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Cross-sphere modelling to evaluate impacts of climate and land management changes on groundwater resources

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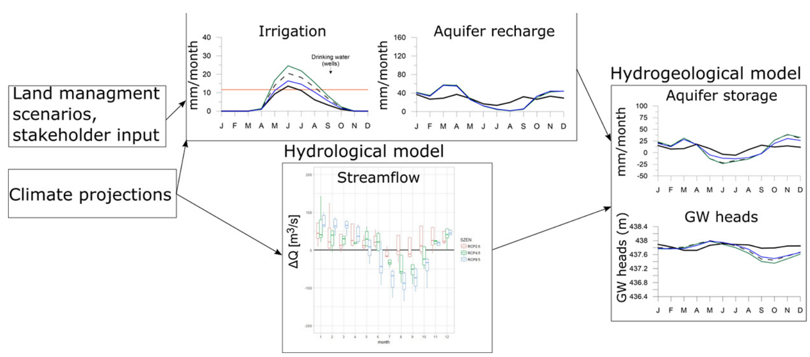
HIGHLIGHTS

- Climate change affects both water resources and agricultural production. Decision making has to balance resources and food production.
- An agricultural crop growth model, a hydrological model and a hydrogeological model were loosely coupled.
- The model indicates to what extent the climate change induced decreasing yield can be balanced by irrigation.
- The irrigation water requirement could increase by 7% (RCP2.6) and by 40% (RCP8.5) by the end of the century.
- Increasing irrigation water abstractions would amplify seasonal groundwater fluctuations.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate change affects both water resources and agricultural production. With rising temperatures and decreasing summer precipitation, it is expected that agricultural production will be increasingly limited by drought. Where surface- or groundwater resources are available for irrigation, an increase in water withdrawals for irrigation is to be expected. Therefore, quantitative approaches are required to anticipate and manage the expected conflicts related to increased water abstraction for irrigation. This project aims to investigate how agricultural production, water demand for irrigation, runoff and groundwater dynamics are affected by future climate change and how climate change impacts combined with changes in agricultural water use affect groundwater dynamics. To answer these research questions, a comprehensive, loosely coupled model approach was developed, combining models from three disciplines: an agricultural plant growth model, a hydrological model and a hydrogeological model. The model coupling was implemented and tested for an agricultural area located in Switzerland in which groundwater plays a significant role in providing irrigation water. Our suggested modelling approach can be easily adapted to other areas.
The model results show that yield changes are driven by drought limitations and rising temperatures. However, an increase in yield may be realized with an increase in irrigation. Simulation results show that the water requirement for irrigation without climate protection (RCP8.5) could increase by 40% by the end of the century with an

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unchanged growing season and by up to 80% with varietal adaptations. With climate change mitigation (RCP2.6) the increase in water demand for irrigation would be limited to 7%. The increase in irrigation (+12 mm) and the summer decrease in recharge rates (~20 mm/month) with decreasing summer precipitation causes a lowering of groundwater levels (40 mm) in the area in the late summer and autumn. This impact may be accentuated by an intensification of irrigation and reduced by extensification.

1. Introduction

Climate change profoundly alters production conditions for agriculture, thus making the need for adaptation unavoidable. In some regions of Switzerland, for example, drought limitations are expected to increase (Fuhrer and Jasper, 2012). Possibilities to adapt to these pressures include changing crop mixtures and/or increasing irrigation (Klein et al., 2013). Irrigation allows minimizing financial risks, especially for the cultivation of arable spring crops and for crops with high revenue such as vegetables and fruits (e.g., Fuhrer et al., 2016).

However, adaptation with a singular focus on maintaining or increasing agricultural production levels bears the risk of maladaptation, e.g. an action that may lead to increased risk of adverse climate-related outcomes, increased vulnerability to climate change, or diminished welfare, now or in the future (IPCC, 2014). While possible adverse side-effects of agricultural adaptations to climate change on soil loss, nutrient leaching, and aquatic biodiversity have been investigated (e.g., Klein et al., 2013; Tendall and Gaillard, 2015), feedbacks between agricultural management adaptations on the hydrological system were not extensively studied so far – leaving a potential risk of maladaptation unexplored. In agricultural regions with exploitable groundwater resources, groundwater abstraction for irrigation is common practice and large-scale irrigation projects continue to be implemented. The increased water use for agriculture can induce tradeoffs affecting other users, e.g. drinking water production or ecosystems and their related services (Alley and Leake, 2004; Gordon et al., 2010).

It is unknown to what extent this drought adaptation strategy impacts groundwater resources. Especially in hot and dry years, groundwater resources may be depleted to a level where extended agricultural groundwater abstraction causes problems. For example, pumping cost significantly increase with falling water tables. Moreover, substantial groundwater abstraction might cause problems for other users or systems relying on groundwater, e.g., drinking water production (both in terms of quality and quantity) or groundwater-dependent ecosystems. In regions with large proportions of organic soils, low water tables can accelerate the degradation of organic soils, thus leading to losses of important carbon stocks (Leifeld et al., 2019): As the water table drops, the capillary rise of water from the water table can become insufficient to maintain a high degree of saturation in the soils, thus increasing their degradation through oxidation of organic material.

As an alternative to increasing irrigation, another adaptation strategy consists of shifting the production of some crops to wetter periods of the year (i.e. winter crops). This affects irrigation water requirements as well as groundwater recharge.

To what extent changing climatic conditions and agricultural management affect water and soil resources has been widely explored with numerical models (Brouziyne et al., 2018). Cropping systems simulation models such as CropSyst (Stöckle et al., 2003) for example, simulate with a high level of detail soil water and plant growth dynamics. Integrated agro-hydrological models such as SWAT (Arnold et al., 1998, 2012) allow for accounting system linkages between plant growth, water demands and the hydrological cycle. Kreins et al. (2015) developed a simulation framework to quantify important aspects related to agriculture and water management, including irrigation water demand, soil water dynamics or groundwater recharge. Large complex simulation frameworks incorporating dynamic simulation modules for hydrology, groundwater flow and quality, agricultural management decisions and water demands as described for example in Barthel et al. (2012) incorporate a wide range of processes and interactions thereof. However, considering their very high degree of complexity and high input data demands, such tools are not easily operable or transferable to other regions.

Few studies explicitly consider groundwater flow processes. The spatial and temporal dynamics of groundwater resources under changing agricultural strategies can in principle be explored with numerical modelling approaches that consider processes such as infiltration, evapotranspiration, groundwater recharge and groundwater flow. However, this is not a straightforward undertaking, as the numerous feedback mechanism between agricultural practices, surface and subsurface water resources need to be jointly considered for current and future climatic forcing. For example, irrigation water requirements are affected by the soil water conditions, crop type and climatic conditions during the growing season. Groundwater recharge under irrigated crops is affected by numerous factors such as irrigation efficiency, the antecedent soil conditions or the soil type. If irrigation water requirements are covered through groundwater abstraction, cones of depression develop in the vicinity of irrigation wells, thus increasing the extent of the unsaturated zone. These processes influence in return soil water content and recharge dynamics.

The explicit integration of groundwater dynamics in such frameworks thus significantly increases the complexity of modelling approaches. Singh (2015), reviewed the current modelling approaches in this context and concluded that "*Very few studies reported so far have considered the determination of optimal cropping pattern that can maximize the net benefit and the corresponding pumping schedule by taking into account the groundwater level within the desired limits so as to mitigate the waterlogging and salinization problems.*" In principle, fully coupled numerical models such as HydroGeoSphere (Aquanty, 2017) or CATHY (Camporese et al., 2010) can simulate the relevant feedback mechanisms between the surface and the subsurface under different agricultural practices (Brunner and Simmons, 2012). Several studies based on these models have been published since the review of Singh (2015) (e.g., De Schepper et al., 2017; Frey et al., 2016) and illustrate the significant potential for such fully coupled simulation approaches. However, the focus of these models is on water fluxes and nutrients but not agricultural production and changes in irrigation water demands. Computationally less demanding approaches which jointly simulate groundwater and agricultural processes such as irrigation or plant water demand have also been suggested, notably by Niswonger (2020). All of the above-mentioned coupled approaches so far are based on simplified vegetation dynamics which for example cannot simulate the reduction to plant and root growth in response to changing availability of water in the soil. Also, the approach of Niswonger (2020) is based on the FAO56 concept, which cannot evaluate changes to yield as a consequence of changing growing cycles or phenological developments. To the best of our knowledge, no single modelling framework has so far been proposed that combines the sophistication of state-of-the-art crop simulation techniques with soil- and groundwater modeling

From a methodological perspective, this paper thus suggests a workflow that combines highly sophisticated crop modelling approaches with a numerical groundwater model simulating subsurface water resources. This combination of approaches allows us to jointly explore crop dynamics and subsurface dynamics, thus providing a quantitative basis for the identified management questions. The proposed workflow is not specific for the analyzed region, it can be employed elsewhere, too.

We apply the above-mentioned model coupling for an important agricultural region in Switzerland, where local groundwater resources play an important role for agricultural irrigation as well as for drinking water supply in the region: The Bernese Seeland aquifer. Possible impacts of climate change on agricultural production and water use as well as on groundwater dynamics are evaluated for a selected set of alternative land management scenarios. An interesting aspect of the study in this respect is the direct involvement of stakeholders, who contributed to the development of land management scenarios.

The Seeland aquifer has a typical agricultural setting in an alluvial plain, with climatic and recharge dynamics which are commonly found in central Europe. The analysis of this region is thus of relevance for other regions with a similar setting. Moreover, the influence of changing climatic conditions on surface water levels and their influence on groundwater dynamics are explored in the context of agricultural adaption.

