Research papers

Climate change effects on groundwater recharge and temperatures in Swiss alluvial aquifers

Jannis Epting [a,*], Adrien Michel [b,c], Annette Affolter [a], Peter Huggenberger [a]

[a] Applied and Environmental Geology, Department of Environmental Sciences, University of Basel, Bernoullistr. 32, 4056 Basel, Switzerland
[b] Ecole Polytechnique Fédérale de Lausanne (EPFL), Laboratory of Cryospheric Sciences, 1015 Lausanne, Switzerland
[c] WSL Institute for Snow and Avalanche Research SLF, 7260 Davos, Switzerland

ABSTRACT

Climate change will have both quantitative and qualitative effects on groundwater resources. These impacts differ for aquifers in solid and unconsolidated rock, in urban or rural locations, and in the principal processes of groundwater recharge.

Having knowledge about the intrinsic key parameters (aquifer geometries, storage properties, groundwater renewal rates, residence times, etc.), the principal groundwater recharge processes, and the temperature imprinting makes it possible to compare and forecast the sensitivity of individual aquifers to climate change.

The sensitivity of future groundwater temperature development for selected climate projections was qualitatively investigated for representative Swiss unconsolidated rock groundwater resources in the Central Plateau as well as the Jura and Alpine region.

For non-urban and rural areas, climate change is expected to have a strong overall impact on groundwater temperatures. In urban areas, however, direct anthropogenic influences are likely to dominate. Increased thermal subsurface use and waste heat from underground structures, as well as adaptation strategies to mitigate global warming, increase groundwater temperatures. Likewise, measurements for the city of Basel show that groundwater temperatures increased by an average of 3.0 ± 0.7 °C in the period from 1993 to 2016, and that they can exceed 18 °C, especially in densely urbanized areas. Similarly, regarding shallow aquifers with low groundwater saturated zone thicknesses, such as in Davos (Canton Grisons), groundwater temperatures will strongly be influenced by changes in groundwater recharge regimes. In contrast, groundwater temperature changes within deep aquifers with large groundwater saturated zone thicknesses, such as in Biel/Bienne (Canton Bern), or in some cases in aquifers with large distances from the land surface to the groundwater table and extended unsaturated zones, such as in Winterthur (Canton Zurich), are strongly attenuated and can only be expected over long time periods.

In the context of the presented research we hypothesized that quantitative groundwater recharge and the associated temperature imprinting of aquifers is primarily determined by infiltrating surface waters (i.e. "river-fed aquifers"). We show that seasonal shifts in groundwater recharge processes could be an important factor affecting future groundwater temperatures. Moreover, the interaction with surface waters and increased groundwater recharge during high runoff periods are likely to strongly influence groundwater temperatures. Accordingly, for the "business as usual" climate change scenario and for the end of the century, a shift in precipitation and river flood events from summer to winter months could be accompanied by an increase in groundwater recharge in comparatively cool seasons, which would be accompanied by a tendency to "cool down" groundwater resources.

1. Introduction

Climate change (CC; IPCC (2014)) is an important topic on the political agenda, not only at national and international level, but also with regard to regional adaptation strategies. In current discussions, questions are raised about many topics, including how water resources are affected quantitatively and qualitatively by increased air temperatures. Although CC is a global phenomenon, it is likely that local water

---

balances will also change (Oni et al., 2014; Porporato et al., 2004). To be able to develop specific adaptation strategies for regions at an early stage, it is thus important to understand local impacts that CC may have.

Groundwater temperatures are influenced by various factors, some of which are interdependent and effective on different spatiotemporal scales. In addition to considering natural thermal influences (e.g. infiltrating surface waters and precipitation, regional groundwater flow, thermal conductivity of the ground cover), anthropogenic inputs must be considered (e.g. thermal groundwater use as well as buildings and tunnel structures). Likewise, we must consider intrinsic properties of aquifers and the influence of anthropogenic activities such as agricultural evolution and urbanization.

Elevated temperatures have complex effects on groundwater quality, including biological, chemical and physical aspects (CEC, 2000; Bates et al., 2008; Brielmann et al., 2009; Jesußek et al., 2013; Kipfer and Livingstone, 2008; Kurylyk et al., 2014; Menberg et al., 2014; Possemiers et al., 2014). For instance, municipal drinking water suppliers and industrial groundwater users will be confronted with considerable investments in drinking water treatment in the context of adaptation strategies. In urban areas especially, with often numerous contaminated industrial sites, an increase in groundwater temperatures can result in changes in microbial activity and groundwater chemistry (catalysis of biodegradation of pollutants, growth of prejudicial bacteria, see Brock and Madigan (1988)). Increased groundwater temperatures additionally changes the solubility of gases and solids (Palmer et al., 1992). Furthermore, temperature induced chemical reactions and mixing of injection water can change the porosities and permeability of an aquifer system (Garcia-Gil et al., 2016; Saripalli et al., 2001). Increased groundwater temperatures also have several practical implications, including e.g. alterations of the thermal use potentials of groundwater resources in general, involving positive and negative impacts on existing geothermal energy systems (GES) and aquifer thermal energy storage (ATES) applications or modification of river stretches where groundwater exfiltrates into surface waters; especially in summer comparatively low temperatures in groundwater recharge zones provide refugia for coldwater fish species during periods of thermal stress.

A clear increasing trend on surface water temperature (both lakes and rivers) has been observed over the last decades at a global scale (Dokulil, 2014; Hannah and Garner, 2015; Morrison et al., 2002; O'Reilly et al., 2015; Watts et al., 2015; Webb, 1996). In Switzerland, a sudden warming of about $+ 1 °C$ has been observed at the end of the 1980s, which was caused by a shift in the Arctic oscillation (Hari et al., 2006). However, recent studies using observations since the 1970s show that this shift is part of an underlying trend of an $+ 0.33 °C$ increase per decade in water temperature, similar to observations for air temperature (Michel et al., 2020). This increasing trend is more marked in the Swiss Plateau lowland catchments than in higher altitude streams. Meanwhile, no clear trend in discharge can be identified over the last few decades.

A correspondingly significant large-scale increase in groundwater temperature - as could be expected as a result of CC and observed regionally for example in Austria (Umweltbundesamt, 2011) - has not yet been observed in Switzerland (BAFU, 2019). However, already since the 1980s, a significant increase in groundwater temperatures (in the order of $+ 1 °C$) has been observed locally for some unconsolidated alluvial aquifers on the Swiss Plateau along the Rhine, Emme, Aare, and Toess rivers, which are fed predominantly by river-bank infiltration (Figura et al., 2011). Likewise, in densely urbanized areas in the city of Basel, groundwater temperatures increased by an average of $3.0 \pm 0.7 °C$ from 1993 to 2016, and locally can exceed $18 °C$ (Mueller et al., 2018). Also, for aquifers with nivo-glacial groundwater regimes, climate-induced increased glacier melt can lead to a decline in groundwater temperature in the medium term if the temperature of the watercourses infiltrating the groundwater decrease due to the melt water ("negative response" to rising air temperatures). At the end of the 1980s, groundwater temperature also rose suddenly in many places due to the Arctic oscillation as the climate in large parts of the northern hemisphere changed abruptly (Figura et al.,

2011; Reid et al., 2016; Serra-Maluquer et al., 2019). During the unusually hot and dry summer of 2003, it was observed that drinking water consumption increased and groundwater temperatures rose to such an extent that in some cases anoxic conditions in the aquifer resulted (Hoehn and Scholtis, 2011). In addition to the effects that increased groundwater temperature has on groundwater quality (Sprenger et al., 2011), problems with drinking water production and possible clogging of drinking water wells by precipitated manganese and iron may be of relevance (Hunt et al., 2002). Such phenomena must also be considered when interpreting the development of groundwater temperatures.

Hydrological climate studies, such as CH2014-Impacts (2014) and NFP61 (2015), estimate that dry periods in Switzerland will occur more frequently in summer in the future, while slightly higher precipitation and a rising snow line in winter (CH2018, 2018) should lead to increased groundwater recharge. The studies also predict that the frequency and intensity of heavy precipitation will increase in the long-term because of CC. As a result, short-term high groundwater levels and spring discharges are likely to occur more frequently in fast-reacting karst and shallow unconsolidated rock aquifers. According to CCHydro (BAFU, 2012), however, Swiss water resources, including groundwater, will only change slightly overall in the future. Nevertheless, local to regional bottlenecks in the water supply could increasingly occur because of a shift in the seasonal distribution of precipitation and runoff.

Regarding the effects of CC on groundwater temperature increase, a distinction must be made between urban and rural aquifers. For non-urban and rural areas, the cumulative effects of CC (temperature imprint associated with the various components of groundwater recharge) are expected to have a strong quantitative and qualitative impact on groundwater resources. In contrast, elevated temperatures observed in urban aquifers are mainly due to local and regional anthropogenic factors while CC only plays a secondary role. Those factors include underground structures and thermal use of the subsurface water and groundwater by a broad variety of shallow and deep, open and closed, systems such borehole heat exchangers, open loop thermal groundwater usage, or energy piles, among others (Bayer et al., 2016; Epting and Huggenberger, 2013). It is therefore to be expected, particularly in urbanized areas, that increased thermal use of the subsurface and adaptation strategies (e.g. more frequent thermal use of aquifers for "cooling" purposes or increased managed aquifer recharge in summer month) in connection with global warming will result in an increase in groundwater temperatures (Epting et al., 2017a; Garcia-Gil et al., 2015). Likewise, anthropogenic adaptation strategies could have a greater influence than CC itself (Sprenger et al., 2011).

Within the framework of the CH2014-Impacts (2014) study, an initial assessment was carried out for future groundwater temperatures and possible groundwater warming for selected aquifers on the Central Plateau. The study was based on the (CH2011, 2011) climate projections and concluded that the essential impact that atmospheric CC will have on aquifers (not only for those in unconsolidated rock deposits) is expected to occur via groundwater recharge. For the aquifers examined, the essential components of groundwater recharge could be distinguished, i.e. the infiltration of river water ("river-fed aquifers") as well as the percolation of precipitation water ("precipitation-fed aquifers"). The results show that groundwater temperatures will rise in summer, especially at locations where groundwater is mainly supplied by infiltrating surface waters. The CH2014-Impacts (2014) study also notes that there are few studies on the influence that the climate has on quantitative and qualitative changes on aquifers in Switzerland. Likewise, those studies did not consider temperature changes in surface waters and thus also increased or decreased temperatures of infiltrating surface waters. The evaluations carried out were limited to statistical relationships between the projected air and groundwater temperatures and are therefore subject to relatively large uncertainties. Accordingly, the CH2014-Impacts (2014) study concluded that further research should focus on suitable groundwater models, temperature-based field experiments, and long-term monitoring.

Most research to date has focused on predicting possible impacts on the hydrology of surface waters, while large regional and coarse-resolution models have been used for groundwater systems to determine their sensitivity to changes in critical input parameters such as precipitation and runoff (York et al., 2002; Yusoff et al., 2002). Likewise, Changnon et al. (1988) and Zektser and Loaiciga (1993) showed that one expected consequence will be changes in recharge to regional groundwater aquifers, thus causing shifts in groundwater levels. With a few exceptions of detailed investigations of very small aquifers (e.g. Malcolm and Soulsby (2000)), most studies concentrate on entire catchment areas and only on changes in percolating precipitation water (i.e. "precipitation-fed aquifers"). Likewise, in a synopsis of CC effects on groundwater recharge Smerdon (2017) highlights the importance of understanding groundwater recharge processes, including timing and location for the characterization of groundwater resource assessment. The author summarizes six review articles (Crosbie et al., 2013; Green et al., 2011; Kurylyk and MacQuarrie, 2013; Meixner et al., 2016; Moeck et al., 2016; Taylor et al., 2013) which illustrate the uncertainty of distribution and trend in future precipitation from General Circulation Models (GCMs) results in varying predictions of recharge, so much so that modelling studies are often not able to predict the magnitude and direction (increase or decrease) of future recharge conditions.
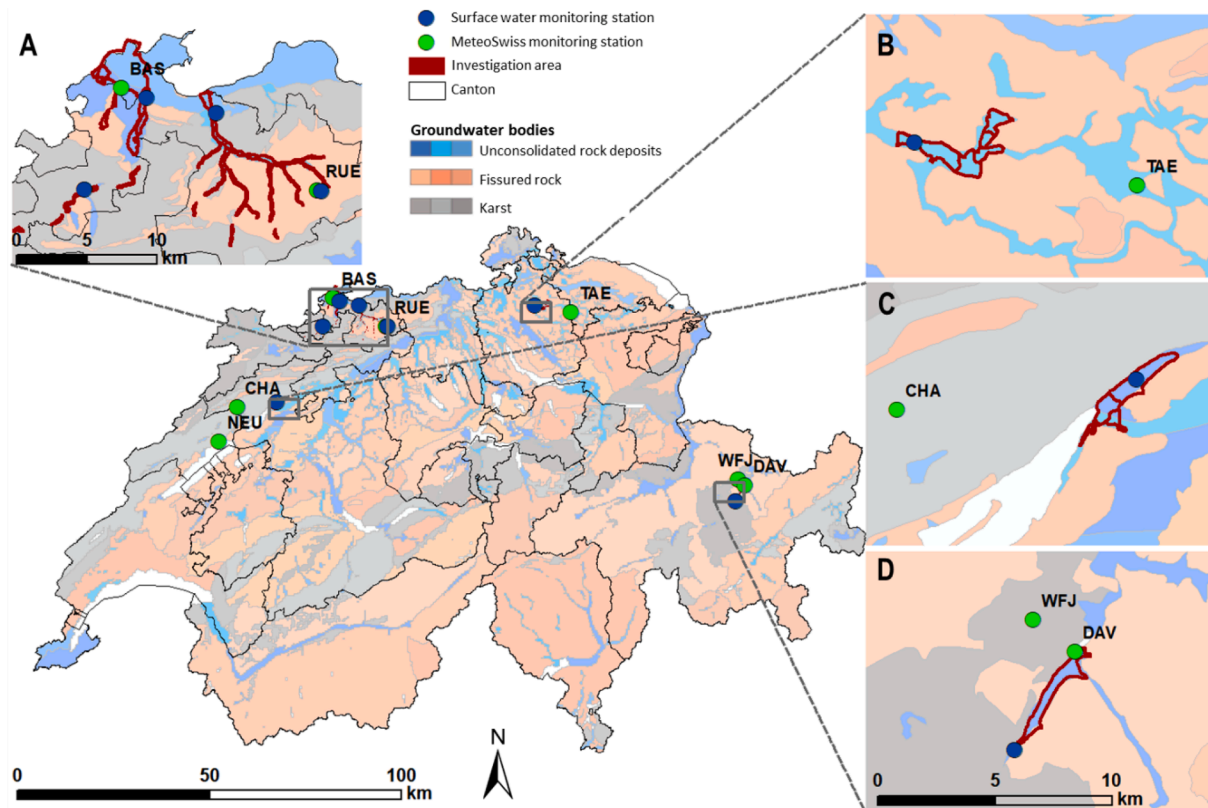
Of interest are coupled hydrologic systems, where changes in surface flow regime and changes in recharge to groundwater interact to affect both groundwater and surface water. However, only a few studies exist which address groundwater-surface water interactions under CC scenarios (e.g. Scibek et al. (2007)). Allen et al. (2004) investigated variations in recharge to an aquifer in British Columbia (Canada) under different CC scenarios and demonstrate the high impact on the groundwater system caused by changes in river-stage elevations. These interactions are particularly important since, in contrast to common

