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Hydrological system behaviour of an alluvial aquifer under climate change

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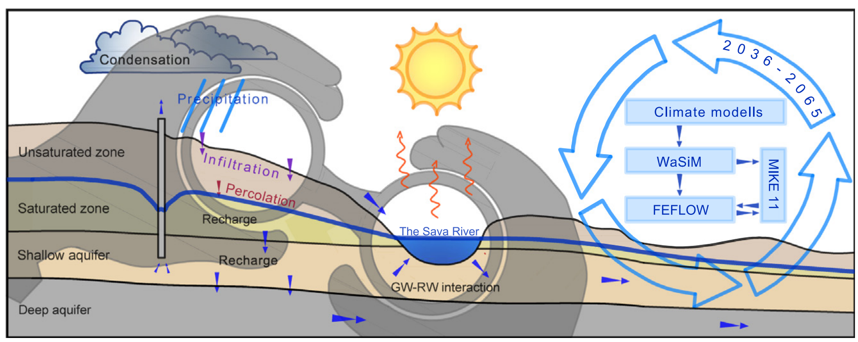
HIGHLIGHTS

- Impacts of projected climate on surface-groundwater interactions are presented.
- The aquifer's sensitivity to the climate is higher if one water source dominates.
- The Ljubljansko polje is not going to suffer due to water scarcity (2036–2065).
- A comprehensive modelling tool approach was applied.

GRAPHICAL ABSTRACT



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ABSTRACT

In this paper, we present an assessment of the sensitivity of groundwater-surface water interactions to climate change in an alluvial aquifer, located in the Ljubljansko polje, Slovenia. The investigation is motivated by a recent assessment of climate change pressures on the water balance in the Sava River Basin (Gampe et al., 2016). The assessment was performed using a comprehensive hydrological modelling approach, which is based on the direct/indirect communication between FEFLOW and WaSiM/MIKE 11. This modelling framework provides a precise simulation of the critical processes in the study domain, which are the main drivers influencing the interactions between precipitation, river water and groundwater under different future climate scenarios. Climate projections were based on the results of the three regional climate models SMHI-RCA4, KNMI-RACMO22E and CLMcom-CCLM4. The results show that there will be higher levels of local precipitation during 2036–2065, the projected river discharge will be larger in the future compared to 2000–2014, and it is unlikely that the Ljubljansko polje will suffer from water scarcity. In addition, amongst the various sections of the Sava River the section between Črnuče and Šentjakob is the one most sensitive to climate change. By running the models under different climate scenarios a deeper insight into aquifer system functioning was obtained. Investigating impacts of climate change on groundwater and interactions between surface water and groundwater on the local scale is a basis for applying such a study on the global scale, which was still not very well investigated.

1. Introduction

Climate change will have a significant impact on the water cycle, and on groundwater resources, which are of high value for health, ecosystems

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and sustainable development (Aslam et al., 2018). Groundwater vulnerability to climate change has already been demonstrated (Aeschbach-Hertig and Gleeson, 2012; Shamir et al., 2015; Dettinger and Earman, 2007; Kundzewicz et al., 2007), but studies on this topic were often ignored, due to their complexity, the relatively slow responsiveness of groundwater to changing climatic conditions, and a lack of data and knowledge (Kurylyk and MacQuarrie, 2013).

Numerical groundwater models are important tools for decision making regarding the management of groundwater resources (White, 2017). These decisions are based on a deep understanding of an aquifer's behaviour under historical, present and future climatic conditions. Particular attention in such a study must be devoted to identify water entering and leaving an aquifer, due to river-groundwater interactions, percolation of local precipitation and water extraction (Green et al., 2011). To date, only limited attention has been given to accurately conceptualizing and parameterizing the surface-groundwater interface (Reid et al., 2009). Moreover, in cases where these processes are critical, they should be integrated into modelling tools (Holman et al., 2012). In addition, when synchronizing multiple hydrological tools a communication link between hydrological and climate models must be established, which is a demanding task, especially due to different spatial scales of both models (NASEM, 2016). For this reason the climate data will need to be downscaled before they are applied to a hydrological model. The standard procedure for forecasting in hydrological modelling is that all the parameters in the calibrated model remain constant, except for the forecast parameter (Anderson et al., 2015).

The aim of this paper is to assess the sensitivity of groundwater-surface water interactions in the Ljubljansko polje to climate change. The work was inspired by a recently published assessment of climate change pressures on the water balance of rivers in the Mediterranean-basin, including the Sava River Basin (SRB) (Gampe et al., 2016). Future climate change projections (2036–2065) were derived from combining four General Circulation Models (GCMs) forcing different Regional Climate Models (RCMs) and one Representative Concentration Pathway (RCP) scenario originating from the EURO-CORDEX initiative (Gampe et al., 2016). A projected decrease in precipitation and a rise in temperature in the SRB under climate change can have either a direct or indirect impact on groundwater in the Ljubljansko polje (Gampe et al., 2016). The aquifer is a major source of water for agricultural, industrial and domestic purposes, and serves the city of Ljubljana and its surrounds. A direct impact can be assessed through changes in recharge rates and an indirect impact due to changes in groundwater use (Taylor et al., 2013). Green et al. (2011) highlights the lack of such studies, despite the fact that groundwater quality is responsive to changing climatic conditions and is linked to land use changes resulting from human activity. For example, changes in groundwater recharge rates, their locations and mechanisms will affect how contaminants are transported. Bračič Železnik et al. (2011) have investigated the impacts of climate change on groundwater quality in the Ljubljansko polje based on correlations between meteorological data, hydraulic head data and the following parameters: turbidity, NO_3^-, TOC, DOC and SAC_{254}, in a single well at Jarški prod, which is located north from the Sava River. Our paper also provides an assessment of the effects of climate change on groundwater quantity, which is based on precise hydrological simulations. The Ljubljansko polje aquifer was used as a case study to assess climate change on water resources within the EU project CC-WaterS, where other modelling tools with a coarser resolution were used than in the investigation provided in this paper (Koeck, 2012). Kundzewicz et al. (2007) claims that knowledge of recharge rates and mechanisms of aquifers are often poor despite their importance in understanding the impacts of climate change on groundwater. A deeper investigation of the water cycle and an assessment of the water balance in the Ljubljansko polje were performed by Vrzel et al. (2018b). In addition, Vrzel et al. (2018a) have developed hydrological modelling tools, with the ability to apply projected climate parameters and provide precise definitions of the processes that drive the water cycle in the region. The hydrology was simulated using three models: 1) a Finite Element subsurface FLOW simulation system (FEFLOW 6.2) for groundwater flow; 2) a physically-based, fully distributed hydrological Water Flow and Balance Simulation Model (WaSiM) for percolation of local precipitation, and 3) a Sava River discharge with a one dimensional (1D) modelling system for rivers and channels–MIKE 11. This investigation describes only the direct impacts of climate change on the aquifer, the same modelling framework can also simulate the indirect impacts of climate change. For instance, projected land use changes can be applied in the WaSiM model, and projected changes of drinking water demand can be applied in the FEFLOW model.

2. The Ljubljansko polje

The Ljubljansko polje is a relatively flat (259.5–327.5 m a.s.l.) ~71 km^2 basin located in central Slovenia surrounded by hills with elevations up to 676 m a.s.l. (Fig. 1). These hills and the bedrock, which can be up to 100 m deep in the central part of the basin, are composed of impermeable Permian and Carboniferous slate, clay-stone and sandstone. The basin was filled with alluvial sediments in Pleistocene and Holocene. In general, these sediments can be divided into five layers: 1) gravel, sand, gravel with sand and silt; 2) conglomerate, clay, conglomerate with lens of clay, 3) gravel with clay, sand with clay, gravel with thin layers of conglomerate, gravel with sand and silt, 4) conglomerate, and 5) gravel with sand and silt. Layers of clay or clay with gravelstone are located only at specific locations, mainly in the south-western part of the basin (Šram et al., 2012).

Urban areas (30%), arable land (22%), industry (19%) and agriculture fields (16%) cover the majority of the basin (Vrzel et al., 2018a).