Specifically, the following questions are addressed with the proposed modelling framework:

- What is the impact of climate change (especially dry spell lengths and extremes of temperature and precipitation) on future water demand for irrigation and groundwater resources?
- How large is the risk of overexploitation of GW resources through intensive irrigation?
- Which alternative land management strategies could reduce the risk of GW overexploitation (e.g., changes in crop mixtures)?
- What is the relevance of climate vs. land-use change impacts on groundwater dynamics?

Concerning the novelty of this study, the combination of state-of-the-art simulation techniques for plant-, soil- and groundwater dynamics goes far beyond the previously suggested simulation approaches discussed above. An interesting aspect in this regard is the explicit simulation of groundwater and the basin-scale hydrological dynamics in the rivers which consider how climate change will affect the hydrographs of the rivers. Moreover, the direct implication of stakeholders to develop the management scenarios provides is rarely done in such modelling approaches.

1.1. Study area

The study area is located in the Swiss plateau (Fig. 1), East of Lake Biel. Its southern part lies in an area that was frequently flooded and consisted of large wetlands in its natural state. To make the land arable and to protect the infrastructure from floods, several large-scale hydrological projects were implemented in the last century, the so-called "Juragewässer Korrekturen" or "Jura water corrections" in English. These projects included the regulation of the lake levels and widespread drainage of the wetlands in the Seeland area. The Aare river was rerouted from its natural flow path during 1875 and 1878 and now enters Lake Biel (inflow: Aare Hagneck) to avoid floods. The inflow of the Aare is significantly more dynamic than the outflow from the lake Biel near the city of Brügg/Aegerten. The Jura-water-correction comprised of this detour and the regulation not only of Lake Biel alone, but also the adjacent Lake Neuchatel and Lake Murten which are all connected via canals. Together they provide an enormous retention storage capacity.

The wider Seeland (Three-Lakes-Region) area features significant groundwater resources, found in its granular aquifers. The aquifers are mainly composed of highly permeable gravels and sands and are intensively exploited to provide drinking water for municipalities. The Hagneck Canal controls the aquifer dynamics in its vicinity by concentrated recharge and diffuse recharge originates from precipitation.

The soils in the southern part of the study area are relatively rich in organic matter making this area particularly suited for arable agriculture (especially vegetables). In the southern part of the study area, vegetable farming covers 14% of the area. In the northern part, cereals (corn, wheat) and sugarbeet are cultivated. We focus our modelling approaches on the area outlined in Fig. 1. The study region was chosen because it features extensive groundwater resources and irrigation water is to a large extent pumped from the aquifer. The small and often perched aquifer systems found in other regions of the wider Seeland do not constitute an important exploitable groundwater resource and are thus not of relevance for this study.

2. Methods

2.1. Identification of soil types

The identification of the different soil types is required for the subsequent modelling approach. Based on the soil suitability map for agricultural production (FOAG, 1980), the study area is composed of three different soil zones (Fig. 2). To derive representative soil profile information for each of the three soil zones, soil profiles were merged and median soil texture values derived. To fill some data gaps, Guelph permeameter tests and soil sampling was carried out during spring 2017 (Rüfenacht, 2017). Within each of the three soil zones, information on cultivated crops is based on the Federal Office of Agriculture (FOAG, 2015, Fig. 2). Each soil zone inheres different kinds of crops. The southern part (Soil1) has more vegetables because of its favourable soil properties. Conversely, surfaces of wheat crop and pasture are more important in the northern part (Soil2 and Soil3).

2.2. Modelling strategy

A loosely coupled model approach is applied to investigate the interactions between climate, agriculture, hydrology, and hydrogeology. By loosely coupled we mean that the different modelling approaches are not integrated into one single large model, but rather that the results of one modelling component constitute the input for another model. The coupling is based on three models: (1) a process-based field-scale crop growth model (CropSyst), (2) a raster-based hydrological model (WaSiM-ETH, Gurtz et al., 2000), and (2) a groundwater model (FeFlow, Diersch, 2014) Fig. 3.

The crop growth model is applied to predict the impacts of climate change on crop production, irrigation demands and the soil water balance for the main crops cultivated in the region under irrigated and rain-fed conditions. The hydrological model is used to simulate impacts on the large-scale hydrological system (i.e., river discharges and levels) in response to different climatic scenarios. Both the agricultural crop model and the hydrological model are coupled with a groundwater model: crop model outputs are used to implement groundwater recharge and irrigation boundary conditions and river water levels simulated with the hydrological model define river boundary conditions (further described hereafter).

Note that the model is not designed to simulate quality aspects such as the transport of pesticides or nutriments. As indicated in Fig. 3, no feedback from the hydrogeological to hydrological or crop model is implemented. The limitations of this simplification are analyzed in discussion Section 4.

2.3. Climate and socio-economic scenarios

The period 1981–2100 was chosen for all simulations and scenarios. Climate projection data was derived from (CH2018, 2018). We thereby utilized statistically downscaled EURO-CORDEX projection data that

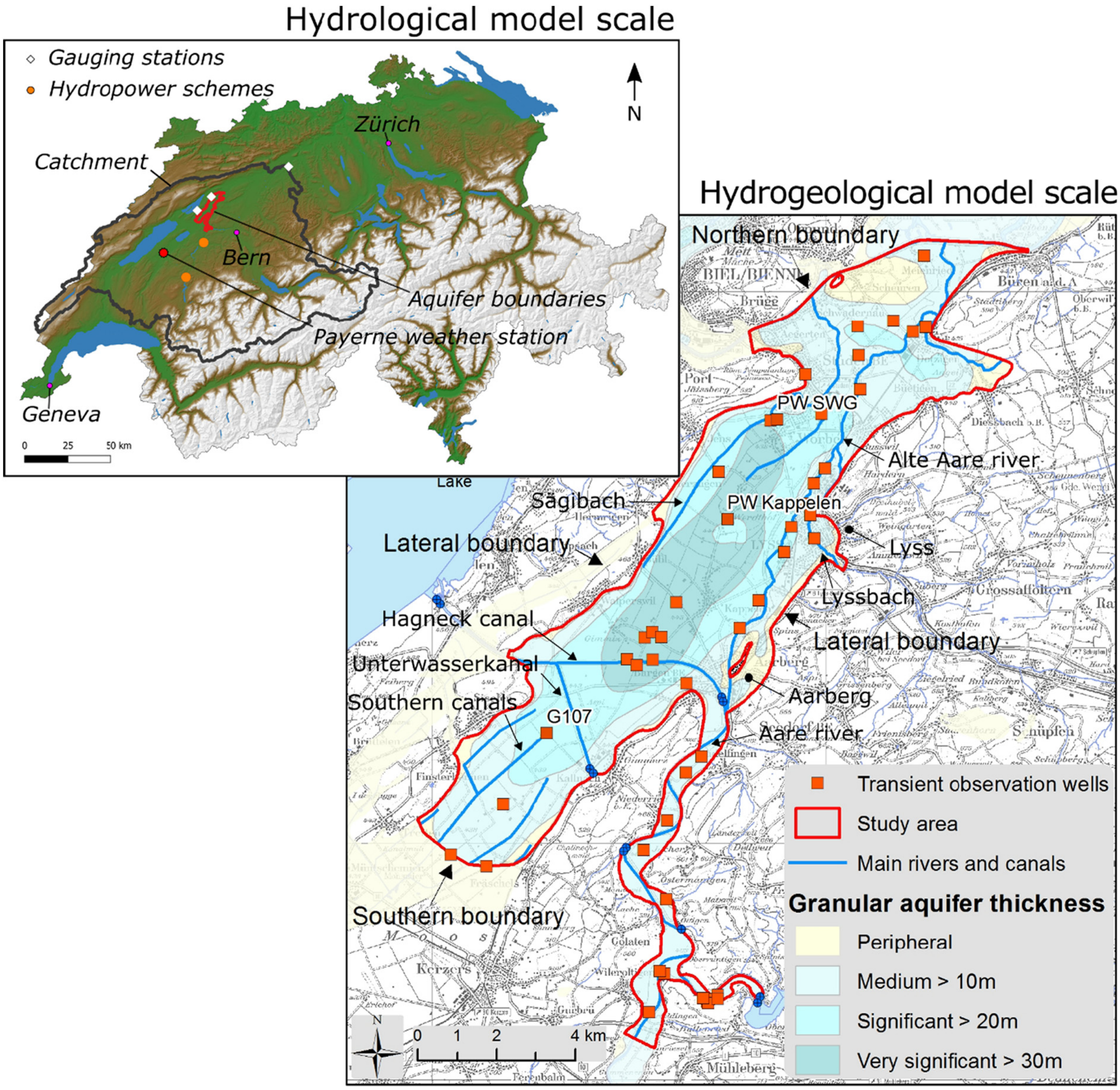

Fig. 1. Study area, illustrated in the main panel of the figure. It shows the extent of the numerical model as well as the main rivers and channels and indicates the thickness of the granular aquifer. The geographical extent of the Seeland is larger than the simulated region. The hydrological catchment of the Seeland is shown in the upper-left panel.

had been downscaled based on the quantile mapping approach to preserve the daily granularity and transient nature of the native RCM simulations. A subset of six downscaled GCM-RCM model chains was chosen from the CH2018 scenario dataset (Table 1). The rationale behind this selection was the availability of all required 5 meteorological parameters (temperature, precipitation, relative humidity, wind speed, and radiation) within the GCM-RCM model run and the coverage of all three emission scenarios RCP8.5, RCP4.5 and RCP2.6. Since no automated weather station of MeteoSwiss is located in the study region, climate input data to the crop model was derived from the station of Payerne (Fig. 1), which is close to the study region and has a very similar climatology. The hydrological model WASIM-ETH required more regional meteorological and climate information. Here, we used the observations and downscaling climate information of all meteorological stations in and around the hydrological Aare catchment, spanning elevations from approx. 500 m to 3000 m asl. As spatially explicit information is required, the interpolation of these stations to a 500 × 500 m raster was achieved by a method that combined elevation-based regression and inverse-distance-weighting for precipitation, and a regression-based interpolation for temperature. Due to the limited spatial data quality of wind speed and radiation, especially in the mountain chains, we omitted these variables for the hydrological model set up.