assumptions of many groundwater protection concepts, groundwater recharge often comprises large fractions of river water infiltration (Huggenberger and Epting, 2011).
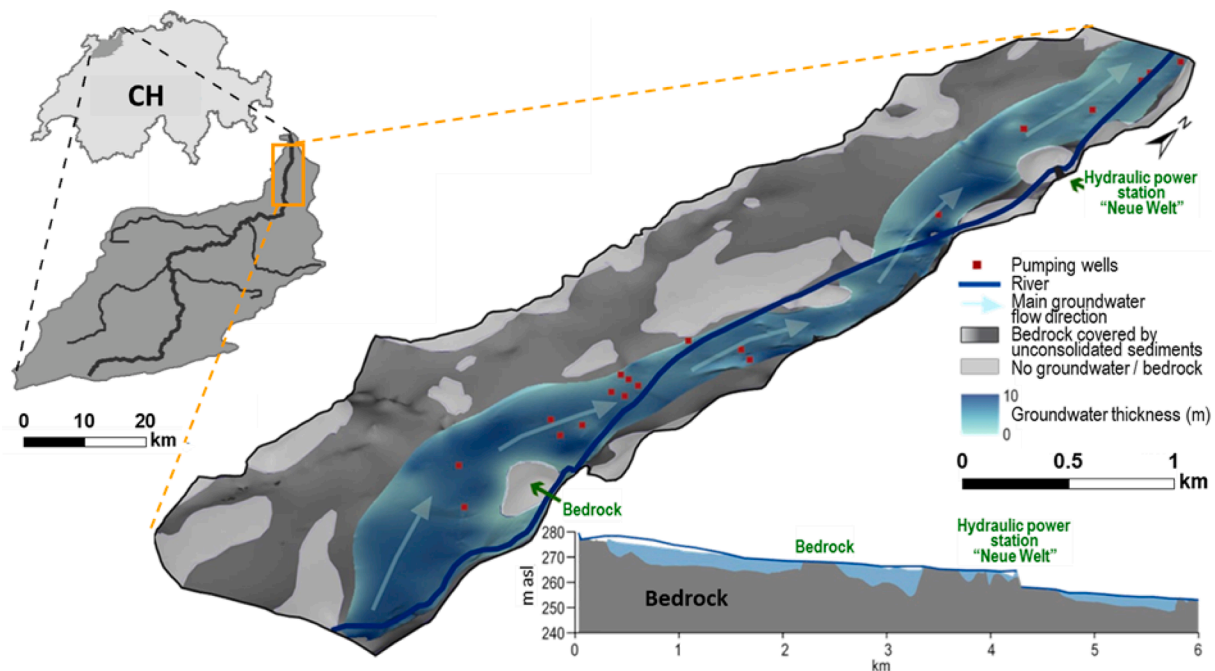
The work presented here originates from the Hydro-CH2018 project and the add-on module called "Current status and temperature development of Swiss unconsolidated rock groundwater resources". Within the scope of this research project, for generally highly productive river valley aquifers, we hypothesized that quantitative groundwater recharge and the associated temperature imprinting of aquifers is primarily determined by infiltrating surface waters (i.e. "river-fed aquifers"). To support this hypothesis, we investigated 38 representative urban and rural Swiss porous aquifers from which we derived intrinsic key parameters such as aquifer geometries, storage properties, groundwater renewal rates, residence times, and the principal groundwater recharge processes, including temperature imprinting. Subsequently, we investigated the effects that seasonal shifts had on the main groundwater recharge components and the sensitivity to future groundwater temperature development for selected climate projections. Specifically, we focused on the aquifers' interaction with surface waters and the increased groundwater recharge during high runoff periods, which are expected to have a strong influence on groundwater temperatures of river-fed aquifers.

2. Investigation areas

Fig. 1 shows the representative urban and rural Swiss porous aquifers (unconsolidated sediments, mainly coarse fluvial gravel deposits in the river valleys) that we selected for the study: (A) urban area and surroundings of Canton Basel-City and the main river valleys of Canton Basel-Land; (B) Winterthur city and the surrounding areas in Canton Zurich; (C) Biel/Bienne city and the surrounding areas in Canton Bern; and (D) the urban area and surroundings of Davos in Canton Grisons.

Fig. 1. Swiss groundwater bodies (FOEN) and river valleys where the aquifers of this study are located. (A) Basel-City (Canton Basel-Stadt BS) and Basel-Land (Canton Basel-Land BL); (B) Winterthur (Canton Zürich ZH); (C) Biel/Bienne (Canton Bern BE); and (D) Davos (Canton Grisons GR). MeteoSwiss stations (Basel Binningen-BAS, Chasseral-CHA, Davos-DAV, Neuchâtel-NEU, Rünenberg-RUE, Tänikon-TAE, Weissfluhjoch-WFJ), and locations along the rivers for which runoff and temperature development were simulated for selected CC scenarios.

Fig. 2. Upper left: Location maps showing the position of the lower Birs valley (cf. Fig. 1A). Center: Main groundwater flow within the perennial water saturated sediments, represented together with the bedrock surface covered by unconsolidated sediments, dry areas or areas with outcropping bedrock as well as drinking water wells; Lower right: longitudinal profile along the River Birs illustrating the "river corridor" concept (modified according to Epting et al. (2015)).

3. Concept and methods

To derive the intrinsic key parameters of the aquifers that we investigated, the aquifer geometries were first delineated. This delineation is related to the regional settings of the aquifers according to the "river corridor" concept (Stanford and Ward, 1993). We describe how a hydraulic and thermal "current state" can be defined for the investigated aquifers, which is a prerequisite that allows us to discuss changes. Subsequently, we explain our approach on how to determine groundwater renewal rates and mean residence times as well as how to assess the relevant processes for groundwater recharge and water balances. Finally, the chosen climate projections are introduced.

3.1. Delineation of aquifer geometries

The lower boundary of the studied aquifers is defined by the bedrock surface shaped during the last glaciations. To enable a systematic evaluation of intrinsic and extrinsic settings and boundary conditions, the aquifers were subdivided to define hydraulic and thermal boundary conditions. A definition of boundary conditions for individual aquifers or aquifer subdomains, which can be understood as management units, makes it possible to quantify inflows, outflows, and different components of groundwater recharge and thermal influences. Such a delineation is not only relevant to managing subsurface resources (practically manageable aquifer units), but also to defining model boundaries or sub boundaries that can be used for mass and heat balance calculations for specific aquifer domains (Epting et al., 2017b).

Having knowledge of aquifer geometries allows us to investigate groundwater resources' sensitivity to, e.g. drought events. Shallow aquifers with relatively small storage volumes and short groundwater residence times empty relatively quickly during drought periods, but subsequently can also rapidly be filled-up again. On the contrary, aquifers with large storage volume and long groundwater residence times, react in a damped and retarded way to individual drought events. Subsequently, more time and more precipitation are required to re-fill

these aquifers. For example, the high yields of the aquifer along the River Langete (Canton Bern) showed practically no reaction during the great drought of 2003 (BUWAL et al., 2004).

The aquifer geometries of the unconsolidated rock groundwater resources were derived based on topographic data along the solid rock surface, the land surface, and the mean groundwater surface. With the information of the aquifer geometries, the storage properties of the aquifers are qualitatively characterized. This information includes (1) the volumes of saturated and unsaturated unconsolidated rock deposits, which are stored in individual aquifers during average hydrological boundary conditions; (2) groundwater saturated zone thicknesses; and (3) depths from the surface to the groundwater table. Also, for individual sites, low and high groundwater levels were considered. Likewise, the seasonal dependence of the percolation of precipitation to the groundwater table as well as thermal influences on especially shallow aquifers were qualitatively evaluated.

3.2. The "river corridor" concept

For the aquifers we studied, we followed the "river corridor" concept of Stanford and Ward (1993), which emphasizes exchange processes between surface waters and groundwater systems (Fig. 2). Many alluvial rivers in Central Europe flow in very porous floodplains, while the base of aquifers in river valleys is characterized by complex bedrock topography. Furthermore, sequences of aquifers are often observed, whereby basins filled with unconsolidated gravel deposits are separated by bedrock steps. The bedrock steps ("knick-points"; Stanford and Ward (1993)) formed as a result of differences in erodibility of the local bedrock or geological formations formed by fluvial or faulting activity (Huggenberger et al., 2013). In river reaches upstream of "knick-points", groundwater is forced out of the aquifer to the surface due to a reduction of the saturated cross-sectional area and a subsurface barrier with lower hydraulic conductivity. Whereas the continuity of the main groundwater flow within the valleys may partially be interrupted by rock steps, there still may be a connection between the unconsolidated rock groundwater

resources via karst and/or fracture systems (Epting et al., 2015, 2018a). Losing and gaining reaches of channels are related to so-called 'knickpoints' or bedrock steps (Stanford and Ward, 1993). Infiltration of river water into groundwater aquifers structured by fluvial outwash materials can reach specific infiltration rates of up to 1 m^3 d^{-1} per m^2 of river bed (Affolter et al., 2010). Exchange rates are controlled by the difference between the river stage and groundwater head, and the hydraulic conductivity of the riverbed. Seasonal variation in the height of the water table and channel stage can alter the magnitude, location, and direction of exchange (Affolter et al., 2010).

3.3. Hydraulic and thermal "current state"

The hydraulic and thermal "current state" describes an average situation, including seasonal, but also event- and use-related variations in groundwater flow and thermal regimes for a defined groundwater area. An inventory of the "current state" of aquifers, or subsurface resources in general, involves assessing the geological, hydrological, and anthropogenic settings (mostly stationary character), as well as boundary conditions (mostly transient character). To assess the anthropogenic changes of subsurface resources that have already occurred, the "current state" can be compared with a "potential natural state" (Epting et al., 2017a).

A differentiated characterization of the hydraulic and thermal "current state" of the aquifers could be performed based on existing data sets, Geographical Information Systems (GIS), hydraulic and temperature measurements in groundwater and surface waters in Canton Basel-City (Epting and Huggenberger, 2013) and in Canton Basel-Land (Epting et al., 2015), (Annex 1). The concept and methodological approaches developed for these aquifers could subsequently be applied to the other selected unconsolidated rock groundwater resources (Fig. 1).

Having a definition of "potentially natural" groundwater temperatures allows us to estimate how strongly thermal groundwater regimes have already been affected by CC or other anthropogenic impacts. Since temporally and spatially high-resolution groundwater heat-transport models currently only exist for Canton Basel-City, for the other investigation areas the warming of the aquifers was evaluated based on long-term temperature measurements in groundwater monitoring wells in relation to annual mean atmospheric temperatures.

3.4. Groundwater renewal rates and mean residence times

A derivation of groundwater flow paths, times and velocities allowed us to estimate renewal rates and mean residence times. These are the basis for assessing aquifer sensitivity to climate and anthropogenic change. The residence time calculation was carried out based on the "Hydrology" tool in ArcMap© and the "GeoTherm" tools developed by Alcaraz et al. (2016). The residence times (τ) can be calculated by using the following formula:

$$\tau = \frac{FL_{GW} \times \phi}{v_{Darcy}} \tag{1}$$

Where FL$_{GW}$ [m] is the groundwater flow length, v_{Darcy} [m s^{-1}] is the Darcy-flow velocity, and ϕ [-] is the effective porosity, ranging between $0 \leqslant \phi \leqslant 1$.

The groundwater flow direction and FL_{GW} can be calculated based on the groundwater head raster data sets (Annex 1). It is assumed that the calculated FL_{GW} describes the travelled distance of a water particle along a flow path within the aquifer towards a draining feature, e.g. a watercourse or hydraulically lower boundary of the aquifer. Renewal rates and mean residence times were derived by investigating a range of realistic aquifer properties (hydraulic permeability and porosity) for the aquifers that we investigated.

3.5. Groundwater recharge & balance

Contrary to the consideration of entire river catchment areas, for which a more or less "closed" water balance can be calculated, additional water components (inflows and outflows) must be considered for aquifers over different boundaries. As an example, Fig. 3 illustrates which water components must be considered for the aquifer of the Aesch and Reinach municipalities (Canton Basel-Land). Table 1 summarizes the main groundwater recharge components. Natural boundary conditions include percolating precipitation, regional groundwater inflow ("imported groundwater regimes") and outflow, inflow from the lateral hillslope catchment areas, and linear interaction of surface waters with groundwater. In addition, in the mountainous regions of the Jura mountains and the Alps, we must consider the interaction of unconsolidated rock groundwater resources with regional karst and fissured rock aquifers. Anthropogenic boundary conditions include groundwater extraction and artificial recharge as well as, for thermal issues, the subsurface and groundwater use for cooling and heating purposes along with thermal influences of underground structures.

Some of the groundwater recharge components are directly influenced by atmospheric CC via hydrological runoff conditions due to changing precipitation patterns and temperatures. Furthermore, the various groundwater recharge components have no linear relationship with precipitation events. Likewise, groundwater recharge also depends on soil water saturation, as well as the duration and intensity of individual precipitation events or vegetation periods. Changes in the various groundwater recharge processes take place at a time scale which is largely unknown.

