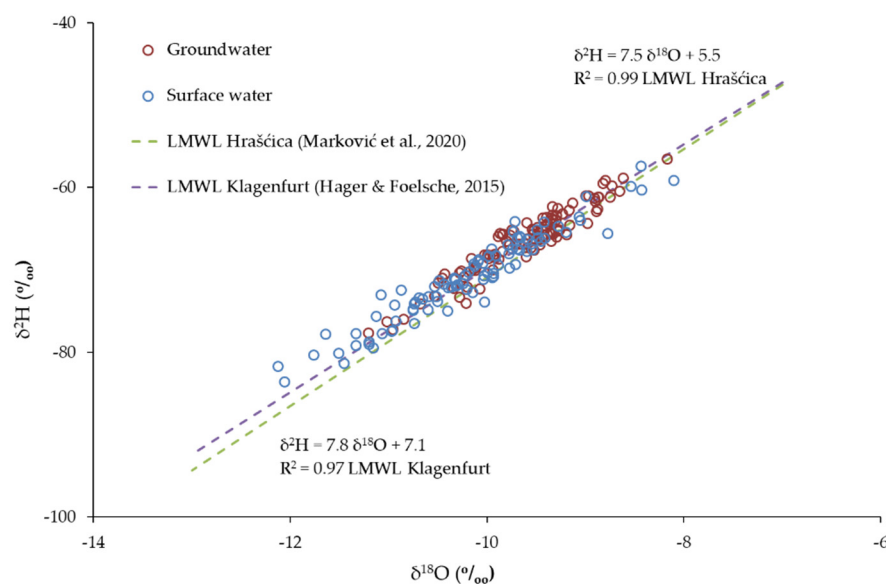
Figure 4. The relationship between $\delta^2 H$ and $\delta^{18}O$ in groundwater and surface water. The presented local meteoric water lines are LMWL Klagenfurt and LMWL Hrašćica.

4.2. Head Contour Maps

The maps of head contours clearly show that aquifer is recharged from both Drava River and accumulation lake for all hydrological conditions (Figure 5). The differences in the groundwater flow net between low, mean, and high groundwater level conditions are barely noticeable, suggesting that groundwater levels predominantly depend on the lake water level, which normally maintains within 1 m. Although the accumulation lake is built to be watertight, a noticeable difference in height between the level of the accumulation and the terrain below causes water seepage (Figure 2, cross section 3–3′). Side drainage ditches exist, but they cannot accept all the water that seeps through, and water flows underneath the ditches into the hinterland. The results are consistent with previous research of the Varaždin aquifer in the period 2008–2017 [6], where authors indicated strong influence of the accumulation lake and Drava River on groundwater levels, keeping the aquifer in the quasi-steady state.

4.3. Mixing Calculations

Possible mixing proportions for both tracers (for Cl^- and $\delta^{18}O$) were successfully calculated for observation wells P-1559, P-1558 and P-1556. However, for observation wells P-1529 and P-1560 the only successful result was obtained by $\delta^{18}O$. The advantage of the water isotopes over chlorides as chemical tracer has also been observed in previous research in different hydrogeological setting [47]. The reason for inclusive results of Cl^- in this study is probably another source of Cl^- in groundwater (mineral weathering/anthropogenic influence), and it was impossible to obtain reliable results. It was observed that the mixing proportion in the observation well P-1559 was 100% surface water, calculated with both tracers regardless on hydraulic conditions within the aquifer. This observation well is the closest to the Drava River (Table 3). However, mixing proportions for other three observation wells which are not far away from the river, P-1558, P-1556 and P-1560, varied depending on hydraulic conditions within aquifer from 58 to 100%, from 59 to 100% and from 68 to 100%, respectively. The reasons for such heterogeneity in calculated propositions between these four observation wells are the distance from the river, local differences in hydraulic conductivity, and the appearance of the low permeable covering layer. The appearance and thickness of the covering layer directly affect the precipitation proportion in groundwater recharge, lowering the precipitation infiltration and increasing the surface runoff. In the observation well P-1529, the farthest one, the surface water mixing

