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Effect of Climate Change on Groundwater Quantity and Quality in Switzerland

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Abstract

This report summarizes the current knowledge on how climate change will impact groundwater quantity, quality and temperature in Switzerland. Climate change will modify groundwater recharge with different effects as a function of altitude: Under pluvial conditions (below 1000 masl), it will lead to a more irregular seasonal distribution with a longer period with little or no recharge during summer and autumn, partly compensated by more recharge in winter. For pluvio-nival conditions (regions with summits up to ~2500 masl), groundwater recharge will increase in winter due to intra-winter melt events and decrease in summer similarly to pluvial conditions. For nivo-glacial conditions (regions with summits > 2500 masl), the period with little recharge in winter will become shorter, while groundwater recharge during summer will decrease due to earlier snowmelt and higher evapotranspiration.

The impacts on groundwater storage and discharge will be most pronounced for pluvial conditions, due to the more extensive period with little recharge, but will vary as function of hydrogeological conditions with smaller and shallow systems showing the largest changes. Groundwater dependant ecosystems tend to be more sensitive to dry and hot periods than water supply. Ecosystems depend on the near-surface presence of groundwater whereas water supply can access deeper parts of stored water. Increased pumping to meet a higher water demand due to climate change often has a larger effect on groundwater storage than climate change directly. Groundwater systems that predominantly rely on infiltrating precipitation are likely more sensitive to climate change compared to systems also fed by infiltrating rivers. The latter recover more rapidly during wet periods. During periods with abundant precipitation, which will become more frequent, groundwater levels can rise rapidly posing risks for belowground infrastructure and/or triggering mass movement.

Groundwater quality is predominantly controlled by anthropogenic factors, which can be modified by climate change. Climate change can influence groundwater quality because the composition of recharge water is modified or because the proportions of water from a different origin change. The composition of infiltrating river water can change for example due to less dilution of treated waste water effluents or leaching of substances to river during intense precipitation. The compositon of water percolating through soils can change as well, especially in agricultural areas, for example leading to more nitrate leaching.

Climate change can influence groundwater temperature in opposite directions. In areas dominated with infiltrating precipitation, the increase in air temperature will propagate to groundwater. However, if river water infiltration is a dominant recharge mechanism, the groundwater temperature can decrease due to higher fraction of recharge during winter. Other factors can dominate over climate change effects such as heat release from below ground infrastructure or geothermal energy use.

In the context of climate change, integrated strategies for groundwater management are required. They have to (i) take into account the combined effect of climate and other changes (e.g. land use, river revitalization) on groundwater systems, (ii) consider interactions of groundwater with other hydrological systems (rivers, lakes, cryosphere) and, (iii) ensures that all groundwater services are met. Furthermore, groundwater protection is important to avoid that groundwater resources that are particularly resilient to climate change become no longer useable due to pollution.

Zusammenfassung

Dieser Bericht fasst den aktuellen Wissensstand zusammen, wie sich der Klimawandel auf die Grundwassermenge, -qualität und -temperatur in der Schweiz auswirken wird. Der Klimawandel wird die Grundwasserneubildung in Abhängigkeit von der Höhenlage unterschiedlich stark beeinflussen. Unter pluvialen Bedingungen (unter 1000 m ü. M.) wird die saisonale Verteilung unregelmässiger, mit längeren Perioden mit geringer oder keiner Neubildung im Sommer und Herbst, die teilweise durch eine höhere Neubildung im Winter kompensiert wird. Bei pluvio-nivalen Verhältnissen (bis ~2500 m ü. M.) wird die Neubildung im Winter aufgrund der winterlichen Schmelzereignisse zunehmen und im Sommer ähnlich wie bei pluvialen Verhältnissen abnehmen. Bei nivo-glazialen Bedingungen (> 2500 m ü. M.) wird der Zeitraum mit geringer Neubildung im Winter kürzer werden, während die Neubildung im Sommer aufgrund der früheren Schneeschmelze und der höheren Evapotranspiration abnehmen wird.

Die Auswirkungen auf die Grundwasserspeicherung und den Grundwasserabfluss werden bei pluvialen Verhältnissen aufgrund des längeren Zeitraums mit geringer Neubildung am stärksten ausgeprägt sein. Die Auswirkungen variieren jedoch in Abhängigkeit von den hydrogeologischen Bedingungen, wobei kleinere und oberflächennahe Systeme am empfindlichsten sind. Grundwasserabhängige Ökosysteme sind in der Regel stärker von Trocken- und Hitzeperioden betroffen als die Wasserversorgung. Ökosysteme sind auf das oberflächennahe Vorhandensein von Grundwasser angewiesen, während die Wasserversorgung auf tiefere Zonen des gespeicherten Wassers zugreifen kann. Die Anpassung an den Klimawandel, insbesondere die verstärkte Wasserentnahme für die Bewässerung, kann die Menge des gespeicherten Grundwassers stärker beeinflussen als die direkten Auswirkungen des Klimawandels. Grundwassersysteme, die überwiegend von infiltrierenden Niederschlägen abhängen, reagieren wahrscheinlich empfindlicher auf den Klimawandel als Systeme, die auch von infiltrierenden Flüssen gespeist werden. Letztere erholen sich rascher bei Niederschlägen. In den häufiger auftretenden Perioden mit reichlichen Niederschlägen kann der Grundwasserspiegel rasch ansteigen und damit Risiken für die unterirdische Infrastruktur darstellen und/oder Massenbewegungen auslösen.