CropSyst and Wasim were run with all these model chains. However, due to the higher computational demand of the groundwater simulations, a smaller subset of model chains was selected for the Feflow model runs. The choice was made based on the most important changes in recharge, irrigation water demand and changes to the discharge regime as estimated with CropSyst and Wasim. Our selection was also including the extremes of emission scenarios. Model chains selected for the hydrogeological model are marked bold X in Table 1.

Socio-economic scenarios were co-designed with regional farmer representatives. In an interview session, stakeholders and farmers were asked to describe the scenarios they are currently planning for. Moreover, the stakeholders were asked to envision how crop mixes and irrigation intensities would change if agricultural land management was extensified and intensified. According to these stakeholders' suggestions, the socio-economic scenario #1 assumes an increase in irrigated crop surface by 20% and a decrease of the rainfed crop by 13.5% and the socio-economic scenario #2 assumes a decrease in irrigated crop surface by 20% and an increase of rainfed crop surface by 13.5%.

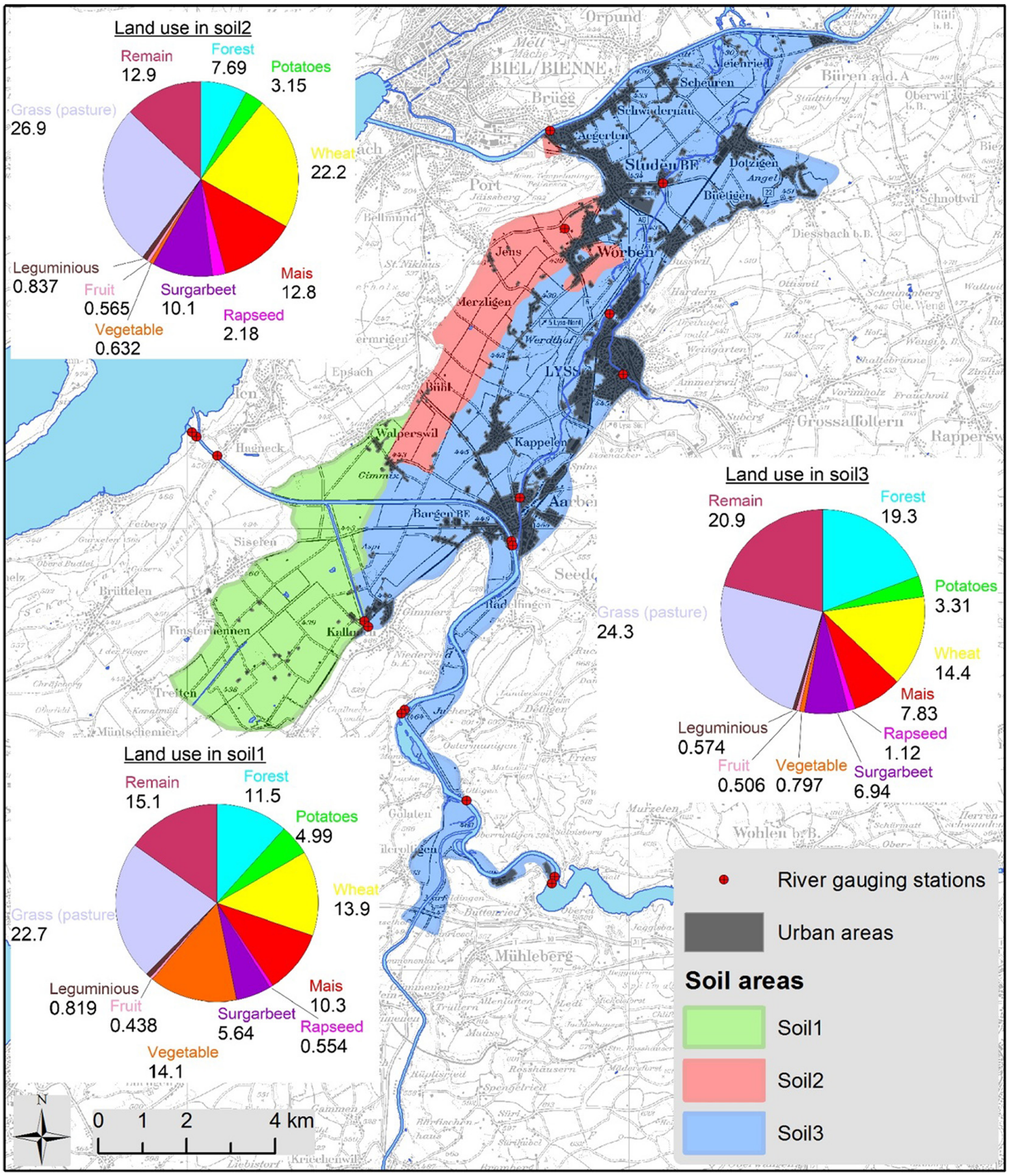

Fig. 2. Soil areas and land use types within the study area.

In addition to these stakeholder-defined scenarios, two more extreme scenarios of intensification and extensification were evaluated to test the sensitivity of the groundwater system to management changes. The socio-economic scenario #3 assumes the full conversion of the current agricultural area to 100% irrigated vegetable cultivation in the soil zone 1 and the socio-economic scenario #4 assumes an extreme extensification scenario where 100% of the current crop area in soil zone 1 is converted to rainfed grassland. Assumed crop shares for the aquifer region for all four land management scenarios are summarized in Table 1.

2.4. Crop modelling

The generic crop model CropSyst (version 4.13.09; Stöckle et al., 2003) has been applied in this study. CropSyst is a multi-year, multi-crop, daily time-step model to simulate cropping systems. It can be used as a tool to study the effect of climate and management on cropping systems productivity for different soil types. Input data requirements of CropSyst are daily weather data, soil characteristics and crop type and management specifications. CropSyst simulates daily biomass accumulation in response to soil, climate and management drivers. Daily biomass growth is calculated as the minimum between radiation-dependent growth (Monteith, 1977) and transpiration-dependent growth (Tanner and Sinclair, 1983). Transpiration-dependent growth can be limited by soil water availability. To estimate plant water uptake, the soil profile is divided into multiple layers. The uptake from each layer is estimated based on the water potential difference between the soil and the plant xylem, multiplied by plant conductance (mainly determined by root conductance). Soil water dynamics are simulated based on the daily cascade approach implemented in CropSyst (Stöckle and Nelson, 2000).

CropSyst was run using crop parameterizations for the crops maize, sugar beet, potato, winter wheat, winter barley, and oilseed rape from Holzkämper et al. (2015), calibrated based on statistical yield data using the procedure described in Klein et al. (2012).

Automatic irrigation was specified to be triggered based on soil water depletion (0.5 maximum allowable depletion). The period of potential irrigation was defined concerning phenological development:

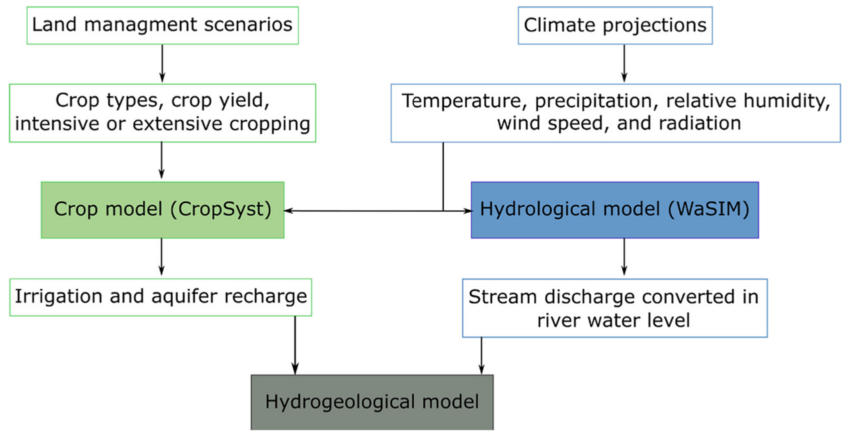

Fig. 3. Overview of methodological approach: Based on climatic scenarios and alternative future land management scenarios, current and future irrigation water demand and recharge are calculated with the agricultural crop model. The hydrological model simulates discharge and lake level dynamics. The calculated recharge, surface water heads and abstraction rates determine the boundary conditions for the spatially distributed FeFlow model.

from the beginning of active growth to the onset of yield formation. If irrigation was triggered, between 15 and 25 mm of irrigation water were applied per day to refill the soil water content.

Daily weather data was derived from the climate projections for the automated weather station of Payerne (located in the South-Western Lowland region, 35 km south-west of the aquifer region) and soil characteristics were specified for three different soil zones in the aquifer region. The definition of zones was based on the national soil suitability map. The specification of soil profiles required as input for CropSyst was based on an analysis of soil profile information within the three soil zones provided by NABODAT (2018): available profile information was aggregated based on defined sublayers of the soil; median values were derived for humus, clay and sand contents in each sub-layer to specify soil texture profiles for CropSyst. A summary of soil texture profiles is provided in the supplementary material.

Simulations were conducted for all three soil types and 15 climate model chains for the main crops grown in the region: grain maize, potato, sugar beet, winter wheat, winter barley, winter rapeseed, grassland and a lettuce vegetable. For all crops except lettuce, parameterizations from previous applications were used (Klein et al., 2014; Holzkämper et al., 2015). Since no yield data were available to calibrate the model for vegetables, the lettuce parameterization was based on studies of Suarez-Rey et al. (2016) and Tei et al. (1996). Thereby, a fixed growing period was assumed between April, 1st and October 31st (equivalent to the current cultivation period for vegetables in the study region).