proportions was in range from 55 to 91%. Generally, higher proportion of the river water was observed during the low groundwater levels.
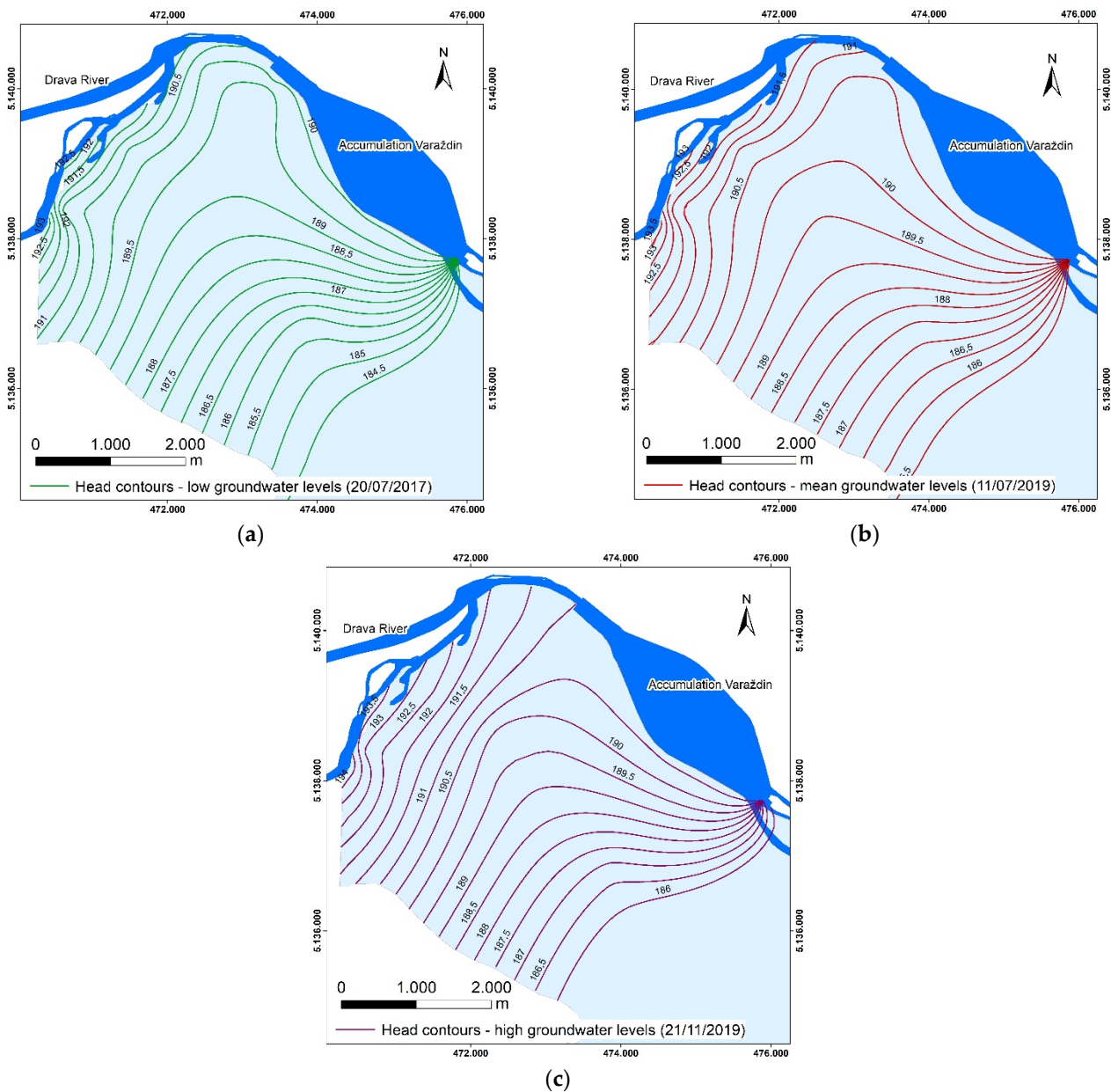

(**a**)

(**b**)

(**c**)

Figure 5. Head contour map for (**a**) low; (**b**) mean; (**c**) high groundwater levels.

The influence of surface waters on the aquifer recharge was also observed through oscillation of water temperatures (Figure 6). As surface waters temperatures changed due to influence of seasonal air temperature oscillations, groundwater temperature also varied due to recharge by surface waters. The amplitude for groundwater was not as high as for the surface waters. Among observation wells, larger amplitude was observed in the well water of P-1556 which represents wells closer to the river than in the well water of more distant P-1529. In addition, the highest temperatures of groundwater were not measured at the same time as for surface waters, there was a few months of delay depending on hydrological/hydraulic conditions within the aquifer and the distance from surface waters. A longer delay was observed in the waters from the farthest observation well P-1529.
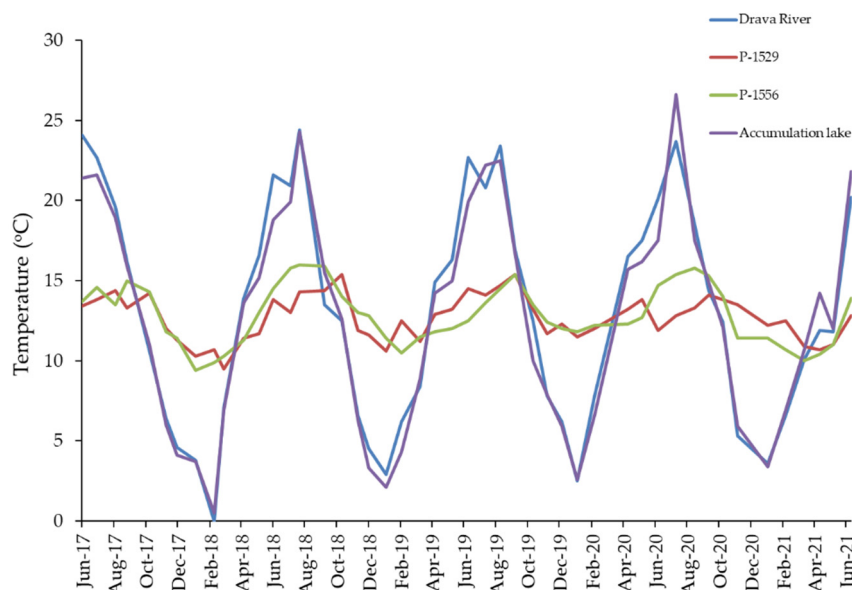
Figure 6. Surface and groundwater temperature oscillation in the monitored period.