Fig. 3 also summarizes the different types of river-groundwater interaction, whereas for our studies the infiltration of surface waters into groundwater represents the most important groundwater recharge component.
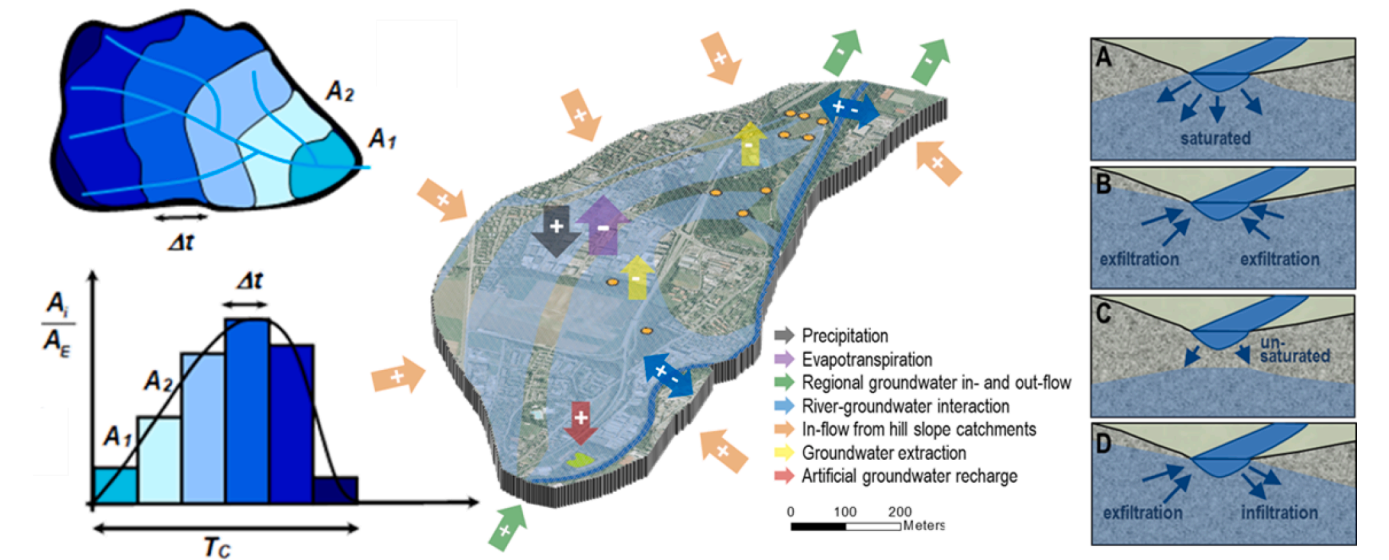
To evaluate the effects that CC has on the interaction of surface waters with groundwater, one must consider the following three relationships: (a) climate-induced hydraulic change: higher/lower groundwater and/or river levels and the associated changes in interaction type; (b) climate-induced temperature change of river water and groundwater; and (c) temperature dependence of viscosity and thus of river bed and aquifer permeability.

The quantification of river section lengths for the different types of interaction allows us to make a qualitative description of the changes expected by the climate projections. Likewise, in the case of extended drought periods, both river and groundwater levels will decrease, river sections with interaction types C and D will increase, and interaction types A and B will decrease (Fig. 3). Accordingly, the exfiltration of groundwater to surface waters decreases, and the infiltration from surface water into groundwater increases.

3.6. Climate projections

To evaluate climate-related changes to the different groundwater recharge components of aquifers, 17 climate projections developed within CH2018 (2018) have been selected (CH-Project-Team, 2018; CH, 2018; Feigenwinter et al., 2018). Based on the description of the climate projection given in CH2018 (2018), these scenarios are representative of the whole range of precipitation and temperature output in the future. The emission scenarios RCP 2.6 (4 scenarios, consistent climate protection, and limitation of warming to 2 °C compared to the pre-industrial state), RCP 4.5 (6 scenarios, medium development with limited climate protection) and RCP 8.5 (7 scenarios, no climate protection) were studied. Table A2.1 (Annex 2) summarizes the 17 selected climate projections. These scenarios have already been used in hydrological application such as in Brunner et al. (2019).

As the CH2018 scenarios only provide daily data, for the modelling of river runoff and temperatures (Michel et al., 2021) developed a disaggregation method which allows to generate hourly values with a

Fig. 3. Upper left: Delineation of areas (A$_i$: sub-area; A$_E$: complete area) of porous aquifers for the evaluation of groundwater flow paths, times and velocities. Lower left: Histogram of the flow time (T$_C$) distribution. Centre: Water balance components of unconsolidated rock groundwater resources, exemplified by the aquifer of the Aesch and Reinach municipalities (c.f. Fig. 2). Right: Types of interaction between surface water and groundwater (modified according to Huggenberger et al. (1998)).

Table 1
Groundwater recharge components.

	Starting position	Hypotheses	Investigation approach
Precipitation	Groundwater recharge from percolating precipitation	Quantitatively negligible compared to other components, also concerning temperature imprinting	Water balance calculation; future development of precipitation and temperatures from climate scenariosSimulations considering evapotranspiration processes and soil water balance (not performed in scope of this study)
Regional in- and outflow	Determined by groundwater hydraulics and interaction with system boundaries, e.g. interaction with up- and down-gradient aquifers	Recharge and temperature imprinting continuously and particularly during "characteristic" precipitation and high runoff events (intensity & duration)	Numerical groundwater modelling and evaluation of regional inflow and outflow budgets
Inflow from hill-slope catchments	Linear inflow into down-gradient aquifers; distinction between subsurface / surface catchment areas (interaction with regional karst and fractured rock groundwater systems)	Influence on groundwater temperatures mainly in peripheral areas; especially in phases of increased groundwater recharge in the hill-slope catchments	Water balance calculation; future development of precipitation and temperatures from climate scenarios
River-groundwater interaction	Determined by river / groundwater hydraulics and conductance of the riverbed; linear inflow and outflow of surface water into the aquifer (infiltration) or groundwater into rivers (exfiltration; "receiving waters")	Recharge and temperature imprinting mainly during "characteristic" precipitation events and high runoff (intensity & duration)	Numerical groundwater modelling and evaluation of infiltration and exfiltration rates; simulation of climate-related changes of surface water runoff and temperatures; transfer to quantitative groundwater recharge via infiltrating surface waters and associated temperature imprinting; quantification of river section lengths with different interaction types

daily cycle. This method uses a delta approach similar to Bosshard et al. (2011) which is widely used (see e.g CH2011 (2011)). Historical and future daily data are averaged for each day of the year (i.e. all first of January, all 2nd of January, and so on…) to obtain a time series length of 365 days. These time series are further smoothed by using harmonic functions. Then the difference between past and future smoothed time series is computed (additive difference for temperature, multiplicative for other variables) to obtain the delta between the two time periods. Finally, the delta is applied to historical hourly data to obtain an hourly time series in the future. The main improvement compared to the work of Bosshard et al. (2011) and what was used in CH2011 is about the choice of the best harmonic to smooth the data to capture the main seasonal signal of the CC projection without adding non-natural noise in the data. In addition, this method allows to correct one of the main

limitations of the CH2018 dataset. Indeed, (Michel et al., 2021) show that the missing inter-variable and inter-station correlation in CH2018 is restored by applying the temporal downscaling algorithm. The meteorological data are downscaled to hourly data for the reference periods 1985–2015, 2040–2070, and 2070–2100.

A benefit of this method is that the time series obtained represent the "mean climate" of the 30 years future periods, with the year-to-year variability being the same as the historical time series used for the downscaling. This method is shown to really capture the monthly or seasonal behavior of the CC scenario. However, the main drawback is that some information is lost by using this approach, in particular regarding extreme events (e.g. for precipitation, with this method the frequency of precipitation remains the same in the future as in the past and only the amplitude is modified, which is an important

simplification). The dataset obtained is nevertheless relevant to study the main trends induced by CC and to analyzing the output at monthly to yearly scale, but it is not suited to study extreme events or short time variations.

These time series are then used in the models *Alpine3D/StreamFlow* over 10-year periods (i.e. 10 years in the middle of the 30-year period where downscaling is applied), since computational limits forbid running the model over 30-year periods. However, the delta method is shown to capture the mean behavior of the 30-year time series, reducing the error made by using shorter time series. In addition, while 30-year time series are the standard, it is recognized by the WMO that for most applications, 10-year time series are perfectly suited (WMO, 2017). The main concern while using short time series is precipitation, which presents oscillations driven by long term oscillations in the climate system. By using 30 years to compute the delta between historical and future time series, we smooth out most of these oscillations. When delta is applied to historical time series, some oscillations from the historical hourly time series itself remain and might be present, especially when we use only 10 years. However, the same historical time series serve as basis for all the periods where downscaling is applied, so this signal will be exactly the same for all the time periods. Consequently, when comparing model output in the past and in the future, we see the impact that the main CC signal has and omit most of the perturbation form large scale atmospheric oscillations. An example for the Eulach catchment is given in Annex 2 (Figs. A2.1 and A2.2), where the difference between the end of the century and the historical period is shown to change by a maximum of 15% for discharge and 8% for temperature when using 10-year instead of 30-year time periods. This uncertainty is not negligible, however small enough to not impact the analysis presented here.

3.7. Discharge and water temperature modelling

In the framework of the Hydro-CH2018 project, the hourly time series have been used with the *Alpine3D* (Lehning et al., 2006) and *StreamFlow* models (Gallice et al., 2016) to simulate water discharge and temperature for the reference periods 1995–2005, 2050–2060 and 2080–2090 (Michel et al., 2020). *Alpine3D* is a physically based snow and soil model which provides output on soil temperature and runoff at the bottom of the soil column. It is based on the *Snowpack* model (Lehning et al., 2002a, 2002b). This model is physically based and most processes, such as the energy balance of the mass fluxes are computed using state-of-the-art formulations. These outputs are then used in *Streamflow*, a semi-distributed physical hydrological mode, to compute the discharge and water temperature. Models source codes are available at: https://models.slf.ch. Examples of the application of these models are e.g. Brauchli et al. (2017), Wever et al. (2017) or (Griessinger et al., 2016). Both models run at 500 m resolution and use as input air temperature, precipitation, relative humidity, and incoming shortwave and longwave radiation from MeteoSwiss point measurement stations. Input meteorological data are extrapolated to the grid with algorithms provided by the meteoIO library (Bavay and Egger, 2014). For the Landwasser catchment, *Alpine3D* uses glacier maps provided by Zekollari et al. (2019) for historical and future periods (obtained with the same CH2018 scenarios).

The water residence time in the soil reservoirs and the ground heat flux need to be calibrated in *StreamFlow*. Table A2.2 (Annex 2) shows the performance of the model over the calibration and verification period, along with the MeteoSwiss stations used in each catchment (more discussion about the calibration is given as supplementary information). For the rivers Birs, Suze and Eulach the Kling-Gupta efficiency (KGE) coefficient (Gupta et al., 2012) that we used to assess discharge performance is above 0.85, which is indeed good. Results are a bit less good for the River Ergolz (0.72) and the River Landwasser (0.62), but still acceptable. Regarding temperature, the mean square error (MSE) computed on daily values is between 0.7 and 1.2 °C for all catchments, except for the River Suze, where it is 1.75 °C.

The further evaluations cover the future periods 2050–2060 and 2080–2090, which were compared to the reference period 1995–2005. In Annex, 2 the ability of the model and CH2018 forcing time series to correctly reproduce discharge and water temperature for the historical period 1995–2015 is discussed. This discussion shows that the model obtains good performances which are comparable to other results in the literature (e.g. Brunner et al., 2020).

Figs. A2.5 and A2.6 (Annex 2) illustrate the simulation results for all projections over the ten-year periods 1995–2005, 2050–2060 and 2080–2090. It is important to notice that the boxplots show the range between different scenarios, but not year-to-year variability. Indeed, the plots show the seasonal mean averaged over the 11 years of simulation for each scenario. This way, the main climatic behavior can be observed, but not potential extreme years. As discussed above, the downscaling method used is not suited for extreme event studies, explaining why they are not discussed in the analysis. Future developments of the downscaling method might focus on not losing information about extreme events as their occurrence might also change in the future.

In contrast, for the stream discharge and temperature simulations, five meteorological variables were used, and only the relative changes of precipitation and temperatures were analyzed to describe the development of the groundwater recharge component by percolating precipitation. Likewise, to derive climate-related changes in quantitative groundwater recharge via infiltrating surface waters and associated temperature effects, it was important to evaluate changed river runoff and temperatures at selected locations along the rivers within the aquifers that we investigated (Fig. 1).

The development of streamflow duration curves (Streamflow Analysis and Assessment Software; Metcalfe and Schmidt (2016)) was investigated (Annex 3), and we paid attention to the different emission scenarios as well as to the seasonal shift of peak runoff. The analysis was possible for all investigation areas except for the groundwater resources in Canton Basel-City. This is because no simulations of runoff and temperature development of the rivers Rhine and Wiese were available from Hydro-CH2018.

4. Results

Table 2 summarizes the main results of the key parameters we evaluated (i.e. aquifer geometries, storage properties, aquifer connectivity with surface waters, and estimated flow paths and times). These key parameters are the basis for discussing the principal groundwater recharge processes in the aquifers that we investigated. These key parameters allow us to identify parameters that significantly influence the sensitivity to CC that the aquifers we investigated have.

In the following parts, the results presented in Table 2 are summarized as are the results from the climate-related changes in quantitative groundwater recharge components for the individual aquifers that we investigated (Figs. 4 to 8). Generally, according to the projections for the annual mean air temperatures CH2014-Impacts (2014), annual mean groundwater temperatures will adapt in the long-term. This temperature response to CC has also been observed for shallow urban groundwater resources (e.g. Taylor and Stefan (2009)).

For all the aquifers we investigated, the simulations indicate that groundwater recharge by percolating precipitation generally shifts to the winter months, which would be accompanied by a tendency to "cool down" groundwater resources. Depending on the emission scenario considered and the point in time in the future, the CH2018 (2018) scenario for the end of the century (compared to the period 2005–2015) predicts that air temperatures, which can be associated with the temperature imprinting of percolating precipitation, will increase by 1 to 3.5 °C (BAS; Canton Basel), by 0.9 to 3.8 °C (RUE; Canton Basel-Land), by 1.1 to 3.6 °C (TAE; Canton Thurgau), by 1.0 to 3.5 °C (NEU; Canton Neuchâtel), by 1.1 to 3.9 °C (CHA; Canton Bern), by 1.2 to 5.0 °C (DAV; Canton Grisons), and by 1.2 to 4.5 °C (WFJ ; Canton Grisons). In short, the increases range from 0.9 to 5.0 °C.