2.5. Hydrological modelling

To assess current and future dynamics and availability of surface water of the Seeland region, the entire hydrological system of the Aare catchment from the mountain headwater catchments up to Murgenthal (Fig. 1) needed to be simulated. The external water supply is required in the combined modelling approach as it defines the boundary condition of the groundwater model. Fig. 5 illustrates the defining inflow boundary conditions for the groundwater model. Observed and simulated

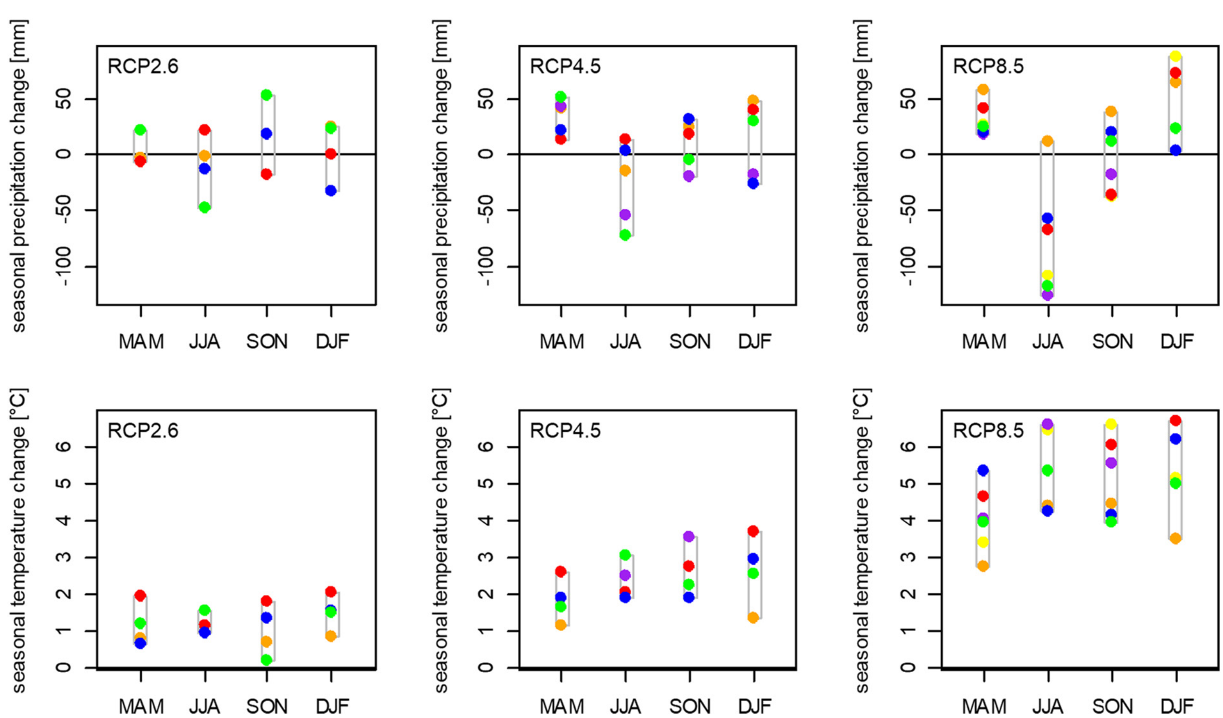

Fig. 4. Projected changes in seasonal precipitation sums and temperatures according to the six model chains listed in Table 1 for the three RCPs.

Table 1
Selected CH2018 model chains (bold X indicate model chains selected for groundwater model simulations, colour code relates to symbol colours in Fig. 4) and description of socio-economic scenarios.

Climate scenarios						
Code	GCM	RCM	Resolution	RCP2.6	RCP4.5	RCP8.5
(yellow)	MOHC-HadGEM2-ES	CLMcom-CCLM4	EUR44			x
(orange)	ICHEC-EC-EARTH	DMI-HIRAM5	EUR11	**X**	x	x
(red)	MOHC-HadGEM2-ES	KNMI-RACMO22E	EUR44	x	x	x
(purple)	CSIRO-QCCCE-CSIRO-Mk3-6-0	SMHI-RCA4	EUR44		x	**X**
(blue)	MIROC-MIROC5	SMHI-RCA4	EUR44	x	x	x
(green)	MPI-M-MPI-ESM-LR	SMHI-RCA4	EUR44	x	x	x

Socio-economic scenarios	
Scenarios	Descriptions
#1	Potatoes, maize, sugarbeet, vegetable (irrigated crops): +20% Wheat, rapeseed, legume family, grassland (rainfed crops): -13.5%
#2	Potatoes, maize, sugarbeet, vegetable (irrigated crops): -20% Wheat, rapeseed, legume family, grassland (rainfed crops): +13.5%
#3	100% irrigated vegetable in soil zone 1
#4	100% rainfed grassland in soil zone 1

discharge dynamics of the Aare at different locations, converted in water levels serve as boundary conditions for the groundwater flow model (see Fig. 3). For the two most dominant inflows, the Aare at Hagneck and Aare at Brügg/Aergerten, the results of the calibration and validation approach are presented.

The representation of the discharge dynamics along the Aare in the project area, the hydrological catchment includes several regulated discharges from lakes (i.e. Lake Thun, Lake Biel) and is influenced by hydropower production in two headwater catchments (e.g. Aare-Brienzwiler, Saane (orange circles in the upper left panel of Fig. 1). To represent these important controls on discharge dynamics, a combination of a hydrological and a hydraulic model was applied: The hydrological model WaSiM-ETH (Schulla, 2017) is used to simulate the natural runoff conditions and the less complex lake level-discharge-alterations of the regulated lakes in the headwater (e.g. Lake Thun). This version of the hydrological model includes snow and glacier melt routines that consider melting of the glaciated areas is hence able to take into account the expected diminishing of glaciated areas under a warmer climate (Huss et al., 2008).

To represent the complex lake level-discharge-regulations of the three interacting lakes of the Jura-waters-corrections (Lake Biel, Lake Murten, Lake Neuchâtel), we applied the hydraulic model RS-MINERVE (Foehn et al., 2020). A model was available through a previous study (Andres et al., 2021). The combination of the two models is as follows: Simulated discharge for rivers relevant to the project are (such as the Aare at Hagneck, the Broye, Seyon, Areuse, Arnon, Mentue, Talent, Chandon, Petit Glane, Arbogne, Orb, and Suze) are simulated applying the hydrological model while the RS-MINERVE system. This model simulates the lake levels of the three lakes and the discharge of the Aare at Brügg/Aegerten.

The hydrological model was set up for the period 2006–2016 and validated for the period 1987–2014. Fig. 5 presents the hydrologic-hydraulic model performance in terms of observed and simulated discharge at the two most influencing cross-sections within the model system. The two presented discharges represent also the hydrological model performance of the Aare river up to Hagneck, and the combined model performance at the Brügg/Aergerten gauge. For both time series, the long term mean hydrograph is presented aside a quantile-quantile plot. The model system works well for both gauges. However, some limitations for the late summer, autumn period are visible: Simulated discharge overestimate the observation, distinctly. The reasons for this overestimation are due to the precipitation correction in the late summer floods of 2005, 2007. These were not included in the calibration phase, resulting in an overestimation of precipitation in 2005 and 2007. However, since the groundwater model FeFlow is running with monthly mean values, this overestimation is of little significance for the overall result.

2.6. Groundwater model

Groundwater models simulate the flow of groundwater based on a discretized formulation of the Darcy equation. On a very basic level, groundwater models assume that a representative elementary volume exists and that the flow remains laminar, e.g. Darcy's law is applicable. The model was developed with the finite element code FEFLOW 7. This numerical simulator was configured to solve the 2D horizontal saturated unconfined groundwater flow equation. The surface of the model is defined by the topography, the bottom by the bedrock elevation. The model boundaries (see Figs. 1 and 5) were implemented in the following way. The northern boundary was defined through the Aare river and the hydraulic heads (water level in the river) are based on either observations for the calibration or on the predictions obtained through the hydrological model. In the southern part, the thickness of the granular aquifer becomes very thin. For the calibration period, observed hydraulic heads were implemented along this boundary and a transfer function based on the relationship between precipitation and groundwater heads was implemented during the simulation of the