The climate of the Ljubljansko polje region is classified as Subcontinental, with an annual mean precipitation of 1089 mm. The driest and the wettest months are January (50 mm) and June (126 mm), respectively. The annual mean air temperature is 10.1 °C, with the lowest temperatures recorded in January (average: −0.3 °C) and the highest temperatures in July (average: 20.3 °C) (Kozjek et al., 2017). Since 1961, the mean yearly temperature in Ljubljana increased for ~2.5 °C, while the amount of yearly precipitation decreased by ~70 mm (ARSO, 2018b). The mean yearly temperature and precipitation from 1960 to 2015 are presented in Fig. 2. The quantity of groundwater in the Ljubljansko polje strongly depends on the availability of water upstream of the Ljubljansko polje–in the Alps, where Alpine, Subalpine or Moderate climates of the hilly regions prevail (Kozjek et al., 2017). The Alpine region receives the highest amount of precipitation throughout the year (2540 mm) with a peak in November (311 mm) and has a low annual mean temperature of 3.1 °C (Kozjek et al., 2017).

A general groundwater flow direction is from NW to SE and is closely related to surface water, especially the Sava River water, which originates in the Julian Alps and represents the main source of water inflow in the aquifer. Percolation of local precipitation also plays an important role in groundwater recharge in the basin (Cerar and Urbanc, 2013; Auersperger et al., 2005; Vrzel et al. 2018b). Impacts of these two groundwater sources on the aquifer differ from location to location. Considering the depths of the wells and their distance from the Sava River, the river water contribute different amount of water to the aquifer. There are also parts of the aquifer that are mostly affected by local precipitation (Fig. 6 in Vrzel et al., 2018b). Hydrological studies have shown that the lateral underground inflows from neighbouring groundwater bodies are important for the water balance in the Ljubljansko polje aquifer (Cerar and Urbanc, 2013; Vrzel et al., 2018b). Vrzel et al. (2018a) have also demonstrated the rapid responsiveness of the aquifer to surface water. However, the system responds differently at different locations. For example, the hydraulic head can oscillate within a 24 hour period at Jarški prod due to increased pressure in the aquifer created by the Sava River, while at Kleče oscillations in the hydraulic head appear one month later. Here local precipitation also contributes a significant amount of water to the aquifer (Vrzel et al., 2018a). Thus, the

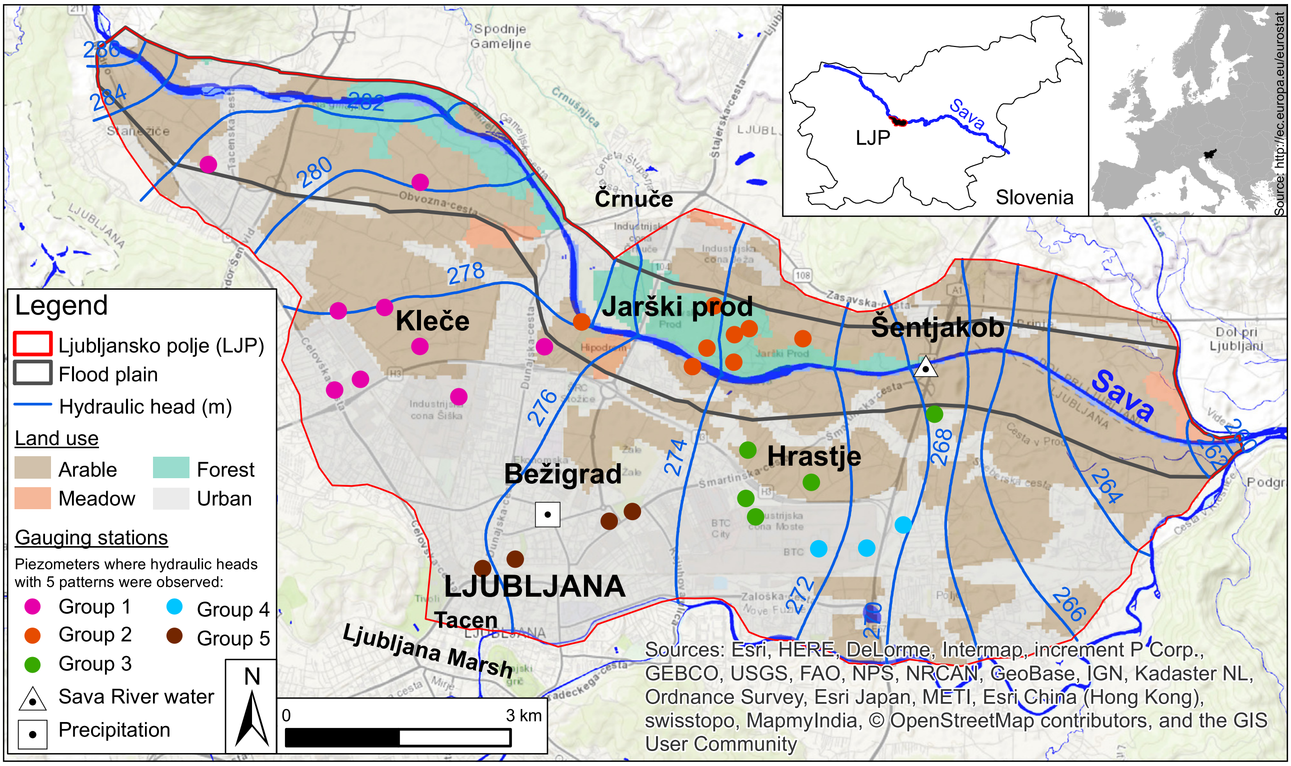

Fig. 1. The Ljubljansko polje with land use and gauging stations of hydraulic heads (piezometers), the Sava River discharge and precipitation. The land use map is from the CORINE Land Cover database (EEA, 2016).

chronological data of the hydraulic heads observed in many piezometers show five oscillation patterns (Fig. 1). However, the subject of this paper are only the first three groups, which are representative for parts of the aquifer where pumping stations, which supply drinking water, are located (Kleče-group 1, Jarški prod-group 2 and Hrastje-group 3). In addition, hydrological and geological data that are required for modelling are available for these areas. The groundwater mean residence time (MRT), which was estimated using the $^3H/^3He$ method, ranged between two and eight years (Vrzel et al., 2018b). The mean Sava River discharge at Šentjakob during 1981–2010 was 82.1 $m^3 s^{-1}$, with a maximum of 117.6 $m^3 s^{-1}$ in November and a minimum of 52.7 $m^3 s^{-1}$ in February (ARSO, 2018a).

3. Methods

3.1. Model setup

In general, hydrological modelling was performed through the direct/indirect coupling of the three dimensional (3D) transient state groundwater flow model (FEFLOW) with the river water flow model (MIKE 11) and the simulated percolation of local precipitation (WaSiM). The modelling framework is presented in Fig. 3. The FEFLOW and MIKE 11 were coupled *via* the ifmMIKE11 plug-in, which is capable of simulating the leaching of river water into the aquifer and *vice versa*. The software is provided by the MIKE Powered by the

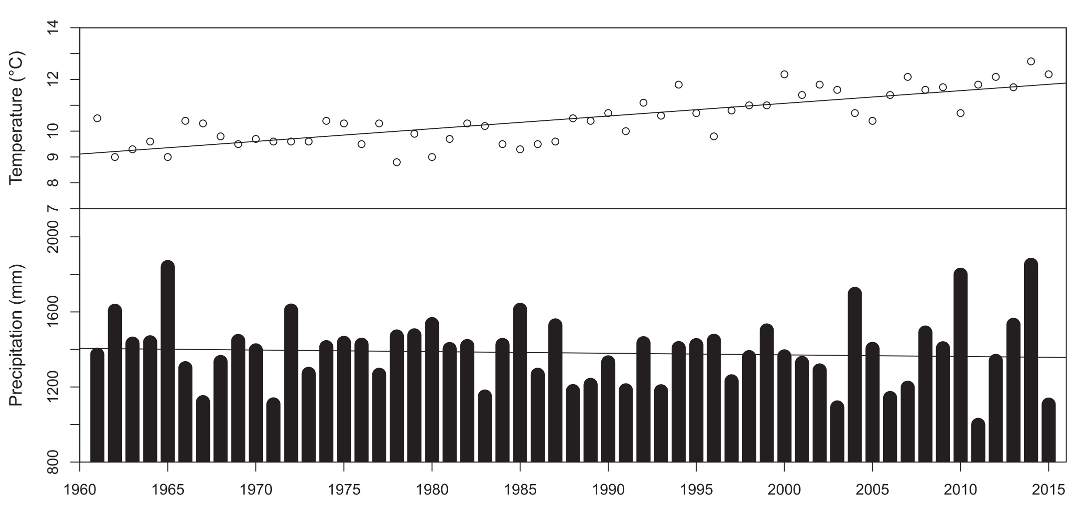

Fig. 2. Mean annual temperature (°C) and mean annual amount of precipitation (mm) over the period 1961–2015. The line shows long-term trend in both parameters.