Table 2
Compilation of some key results for the investigated aquifers, including aquifer geometries, aquifer connectivity to surface waters, and estimated flow paths and times.

| | River | GW-resources | Mean GW-thickness | Distance from surface to groundwater table Share of whole GW-resource area [%] | | | Surface water density Length of surface water / GW-resource area | Flow paths | Flow times |
			[m]	[0–1 m]	[1–10 m]	[10–50 m]	[km km^{-2}]	[m]	[d]
Basel-Stadt		Total	5.3	5.4	41.3	53.3	1.2	1745	359.4
		Kleinhüningen	7.5	7.8	91.5	0.6	4.3	1641	162.7
		Kleinbasel	7.7	9.6	58.9	31.5	1.6	618	41.7
		Grossbasel Süd-Ost	2.1	3.0	36.9	60.1	1.5	1682	658.7
		Grossbasel Nord-West	5.8	2.7	8.9	88.4	0.7	2787	587.2
Basel-Land	Birs	Liesberg	3.9	12.2	87.6	0.2	6	191	20.8
		Laufen (Birshollen)	6.3	19.1	80.6	0.3	8.7	168	4.0
		Laufen (Stadt)	5.6	3.4	96.1	0.6	4.4	489	13.5
		Zwingen	5.4	4.3	90.2	5.5	5.6	725	20.4
		Grellingen	7.8	5.2	68.2	26.6	8.3	257	3.7
		Duggingen	7.6	10.8	78.8	10.4	8.3	463	0.6
		Aesch-Reinach	6.6	0.6	20.6	78.8	2.1	2533	6.0
		Arlesheim/Münchenstein	6.5	1.2	81.1	17.7	0.1	769	12.2
		Münchenstein	4.4	2.2	92.4	5.4	3.2	488	17.8
	Birsig	Therwil/Oberwil	3.3	18.1	81.9	0.0	8.8	339	7.0
		Bottmingen/Binningen	5.2	6.5	93.2	0.3	10.4	405	5.9
	Ergolz	Ormalingen	4.5	7.2	92.8	0.0	21.1	851	7.6
		Gelterkinden/Sissach	8.4	1.9	82.0	16.0	6.6	1505	20.0
		Sissach	10.8	0.9	38.9	60.2	4.5	1367	34.9
		Lausen	6.7	1.3	60.8	37.9	11.1	479	9.0
		Liestal	8.5	2.3	47.6	50.1	3.4	738	8.8
		Füllinsdorf/Augst	6.5	1.7	20.2	78.1	3.7	952	16.4
	Ergolz tributaries	Tecknau/Gelterkinden (Eibach)	4.9	2.9	90.2	6.9	9.7	2168	18.7
		Rümlingen/Thürnen (Homburgerbach)	6.4	6.6	88.4	5.0	11.2	844	7.3
		Eptingen (Dietgerbach)	7.0	0.7	86.4	13.0	13.1	570	2.9
		Dietgen/Sissach (Dietgerbach)	5.0	13.8	61.7	24.5	7.4	664	4.1
		Waldenburg (Vordere Frenke)	5.3	15.7	76.1	8.2	19.3	510	2.0
		Oberdorf (Vordere Frenke)	9.2	5.4	91.4	3.2	24.8	487	4.5
		Bennwil/Hölstein (Walibach)	3.8	5.8	92.2	2.0	17.6	2513	10.7
		Niederdorf/Hölstein (Vordere Frenke)	5.6	3.0	89.4	7.6	8.3	939	6.0
		Hölstein/Bubendorf (Vordere Frenke)	4.8	1.0	96.0	3.0	9.1	2683	24.5
		Reigoldswil/Ziefen (Hintere Frenke)	2.4	71.2	28.7	0.1	29.2	220	1.6
		Ziefen/Bubendorf (Hintere Frenke)	4.7	5.7	93.7	0.6	10.9	466	3.2
		Bubendorf (Frenke)	6.8	0.2	85.6	14.2	4.1	807	7.6
		Bubendorf/Liestal (Frenke)	8.8	1.1	63.8	35.1	3.1	1436	7.6
		Nuglar Liestal (Orisbach)	8.8	43.8	49.9	6.3	12.9	746	7.5
ZH	Eulach	Winterthur	24.5	1.2	34.1	64.7	2.0	6068	25.6
BE	Suze	Biel	71.7	2.1	90.6	7.3	3.3	6293	61.4
GR	Landwasser	Davos	1.8	2.3	58.8	38.9	9.0	6811	7.8

In addition, the evaluation of the seasonal runoff duration lines (hydrological year) show that fewer events with high runoff will occur, especially for the months July to September and for all emission scenarios considered (Fig. A3.1; Annex 3). If we assume that quantitative groundwater recharge and the associated temperature imprinting of groundwater occurs mainly during "characteristic" events with high runoff (intensity & duration), a tendency to "cool down" groundwater resources can be expected.
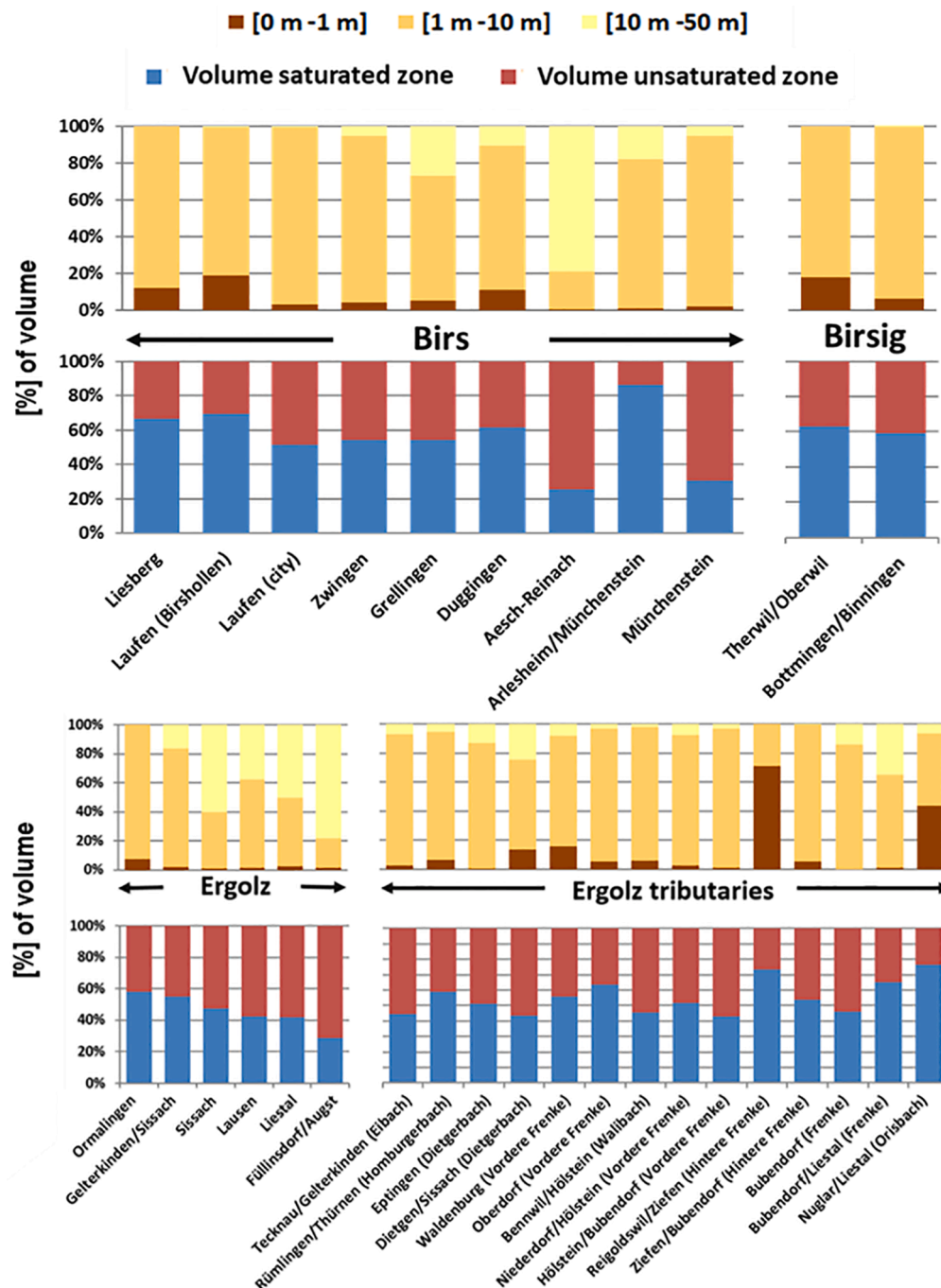
4.1. Canton Basel-City

In recent years, groundwater temperatures in Canton Basel-City have continuously been higher than annual mean air temperatures, which can be regarded as reference temperatures for thermally unaffected groundwater. The rise in groundwater temperatures is mainly due to the waste heat introduced by underground structures (buildings and infrastructure), increasing surface sealing, and increased use of groundwater

for cooling purposes (Epting et al., 2013). At about half of all groundwater monitoring sites located in urban areas, the groundwater temperature was 3.0 ± 0.7 °C higher than mean air temperatures (Mueller et al., 2018).

An evaluation of the River Rhine in the investigated aquifers shows that, except during flood events and low groundwater levels, the River Rhine is largely a receiving watercourse and the process of groundwater exfiltration dominates (interaction type B, Fig. 3). Accordingly, groundwater recharge and temperature imprinting by means of infiltrating surface water plays a minor role and therefore has not been further investigated in the present study. Nevertheless, the River Rhine in Basel has shown an increase of about + 3 °C between 1960 and 2010 (FOEN, 2012).

For the four investigated aquifers in Basel-City, distances from the surface to the groundwater table largely exceed 10 m, particularly on the left-hand side (i.e. west bank) of the River Rhine. Therefore, changes in seasonal temperature regimes will affect only part of the aquifers. The

Fig. 4. Distribution of classes for distance from the surface to the groundwater table as well as calculated volumes of the groundwater saturated and unsaturated zones of the 31 aquifers in Canton Basel-Land.
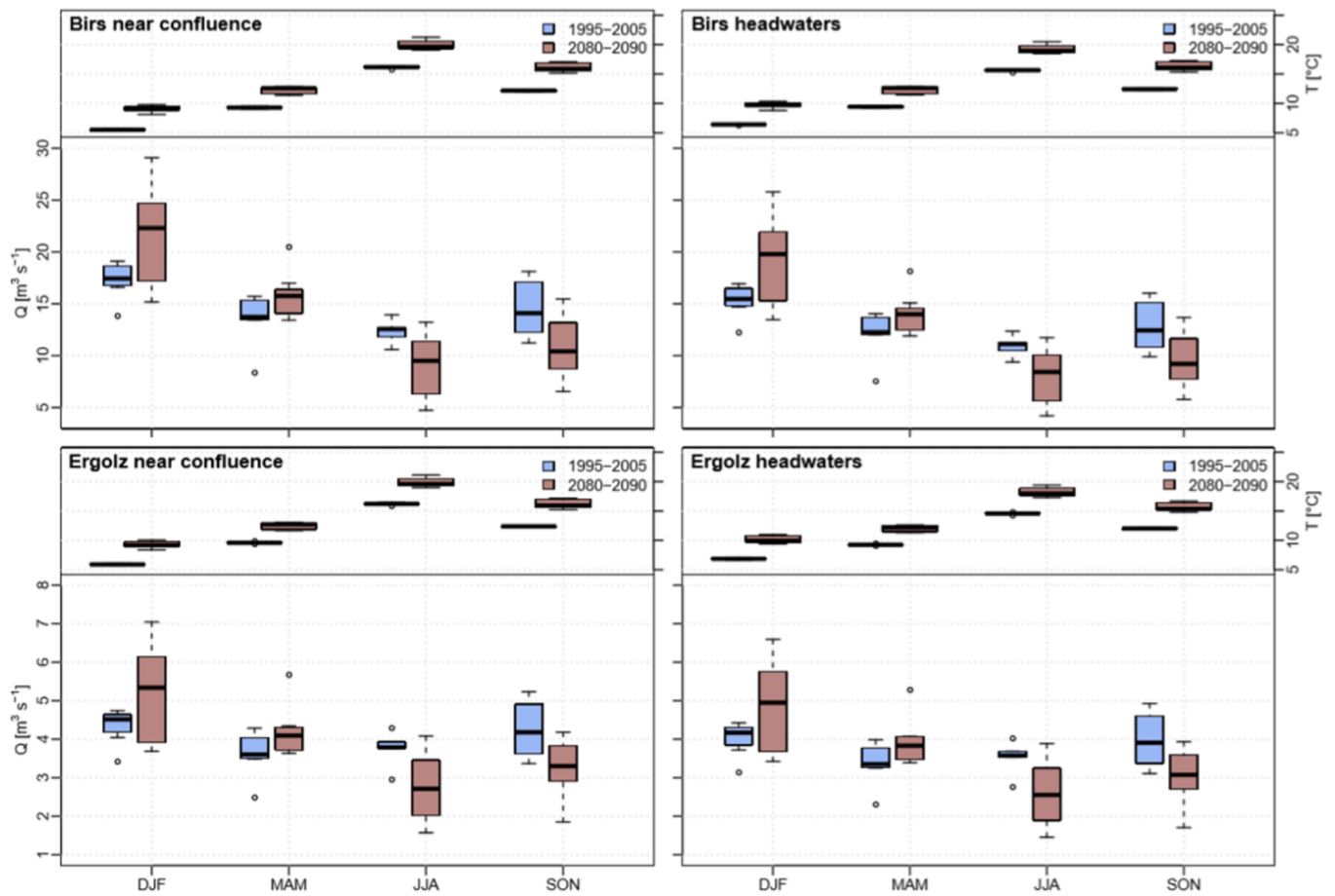
mean groundwater saturated zone thicknesses are 2.1 to 7.7 m and estimated mean groundwater renewal times range between 42 and 659 days (Table 2).