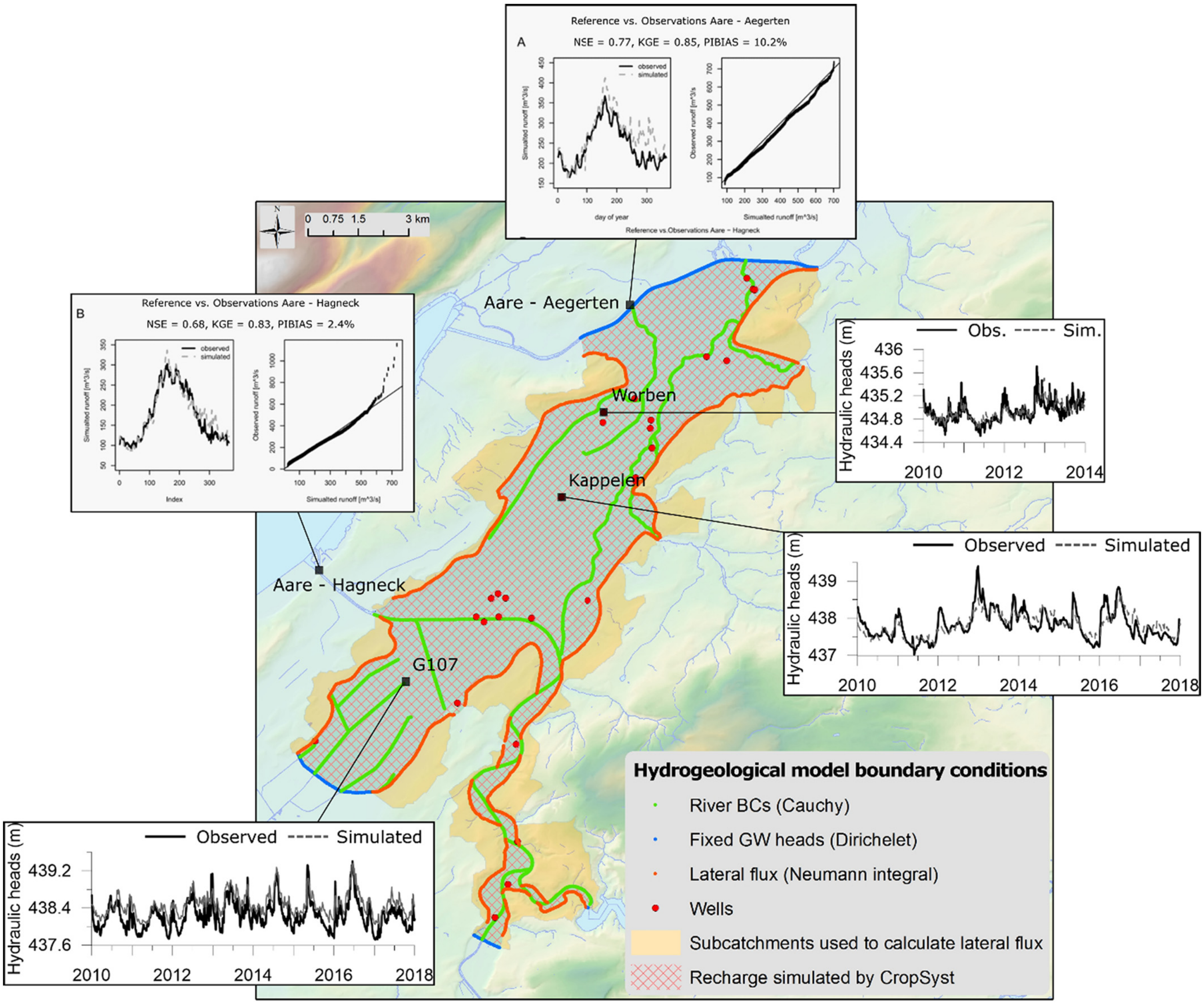

Fig. 5. Hydrogeological model boundaries, boundary conditions and performances and hydrological model performance illustrated as long term mean values (1987–2014). Model efficiency (ME) was calculated using the Nash-Sutcliffe-criterion, the Kling-Gupta-Efficiency (KGE), and the percentual BIAS (PBIAS).

climate scenario. The boundaries on the east and west were set along a clearly defined interface between the alluvial valley deposit and consolidated sedimentary rocks featuring low permeability. The topographical catchment exceeds the extent of the granular aquifer. To account for the lateral fluxes originating from these sub-catchments, we calculated monthly mean water balances (precipitation-evapotranspiration) of each sub-catchment and added the residual fluxes as a lateral inflow boundary condition.

Recharge rates and irrigation demand are available through the CropSyst analysis. The recharge rates are implemented in the model through boundary conditions. To account for the various soil properties and the irrigation demands of the various crops, different irrigation fluxes were calculated for the three soil areas. To simulate river-aquifer interactions, Cauchy boundary conditions were employed using observed river water levels interpolated between different gauging stations (presented in Fig. 1). The interaction between river and aquifer is then calculated as a difference of potential between the river water level and the groundwater heads and can be calibrated by adjusting a coefficient representing the river bed transmissivity. Finally, well boundary conditions were implemented to reproduce water withdrawal of municipal pumping wells.

The groundwater model calibration was carried in two steps. The first one was the calibration in steady-state to reproduce the mean conditions of the aquifer. In a second step, the calibration was expanded to transient simulations to reproduce the daily mean and seasonal dynamics. To calibrate the steady-state model, more than 200 groundwater head observations (Fig. I of supplementary material) and the estimated or measured river-aquifer interactions (WWA, 2004) were used for adjusting the transmissivity of the river beds and the hydraulic conductivity using an inverse calibration methodology with pilot points (Fig. I, supplementary material). Pilot points allow to consider heterogeneity of the subsurface and offer a flexible and highly efficient way to calibrate hydrogeological models (Moeck et al., 2015). The results summarized in Table II (in supplementary material) showing simulated and observed water balance components and interaction between river and aquifer suggest that the calibrated model is perfectly capable of reproducing the groundwater flow of the aquifer and the role of rivers (and canals) which sometimes are infiltrating or draining. In term of groundwater heads, Fig. II (in supplementary material) shows that the model can reproduce the piezometric levels with a mean error of 16 cm. In addition, the pilot point methodology allowed to reproduce the observed large-scale hydraulic conductivity heterogeneity of the aquifer and the

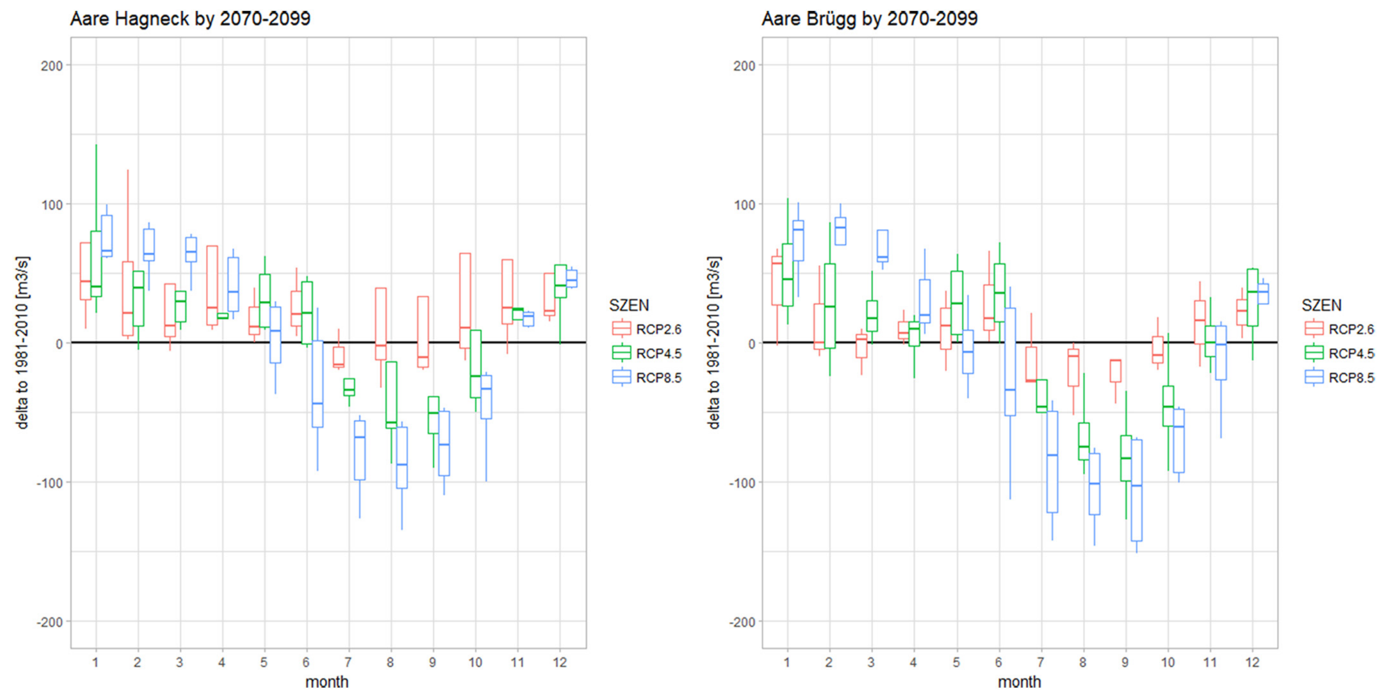

Fig. 6. Monthly mean differences in discharge by 2070–2099 from 1981 to 2010 for the three emission scenarios at two gauges: Aare-Hagneck, and Aare Brügg. Boxplots are based on 6 (RCP8.5), 5 (RCP4.5), and 4 (RCP2.6) climate model data inputs.

location of former meanders (reported in WWA, 2004) characterized by higher hydraulic conductivity (Fig. III). Then, the model was calibrated in transient conditions using the simulated mean groundwater heads of the steady-state model as the starting point. The transient calibration used the observed daily groundwater heads of the period 2010–2016 at 40 observation wells to define the objective function. The locations of the observation wells are presented in Fig. 1. The calibration parameter for the transient simulations was the porosity of the aquifer. Fig. 6 shows the simulated and observed groundwater heads in three observation wells located for each soil zone. The model can simulate the daily mean groundwater dynamics and also the seasonal dynamics with periods including both high and low groundwater heads. The simulated, daily mean root mean square error of all 40 observations wells is 15 cm. The model development and the calibration procedure are described in detail in Cochand et al. (2019).

After the model calibration, the model can be used to simulate long term predictions using the simulated river discharge rates presented in Section 2.5 by converting the discharge rates to water levels. This was done by using the available relation between discharge rate and water level). These water levels were subsequently implemented through river boundary conditions. The current climate recharge and irrigation boundary conditions were replaced by the CropSyt predictions. Finally, the lateral fluxes from the consolidated sedimentary rock were also modified by using the same methodology but with climate model chain outputs instead of observed meteorological data.