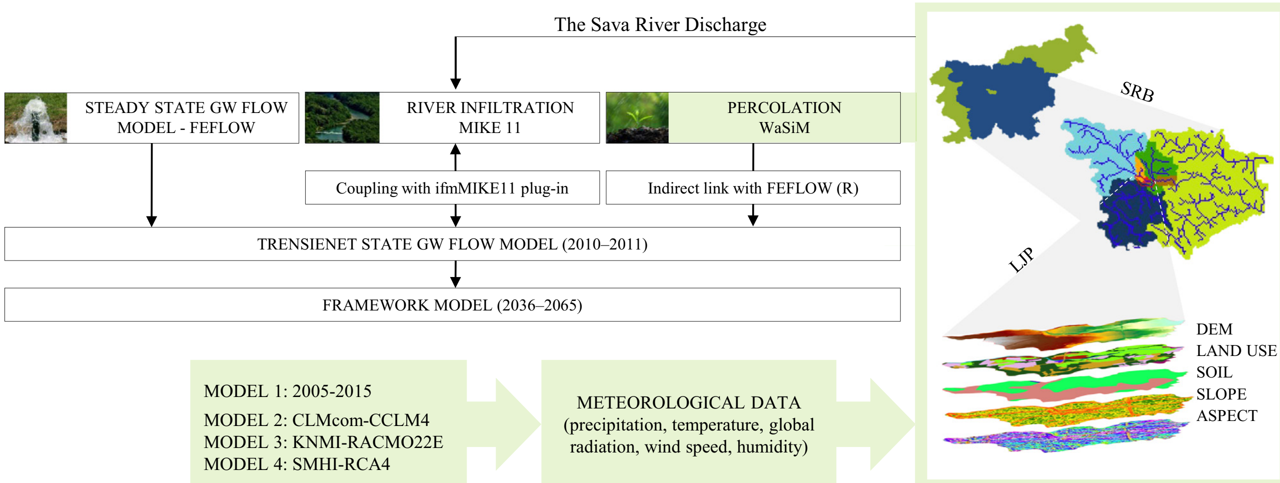

Fig. 3. Modelling framework.
(Sources: the land use map (EEA, 2016); Slovenian shape (ESTAT, 2010)).

Danish Hydraulic Institute (DHI). The calculation of an arbitrary flow of water through 3D canals in MIKE 11 is based on the Saint-Venant equations. The advantage of MIKE 11 is its capacity to handle 1D linear interpolation, which is important in the study of hydrodynamic river processes. Groundwater flow was simulated using a standard (saturated) groundwater flow equation–Darcy's law. The slices on the top and bottom of the unconfined model-layer are fixed, and in the case when groundwater rises above the surface, the aquifer is treated as confined. The model is based on daily data from 2010 to 2011 and has 110,249 elements per sub-layer (eight sub-layers in total). The underground recharge and discharge were defined in the model with the hydraulic head boundary condition. For this purpose, the assigned hydraulic heads were estimated from the hydraulic heads measured in the wells situated closest to the boundary. Since data does not exist for future conditions, 30-year mean hydraulic heads for each calendar day (observed in the closest piezometers) were used to define the hydraulic head boundary condition in the forecast model.

Groundwater recharge is known to be sensitive to climate (precipitation and temperature regimes), local geology and soil, topography, vegetation, surface water hydrology, and land use activities (*e.g.*, urbanization, woodland establishment, crop rotation, and irrigation practices) (de Vries and Simmers, 2002; Holman, 2006; McMahon et al., 2006; Green et al., 2007; Candela et al., 2009). WaSiM is capable of handling these parameters and takes them into account when calculating the percolation of local precipitation (Schulla, 2015), which benefits this study, since the determination of surface water bodies in a groundwater model has a substantial effect on the model's predictive ability (White, 2017). In this study, two WaSiM models were developed. The first one has a spatial resolution of 1 km and its domain includes the entire Slovenian part of the SRB, while the second model was developed

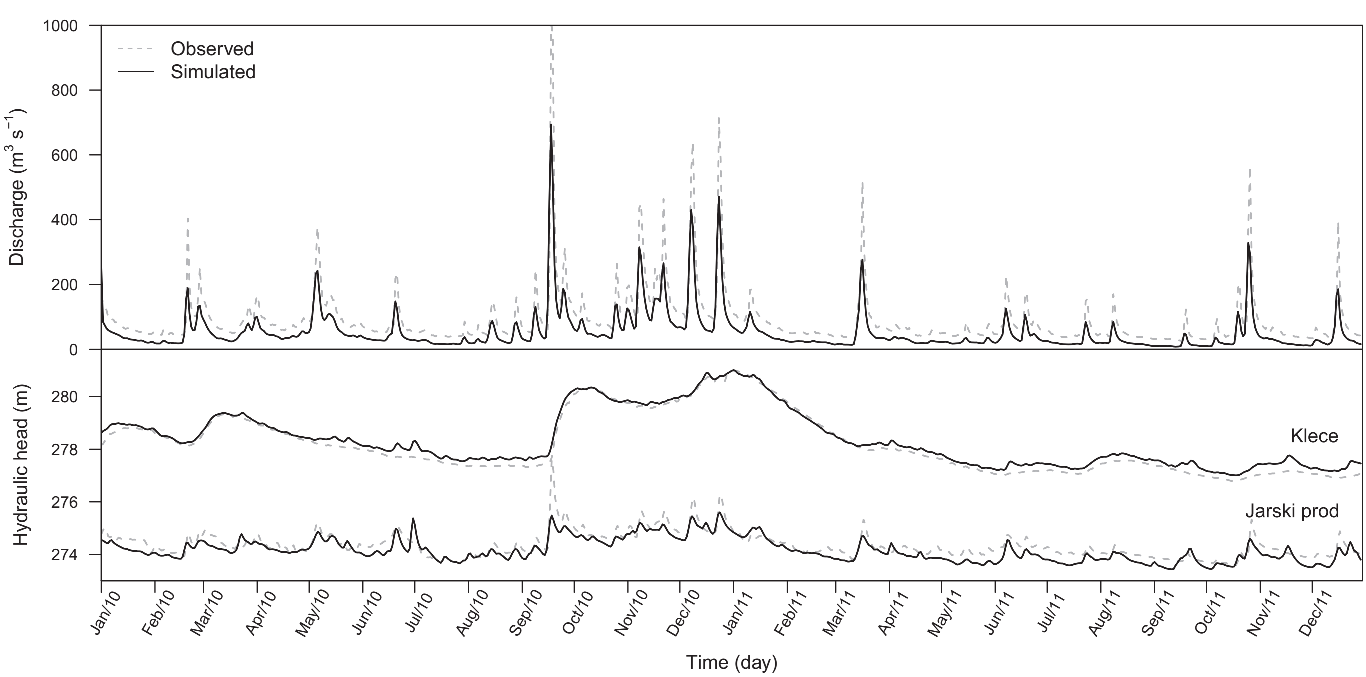

Fig. 4. Observed and simulated Sava River discharge and hydraulic heads at Kleče (group 1) and Jarški prod (group 2) wells. Hydraulic heads were simulated in FEFLOW for the period 2010–2011.

Table 1
Total amount of local precipitation and percolation, and mean discharge of The Sava River over the period 2036–2065 in the Ljubljansko polje together with the amount of precipitation upstream of the Ljubljansko polje, in the Alps.

	CLMcom-CCLM4	KNMI-RACMO22E	SMHI-RCA4
Total local precipitation (mm)	1613	1598	1473
Total of precipitation upstream from the LJP – in the Alps (mm)	1,146,517	1,554,455	842,021
Discharge in the Sava River ($m^3\ s^{-1}$)	105	142	77
Total percolation (mm)	296	228	284

specifically for the Ljubljansko polje with a spatial resolution of 50 m. Both models have a daily temporal resolution and they are based on the meteorological data from 2008 to 2014. For the MIKE 11 model, the required input (Sava River discharge) was simulated with the WaSiM model that covers the SRB. The WaSiM model for the Ljubljansko polje calculated distributed percolation of local precipitation, which was used as an input for the FEFLOW model using the following equation:

$$q_v = K_{korr} \cdot k_f \cdot e^{-\frac{S_i}{m}} \quad (1)$$

where q_v is percolation (mm), K_{korr} is scaling parameter for considering unsaturated soils as well as preferred flow paths (−), S_i is local saturation deficit (mm), m is recession parameter (see generation of baseflow) (mm) and k_f is saturated hydraulic conductivity (mm h^{-1}) (Schulla, 2015).