By means of heat-transport modelling in FeFlow©, groundwater and energy balances could be investigated (Mueller et al., 2018). For all four aquifers, groundwater exfiltration into the River Rhine as receiving watercourse dominates (see above). Three exceptions are the infiltration of surface water of the River Wiese, locally along the River Rhine in vicinity of a river dam, and the Birsfelden hydroelectric power plant. Furthermore, the regional inflows are essential groundwater recharge components, whereas the percolation of precipitation plays a negligible role compared to the other boundary conditions. Given the high degree of sealing in the urban areas of Basel, and the higher evapotranspiration
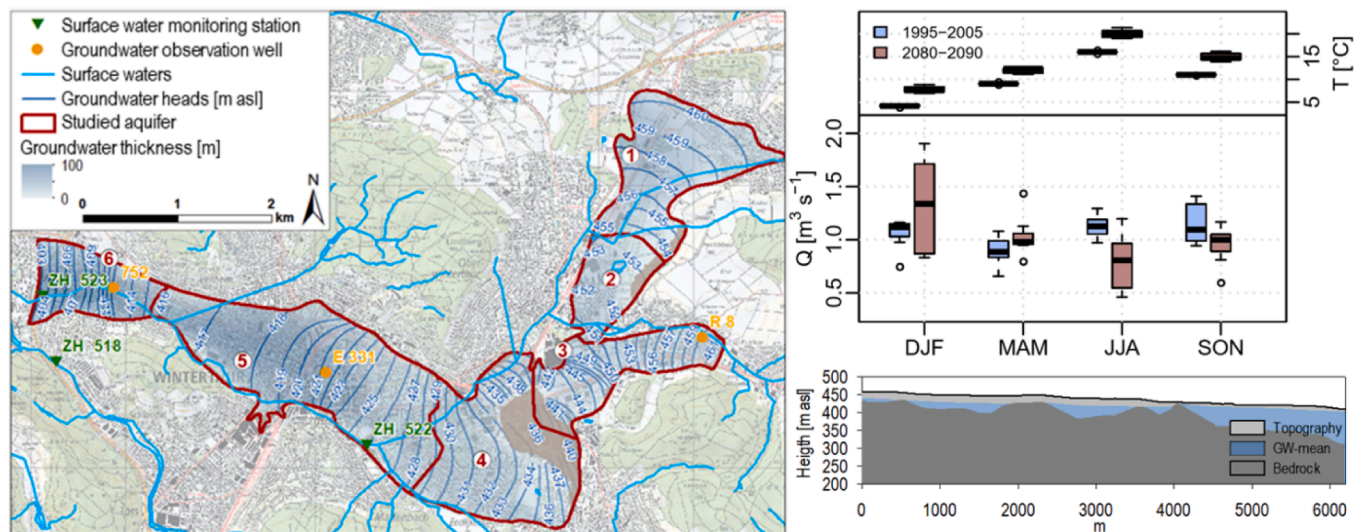
losses in summer, the changes in groundwater recharge, and thus the effects on groundwater temperatures, will be even smaller compared to rural areas. The heat flow over the earth's surface, which represents the thermal interaction with the atmosphere, is comparatively large, but balances out over the year. The heat flow associated with the regional groundwater flow and surface waters, as well as the heat input of buildings reaching into the groundwater saturated zone, are essential for the temperature regime.
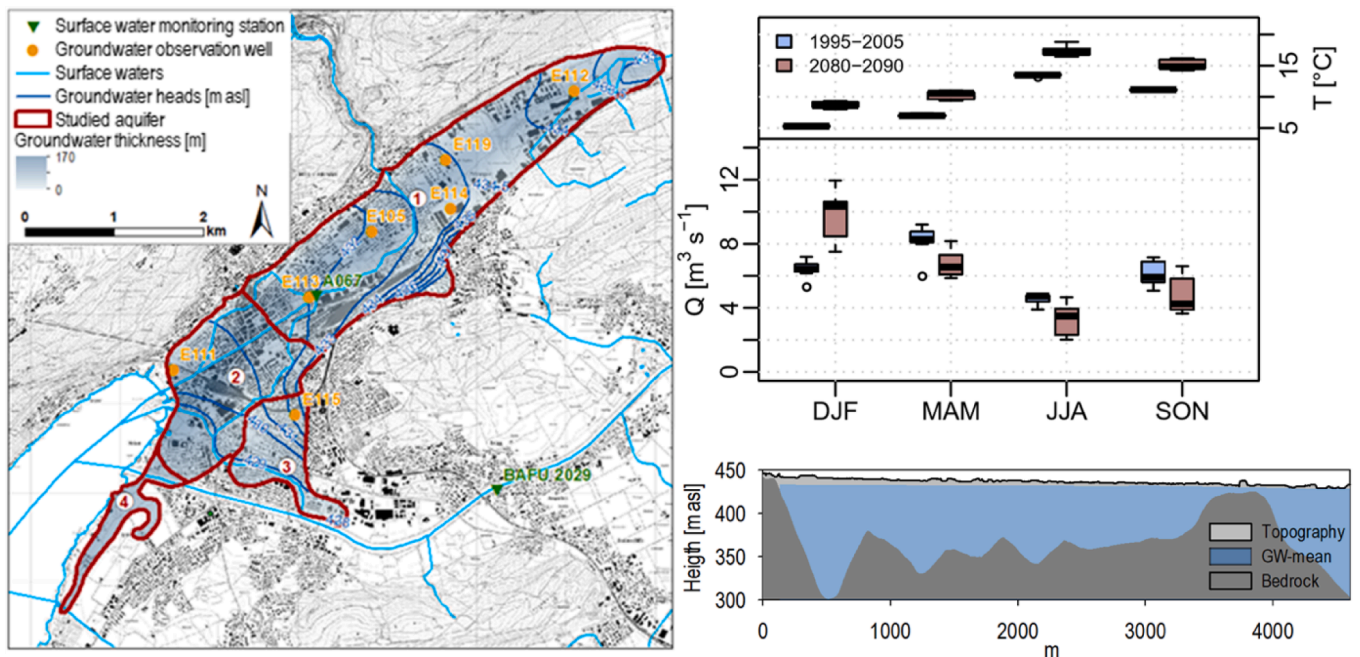
4.2. Canton Basel-Land

For the Canton Basel-Land, 31 aquifers located in the valleys along the main watercourses were evaluated (Table 2; Figs. 1 and 4). The
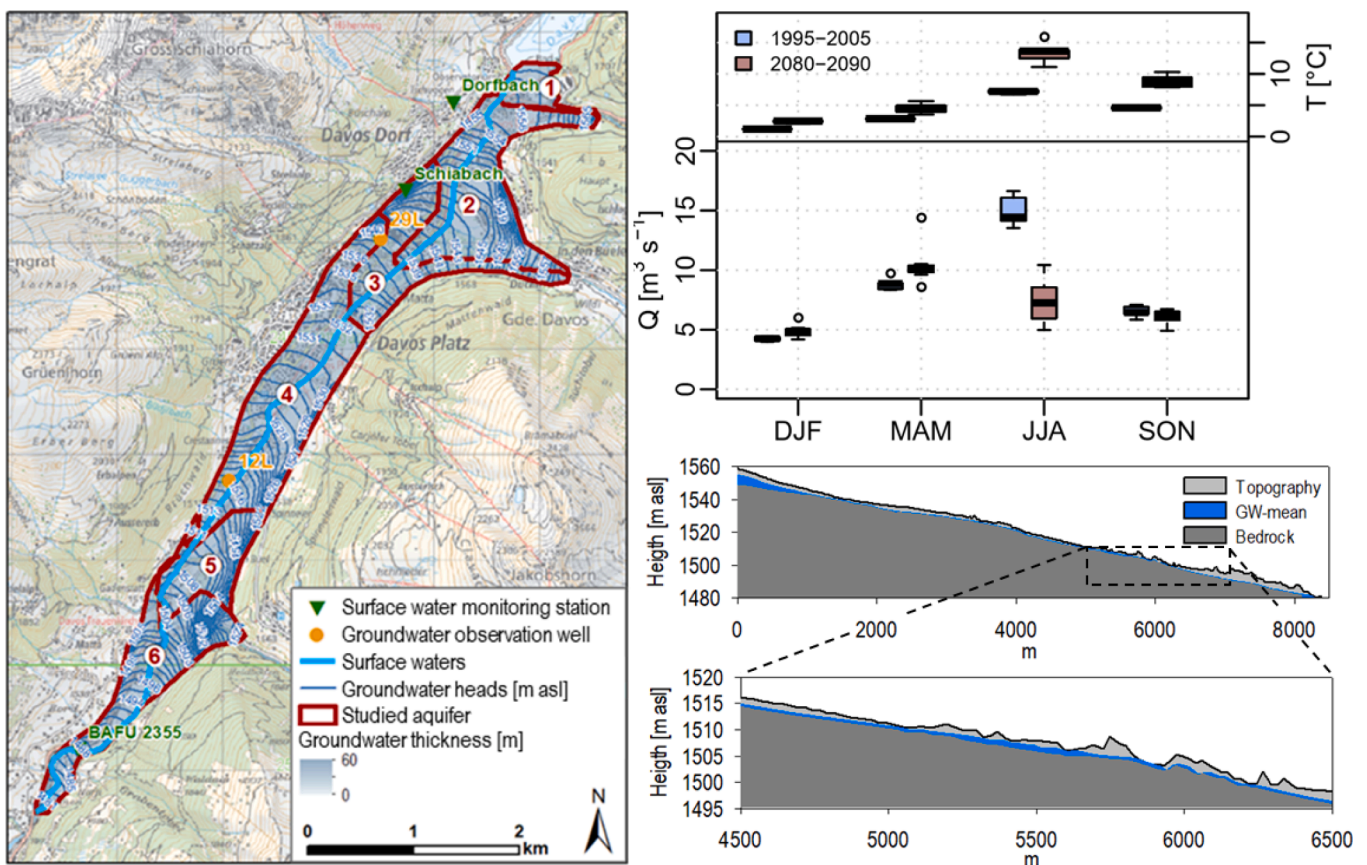
Fig. 5. Simulated river discharge (Q) and water temperature (T) obtained with RCP 8.5 scenarios for the reference periods 1995–2005 and for the time-period 2080–2090. Data are averaged for all seasons over the time-period for each scenario, therefore, boxplots show only scenarios variability and not interannual variability. Thick lines in boxplots are the median. Boxes represent the first and third quartiles of the data, whiskers extend to points up to 1.5 time the box range (i.e. up to 1.5 time the first to third quartiles distance), and extra outliers are represented as circles.

Fig. 6. Left: Aquifer of Winterthur (Canton Zurich) illustrating groundwater head and thickness, including groundwater and surface water monitoring stations; for 6 subdomains groundwater flow length and times were evaluated. Upper right: Simulated river discharge (Q) and water temperature (T) obtained with RCP 8.5 scenarios for the reference periods 1995–2005, and for the time-period 2080–2090. Lower right: Progression of the River Eulach related to the bedrock and the surface topography for a mean groundwater head situation.

Fig. 7. Left: Aquifer of Biel/Bienne (Canton Bern) illustrating groundwater head and thickness, including groundwater and surface water monitoring stations; for 4 subdomains groundwater flow length and times were evaluated. Upper right: Simulated river discharge (Q) and water temperature (T) obtained with RCP 8.5 scenarios for the reference periods 1995–2005, and for the time-period 2080–2090. Lower right: Progression of the River Suze related to the bedrock and the surface topography for a mean groundwater head situation.

Fig. 8. Left: Aquifer of Davos (Canton Grisons) illustrating groundwater head and thickness, including groundwater and surface water monitoring stations; for 6 subdomains groundwater flow length and times were evaluated. Upper right: Simulated river discharge (Q) and water temperature (T) obtained with RCP 8.5 scenarios for the reference periods 1995–2005, and for the time-period 2080–2090. Lower right: Progression of the River Landwasser related to the bedrock and the surface topography for a mean groundwater head situation, including a close-up of the river section between 4,500 and 6,500 m, where the river can encounter the groundwater table locally.

groundwater saturated zone thicknesses range between 2.4 and 10.8 m. For the aquifers along the rivers Birs and Birsig, distances from the surface to the groundwater table mainly range between 1 and 10 m. One exception is the aquifer near the Aesch and Reinach municipalities, where distances range between 10 and 50 m. Generally, for the aquifers along the River Ergolz, the distances from the surface to the groundwater table, as well as the volume of the groundwater saturated zone of the aquifers, increase from the headwaters to the confluence with the River Rhine. Estimated mean groundwater renewal times range between 0.6 and 34.9 days.

In the catchment of the rivers Birs and Ergolz, annual precipitation sums amount to 1,296 and 1,111 mm, respectively, and evaporation heights are 503 and 557 mm, respectively (standard period 1981–2010; https://hydromaps.ch). This results in estimates of potential groundwater recharge by means of percolating precipitation of 793 and 554 mm, respectively. Converted to the area of the aquifers we investigated (Table 2), estimated potential groundwater recharge by means of percolating precipitation ranges between 4.2 and 39 l s^{-1} (aquifers along the River Birs), and between 2.1 and 33 l s^{-1} (aquifers along the River Ergolz), excluding surface water runoff. For those aquifers for which groundwater flow models exist along the lower valleys of the River Birs (Affolter et al., 2010; Epting et al., 2018b), and the rivers Ergolz and Frenke (Epting et al., 2018b), groundwater budgets for different hydrological and operational boundary conditions could be calculated and evaluated (Annex 4). The evaluations show that, except for the aquifer located upstream of the municipality Laufen, the infiltration of surface water during flood events can increase by orders of magnitude because of changed hydraulics within the rivers and aquifers as well as the transient character of river bed permeability. For the different river sections, an indirect correlation between groundwater recharge by infiltrating surface water and discharge level in the rivers could be shown (Epting et al., 2018b). Further relevant boundary conditions are the regional groundwater flow. Quantitatively, the share of the inflow via hillslope areas and, if available, artificial groundwater recharge and extraction, is of varying relevance for the different modelled aquifers. Interactions with regional karst systems can be important, whereas the percolation of precipitation is quantitatively insignificant.

For the rivers Birs and Ergolz, different locations in the headwaters and near the confluence with the River Rhine were evaluated for the RCP 8.5 scenarios, and for the reference periods 1995–2005 and 2080–2090 (Figs. 1 and 5). Because of decreased runoff during summer (JJA) and autumn (SON) months for all sites, it can be expected that groundwater recharge by means of infiltrating surface water also decreases. This effect could be associated with a reduction of groundwater recharge by means of comparatively "warm" surface water infiltration. In contrast, in winter (DJF) runoff tends to increase, but less in spring (MAM) months. Likewise, this effect could be associated with an increase of groundwater recharge by means of comparatively "cold" surface water infiltration. All in all, these developments would be accompanied by a tendency to "cool down" groundwater resources.

Fig. A2.5 in Annex 2 summarizes the simulation results for all RCPs and time-periods. With respect to RCP 2.6 and 4.5, no major change in mean is expected, but it is expected in the variability of river runoff. Compared to the hypothesized tendency to "cool down" groundwater for climate projection RCP 8.5, due to the shift of runoff and associated elevated groundwater recharge from summer to winter, this effect would not occur for the RCP 2.6 and 4.5 scenarios. Eventually, only the "warming" effect of raising surface water temperatures would remain.

4.3. Winterthur – Canton Zurich

In recent years, groundwater temperatures measured in the city of Winterthur and its surroundings were only slightly higher than the annual mean air temperature. The groundwater saturated zone

thickness can reach up to 105 m, whereas distances from the surface to the groundwater table largely exceed 10 m, for which neither daily nor seasonal temperature fluctuations play a role. Estimated mean groundwater residence times range between 17 and 26 days (Table 2).

In the catchment of the River Eulach, annual precipitation sums amount to 1,178 mm and evaporation height are 497 mm (Winterthur CHZH-009; standard period 1981–2010; https://hydromaps.ch). This results in estimates of potential groundwater recharge by means of percolating precipitation of 681 mm. For the area of the investigated aquifer of approx. 9.3 km^2 (Table 2), this groundwater recharge component results in 180 l s^{-1}, excluding surface water runoff. In addition, there is a further reduction of percolating recharge in urbanized areas characterized by surface sealing. Therefore, compared to the regional groundwater inflow and outflow, the areal groundwater recharge from percolating precipitation is low. This is probably also the case for the not yet quantified interaction with surface waters. Results of groundwater flow modelling (Alberich, 1997) show that groundwater budgets are mainly characterized by regional groundwater inflow and outflow (920 l s^{-1} from Northeast; 2,500 l s^{-1} from East). The influence of the inflow via the lateral hill-slope areas (approx. 22 l s^{-1}) is very low.

Fig. 6 shows a cross-section of the aquifer along the River Eulach. Over large areas, the river is separated from the groundwater table by a thick unsaturated zone. However, between river lengths 4.8 and 5.2 km, the river can be in contact with the groundwater table.