Based on the mixing model results, a conceptual model of aquifer recharge is proposed (Figure 7).
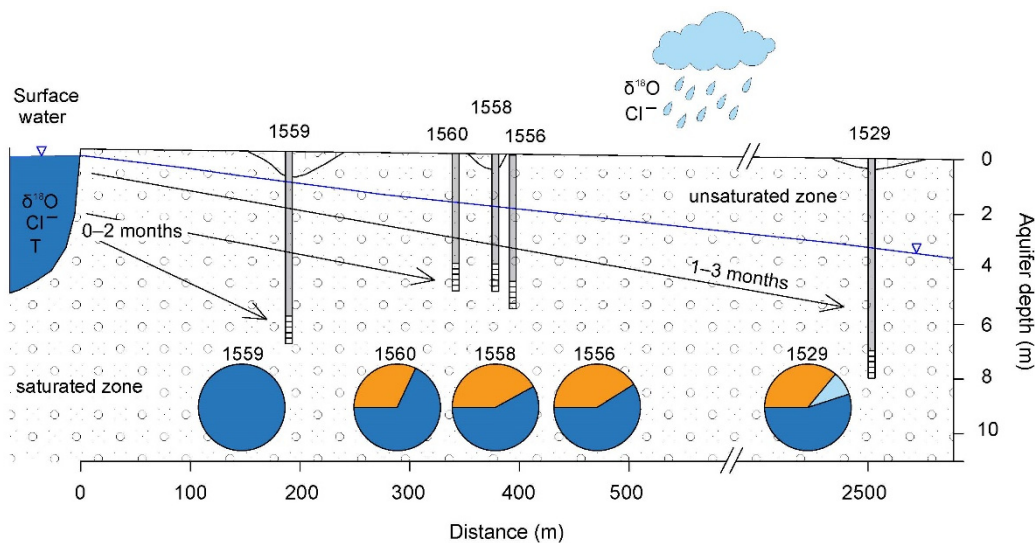

Figure 7. Conceptual model of the groundwater recharge at the NW part of the Varaždin aquifer. Pie charts represent recharge share for each observation well from surface water (blue color), precipitation (light blue color), and interchangeable recharge depending on hydrological conditions (orange color).

5. Conclusions

The main goal of this research was to explore the interaction between precipitation, surface water, and groundwater at the NW edge of the Varaždin alluvial aquifer using multi component approach. The conducted research resulted in the following conclusions:

- Stable isotopes compositions showed that surface waters are mainly recharged by precipitation from higher altitudes and less from the precipitation of the study area. The isotope fingerprint of surface waters was visible in groundwater as a consequence of recharge.
- The head contour maps show that aquifer is recharged from Drava River and accumulation lake for low, mean, and high groundwater level conditions. The groundwater

levels depend greatly on the surface water level, and remain in a quasi-steady state for all hydrological conditions.

- Calculation of mixing proportions using natural tracers (δ^{18}O and Cl$^-$) showed that surface waters are the dominant source of groundwater recharge with contribution between 55 and 100%. The proportion of surface water in groundwater decreases with distance from the Drava River/accumulation lake, lack of covering layer, and unfavorable hydraulic conditions within the aquifer.
- The water temperature analysis confirmed that close observation wells depend more on the recharge from surface water than distant one. The results indicate a time delay of few months in cyclic water temperature oscillations between surface water and groundwater. However, for more conclusive results in terms of mean groundwater residence time, additional parameters need to be considered and studied in future research.
- Since obtained results showed that groundwater recharge is strongly dependent on surface water in the study area, any change in surface water quantity as a result of climate change and/or anthropogenic influence could potentially affect groundwater reserves. This part of the aquifer should be carefully considered in future water management plans to ensure sustainable groundwater supply.

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