The hydrological parameters (hydraulic conductivity (K_x, K_y, K_z), specific yield (S_y) and transfer rates) were estimated from previous studies, which were recalculated twice–during the calibrations of the steady and transient state groundwater flow models. In FEFLOW, two types of boundary conditions (BC) were applied and are graphically presented in Vrzel et al. (2018a). Dirichlet BC defines underground groundwater fluxes in or out of the aquafer at the lateral boundary layers where the bedrock is deep. The Sava River was defined with the Cauchy BC, which was also used for coupling FEFLOW with MIKE 11 (Vrzel et al., 2018a).

A calibration of the presented modelling framework was done in several steps. The WaSiM model was calibrated using the following: soil moisture measured in Kleče (01.01.2012–31.08.2012), hydraulic heads (01.01.2010–31.12.2014) and real evapotranspiration (ET), which was compared with actual ET in Ljubljana (01.01.2010–31.12.2014). FEFLOW and MIKE 11 models were calibrated together, due to their direct communication link, in five steps. Manual and automatic trial-and-error history matching of hydraulic heads, the Sava River discharge and groundwater MRT in FEFLOW, MIKE 11 and FePEST were used. Time periods 01.04.2010–30.04.2010 and 2010–2011 were calibration and validation periods of the transient state groundwater flow model, respectively. Results of the calibration are presented in Fig. 4. A detailed description of all the calibration and validation procedures, input data and results are given in Vrzel et al. (2018a).

3.2. Climate projections

A comparison of climate projections for the period 2035–2065 and data collected between the reference period 1981–2010 reveal an increase of climate change pressure on the water cycle in the Ljubljansko polje (Gampe et al., 2016). These projections are derived from a combination of four General Circulation Models (GCMs) forcing different Regional Climate Models (RCMs) under Representative Concentration Pathway 8.5 (RCP8.5) at a 12 km resolution originating from the EURO-CORDEX initiative (Jacob et al., 2014). Using the entire ensemble for consecutive modelling exercises would be computationally too demanding and, therefore, it was necessary to make a sub-selection. For this, a clustering approach was applied in order to condense the available simulations to three GCM-RCM combinations while still preserving the original spread of the climate change signals (Wilcke and Bärring, 2016). This led to the selection of the following GCM-RCM combinations: HadGEM2-ES-RCA4 (referred to as SMHI-RCA4), EC-EARTH-RACMO22E (KNMI-RACMO22E), and EC-EARTH-CCLM4-8-17 (CLMcom-CCLM4). The resolution of these RCMs is still too coarse for hydrological applications, and an additional interpolation, often referred to as downscaling, to a finer scale is required (Fowler et al., 2007; Holman et al., 2012).

In this study, the downscaling algorithm SCALMET (Marke, 2008) was applied to further disaggregate the RCM simulations to a 1 km grid. The approach is mass and energy conserving, respects the climatology and the main distributions of the original simulations, and has been applied in previous studies (*e.g.* Prasch et al., 2015). Precipitation and mean, minimum and maximum air temperature were downscaled using constant lapse rate remapping. Relative humidity, shortwave incoming radiation and wind speed were also disaggregated. This procedure was chosen since there is no information on standardized lapse rates for these variables and the limited number of observations for these variables hinders the calculation of

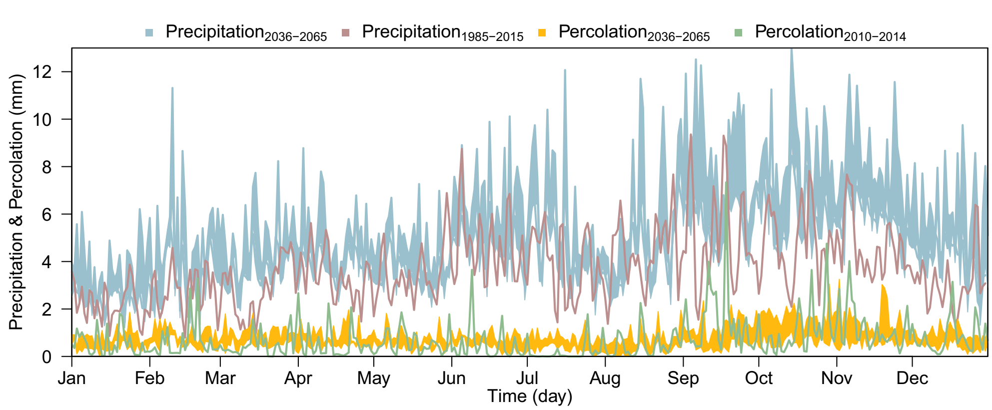

Fig. 5. Comparison of the simulated and observed precipitation, and simulated percolation. Precipitation and percolation are given in a range that includes results of all the three Regional Climate Models (RCMs).

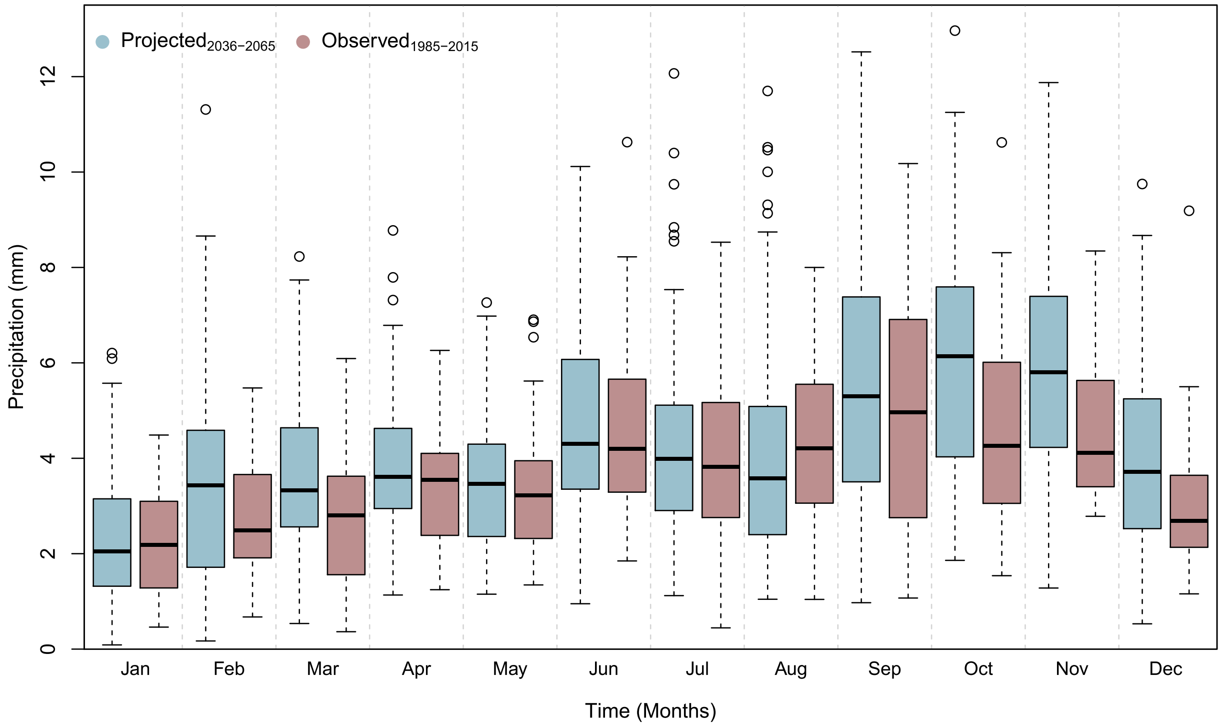

Fig. 6. Box plots of the simulated and observed precipitation.

lapse rates. In addition, data sets needed to evaluate the downscaling are also not available.