For the River Eulach, the results of the simulations for the RCP 8.5 scenarios and for the reference periods 1995–2005 and 2080–2090 show (Figs. 1 and 6) that runoff during summer (JJA) decreases, although it is less during the autumn (SON) months. In summer, this decrease could be associated with a reduction of groundwater recharge by means of comparatively "warm" surface water infiltration. In contrast, in winter (DJF) months runoff tends to increase, but it is less in spring (MAM). Likewise, this increase could be associated with an increase of groundwater recharge by means of comparatively "cold" surface water infiltration. All in all, these developments would be accompanied by a tendency to "cool down" groundwater resources.

Fig. A2.6 in Annex 2 summarizes the simulation results for all RCPs and reference periods. With respect to RCP 2.6 and 4.5, different behaviors for means are expected, and also for the variability of river runoff. However, for RCP 2.6, river discharge in the winter months (DJF) also is expected to decrease. Likewise, future temperature developments are indistinct for these climate projections and groundwater resource.

4.4. Biel/Bienne – Canton Bern

In general, both groundwater levels and temperatures of most monitoring stations in Biel show a high variability and strong trends towards temperature increases (https://www.map.apps.be.ch). The aquifer is limited locally and is not in contact with the large aquifer of the River Aare (Fig. 7). Furthermore, deep groundwater recharge through confined artesian aquifers may exist (i.e. karstification of the limestones and dolomites).

Near Lake Biel at the south-western boundary, groundwater saturated zone thicknesses can reach up to 167 m, whereas distances from the surface to the groundwater table largely range between 1 and 10 m, for which daily and seasonal temperature fluctuations play a role. Estimated mean groundwater recharge times are 61.4 days (Table 2).

In the catchment of the River Suze, annual precipitation sums amount to 1,411 mm and evaporation height are 497 mm (Biel 137897; standard period 1981–2010; https://hydromaps.ch). This results in estimates of potential groundwater recharge by means of percolating precipitation of 914 mm. For the aquifer we investigated with an area of approx. 8.2 km^2 (Table 2), this groundwater recharge component results in 240 l s^{-1}, excluding surface water runoff. Since most of the slopes around the unconsolidated groundwater near Biel are built-up, most of

the slope inflows are captured and an inflow via the lateral slope catchment areas is negligible in the overall water balance. Therefore, the inflow via the lateral hill slope catchments, and groundwater recharge from percolating precipitation, indicate that these groundwater recharge components play a subordinate role.

Fig. 7 also shows a cross-section through the aquifer along the River Suze. The thickness of the unsaturated zone below the river decreases from about 10 to almost 0 m from the inflow into the aquifer to the confluence with Lake Biel. During high runoff, there are areas where the river can encounter the groundwater table.

For the River Suze, the results for all RCP scenarios (Figs. 1 and 7, Fig. A2.6 in Annex 2) show that runoff during summer (JJA), autumn (SON) and spring (MAM) months decreases. Particularly, for the summer months, this decrease could be associated with a reduction of groundwater recharge by means of comparatively "warm" surface water infiltration. In contrast, in winter (DJF) months, runoff tends to increase. Likewise, this increase could be associated with an increase of groundwater recharge by means of comparatively "cold" surface water infiltration. All in all, these developments would be accompanied by a tendency to "cool down" groundwater resources.

4.5. Davos – Canton Grisons

The groundwater temperatures measured in Davos are strongly influenced by the interaction with the River Landwasser. Over large areas of the Landwasser valley, the groundwater saturated zone thicknesses are comparatively low, and on average less than 2 m. Near the River Landwasser and its tributaries, distances between the surface and the groundwater table largely range between 1 and 10 m. To the hill slopes on the valley margins, distances often are above 10 m. Estimated mean groundwater recharge times are only 7.8 days (Table 2).

Results of groundwater modelling performed by GEOTEST AG show that groundwater budgets are characterized mainly by regional groundwater flow (approx. 30 to 65 l s^{-1}) and inflow from the hill slope catchments (approx. 132 l s^{-1}), by the interaction with surface waters (infiltration 180 l s^{-1}; exfiltration 279 l s^{-1}), but also by groundwater use (approx. 113 l s^{-1}). In the catchment of the River Landwasser, annual precipitation sums amount to 1,032 mm and evaporation heights are 328 mm (Frauenkirch CH-0169; standard period 1981–2010; https://hydromaps.ch). This results in estimates of potential groundwater recharge by means of percolating precipitation of 704 mm. For the aquifer we investigated with an area of approx. 5.4 km^2 (Table 2), this groundwater recharge component results in 120 l s^{-1}, excluding surface water runoff. Therefore, the estimation of groundwater recharge from percolating precipitation shows that this groundwater recharge component is lower compared to other groundwater recharge components. Fig. 8 also shows a cross-section through the aquifer along the River Landwasser, over large areas the river is separated from the groundwater table by an unsaturated zone. However, between river lengths 5.5 and 6 km, the river can encounter the groundwater table locally and groundwater can exfiltrate into the watercourse.

The results for all RCP scenarios of the simulations for the River Landwasser (Figs. 1 and 8, Fig. A2.6 in Annex 2) show that runoff during summer (JJA) months decreases. Particularly, for the summer months and given the higher evapotranspiration losses in summer, this decrease could be associated with a reduction of groundwater recharge by means of comparatively "warm" surface water infiltration, an effect which could be accompanied by a tendency to "cool down" groundwater resources. In contrast, in winter (DJF) months, runoff tends to increase. Likewise, this effect could be associated with an increase of groundwater recharge by means of comparatively "cold" surface water infiltration.

The evaluation of the seasonal runoff duration lines (hydrological year) for the different emission scenarios shows that tendentially higher runoff for the months October to June can be expected (Fig. A3.1; Annex 3) along with the lower runoff for the months July to September seen in all the all aquifers we investigated.

5. Discussion

Our evaluation of the aquifers, including groundwater saturated and unsaturated zones, allowed us to assess their sensitivity to changes in groundwater saturated zone thickness and/or the distance from the surface to the groundwater table. Generally, beyond 1 m below the earth's surface, temperatures are insensitive to diurnal cycles of air temperature and solar radiation, and temperature variations beyond 9 to 12 m below the earth's surface are insensitive to seasonal cycles (ASHRAE, 1991; Florides and Kalogirou, 2005; Kalogirou and Florides, 2004). For all aquifers we investigated, there are only a few areas where the distance from the surface to the groundwater table is below 1 m (penetration depth of daily atmospheric temperature signals). With some exceptions, distances between the surface and the groundwater table range between 1 and 10 m (penetration depth of seasonal atmospheric temperature signals; e.g. Epting et al. (2013)). Only some aquifers have average groundwater saturated zone thicknesses below 5 m (Table 2). The density of watercourses, as a measure for interaction of aquifers with surface waters, also varies greatly. There are very low densities for Basel-City and, in some cases, comparatively high densities for individual aquifers in Basel-Land and Davos (Table 2). Depending on the distance to watercourses or aquifer outlets, estimated groundwater renewal rates range from a few days to more than a year (Table 2).
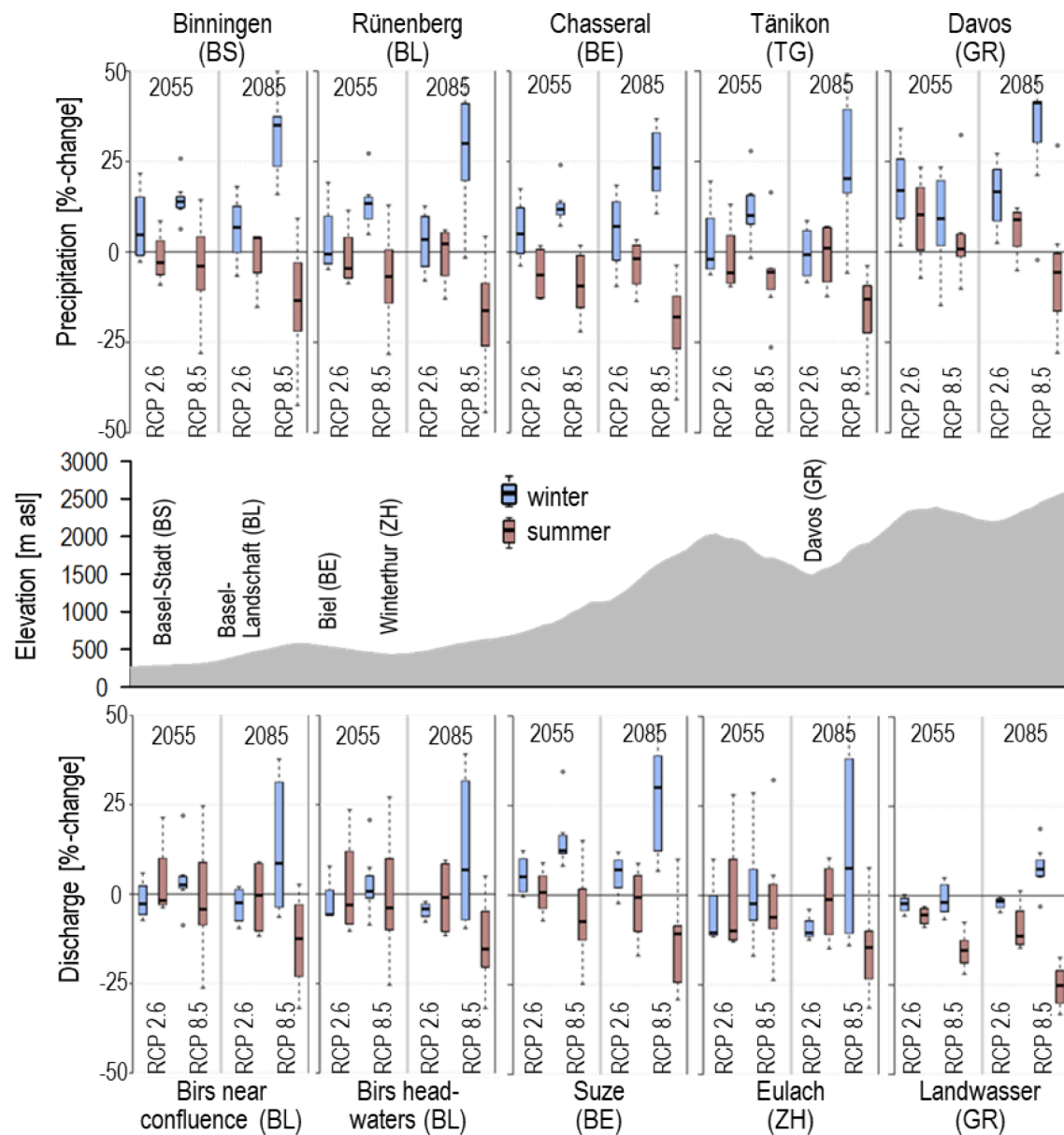
An evaluation of the surface waters in the aquifers we studied shows that the River Rhine in Canton Basel-City is primarily a receiving watercourse and that groundwater exfiltration into the river dominates, except during periods of high runoff and low groundwater levels. Accordingly, for most areas in Basel, water infiltration from the River Rhine is a subordinate groundwater recharge component. Different types of interaction between surface waters and the aquifers can be observed for Canton Basel-Land, where groundwater flow in the valleys is partially interrupted by rock steps. Nevertheless, there is often a connection between the aquifers via karst and/or fracture systems (Epting et al., 2018a). The River Eulach in Winterthur and, for the most part, the River Landwasser in Davos, are decoupled from the groundwater table, even for different hydrological conditions. The River Suze in Biel/Bienne is also largely decoupled from the groundwater table; only at the estuary into Lake Biel is the river connected to the groundwater table. Here processes of surface water infiltration into the aquifer dominate, which represent temperature imprinting and an important component of groundwater recharge.

Within the scope of the research carried out here, the role of "regional flood events" in connection with increased groundwater recharge could be investigated. However, the effect that local events, such as thunderstorms in summer, have on runoff generation and groundwater recharge could not be further investigated. Even so, it is expected that during extreme events, especially in the headwaters and middle reaches of watercourses, infiltration rates of surface waters will increase in the short-term (i.e. "local flooding").

While snow covers plays a minor role in most of the catchments, it is an important factor within the Landwasser catchment around Davos. In future, the increase of snowmelt and liquid precipitation in winter can come along with an increase of snowmelt and runoff in spring (Fig. A2.6 in Annex 2). Again, more comparatively "cold" surface water would presumably infiltrate the aquifer in spring months, which would tend to "cool down" groundwater resources.

5.1. Development of groundwater recharge and groundwater temperatures

For the aquifers we investigated, it is expected that a change in groundwater recharge through the percolation of precipitation plays a minor role in the overall water balance. However, a change of inflow via regional groundwater flow components because of changed groundwater recharge in the upstream catchment areas can play a more important role ("imported groundwater regime"). In the case of groundwater exfiltrating settings (Fig. 3), larger hydraulic gradients

Fig. 9. Trends in precipitation and discharge which can be associated with the different groundwater recharge components from percolating precipitation and infiltrating surface waters. Shown here are the simulation results for the aquifers and the summer (June to September) and winter (December to March) hydrological half-year periods. Changes in % are shown for the RCP 2.6 and 8.5 emission scenarios, as well as for the time-periods 2050–2060 and 2080–2090, compared to the time-period 1995–2005.

from the groundwater to the surface waters, associated with increased groundwater exfiltration, would result from more frequent and longer-lasting drought periods and lower river stages. In Alpine regions, such as Davos, a reduced inflow via regional groundwater flow components from the hill-slope catchment, and changes in snowmelt water contribution, may play a more important role (see also above).

Fig. 9 summarizes the precipitation development and the simulation results for the surface water runoff for the hydrological half-year periods, and also for the RCP 2.6 and 8.5 emission scenarios for the years 2055 and 2085 in comparison to the reference year 2000. Apart from the River Landwasser aquifer in Davos, all the climate projections for the aquifers we investigated show that, compared to the reference year 2000, precipitation increases from October to March and decreases from April to September. Those half-year periods roughly coincide with

autumn and winter on the one hand, and spring and summer on the other hand.

Diverse developments can be observed in the simulation results for surface water runoff for the hydrological half-year periods and for the RCP 2.6 and 8.5 emission scenarios. For the rivers Birs and Ergolz in Canton Basel-Land, and for climate projection RCP 8.5, surface runoff shifts from summer to winter. However, with respect to the RCP 2.6 and 4.5 scenarios (cf. Fig. 2.4; Annex 2), no major change in mean is expected, although change is expected in the variability of river runoff. For the River Suze in Biel/Bienne for all RCP scenarios (cf. Fig. A2.6 in Annex 2), runoff decreases in summer and increases in winter. For the River Eulach in Winterthur, and for the River Landwasser in Davos, an overall reduction of future surface water runoff is expected, apart from the winter half-year period for RCP 8.5 and the year 2085.