3. Results

3.1. Estimated changes in discharge

According to the combined, hydrological and hydraulic model results discharge by the end of the century will be altered mostly seasonally, showing an increase in winter, almost unchanged discharges in spring, a decrease in summer and early autumn (Fig. 6). The magnitude of this change is a function of the emission scenario assumed, with RCP8.5 leading to the highest change signal in most cases. It is noticeable that the simulated change does not alter linearly with increasing greenhouse-gas emissions, but the change signal strongly aggravates from RCP4.5 to the RCP 8.5 emission scenarios, for the winter season, and already from RCP2.6 to RCP4.5 for the summer change signal. These seasonal change signals mount up to around 5%, 10–15% for RCP 4.5, and 30% for the RCP8.5 (for detailed numbers, see Table III in supplementary material). The strongest decrease in water supply occurs in July, August, and September. This decrease, however, is compensated by the increase in rain in January and February. During the sowing and germination period for maize and potato (Apr-Jun), the influence on the water supply is rather small and even positive or the RCP 2.6 and RCP4.5 (−6% - +12%), while a decrease of up to 20% (Jun, Aare-Hagneck) must be considered under the RCP8.5 scenario. Despite this strong seasonal alteration, the annual amount of water supply is not changing markedly, with only minor annual decreases under RCP2.6 and RCP4.5 scenarios (− 1% - 2.6%), by the end of the century in comparison to the 1981–2010 conditions. Assuming the RCP8.5 the annual decrease in water supply aggravates to −10%.

However, these values reflect only the median change signals of the model ensemble. The variability of the simulated changes across the different model chains used is depicted by the spread of boxplots in Fig. 6. Especially for the Aare, Brügg gauge huge spreads can be seen from June to November, particularly under RCP8.5. These spreads are in line with the stronger deviations found for the reference periods and partly refer to the same reason for a higher sensitivity of the model to high flows at the gauge Aare, Brügg. However, the influence of high flows on the variability can also be seen at the discharge gauges of Aare, Hagneck: The boxplots representing the RCP2.6 and RCP4.5 show a larger spread at the upper part of the interquartile range indicating high flows projected by a single or two of the model ensemble members. The large variabilities are hence interpreted as a result of natural climate variability simulated by the different model chains.

3.2. Climate change impacts on crop yields, irrigation water demands and soil water drainage

Yield change estimates for dominant spring crops and all considered climate model chains are presented in Fig. 7. Simulation results show that yields of all crops except grain maize are negatively affected by climate change. Potato and sugar beet yields are projected to decrease

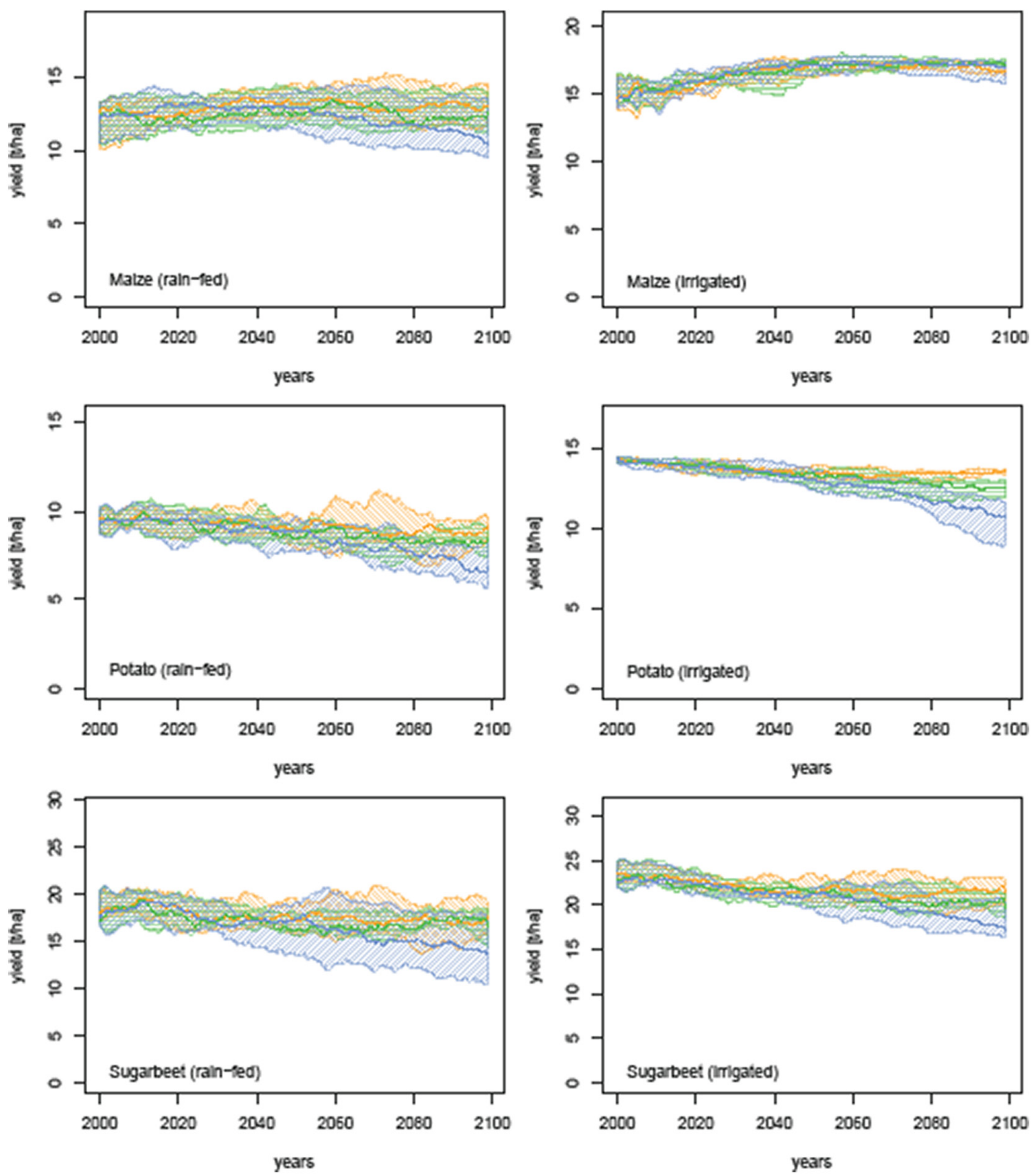

Fig. 7. Ensemble estimated of 20-year average yields for dominant spring crops under rainfed and irrigated conditions based on climate model projections of RCP 2.6 (orange), 4.5 (green) and 8.5 (blue); bold lines show ensemble medians, bounds indicate climate projection uncertainty based on the ensemble described in Table 1 (only results of soil type 1 are shown here since variation between soil types had hardly any effect on estimates of interest).

both under irrigated and rain-fed conditions. This implies that temperature increases are the major driver of negative yield changes: accelerated phenological development leads to a shortening of growth and grain filling periods and thus reduces yield potentials. This decrease cannot be compensated through irrigation even though the yield level can generally be increased through irrigation. Only for grain maize, which matures relatively late in comparison to other crops considered in this study and where we have assumed a medium-late maturing variety in the base setting (GDD requirement for maturation 1850 with base temp 6 °C), noticeable yield increases were projected (most pronounced under irrigated conditions). Yield losses are generally the most severe with RCP 8.5, while RCP2.6 shows the smallest yield reductions.

These results imply that serious reductions in agricultural productivity due to shortened growing cycles with accelerated phenological development would have to be expected with RCP8.5, unless adequate adaptation measures are taken (e.g. selection of later-maturing varieties).

Fig. IV (in supplementary material) shows the projected changes in seasonal irrigation water demands for the spring crops considered in this study (grain maize, potato and sugar beet) as well as for lettuce (with literature-based parameterization and an assumed fixed growing season from April 1st and October 31st, equivalent to the current cultivation period for vegetables in the study region).

The impact of climate projection uncertainty on estimates of irrigation water demands is generally large. However, crop model projections suggest a clear increase in irrigation water demands for grain maize under RCP8.5. For potato, the projected increase is less pronounced due to shortened growing cycles with accelerated phenological development at higher temperatures, which leads to a shift of the growing cycle towards to period of the year, when drought limitations are less frequent ("drought avoidance"). In the case of sugar beet, this effect could even result in decreasing trends of seasonal irrigation water demands. The largest increase in irrigation water demand was estimated for lettuce with the fixed growing season – highlighting the relevance