RCMs are prone to model biases especially on the regional scale (Dosio, 2016; Kotlarski et al., 2014), and for this reason bias correction is needed to accurately reproduce the hydrological quantities for the reference period. In this case, a distribution-based bias correction procedure (Yang et al., 2010) was applied to the three RCMs. The downscaled reanalysis dataset MESAN (Häggmark et al., 2000) served as the reference data set for precipitation, air temperature and wind speed. Once corrected for bias, the RCMs are in better agreement with regional observations.

The derived high resolution, bias corrected, climate data (SMHI-RCA4, KNMI-RACMO22E and CLMcom-CCLM4) served as the input data for both WaSiM setups. Long-term climatological mean for each day of the year were derived from the climate projections and used to drive FEFLOW. This was necessary to overcome computational issues, since it requires approximately 24 h of modelling time to generate a year's worth of data.

4. Results and discussion

Climate variability, especially variability in precipitation, can have substantial effects (Green et al., 2011) on the main groundwater sources in the Ljubljansko polje–the Sava River and percolation of local precipitation. Mayer and Congdon (2008) even claim that such changes will not have only environmental but also economic consequences. The International Panel on Climate Change (IPCC) Fourth Assessment Report noted that groundwater levels correlate more strongly with precipitation than they do with temperature in general, while temperature becomes more important for shallow aquifers (Kundzewicz et al., 2007). Since the Ljubljansko polje aquifer is classified as a deep aquifer, where hydraulic heads may be up to 30 m deep, the temperature is not included in the interpretation of the results in this paper. Nevertheless, investigating correlations between groundwater and surface water temperatures would be interested due to the high sensitivity of groundwater on surface water in the Ljubljansko polje.

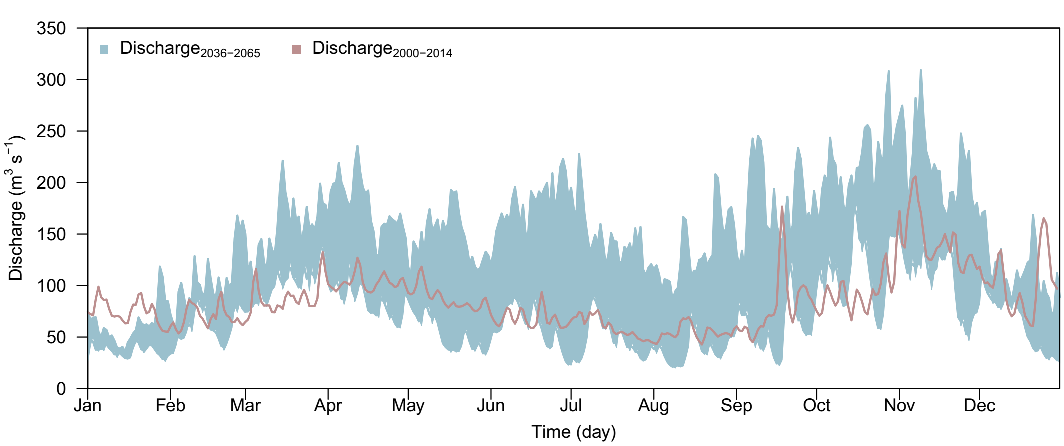

Fig. 7. The Sava River discharge–for the period 2002–2014 and simulated water levels.

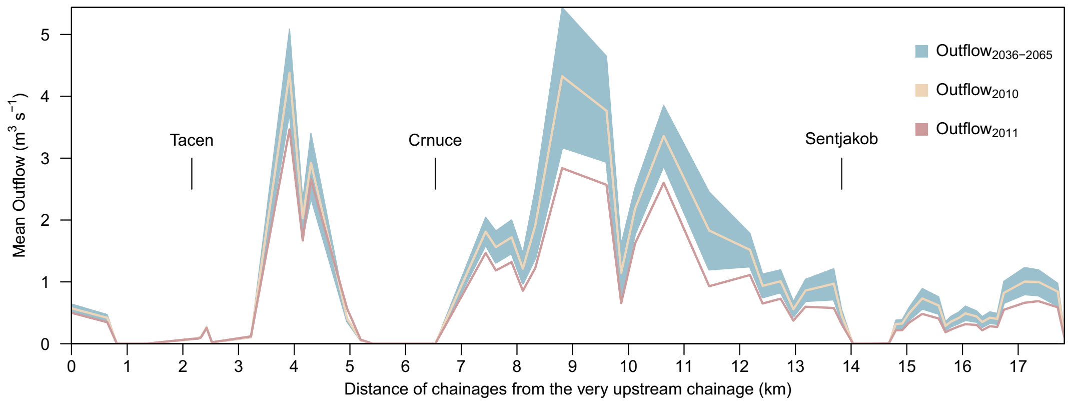

Fig. 8. Locations where the Sava River water leaches into the aquifer and flux quantification for 2010, 2011 and 2036–2065.

4.1. Climate projections for the Ljubljansko polje (2036–2065)

A closer look at the projected climate conditions for the Ljubljansko polje identifies three variations, which make the system behave differently. Studying these reactions can serve as a tool for understanding the hydrology of the Ljubljansko polje. Table 1 gives the total amounts of local precipitation, the total amounts of percolation (of daily means for the period 2036–2065), mean Sava River discharge (2036–2065) in the Ljubljansko polje, and the total amount of precipitation upstream of the Ljubljansko polje, calculated with the WaSiM models forced with RCMs data. The CLMcom-CCLM4 input data gave the highest level of projected local precipitation and percolation, while the KNMI-RACMO22E input data resulted in the highest level of precipitation in the Alps and the highest water level in the Sava River. The driest conditions were simulated using the SMHI-RCA4 input data. Gobiet et al. (2014) indicated clear signal of increased precipitation in winter and decreases in summer by the end of 21st century in the Alps. While this signal is not so clear if a shorter period–until the mid-21st century is considered. In addition, results show that a possible negative stress on the Sava River Basin due to climate change, as presented by Gampe et al. (2016), is not relevant for the Ljubljansko polje. However, higher projected precipitation than the observed in the past in the Ljubljansko polje agrees with projections for the Adige River Basin, Italy (Gampe et al., 2016). Climate conditions in the Ljubljansko polje and the Adige River Basin are under strong influences of the Alps.

The projected precipitation events for the Ljubljansko polje were compared with the precipitation data recorded in Ljubljana between 1985 and 2015 (mean of yearly sums is 1365 mm). The comparison shows a slightly higher level ($\Delta = 196.3$ mm) of simulated precipitation over a calendar year (mean of three precipitation projections of yearly sums is 1561 mm), especially in November (Fig. 5). Standard deviations (SD) of mean daily precipitation over the observed and projected periods are 3.5 mm and 2.2 mm, respectively. Box plots (Fig. 6) indicate the possibility of heavy rain events, which will increase the likelihood of flooding (Green et al., 2011; Bates et al., 2008). Rajczak et al. (2013) writes that there will be an intensification of heavy precipitation events in the Alps during the autumn and a decrease in the mean precipitation, while there will be increases in heavy precipitation events during spring and autumn in the Mediterranean regions. Bračič Železnik et al. (2011) identified a correlation between heavy precipitation events and groundwater quality in the Ljubljansko polje, based on the microbiological activity in the groundwater, which increases with rising hydraulic heads.

4.2. Percolation

The projected percolation (yearly sum of daily values 269 mm) is presented in Fig. 5. The results show that the lowest amount of percolation is at the end and beginning of a calendar year, and from late July to early August, while the highest percolation (3.3 mm) occurs from mid-September to mid-November. The mean SD of daily mean projected percolation is 0.4 mm. The snow cover and frozen soil make percolation difficult in winter, while in the summer, the percolation is limited due to high evaporation (ARSO, 2018b; ARSO, 2018c). However, a frozen soil is not completely impermeable as is shown in a study provided by Stadler et al. (2000). Winter and summer seasons have also the largest range between maximal and minimal levels of projected precipitation (0.1–12.3 mm) and percolation (0.8×10^{-5}–1.8 mm).