Generally, if runoff during summer (JJA) and autumn (SON) months decreases, it can be expected that groundwater recharge by means of infiltrating surface water will also decrease. This effect as observed could be associated with a reduction of groundwater recharge by means of comparatively "warm" surface water infiltration. Furthermore, this effect comes along with higher evapotranspiration losses during the vegetation period, especially in summer. In contrast, increased runoff in winter (DJF) and spring (MAM) could be associated with an increase of groundwater recharge by means of comparatively "cold" surface water infiltration. All in all, we observed these developments for the RCP 8.5 scenarios, and between the periods 1995–2005 and 2080–2090, for the rivers Birs and Ergolz in Canton Basel-Land, the River Eulach in Winterthur and the River Suze in Biel/Bienne. It is expected that these developments would be accompanied by a tendency to "cool down" groundwater. However, with respect to the RCP 2.6 and 4.5 emission scenarios, different behaviors are expected for both the mean and also the variability of river runoff, whereas decreased discharge in the winter (DJF) months are expected, e.g. for the River Eulach in Winterthur. The hypothesized tendency of groundwater to "cool down" in the RCP 8.5 scenario is due to the shift in runoff and to the associated elevated groundwater recharge from summer to winter. But this effect would not occur for RCP 2.6 and 4.5. Eventually, only the "warming" effect caused by rising surface water temperatures would remain.

5.2. Utilization potentials / adaptation strategies

Many subsurface use interests in urban areas often conflict, requiring new use concepts to be developed for a differentiated assessment and sustainable use of groundwater and thermal energy of the shallow subsurface. Such concepts in energy planning should make it possible to consider thermal use potentials, e.g. for individual districts, while at the same time also considering the qualitative aspects of urban aquifers and the legal requirements for groundwater protection.

The knowledge we now have on the variability of hydraulic and thermal groundwater regimes for representative Swiss unconsolidated rock groundwater resources offers a basis to formulate local adaptation strategies. Likewise, "waste heat" related to elevated groundwater temperatures in urban aquifers could be used in a targeted and efficient manner. Having optimization strategies for the documentation of long-term temperature changes at reference sites would enable researchers to differentiate anthropogenic-induced changes from climate-induced changes in aquifers.

The concepts and methodological approaches developed here can enable public authorities to compare characteristic hydraulic and thermal boundary conditions of aquifers and to assess how sensitive the relevant groundwater recharge processes are to CC. Comparing the hydraulic characteristics (e.g. aquifer properties, groundwater recharge, interaction with surface waters, etc.) and thermal boundary conditions (e.g. seasonal temperature signals, anthropogenic heat input, etc.) in the Swiss groundwater resources that we have studied here can serve as a basis to be transferred to groundwater resources in general.

Anthropogenic adaptation strategies (e.g. decreased river and increased groundwater abstraction, artificial recharge of river water to replenish groundwater resources) could have effects on groundwater resources that could be greater than the effects of CC itself. Concerning future groundwater use, it can be assumed that groundwater extraction and artificial recharge will increase during extended droughts. Further reduction of residual water flow rates in rivers (e.g. required for ecosystems) certainly is a problematic development, especially for those with low discharges such as the rivers Birs and Ergolz in Canton Basel-Land. Since such situations will occur mainly in the summer months, and since comparatively warm surface water will be artificially recharged, it can be expected that groundwater temperatures will thus rise accordingly. For example, the high maximum surface water temperatures of the River Rhine above 26 °C in summer already observed will affect the drinking water supply in the Basel region where, by means

of different systems, surface water is artificially recharged to the aquifer. Likewise, it should not be forgotten that extractions of surface water and groundwater can intensify low-water runoff situations in rivers. In agricultural areas, during periods of low precipitation, water withdrawals from watercourses are expected to increase. Reduced quantities of low-water runoff would accordingly also reduce groundwater recharge due to reduced infiltration of surface water.

5.3. Requirements monitoring systems / pilot studies for long-term monitoring

Thanks to the increased availability of comparatively inexpensive temperature sensors, more and more temperature data have been collected since the 1980s. Data from observation networks provide valuable information on temperature distributions in groundwater resources and are prerequisites for model calibration and validation. However, they are inappropriate for studying specific thermal processes, such as the heat transport from the surface via the unsaturated zone to the groundwater table, the influence of subsurface structures, the river-groundwater interactions, etc. For this reason, the installation of depth-oriented monitoring systems is recommended. Such systems allow researchers to draw conclusions about vertical temperature distributions in the groundwater or in the unsaturated zone, as well as determine the effects that aquifer heterogeneities have on subsurface temperature distributions (Epting et al., 2013).

For the aquifers investigated in this study, deficits in the available data were shown. Despite cases of insufficient data, this analysis nevertheless allows monitoring concepts to be adjusted and optimized at cantonal level. Furthermore, it is recommended, especially in urbanized areas, to systematically collect data on thermal groundwater use (e.g. extraction and recharge quantities, and temperatures) and on the spatial distribution of building structures in the subsurface. With such data, researchers will be able to quantify the anthropogenic influences on shallow subsurface hydraulic and thermal regimes.

5.4. Research gaps and open questions

It must be noted that future development as well as spatial and temporal dynamics of groundwater temperatures cannot satisfactorily be captured only by statistical evaluations or by spatially interpolated temperature distributions. Flow and heat transport modelling are required to understand the relevant hydraulic and thermal processes. Only then can heat balances and thermal utilization potentials be calculated, and the thermal effects of future uses of the shallow subsurface be quantified. In urbanized areas especially, it is expected that an increased thermal use of the subsurface as well as adaptation strategies in connection with global warming ("positive and negative responses") will further impact aquifer temperatures (Epting and Huggenberger, 2013). This complex interplay of the various natural and anthropogenic influencing factors can only be adequately analyzed by using flow and heat transport models. In addition, such models make it possible to quantify the interaction of surface waters with groundwater both spatially and temporally and investigate in greater depth the quantitative and qualitative effects of CC by means of scenario calculations.

Likewise, with reasonable effort and further investigations, river sections could be evaluated regarding their interaction with groundwater under different hydrological boundary conditions. Seasonal changes about the occurrence of extreme events could also be studied. The possible hydraulic and thermal effects that CC has on surface waters and groundwater could thus be clarified.

6. Conclusions

A significant, large-scale increase in groundwater temperature, as would be expected because of CC, has not yet been observed in

Switzerland, although it is clearly observed for surface water temperature (BAFU, 2019). One reason for this observation could be underestimations of quantitative increases of groundwater recharge in the hydrological winter half-year, which tend to "cool down" aquifers. Accordingly, for the aquifers we studied, both for the "business as usual" CC scenario and for the end of the century, groundwater recharge via percolating precipitation and infiltrating surface waters increasingly will take place in comparatively "cold" months. That change would be accompanied by a tendency to "cool down" groundwater. In addition, the quantitative share of groundwater recharge decreases in comparatively "warm" months, a process which is intensified by increased evapotranspiration during the vegetation growth period.

To understand the future development of groundwater temperatures, it is necessary to take a differentiated view of geological site conditions and relevant hydrogeological processes, including the processes of groundwater recharge, "positive and negative responses" as well as direct anthropogenic influences. These fundamentals are essential for understanding the response of aquifers to anthropogenic and CC impacts.

Within the scope of this research project, it was possible to show which basic information is required to characterize hydraulic and thermal "current states" of aquifers. Together with the derivation of key parameters, such as storage properties, water balance dynamics, renewal rates, and an evaluation of the relevant groundwater recharge processes, the tools developed here make it possible to perform an initial assessment on how sensitive aquifers are to the effects of CC.

For the valley aquifers we investigated, the interaction with surface waters and increased groundwater recharge during high runoff might have a strong influence on groundwater temperature. Likewise, the exceedance of "characteristic" hydraulic threshold values (e.g. relation of river stage to groundwater table along bedrock steps) for individual aquifers can be accompanied by increased groundwater recharge.

For our studies, we did not follow the commonly used catchment approach, but used the "river corridor" concept of Stanford and Ward (1993) and concentrated instead on aquifers located in river valleys. Such aquifers are most productive not only for water supply but also for agriculture. Accordingly, they are locations where decisions must be taken for groundwater resource management and the development of adaptation strategies. The decisive factor for stakeholders is maintaining water supply and quality for different conditions. Our studies show that by applying relatively simple methods at reasonable costs, the sensitivity of aquifers to climate or anthropogenic induced changes can be assessed. In general, not all aquifers will react in the same way and only appropriate monitoring systems for groundwater and surface waters facilitate to adequately capture the individual relevant hydrological and hydrogeological processes.

CRediT authorship contribution statement

Epting Jannis: Conceptualization, Methodology, Writing - original draft. **Michel Adrien:** Methodology, Software, Validation, Formal analysis, Writing - original draft. **Affolter Annette:** Data curation, Visualization. **Huggenberger Peter:** .

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.

Acknowledgements

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.hydroa.2020.100071.

References

(CEC), C.o.t.E.C., 2000. Directive of the European Parliament and of the Council establishing a framework for Community action in the field of water policy: Joint text approved by the Conciliation Committee. 1997/0067(COD). C5-0347/00.

Affolter, A., Huggenberger, P., Scheidler, S., Epting, J., 2010. Adaptive groundwater management in urban areas Effect of surface water-groundwater interaction using the example of artificial groundwater recharge and in- and exfiltration of the river Birs (Switzerland). Grundwasser 15 (3), 147–161. https://doi.org/10.1007/s00767-010-0145-6.

Alberich, 1997. Diffuse Grundwasserbelastung durch undichte Abwasserkanäle – Quantifizierung am Beispiel der Stadt Winterthur, Siedlungswasserwirtschaft und Gewässerschutz", Institut für Hydromechanik und Wasserwirtschaft, ETH-Zürich.

Alcaraz, M., Garcia-Gil, A., Vazquez-Sune, E., Velasco, V., 2016. Advection and dispersion heat transport mechanisms in the quantification of shallow geothermal resources and associated environmental impacts. Sci. Total Environ. 543, 536–546. https://doi.org/10.1016/j.scitotenv.2015.11.022.

Allen, D.M., Mackie, D.C., Wei, M., 2004. Groundwater and climate change: a sensitivity analysis for the Grand Forks aquifer, southern British Columbia, Canada. Hydrogeol. J. 12 (3), 270–290. https://doi.org/10.1007/s10040-003-0261-9.

ASHRAE, 1991. Handbook of Fundamentals, Atlanta.

BAFU, 2012. Auswirkungen der Klimaänderung auf Wasserressourcen und Gewässer. Synthesebericht zum Projekt «Klimaänderung und Hydrologie in der Schweiz» (CCHydro), Bern.

BAFU, 2019. Zustand und Entwicklung Grundwasser Schweiz. Ergebnisse der Nationalen Grundwasserbeobachtung NAQUA, Stand 2016, Bern.

Bates, B.C., Kundzewicz, Z.W., Wu, S., Palutikof, J.P. 2008. Climate change and water. (Technical paper of the Intergovernmental Panel on Climate Change.).

Bavay, M., Egger, T., 2014. MeteoIO 2.4.2: A preprocessing library for meteorological data. Geosci. Model Dev. 7 (6), 3135–3151. https://doi.org/10.5194/gmd-7-3135-2014.

Bayer, P., Rivera, J.A., Schweizer, D., Schärli, U., Blum, P., 2016. Extracting past atmospheric warming and urban heating effects from borehole temperature profiles. Geothermics 64, 289–299.

Bosshard, T., Kotlarski, S., Ewen, T., Schar, C., 2011. Spectral representation of the annual cycle in the climate change signal. Hydrol. Earth Syst. Sci. 15 (9), 2777–2788. https://doi.org/10.5194/hess-15-2777-2011.

Brauchli, T., Trujillo, E., Huwald, H., Lehning, M., 2017. Influence of slope-scale snowmelt on catchment response simulated with the Alpine3D model. Water Resour. Res. 53 (12), 10723–10739. https://doi.org/10.1002/2017wr021278.

Brielmann, H., Griebler, C., Schmidt, S.I., Michel, R., Lueders, T., 2009. Effects of thermal energy discharge on shallow groundwater ecosystems. FEMS Microbiol. Ecol. 68 (3), 273–286. https://doi.org/10.1111/j.1574-6941.2009.00674.x.

Brock, T.D., Madigan, M.T., 1988. Biology of microorganisms. Prentice-Hall, Englewood Cliffs, NJ.

Brunner, M.I., et al., 2019. Present and future water scarcity in Switzerland: Potential for alleviation through reservoirs and lakes. Sci. Total Environ. 666, 1033–1047. https://doi.org/10.1016/j.scitotenv.2019.02.169.

Brunner, M.I., Melsen, L.A., Newman, A.J., Wood, A.W., Clark, M.P., 2020. Future streamflow regime changes in the United States: Assessment using functional classification. Hydrol. Earth Syst. Sci. 24 (8), 3951–3966. https://doi.org/10.5194/hess-24-3951-2020.

BUWAL, BWG, MeteoSchweiz, 2004. Auswirkungen des Hitzesommers 2003 auf die Gewässer, Bundesamt für Umwelt, Wald und Landschaft, Bern.

CH2011, 2011. Swiss Climate Change Scenarios CH2011. ISBN: 978-3-033-03065-7.

CH2014-Impacts, 2014. Toward Quantitative Scenarios of Climate Change Impacts in Switzerland, Bern, Schweiz.

CH2018-Project-Team, 2018. CH2018 – Climate Scenarios for Switzerland. National Centre for Climate Services. https://doi.org/10.18751/Climate/Scenarios/CH2018/1.0.

CH2018, 2018. CH2018 – Climate Scenarios for Switzerland, Technical Report, Zurich.

Changnon, S.A., Huff, F.A., Hsu, C.F., 1988. Relations between Precipitation and Shallow Groundwater in Illinois. J. Climate 1 (12), 1239–1250. https://doi.org/10.1175/1520-0442(1988)001<1239:Rbpasg>2.0.Co;2.

Crosbie, R.S., et al., 2013. An assessment of the climate change impacts on groundwater recharge at a continental scale using a probabilistic approach with an ensemble of GCMs. Clim. Change 117 (1), 41–53. https://doi.org/10.1007/s10584-012-0558-6.

Dokulil, M.T., 2014. Impact of climate warming on European inland waters. Inland Waters 4 (1), 27–40. https://doi.org/10.5268/Iw-4.1.705.

Epting, J., García-Gil, A., Huggenberger, P., Vázquez-Suñe, E., Mueller, M.H., 2017a. Development of concepts for the management of thermal resources in urban areas – Assessment of transferability from the Basel (Switzerland) and Zaragoza (Spain) Case Studies. J. Hydrol. https://doi.org/10.1016/j.jhydrol.2017.03.057.