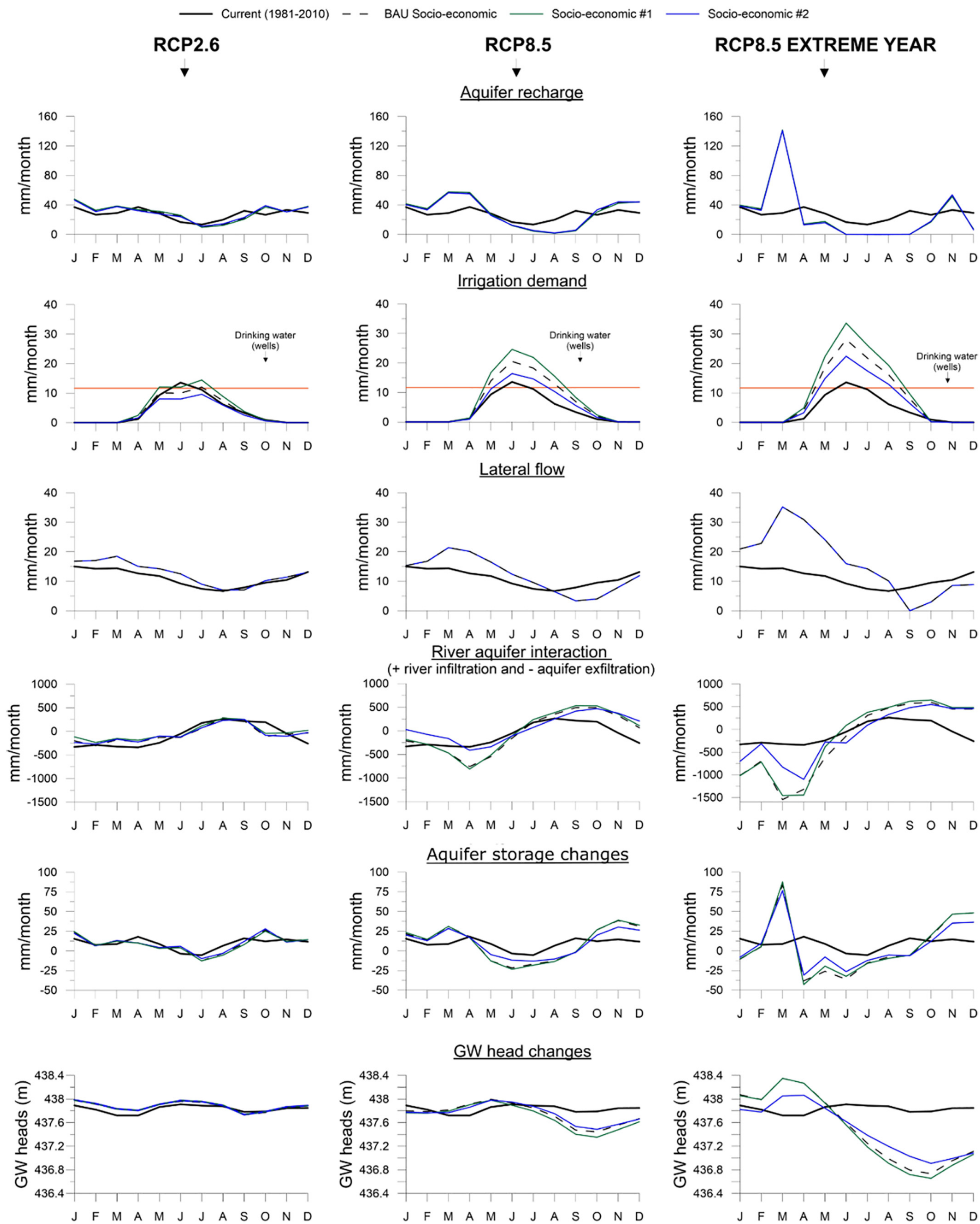

Fig. 8. Simulated water balance of the aquifer for RCP2.6 and 8.5 climate scenarios and two socio-economic (#1 and #2) scenarios.

of the duration of the growing cycle for the estimates of changes in irrigation water demands.

The annual sums of soil water drainage are largely unaffected by climate change (see Fig. V in supplementary material) According to ANOVA-based variance partitioning of all simulation runs, model projection uncertainty was found to be the greatest source of variability in soil water drainage change (73%); differences in crop type explained 10% of the variation in soil water drainage changes, and soil type differences explained only 5%. The variance attributed to crop types can be explained through differences in plant water use and seasonal variation thereof (crops differ in transpiration use efficiency and lengths of growing cycles). Variance attributed to soil types can be explained by differences in soil permeability. Climate and land management change impacts on aquifer dynamics.

For assessing the combined impact of climate change and management on aquifer dynamics, monthly aquifer water balances considering mean aquifer recharge, irrigation demand, lateral flow, river-aquifer interactions, and changes in aquifer storage were elaborated. Fig. 8 shows the water balances of the entire study area for the two simulated climate scenarios (DMI-HIRAM5 RCP2.6 and SMHI-RCA4 RCP8.5) and two socio-economic (#1 and #2) scenarios.

For all scenarios with RCP2.6 emission scenario (first column in Fig. 8), the impact on each component of the water balance is small. Although irrigation demands change slightly, groundwater heads remain almost unchanged. River-aquifer interactions also are not markedly affected by changes in river water levels and recharge rates do not change significantly.

Changes in the water balance components are much more pronounced with the RCP8.5 emission scenario (middle column in Fig. 8). Seven observations are made: (I) Changes in aquifer recharge may be observed with a significant increase of about 50% in March and April (MA) and a recharge close to 0 mm/month as opposed to 20 mm/month in August and September (AS). (II) Irrigation demand is expected to increase by 30% to 65% depending on the socio-economic scenario. Moreover, irrigation demand exceeds largely water demand for drinking water (orange line). Note that no estimates on future drinking water demand were considered, the drinking water demand is set equal to the current demand. (III) The lateral flows are also affected and follow the same trend as recharge, with a higher amount at the end of the winter and the beginning of spring and a decrease in September and October (SO). (IV) It can be seen that river buffer observed changes by draining more water in March and April and by infiltrating more water from September to December. (V) Changes in aquifer storage are lower during the warm season and higher in the cold season. (VI), groundwater heads changes follow the same trend with higher or unchanged groundwater heads from January to June and lower groundwater heads from July to December. However, changes are limited with a maximum decrease in groundwater heads of 30 cm. Generally, the differences between socio-economic scenarios are limited. (VII) The third column of Fig. 8 shows an extreme year to assess the lower bound of the impact. In general, changes of all components are more accentuated; the period with no recharge is longer than the current period, the irrigation may be up to 200% higher, changes of lateral flows are higher, rivers may drain 3 times more water in winter and infiltrate 50% more from September to December, a decrease in aquifer storage of 25 mm/month is observed during the warm season and the groundwater head decrease may reach 1 m, compared to the current situation.

To provide a better understanding of the impact of land management, Fig. 9 presents the water balance of the soil 1 area in which more intense socio-economic scenarios (#3 and #4) were implemented.

For scenarios with RCP 2.6 emissions scenarios (column 1), the socio-economic scenario #3 shows a significant increase (+400%) in irrigation demand. This irrigation demand is partially compensated by river infiltration and lateral flow which increase during the same period. Therefore, a decrease in aquifer storage is observed in June, July and August and in piezometer G107 close to the irrigation canals (see Fig. 5), groundwater heads remain unchanged. No significant change is observed in the two other scenarios.

Changes in groundwater dynamics are linked to changes in river dynamics because of their close interconnectedness. Fig. 6 shows that the Aare River discharge will increase in spring due to winters with more rain and less snow and decrease in summer due to a smaller contribution of snowmelt. Consequently, groundwater dynamics follow the same trend (Fig. 8 "GW head changes"), with higher groundwater heads in winter and spring (about 20 cm higher on average, RCP8.5), and low groundwater heads in summer (about 40 cm lower on average, RCP8.5). This process is even accentuated by the changes in recharge (Figs. 8 and 9 "aquifer recharge") which follow the same pattern with a decrease during the warm period and an increase during the cold period. Finally, it can be seen that changes in groundwater heads are mainly observed for the scenario RCP8.5 and not for RCP2.6 for which only a slight increase during winter is observed.

4. Discussion

The proposed modelling approach is straightforward to implement in other project areas. The coupling suggested allows combining the most advanced features of current hydrogeological, hydrological and crop production modelling frameworks (Fig. 5). A limitation of our approach is that two feedback mechanisms cannot be considered: The influence of the water table on the crop-simulations, and the influence of the water table on the infiltration rates of the river. If the capillary rise is significant, high water tables change the moisture content in the root zone and result in a higher evaporation rate. The crop-simulations assume a deep-water table, thus neglecting this feedback mechanism might overestimate irrigation demands. In soils where the capillary rise is significant (e.g. clay soils), this effect could indeed be relevant. However, for organic soils such as the ones found in the Seeland capillary rise is only a few centimeters (Hillel, 2003), thus the influence of this is not relevant. The second feedback mechanism not explicitly considered is the influence of the water table on the infiltration rates from the rivers. However, the infiltration rates along the river constitute only 0.2% of the discharge (WWA, 2004), the effect on surface water levels is thus marginal. To consider these feedbacks explicitly, a fully coupled approach such as HydroGeoSphere would need to be employed. As mentioned earlier, however, no currently available physically-based model has reached the sophistication of the crop-modelling approach we employed here.

4.1. Impact of climate change on hydrology

Regarding hydrological projections (Fig. 6 and Table III in supplementary material), the results of this study are well aligned with estimates made by CH2014-Impacts (2014) or FOEN (2012) which are amongst the most exhaustive impact studies in Switzerland. Both studies anticipated an increase in streamflow in winter and a decrease in streamflow in summer for the end of the century. However, predictions made in CH2014-Impacts (2014) are the results of 10 climate change scenarios and consequently, their predictions have more uncertainties. Nevertheless, predictions made in this study, e.g. an increase of 30% in winter and a decrease of 35% in summer for the less optimistic scenario is in perfect accordance with the above-mentioned studies.

4.2. Impact of climate change on crop productivity

Regarding the estimated impacts of climate change on crop productivity (Fig. 7), the results of this study are in line with the findings of other studies conducted in these two disciplines. For example, Klein et al. (2014) estimated the negative impacts of climate change on crop productivity and increasing irrigation water demands for a study region close to the case study considered here. Increases in grain maize climate