4.3. The Sava River discharge

Simulated discharge ($\text{mean}_{2010–2011}$ 53.3 $m^3\ s^{-1}$) in the Sava River is slightly lower than discharge observed over the period 2000–2014 ($\text{mean}_{2000–2014}$ 88.09 $m^3\ s^{-1}$) (Fig. 7). Similar projections were published by ISRBC (2013). Furthermore, the range between the highest

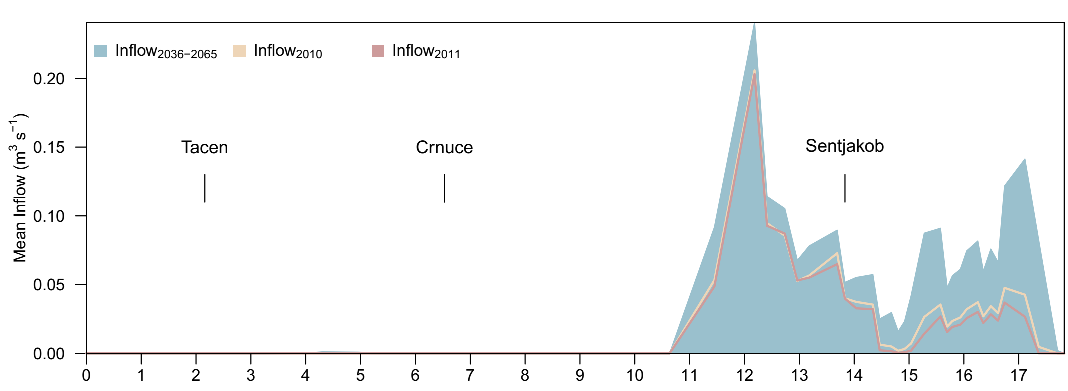

Fig. 9. Locations where groundwater flows into the Sava River channel and flux quantification for 2010, 2011 and 2036–2065.

and the lowest discharges is greater (SD = 68.3 $m^3 s^{-1}$) than in the precipitation data (SD = 2.2 mm) (Figs. 5 and 7). This is likely due to differences in the projected precipitation (Δ = 139.7 mm) upstream from the Ljubljansko polje, which is strongly associated with the Sava River discharge, since both of the Sava River's two springs are located in the Alps.

4.4. River water-groundwater interactions

The spatiotemporal response of river discharge to the level of precipitation can affect aquifer yield, discharge, and groundwater flow directions. For example, gaining streams may become losing streams and groundwater divides may move position (Dragoni and Sukhija, 2008). Similarly, Winter (1999) demonstrated that climatic conditions affect the groundwater flow direction and the relation between surface water bodies and subsurface water resources. However, changes in the groundwater flow direction due to climate conditions were not projected for the Ljubljansko polje.

Figs. 8 and 9 show leaching of the Sava River water into the aquifer and *vice versa*. The Sava River water–groundwater interface between Črnuče and Šentjakob was identified as the most sensitive region to climatic conditions, because of the large discrepancy between maximum and minimum quantity of gained groundwater (Fig. 8). Alternatively, this flux remains relatively constant between Tacen and Črnuče, which is the seepage area for the wells located in Kleče (Vrzel et al., 2018a). Although the leaching of groundwater into the Sava River channel is relatively small, the impact of climate change on these fluxes was projected, as well as in the Kiskatinaw River in Mainstem, Canada, which was studied by Saha et al. (2017). The locations where leaching/gaining of river/groundwater interactions take place are not expected to be relocated in the future.

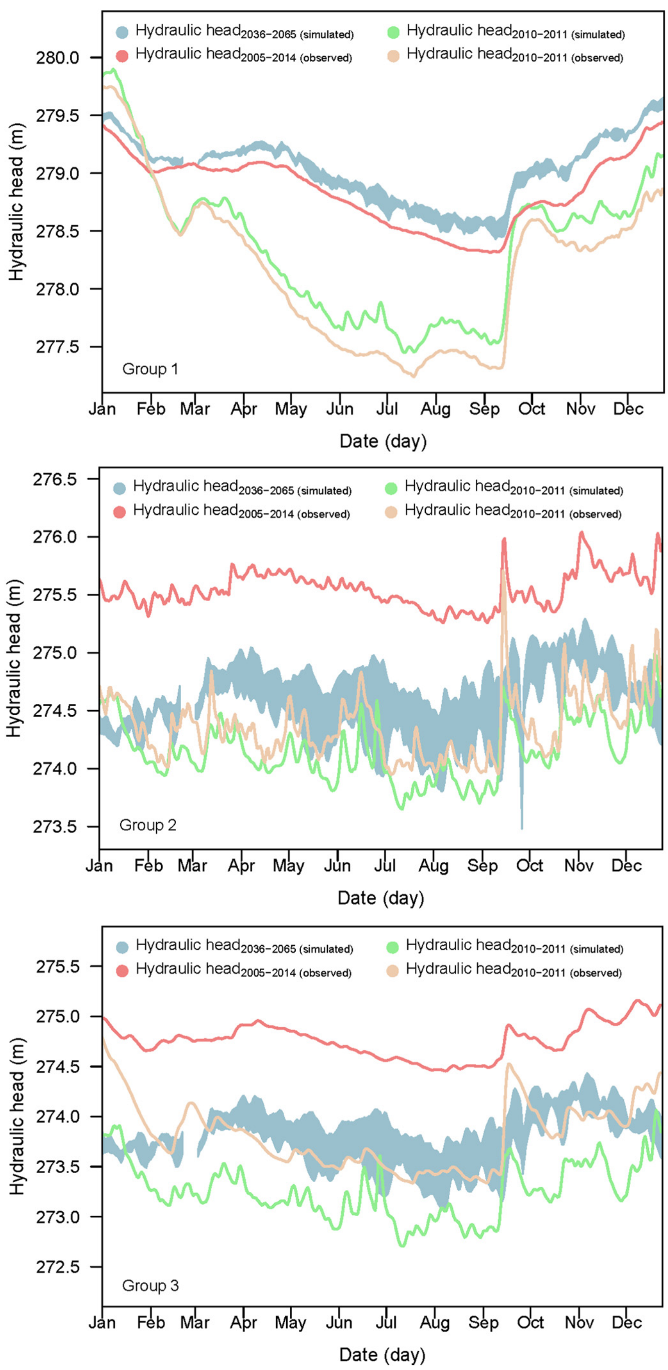

Fig. 10. Observed, simulated and projected hydraulic heads in groundwater wells for groups 1–3.

4.5. Hydraulic head

Increasing precipitation in the future can raise the hydraulic head and increase the risk of flooding (Green et al., 2011). For example, Farkas et al. (2014) writes about increases in percolated water for the periods 2021–2050 and 2071–2010 in the Bükk Mountains, Hungary. However, the results do not provide reliable information as to whether the hydraulic heads will rise or fall in the future. With the exception of Kleče (group 1), the hydrological model suggests there will be slightly lower hydraulic heads for the calibration period 2010–2011. The results show that a drastic change in the elevation of the hydraulic head in the Ljubljansko polje is unlikely (Fig. 10). Projected hydraulic heads in Kleče are slightly higher than those hydraulic heads observed during the reference period; however, this does not necessarily mean that the hydraulic heads will rise, since the reference model gives slightly higher hydraulic heads for group 1. Simulated hydraulic heads for groups 2 and 3 are lower than in the reference period. Furthermore, from these results it cannot be stated that hydraulic heads will drop in the future.

Hydraulic heads under projected climate conditions are harmonized for group 1, whereas, they are more diverse for groups 2 and 3, with discrepancies observed between 1 m and 0.5 m, respectively. This is connected to variations in the sensitivity of the Sava River water–groundwater interface to changing climate conditions (Figs. 8 and 9). This is the main seepage area for groups 1, 2 and 3. Scibek and Allan (2006) also observed a higher impact of river water perturbation than recharge perturbation on the groundwater table in an unconfined alluvial aquifer near Grand Forks, Canada. In group 2, the simulated and observed hydraulic head for the period 2010–2011 does not deviate for >0.5 m. Two explanations can account for the different responses of the hydraulic heads to RCM conditions in groups 1–3. First, a correlation between the projected range of hydraulic heads and the system responsiveness was observed, *i.e.*, a faster system response coincides with a wider range between the maximum and minimum simulated hydraulic heads. Maxwell et al. (2016) suggests that the MRT is controlled by the hydrological properties of a geological layer. This could also be a case in our study, where correlation between the system responsiveness and hydrological parameters of alluvial sediments were found. The second is that the system is more sensitive to climate conditions when only one source of groundwater prevails. In groups 2 and 3, the Sava River water and local precipitation are the dominant groundwater sources, respectively, and an equal contribution of both sources in group 1 explains the harmonized data for the projected hydraulic heads is this area. The estimated fractions of river water and local precipitation in groundwater for groups 1, 2 and 3 can be found in Vrzel et al. (2018b). In general, estimates of the fractions of river water and local precipitation are similar in the group 1, while Sava River water dominates in the group 2 and local precipitation in the group 3.