Epting, J., Handel, F., Huggenberger, P., 2013. Thermal management of an unconsolidated shallow urban groundwater body. Hydrol. Earth Syst. Sci. 17 (5), 1851–1869. https://doi.org/10.5194/hess-17-1851-2013.

Epting, J., Huggenberger, P., 2013. Unraveling the heat island effect observed in urban groundwater bodies – Definition of a potential natural state. J. Hydrol. 501, 193–204. https://doi.org/10.1016/j.jhydrol.2013.08.002.

Epting, J., et al., 2015. Analyse von Grundwasserkörpern mit GIS. GIS-Tool GSIA - Basis für das Prozessverständnis der Interaktion von Grundwassersystemen. Aqua & Gas 7 (8), 72–79.

Epting, J., et al., 2018a. Spatiotemporal scales of river-groundwater interaction – The role of local interaction processes and regional groundwater regimes. Sci. Total Environ. 618, 1224–1243. https://doi.org/10.1016/j.scitotenv.2017.09.219.

Epting, J., et al., 2018b. Spatiotemporal scales of river-groundwater interaction - The role of local interaction processes and regional groundwater regimes. Sci. Total Environ. 618, 1224–1243. https://doi.org/10.1016/j.scitotenv.2017.09.219.

Epting, J., et al., 2017b. Spatiotemporal scales of river-groundwater interaction – The role of local interaction processes and regional groundwater regimes. Sci. Total Environ. 20 https://doi.org/10.1016/j.scitotenv.2017.09.219.

Feigenwinter, I. et al. 2018. Exploring quantile mapping as a tool to produce user-tailored climate scenarios for Switzerland.

Figura, S., Livingstone, D.M., Hoehn, E., Kipfer, R., 2011. Regime shift in groundwater temperature triggered by the Arctic Oscillation. Geophys. Res. Lett. 38 https://doi.org/10.1029/2011gl049749.

Florides, G., Kalogirou, S. 2005. Annual ground temperature measurements at various depths, 8th REHVA World Congress, Clima, Lausanne.

FOEN, 2012. Effects of climate change on water resources and watercourses, Environmental studies, Bern.

Gallice, A., et al., 2016. StreamFlow 1.0: An extension to the spatially distributed snow model Alpine3D for hydrological modelling and deterministic stream temperature prediction. Geosci. Model Dev. 9 (12), 4491–4519. https://doi.org/10.5194/gmd-9-4491-2016.

Garcia-Gil, A., et al., 2016. A reactive transport model for the quantification of risks induced by groundwater heat pump systems in urban aquifers. J. Hydrol. 542, 719–730. https://doi.org/10.1016/j.jhydrol.2016.09.042.

Garcia-Gil, A., Vazquez-Sune, E., Sanchez-Navarro, J.A., Lazaro, J.M., 2015. Recovery of energetically overexploited urban aquifers using surface water. J. Hydrol. 531, 602–611. https://doi.org/10.1016/j.jhydrol.2015.10.067.

Green, T.R., et al., 2011. Beneath the surface of global change: Impacts of climate change on groundwater. J. Hydrol. 405 (3–4), 532–560. https://doi.org/10.1016/j.jhydrol.2011.05.002.

Griessinger, N., Seibert, J., Magnusson, J., Jonas, T., 2016. Assessing the benefit of snow data assimilation for runoff modeling in Alpine catchments. Hydrol. Earth Syst. Sci. 20 (9), 3895–3905. https://doi.org/10.5194/hess-20-3895-2016.

Gupta, H.V., Clark, M.P., Vrugt, J.A., Abramowitz, G., Ye, M., 2012. Towards a comprehensive assessment of model structural adequacy. Water Resour. Res. 48 https://doi.org/10.1029/2011wr011044.

Hannah, D.M., Garner, G., 2015. River water temperature in the United Kingdom: Changes over the 20th century and possible changes over the 21st century. Prog. Phys. Geog. 39 (1), 68–92. https://doi.org/10.1177/0309133314550669.

Hari, R.E., Livingstone, D.M., Siber, R., Burkhardt-Holm, P., Guttinger, H., 2006. Consequences of climatic change for water temperature and brown trout populations in Alpine rivers and streams. Glob. Change Biol. 12 (1), 10–26. https://doi.org/10.1111/j.1365-2486.2005.001051.x.

Hoehn, E., Scholtis, A., 2011. Exchange between a river and groundwater, assessed with hydrochemical data. Hydrol. Earth Syst. Sci. 15 (3), 983–988. https://doi.org/10.5194/hess-15-983-2011.

Huggenberger, P., Epting, J., 2011. In: Urban Geology - Process-Oriented Concept for Adaptive and Integrated Resource Management. Springer, Basel. https://doi.org/10.1007/978-3-0348-0185-0.

Huggenberger, P., Epting, J., Scheidler, S., 2013. Concepts for the sustainable management of multi-scale flow systems: the groundwater system within the Laufen Basin, Switzerland. Environ. Earth Sci. 69 (2), 645–661. https://doi.org/10.1007/s12665-013-2308-0.

Huggenberger, P., Hoehn, E., Beschta, R., Woessner, W., 1998. Abiotic aspects of channels and floodplains in riparian ecology. Freshw. Biol. 40 (3), 407–425. https://doi.org/10.1046/j.1365-2427.1998.00371.x.

Hunt, H., Schubert, J., et al. 2002. Operation and maintenance considerations, in Riverbank filtration: Improving source-water quality. Water science and technology library 43. Dordrecht, Netherlands: Kluwer Academic Publishers.

IPCC, 2014. Climate Change 2014: Synthesis Report, IPCC, Geneva, Switzerland.

Jesußek, A., Grandel, S., Dahmke, A., 2013. Impacts of subsurface heat storage on aquifer hydrogeochemistry. Environ. Earth Sci. 69, 1999–2012. https://doi.org/10.1007/s12665-012-2037-9 (2012).

Kalogirou, S., Florides, G. 2004. Measurements of Ground Temperature at Various Depths.

Kipfer, R., Livingstone, D.M. 2008. Water resources and climate change. In: News, E. (Ed.).

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. https://doi.org/10.1016/j.jhydrol.2013.03.043.

Kurylyk, B.L., MacQuarrie, K.T.B., McKenzie, J.M., 2014. Climate change impacts on groundwater and soil temperatures in cold and temperate regions: Implications, mathematical theory, and emerging simulation tools. Earth Sci. Rev. 138, 313–334. https://doi.org/10.1016/j.earscirev.2014.06.006.

Lehning, M., Bartelt, P., Brown, B., Fierz, C., 2002a. A physical SNOATACK model for the Swiss avalanche warning Part III: Meteorological forcing, thin layer formation and evaluation. Cold Reg. Sci. Technol. 35 (3), 169–184. https://doi.org/10.1016/S0165-232x(02)00072-1.

Lehning, M., Bartelt, P., Brown, B., Fierz, C., Satyawali, P., 2002b. A physical SNOWPACK model for the Swiss avalanche warning Part II: Snow microstructure. Cold Reg. Sci. Technol. 35 (3), 147–167. https://doi.org/10.1016/S0165-232x(02)00073-3.

Lehning, M., et al., 2006. ALPINE3D: a detailed model of mountain surface processes and its application to snow hydrology. Hydrol. Process. 20 (10), 2111–2128. https://doi.org/10.1002/hyp.6204.

Malcolm, R., Soulsby, C., 2000. Modeling the potential impact of climate change on a shallow coastal aquifer in northern Scotland. In: Robins, N.S., Misstear, B.D.R. (Eds.), Groundwater in the Celtic Regions: Studies in Hard Rock and Quaternary Hydrogeology. Geological Society, London, pp. 191–204.

Meixner, T., et al., 2016. Implications of projected climate change for groundwater recharge in the western United States. J. Hydrol. 534, 124–138. https://doi.org/10.1016/j.jhydrol.2015.12.027.

Menberg, K., Blum, P., Kurylyk, B.L., Bayer, P., 2014. Observed groundwater temperature response to recent climate change. Hydrol. Earth Syst. Sci. 18 (11), 4453–4466. https://doi.org/10.5194/hess-18-4453-2014.

Metcalfe, R.A., Schmidt, B.J. 2016. Streamflow Analysis and Assessment Software (version 4.1): Reference Manual.

Michel, A., Brauchli, T., Lehning, M., Schaefli, B., Huwald, H., 2020. Stream temperature and discharge evolution in Switzerland over the last 50 years: Annual and seasonal behaviour. Hydrol. Earth Syst. Sci. 24 (1), 115–142. https://doi.org/10.5194/hess-24-115-2020.

Michel, A., Sharma, V., Lehning, M., and Huwald, H., 2021, provisionally accepted for Journal of Climatology. Climate change scenarios at hourly time-step over Switzerland from an enhanced temporal downscaling approach.

Moeck, C., Brunner, P., Hunkeler, D., 2016. The influence of model structure on groundwater recharge rates in climate-change impact studies. Hydrogeol. J. 24 (5), 1171–1184. https://doi.org/10.1007/s10040-016-1367-1.

Morrison, J., Quick, M.C., Foreman, M.G.G., 2002. Climate change in the Fraser River watershed: flow and temperature projections. J. Hydrol. 263 (1–4), 230–244. https://doi.org/10.1016/S0022-1694(02)00065-3.

Mueller, M.H., Huggenberger, P., Epting, J., 2018. Combining monitoring and modelling tools as a basis for city-scale concepts for a sustainable thermal management of urban groundwater resources. Sci. Total Environ. 627, 1121–1136. https://doi.org/10.1016/j.scitotenv.2018.01.250.

NFP61, 2015. Nachhaltige Wassernutzung in der Schweiz. Gesamtsynthese des Nationalen Forschungsprogramms NFP61 «Nachhaltige Wassernutzung», Bern.

O'Reilly, C.M., et al., 2015. Rapid and highly variable warming of lake surface waters around the globe. Geophys. Res. Lett. 42 (24), 10773–10781. https://doi.org/10.1002/2015gl066235.

Oni, S.K., Futter, M.N., Molot, L.A., Dillon, P.J., Crossman, J., 2014. Uncertainty assessments and hydrological implications of climate change in two adjacent agricultural catchments of a rapidly urbanizing watershed. Sci. Total Environ. 473, 326–337. https://doi.org/10.1016/j.scitotenv.2013.12.032.

Palmer, C.D., Blowes, D.W., Frind, E.O., Molson, J.W., 1992. Thermal-energy storage in an unconfined aquifer. 1. Field injection experiment. Water Resour. Res. 28 (10), 2845–2856.

Porporato, A., Daly, E., Rodriguez-Iturbe, I., 2004. Soil water balance and ecosystem response to climate change. Am. Nat. 164 (5), 625–632. https://doi.org/10.1086/424970.

Possemiers, M., Huysmans, M., Batelaan, O., 2014. Influence of Aquifer Thermal Energy Storage on groundwater quality: A review illustrated by seven case studies from Belgium. J. Hydrol. Reg. Stud. 2, 20–34.

Reid, P.C., et al., 2016. Global impacts of the 1980s regime shift. Glob. Change Biol. 22 (2), 682–703. https://doi.org/10.1111/gcb.13106.

Saripalli, K.P., Meyer, P.D., Bacon, D.H., Freedman, V.L., 2001. Changes in hydrologic properties of aquifer media due to chemical reactions: A review. Crit. Rev. Environ. Sci. Technol. 31 (4), 311–349. https://doi.org/10.1080/20016491089244.

Scibek, J., Allen, D.M., Cannon, A.J., Whitfield, P.H., 2007. Groundwater-surface water interaction under scenarios of climate change using a high-resolution transient groundwater model. J. Hydrol. 333 (2–4), 165–181. https://doi.org/10.1016/j.jhydrol.2006.08.005.

Serra-Maluquer, X., et al., 2019. Geographically structured growth decline of Rear-Edge Iberian Fagus sylvatica Forests after the 1980s shift toward a warmer climate. Ecosystems 22 (6), 1325–1337. https://doi.org/10.1007/s10021-019-00339-z.

Smerdon, B.D., 2017. A synopsis of climate change effects on groundwater recharge. J. Hydrol. 555, 125–128. https://doi.org/10.1016/j.jhydrol.2017.09.047.

Sprenger, C., et al., 2011. Vulnerability of bank filtration systems to climate change. Sci. Total Environ. 409 (4), 655–663. https://doi.org/10.1016/j.scitotenv.2010.11.002.

Stanford, J.A., Ward, J.V., 1993. An ecosystem perspective of alluvial rivers – connectivity and the hyporheic corridor. J. North Am. Benthol. Soc. 12 (1), 48–60.

Taylor, C.A., Stefan, H.G., 2009. Shallow groundwater temperature response to climate change and urbanization. J. Hydrol. 375 (3–4), 601–612. https://doi.org/10.1016/j.jhydrol.2009.07.009.

Taylor, R.G., et al., 2013. Ground water and climate change. Nat. Clim. Change 3 (4), 322–329. https://doi.org/10.1038/Nclimate1744.

Umweltbundesamt, 2011. Trends der Grundwassertemperatur. Untersuchungen von Daten der Überwachung des Gewässerzustandes in Österreich, Wien.

Watts, G., et al., 2015. Climate change and water in the UK – Past changes and future prospects. Prog. Phys. Geog. 39 (1), 6–28. https://doi.org/10.1177/0309133314542957.

Webb, B.W., 1996. Trends in stream and river temperature. Hydrol. Process. 10 (2), 205–226.

Wever, N., Comola, F., Bavay, M., Lehning, M., 2017. Simulating the influence of snow surface processes on soil moisture dynamics and streamflow generation in an alpine catchment. Hydrol. Earth Syst. Sci. 21 (8), 4053–4071. https://doi.org/10.5194/hess-21-4053-2017.

WMO, 2017. WMO Guidelines on the Calculation of Climate Normals, Geneva, Switzerland.

York, J.P., Person, M., Gutowski, W.J., Winter, T.C., 2002. Putting aquifers into atmospheric simulation models: an example from the Mill Creek Watershed, northeastern Kansas. Adv. Water Resour. 25 (2), 221–238. https://doi.org/10.1016/S0309-1708(01)00021-5.

Yusoff, I., Hiscock, K.M., Conway, D., 2002. Simulation of the impacts of climate change on groundwater resources in eastern England. Sustain. Groundw. Dev. 193, 325–344. https://doi.org/10.1144/Gsl.Sp.2002.193.01.24.

Zekollari, H., Huss, M., Farinotti, D., 2019. Modelling the future evolution of glaciers in the European Alps under the EURO-CORDEX RCM ensemble. Cryosphere 13 (4), 1125–1146. https://doi.org/10.5194/tc-13-1125-2019.

Zektser, I.S., Loaiciga, H.A., 1993. Groundwater fluxes in the global hydrologic-cycle - past, present and future. J. Hydrol. 144 (1–4), 405–427.