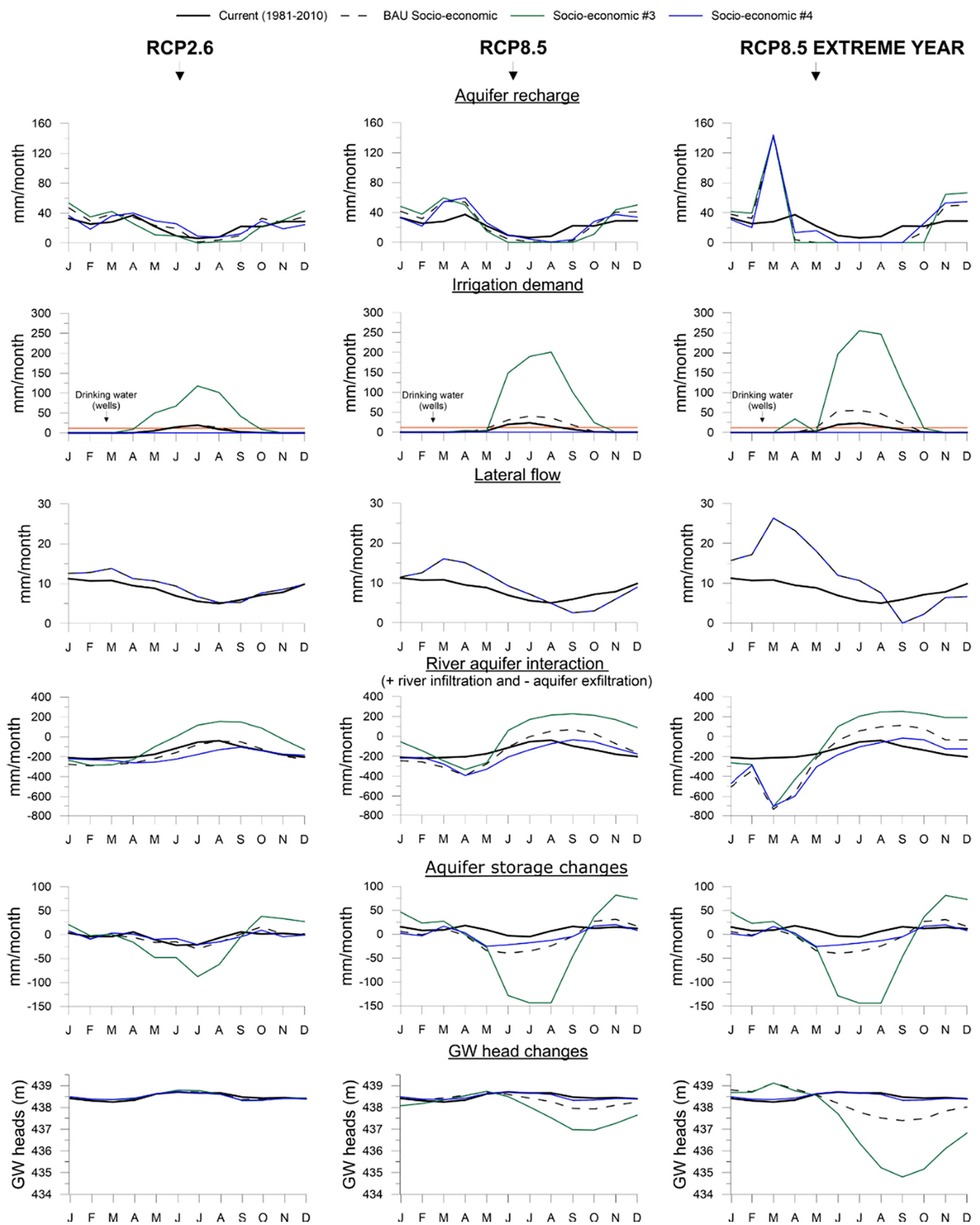

Fig. 9. Simulated water balance of Soil 1 using the groundwater model. The following scenarios were used: BAU socio-economic, socio-economic #3, socio-economic #4 and climate scenarios.

suitability over the past decades in Switzerland were also identified by Holzkämper et al. (2015). In line with the findings of this study, Holzkämper (2020) identified increasing yield potentials for late-maturing varieties of grain maize in particular and potentials for limiting agricultural water use by cultivating earlier-maturing varieties.

4.3. Impact of land-use

Concerning the influence of land use, four alternative scenarios were tested. Developments towards intensification of agricultural land management (also, but not only based on increased inputs of irrigation water) could become reality considering that soil fertility and climatic suitability for production are currently high. Following initiatives of single farmers and farmer cooperatives, irrigation infrastructure developments are currently ongoing to secure water resources for irrigation in the region in the long term. Concerning these observed developments up to now, a scenario such as the moderate intensification scenario can be considered likely. A more extreme scenario as tested here with scenario #3 may even be possible if we consider that groundwater from the region might be exported to areas in need of irrigation outside of the actual aquifer region. Especially in regions further South such as the Broye region, where irrigation water was traditionally abstracted from the channel of the Broye river, but irrigation bans were more frequently enacted in recent drought years, farmers are in increasing need of addtional water resources (Klein et al., 2013). The pressure to produce more intensively is not only driven by farmers' commercial interests, but also by the political will to achieve a high level of self-sufficiency. Also, considering that the main import countries for vegetable products in Switzerland are Mediterranean countries such as Spain and Italy, where agricultural production is expected to be more severely affected by climate change, the relevance of inland vegetable may increase more in the future.

4.4. Methodology

Numerous studies have been published on the influence of climate change on groundwater resources, as comprehensively discussed in the review of Amanambu et al. (2020). However, few studies have so far jointly investigated the combined impact of climate and land management changes on groundwater as we have done in this study. The application of our modelling approach to the Seeland provides an interesting example of the relative importance of climate change versus changes to land use. Our study clearly shows that for the Seeland aquifer the implications for groundwater are predominately controlled through land-use changes, and not through climate change.

An interesting result of this modelling approach is that in some cases, the increase in irrigation demand is relatively low because of the faster maturation period. Such effects could not be accounted for by methods assuming static crop development cycles such as the classical crop-coefficient based FAO56 approaches (Allen et al., 1998) are employed. Through the subsequent coupling with the hydrogeological model, the influence of increased groundwater-based irrigation was quantified. Also, we showed that increased abstraction can to a certain extent be compensated through increased river infiltration. Albeit small, these changes affect the discharge of the rivers. The proposed modelling approach thus allows for the food-water nexus to be explored explicitly for different land-use and climate scenarios and identify potential maladaptive strategies.

4.5. Local and political perspectives

For the Seeland aquifer itself, several conclusions can be drawn. Impacts on groundwater dynamics are expected to be moderate if the current land-use would be maintained (Fig. 8). However, groundwater resources could be overexploited in the future, if agricultural production would be strongly intensified through increased groundwater abstractions to irrigate crop types such as fresh vegetables (Fig. 9). Different climatic and land-use scenarios were explored. The moderate (RCP26) and even more accentuated (RCP85) scenarios consistently resulted in a limited effect on groundwater resources under current land-use. Irrigation water demand can be compensated without major drawdowns in the aquifer. On the other hand, with the more intensive land-use scenarios (#3 and #4) the water balance of the aquifer is changed significantly. However, to a certain extent, these drawdowns are compensated through the increased infiltration from the rivers.

However, the political debate concerning future land management developments in the region is vivid and in the interest of wetland biodiversity, nature conservation and preservation of organic soils as important carbon stocks, perspectives of extensifying land use in the region are also discussed. In this context, also the extensification scenarios can be considered realistic, assuming stronger conservation policies and increased access to agricultural subsidies (Bolliger et al., 2007; Hagemann et al., 2020).

5. Conclusions

Agricultural production is influenced by a multitude of socio-economic factors (e.g. commercial interests of producers, consumer demands, market dynamics, governance structures), while relying on local and regional soil and water resources. This resource use may sometimes conflict with other societal interests and demands (e.g. nature conservation, drinking water production).

To address such challenges, integrated quantitative assessments such as the one presented in this study can be of high value to support evidence-based decision-making in the development of integrated water management strategies.

In this context, we provide a novel modelling framework that can be used to quantitively explore different agricultural adaptation strategies. We proposed a loose coupling of an agricultural, hydrological and hydrogeological model to analyse the interactions and feedback mechanisms between agricultural adaption and production, climate change as well as groundwater dynamics. The novel modelling approach combined state-of-the-art simulators for all of these domains. The loose coupling brings along a range of advantages. For example, the rivers in the project area are strongly influenced by changing climatic conditions across the entire hydrological catchment, which greatly exceeds the project area. The proposed combination of models allows accounting for these changes, e.g. glacier melt and rising snow lines in the alpine area of the catchment. The simulation of crops goes beyond the capacities of current integrated hydrogeological models or groundwater models which are combined with the FAO56 approach. For example, crop yields, as well as changes to the irrigation water demand, are calculated dynamically. The model coupling is flexible and able to handle a wide range of different combinations of land management and climate change scenarios. With respective parameter adjustments, the framework could be applied to other regions to study similar issues, for example in the context of more efficient agricultural water resources management or in the context of water use conflicts.

The application of the developped approach in the Seeland using a selected set of land-use and climate scenarios showed that groundwater dynamics in the region are more sensitive to changes in land management than to changes in climate. It was found that an increase in irrigation water use could result in an amplification of seasonal fluctuations in groundwater tables with reductions in water table depths in late summer and autumn. Such changes might have implications on pumping costs, groundwater quality and the biodiversity of aquatic ecosystems connected to stable groundwater tables. As results from the crop model simulations show, such reductions in agricultural water use might be achieved with earlier maturing crops for which the growing cycle would fall into a period of the year with lower water deficits. However, crop model results also suggest that such a strategy might be associated with reduced crop productivity. To maintain productivity while limiting agricultural water use, further adaptation can be explored, such as planting crops and varieties with greater resilience to drought stress; increasing the efficiency of irrigation; reductions of evaporation losses through mulching or cover cropping; increasing soil water retention through reduced tillage and/or cover cropping, or enriching soil organic matter contents. Also, groundwater abstraction should be systematically documented and every abstraction accounted for.

The study suggests that climate change impacts and possible changes in land use and management have to be considered jointly with the surface and subsurface water resources. The ever increasing population, climate change and political aspects as for example the maintenance of a certain level of self –sufficiency greatly increase the complexity of agricultural strategies. A quantitative analysis as presented here can help stakeholders as well as policymakers to anticipate water use conflicts, prevent maladaptation and to develop targeted and informed agricultural practices for current and future climate conditions. Such foresight is especially needed to prevent maladaptive development pathways in agricultural water management, where legal decisions and investments are made with a long-term planning horizon.

CRediT authorship contribution statement

Fabien Cochand: Hydrogeological modelling, Methodology, Conceptualization, Writing- Original draft preparation.
Annelie Holzkämper: Crop modelling, Methodology, Conceptualization, Writing- Original draft preparation.
Ole Rössler: Hydrological modelling, Methodology, Conceptualization. Writing- Original draft preparation.
Philip Brunner: Conceptualization, Writing - Review & Editing, Funding acquisition.
Daniel Hunkeler: Conceptualization, Writing - Review & Editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.148759.

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