4.6. Limitations of the study

The simulation was limited by the poor knowledge of underground recharge of the Ljubljansko polje aquifer from the neighbouring groundwater bodies. In this study, recharge was defined by the Dirichlet BC, during the calibration of the steady state groundwater flow model, where initial hydraulic heads were observed in the piezometers located close to this BC. Because hydraulic heads are not known for future, mean daily observations for the Dirichlet BC, measured in the period 2005–2014 were applied for hydrological projections. Additionally, despite an existence of many required data, some parameters had to be estimated. For example, Manning's and leaching coefficients, soil, and land use properties, as well as the physical framework of the model at certain areas of the study domain. Also, the computation of these models is demanding. Nevertheless, such an approach provides an information of system responsiveness on different climatic conditions in future, which is important for water management.

5. Conclusions

The climate projections and the hydrological model results indicate that the Ljubljansko polje will not suffer from increased water scarcity under future climatic conditions. In fact, a slightly higher level of precipitation is projected. Moreover, hydrological variation controls key habitat conditions within the river channel, floodplains and in stream-influenced groundwater zones (Richter et al., 1998). Modifications to a river's flow regime can, therefore, have a strong impact on ecological processes in the river (Stagl and Hattermann, 2016), and for this reason, this work is relevant for future investigation in the Ljubljansko polje. Possibilities of occurrence of heavy precipitation events in the future were identified, which may have an impact on groundwater quality and flooding. Further, investigating how the hydraulic head responds to changing climate conditions provides a valuable insight into the aquifer mechanisms, such as the behaviour of the system under different hydrological conditions. An important finding is that the aquifer is more sensitive to the climate at locations when one of the main groundwater sources dominates.

Many published papers stress the existence of a knowledge gap in our understanding of climate impacts on groundwater and on its interaction with surface water. In addition, the availability of large data sets differs from country to country, which leads to greater uncertainty of such studies at the global scale. However, small case studies, can be used to evaluate results at a global scale.

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References

Aeschbach-Hertig, W., Gleeson, T., 2012. Regional strategies for the accelerating global problem of groundwater depletion. Nat. Geosci. 5, 853–861.

Anderson, M.P., Woessner, W.W., Hunt, R.J., 2015. Applied Groundwater Modeling, Simulation of Flow and Advective Transport. second ed. Elsevier Inc., London, UK.

ARSO-Slovenian Environment Agency, 2018a. Hydrological data archive. http://vode.arso.gov.si/hidarhiv/pov_arhiv_tab.php?p_vodotok=Sava&p_postaja=3570, Accessed date: 7 June 2018.

ARSO-Slovenian Environment Agency, 2018b. Archive of measurements. http://www.meteo.si/met/sl/archive/, Accessed date: 30 July 2018.

ARSO-Slovenian Environment Agency, 2018c. Average monthly evapotranspiration values in the period 1971–2000. http://meteo.arso.gov.si/met/sl/agromet/period/etp/, Accessed date: 30 July 2018.

Aslam, R.A., Shrestha, S., Pandey, V.P., 2018. Groundwater vulnerability to climate change: a review of the assessment methodology. Sci. Total Environ. 612, 853–875. https://doi.org/10.1016/j.scitotenv.2017.08.237.

Auersperger, P., Čenčur Curk, B., Jamnik, B., Janža, M., Kus, J., Prestor, J., Urbanc, J., 2005. Dinamika podzemne vode. In: Rejec Brancelj, I., Smrekar, A., Kladnik, D. (Eds.), Podtalnica Ljubljanskega polja. Založba ZRC, Ljubljana, pp. 39–61.

Bates, B., Kundzewicz, Z.W., Wu, S., Palutikof, J.P. (Eds.), 2008. Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change. IPCC Secretariat, Geneva, p. 210.

Bračič Železnik, B., Čenčur Curk, B., Souvent, P., 2011. Drinking water quality under changing climate conditions. Water Qual.: Curr. Trends and Expected Climate Change Impacts. 348, pp. 101–105.

Candela, L., von Igel, W., Javier Elorza, F., Aronica, G., 2009. Impact assessment of combined climate and management scenarios on groundwater resources and associated wetland (Majorca, Spain). J. Hydrol. 376, 510–527. https://doi.org/10.1016/j.jhydrol.2009.07.057.

Cerar, S., Urbanc, J., 2013. Carbonate chemistry and isotope characteristics of groundwater of Ljubljansko polje and Ljubljansko barje aquifers in Slovenia. Sci. World J., 1–11 https://doi.org/10.1155/2013/948394.

de Vries, J.J., Simmers, I., 2002. Groundwater recharge: an overview of processes and challenges. Hydrogeol. J. 10, 5–17. https://doi.org/10.1007/s10040-001-0171-7.

Dettinger, M.D., Earman, S., 2007. Western ground water and climate change—pivotal to supply sustainability or vulnerable in its own right? Ground Water News and Views. 4. Assoc. of Ground Water Sci. and Engineers Newsletter, pp. 4–5

Dosio, A., 2016. Projections of climate change indices of temperature and precipitation from an ensemble of bias-adjusted high-resolution EURO-CORDEX regional climate models. J. Geophys. Res. Atmos. 121, 5488–5511. https://doi.org/10.1002/2015JD024411.

Dragoni, W., Sukhija, B.S., 2008. Climate change and groundwater: a short review. Geol. Soc. Spec. Publ. 288, 1–12. https://doi.org/10.1144/SP288.1.

EEA (European Environmental Agency), 2016. CORINE land cover database of the year 2006. https://www.eea.europa.eu/data-and-maps/data/clc-2006-raster-4#tab-european-data, Accessed date: 10 June 2018.

ESTAT (European Commission, Eurostat, GISCO), 2010. Countries, 2006-administrative units-view. http://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/countries, Accessed date: 10 June 2018.

Farkas, C., Gelybó, G., Bakacsi, Z., Horel, Á., Hagyó, A., Dobor, L., Kása, I., Tóth, E., 2014. Impact of expected climate change on soil water regime under different vegetation conditions. Biologia 69, 1510–1519. https://doi.org/10.2478/s11756-014-0463-8.

Fowler, H.J., Blenkinsop, S., Tebaldi, C., 2007. Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. Int. J. Climatol. 27, 1547–1578. https://doi.org/10.1002/joc.1556.

Gampe, D., Nikulin, G., Ludwig, R., 2016. Using an ensemble of regional climate models to assess climate change impacts on water scarcity in European river basins. Sci. Total Environ. 573, 1503–1518. https://doi.org/10.1016/j.scitotenv.2016.08.053.

Gobiet, A., Kotlanski, S., Beniston, M., Heinrich, G., Rajczak, J., Stoffel, M., 2014. 21st century climate change in the European Alps–a review. Sci. Total Environ. 493, 1138–1151. https://doi.org/10.1016/j.scitotenv.2013.07.050.

Green, T.R., Bates, B.C., Charles, S.P., Fleming, P.M., 2007. Physically based simulation of potential effects of carbon dioxide-altered climates on groundwater recharge. Vadose Zone J. 6, 597–609. https://doi.org/10.2136/vzj2006.0099.

Green, T.R., Taniguchi, M., Kooi, H., Gurdak, J.J., Allen, D.M., Hiscock, K.M., Treidel, H., Aureli, A., 2011. Beneath the surface of global change: impacts of climate change on groundwater. J. Hydrol. 405, 532–560. https://doi.org/10.1016/j.jhydrol.2011.05.002.

Häggmark, L., Ivarsson, K.I., Gollvik, S., Olofsson, P.O., 2000. Mesan, an operational mesoscale analysis system. Tellus A 52, 2–20. https://doi.org/10.1034/j.1600-0870.2000.520102.x.

Holman, I.P., 2006. Climate change impacts on groundwater recharge-uncertainty, shortcomings, and the way forward? Hydrogeol. J. 14, 637–647. https://doi.org/10.1007/s10040-005-0467-0.

Holman, I.P., Allen, D.M., Cunthbert, M.O., Goderniaux, P., 2012. Towards best practice for assessing the impacts of climate change on groundwater. Hydrogeol. J. 20, 1–4. https://doi.org/10.1007/s10040-011-0805-3.

ISRBC–International Sava River Basin Commission, 2013. Sava River Basin Management Plan, Background Paper No. 10, Climate Change and RBM Planning.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O.B., Bouwer, L.M., Braun, A., ... Georgopoulou, E., 2014. EURO-CORDEX: new high-resolution climate change projections for European impact research. Reg. Environ. Chang. 14, 563–578.

Koeck, R. (Ed.), 2012. Climate Change and Impacts on Water Supply "CC-WaterS", Project Report.

Kotlarski, S., Keuler, K., Christensen, O.B., Colette, A., Déqué, M., Gobiet, A., Goergen, K., Jacob, D., Lüthi, D., van Meijgaard, E., Nikulin, G., Schär, C., Teichmann, C., Vautard, R., Warrach-Sagi, K., Wulfmeyer, V., 2014. Regional climate modeling on European scales: a joint standard evaluation of the EURO-CORDEX RCM ensemble. Geosci. Model Dev. 7, 1297–1333. https://doi.org/10.5194/gmd-7-1297-2014.

Kozjek, K., Dolinar, M., Skok, G., 2017. Objective climate classification of Slovenia. Int. J. Climatol. 37, 848–860. https://doi.org/10.1002/joc.5042.

Kundzewicz, Z.W., Mata, L.J., Arnell, N.W., Doll, P., Kabat, P., Jimenez, B., Miller, K.A., Oki, T., Sen, Z., Shiklomanov, I.A., 2007. Freshwater resources and their management. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Cambridge University Press, Cambridge, pp. 173–210.

Kurylyk, B.L., MacQuarrie, K.T.B., 2013. The uncertainty associated with estimating future groundwater recharge: a summary of recent research and an example from a small unconfined aquifer in a northern humid-continental climate. J. Hydrol. 492, 244–253.

Marke, T., 2008. Development and Application of a Model Interface to Couple Land Surface Models with Regional Climate Models for Climate Change Risk Assessment in the Upper Danube Watershed. (Dissertation). Ludwig-Maximilians-Universität München, Faculty of Geosciences.

Maxwell, R.M., Condon, L.E., Kollet, S.J., Maher, K., Haggerty, R., Forrester, M., 2016. The imprint of climate and geology on the residence times of groundwater. Geophys. Res. Lett. 43, 701–708. https://doi.org/10.1002/2015GL066916.

Mayer, T.D., Congdon, R.D., 2008. Evaluating climate variability and pumping effects in statistical analyses. Ground Water 46 (2), 212ernd.

McMahon, P.B., Dennehy, K.F., Bruce, B.W., Bohlke, J.K., Michel, R.L., Gurdak, J.J., Hurlbut, D.B., 2006. Storage and transit time of chemicals in thick unsaturated zones under rangeland and irrigated cropland, High Plains, United States. Water Resour. Res. 42, 1–18. https://doi.org/10.1029/2005WR004417.

NASEM - National Academies of Sciences, Engineering, and Medicine, 2016. From Maps to Models: Augmenting the Nation's Geospatial Intelligence Capabilities. The National Academies Press, Washington, DC. https://doi.org/10.17226/23650.

Prasch, M., Marke, T., Strasser, U., Mauser, W., 2015. Large scale distributed hydrological modelling. In: Sharma, N., Flügel, W.-A. (Eds.), Applied Geoinformatics for Sustainable Integrated Land and Water Resources Management (ILWRM) in the Brahmaputra River basin. Springer, New Delhi, pp. 37–43.

Rajczak, J., Pall, P., Schär, C., 2013. Projections of extreme precipitation events in regional climate simulations for Europe and the Alpine Region. J. Geophys. Res. Atmos. 118, 3610–3626. https://doi.org/10.1002/jgrd.50297.

Reid, M., Cheng, X., Banks, E.W., Jankowski, J., Jolly, I., Kumar, P., Lovell, D., Mitchell, M., Mudd, G., Richardson, S., Silburn, M., Werner, A., 2009. Catalogue of Conceptual Models for Groundwater–Stream Interaction in Eastern Australia. (eWater Technical Report). eWater Cooperative Research Centre, Canberra.

Richter, B.D., Baumgartner, J.V., Braun, D.P., Powell, J., 1998. A spatial assessment of hydrologic alteration within a river network. Regul. Rivers Res. Manag. 14, 329–340. https://doi.org/10.1002/(SICI)1099-1646(199807/08)14:4<329::AID-RRR505>3.0.CO;2-E.

Saha, G.C., Li, J., Thring, R.W., Hirshfield, F., Paul, S.S., 2017. Temporal dynamics of groundwater-surface water interaction under the effects of climate change: a case study in the Kiskatinaw River Watershed, Canada. J. Hydrol. 551, 440–452. https://doi.org/10.1016/j.jhydrol.2017.06.008.

Schulla, J., 2015. Model Description WaSiM (Water Balance Simulation Model). Hydrology Software Consulting J, Schulla, Zurich.

Scibek, J., Allan, D.M., 2006. Modeled impacts of predicted climate change on recharge and groundwater levels. Water Resour. Res. 42, W11405. https://doi.org/10.1029/2005WR004742.

Shamir, E., Megdal, S.B., Carrillo, C., Castro, C.L., Chang, H., Chief, K., Corkhill, F.E., Eden, S., Georgakakos, K.P., Nelson, K.M., Prietto, J., 2015. Climate change and water resources management in the Upper Santa Cruz River, Arizona. J. Hydrol. 521, 18–33. https://doi.org/10.1016/j.jhydrol.2014.11.062.

Šram, D., Brenčič, M., Lapajne, A., Janža, M., 2012. Perched aquifers spatial model: a case study for Ljubljansko polje (central Slovenia). Geologija 55, 107–116. https://doi.org/10.5474/geologija.2012.008.

Stadler, D., Stähli, M., Aeby, P., Flühler, H., 2000. Dye tracing and image analysis for quantifying water infiltration into frozen soils. Soil Sci. Soc. Am. J. 64, 505–516. https://doi.org/10.2136/sssaj2000.642505x.

Stagl, J.C., Hattermann, F.F., 2016. Impacts of climate change on riverine ecosystems: alterations of ecologically relevant flow dynamics in the Danube River and its major tributaries. Water 8, 1–25. https://doi.org/10.3390/w8120566.

Taylor, R.G., Scanlon, B., Döll, P., Rodell, M., van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J.S., Edmuns, M., Konikow, L., Green, T.R., Chen, J., Taniguchi, M., Bierkens, M.F.P., MacDonald, A., Fan, Y., Maxwell, R.M., Yechieli, Y., Gurdak, J.J., Allen, D.M., Shamsudduha, M., Hiscock, K., Yeh, P.J.-P., Holman, I., Treidl, H., 2013. Ground water and climate change. Nat. Clim. Chang. 3, 322–329. https://doi.org/10.1038/NCLIMATE1744.

Vrzel, J., Ludwig, R., Vižintin, G., Ogrinc, N., 2018a. Integrated approach to the study of hydrology in Ljubljansko polje in Slovenia and its simulation. J. Hydrol. (under review).

Vrzel, J., Solomon, D.K., Blažeka, Ž., Ogrinc, N., 2018b. The study of the interactions between groundwater and Sava River water in Ljubljansko polje aquifer (Slovenia). J. Hydrol. 556, 384–396. https://doi.org/10.1016/j.jhydrol.2017.11.022.

White, J.T., 2017. Forecast first: An argument for groundwater modeling in reverse. Groundwater 55, 660–664. https://doi.org/10.1111/gwat.12558.

Wilcke, R.A.I., Bärring, L., 2016. Selecting regional climate scenarios for impact modelling studies. Environ. Model. Softw. 78, 191–201. https://doi.org/10.1016/j.envsoft.2016.01.002.

Winter, T.C., 1999. Relation of streams, lakes, and wetlands to groundwater flow systems. Hydrogeol. J. 7, 28–45. https://doi.org/10.1007/s100400050178.

Yang, W., Andréasson, J., Graham, L.P., Olsson, J., Rosberg, J., Wetterhall, F., 2010. Distribution based scaling to improve usability of regional climate model projections for hydrological climate change impacts studies. Hydrol. Res. 41, 211–229. https://doi.org/10.2166/nh.2010.004.