Die Grundwasserqualität wird in erster Linie von anthropogenen Faktoren bestimmt, die durch den Klimawandel modifiziert werden. Die Grundwasserqualität kann sich ändern, weil sich die Zusammensetzung des Wassers das zur Neubildung beiträgt ändert oder weil sich die Anteile von Wasser aus unterschiedlichen Herkunft verschieben. Die Zusammensetzung des infiltrierenden Flusswassers kann sich z. B. durch eine geringere Verdünnung der behandelten Abwässer oder durch die Auswaschung von Stoffen in den Fluss bei starken Niederschlägen ändern. Auch die Zusammensetzung von Wasser, das durch Böden versickert, kann sich ändern, insbesondere in landwirtschaftlichen Gebieten, beispielsweise aufgrund einer höheren Nitratauswaschung.

Der Klimawandel kann die Grundwassertemperatur in unterschiedlicher Richtung beeinflussen. In Gebieten, in denen Niederschläge versickern, wird sich der Anstieg der Lufttemperatur voraussichtlich auf das Grundwasser übertragen. Wenn jedoch die Infiltration von Flusswasser ein vorherrschender Neubildungsmechanismus ist, kann die Grundwassertemperatur aufgrund des höheren Anteils der Anreicherung im Winter sinken. Andere Faktoren können gegenüber den Auswirkungen des Klimawandels dominieren, z. B. die Wärmefreisetzung durch unterirdische Infrastrukturen und die Nutzung geothermischer Energie

Die Grundwasserbewirtschaftung sollte (i) die Wechselwirkungen zwischen klimabedingten und anderen Veränderungen berücksichtigen, (ii) andere hydrologische Systeme, die das Grundwasser beeinflussen (Flüsse, Seen, Cryosphäre), einbeziehen und (iii) sicherstellen, dass alle Grundwasserdienstleistungen erfüllt werden. Darüber hinaus ist der Grundwasserschutz wichtig, um zu vermeiden, dass Grundwasserressourcen, die besonders widerstandsfähig gegenüber dem Klimawandel sind, aufgrund von Verschmutzung nicht mehr genutzt werden können.

Résumé

Ce rapport résume l'état actuel des connaissances sur la manière dont le changement climatique affectera la quantité, la qualité et la température des eaux souterraines en Suisse. On s'attend à ce que le changement climatique modifie la recharge des eaux souterraines de manière différenciée selon l'altitude. Dans des conditions pluviales (en-dessous de 1000 m d'altitude), la recharge sera plus différenciée en fonction de saisons, avec une période prolongée de recharge faible ou nulle en été et en automne, partiellement compensée par une recharge plus importante en hiver. Pour les conditions pluvio-nivale (régions avec des sommets jusqu'à 2500 m l'altitude) la période hivernale, qui représente la période sèche actuellement, deviendra plus courte et entrecoupée d'événements de fonte. La recharge en période estivale diminuera en raison d'une fonte de neige terminée plus tôt et d'un accroissement de l'évapotranspiration. Dans des conditions nivo-glaciaire (régions dominées par des sommets au-dessus de 2500 m d'altitude), la sécheresse hivernale deviendra plus courte, tandis que la recharge diminuera en été.

L'impact sur les réserves et les flux d'eaux souterraines sera donc le plus prononcé pour les régions pluviales en raison de périodes prolongées de faible recharge en automne, mais dépendra du contexte hydrogéologique, les systèmes les plus vulnérables étant les petites nappes proches de la surface. Les écosystèmes dépendant des eaux souterraines peu profondes seront particulièrement touchés, alors que les captages d'eau, plus profonds, sont un peu moins sensibles. Dans les faits, l'augmentation des pompages liés à l'augmentation des besoins en eaux suite au changement climatique, notamment pour l'irrigation, seront plus importants que l'effet direct du changement sur la recharge. Les systèmes d'eau souterraine qui dépendent principalement de l'infiltration directe des précipitations sont probablement plus sensibles au changement climatique que ceux qui sont également alimentés par des rivières. Lors de périodes de précipitations abondantes, de plus en plus fréquentes, le niveau des nappes phréatiques pourrait monter rapidement et présenter ainsi des risques pour les infrastructures souterraines et/ou déclencher des glissements de terrain.

La qualité des eaux souterraines est principalement contrôlée par des facteurs anthropiques, qui peuvent être modifiés par le changement climatique. Ce dernier peut influencer la qualité des eaux souterraines parce que la composition de l'eau de recharge est modifiée ou parce que les proportions d'eau d'origines différentes changent. La composition de l'eau de rivières infiltrées peut changer, par exemple en raison d'une moindre dilution des effluents de stations d'épuration ou de la lixiviation de substances agricoles lors de précipitations intenses. La composition de l'eau qui s'infiltre dans les sols peut également changer, en particulier dans les zones agricoles, ce qui entraîne par exemple une augmentation du lessivage des nitrates.

Le changement climatique peut influencer la température des eaux souterraines dans différentes directions. Dans les zones où les précipitations s'infiltrent directement, l'augmentation de la température de l'air se répercutera probablement sur les eaux souterraines. Toutefois, si l'infiltration provient principalement d'une rivière infiltrante, la température des eaux souterraines pourrait diminuer en raison de la proportion plus élevée de recharge en hiver. D'autres facteurs peuvent dominer par rapport aux effets du changement climatique, comme le dégagement de chaleur par les infrastructures souterraines ou l'utilisation de l'énergie géothermique.

Dans le contexte du changement climatique, des stratégies intégrées de gestion des eaux souterraines sont nécessaires. Elles doivent : (i) prendre en compte l'effet combiné du climat et d'autres changements (par exemple, l'utilisation des terres, la revitalisation des rivières) sur les systèmes d'écoulements souterrains, (ii) considérer les interactions des eaux souterraines avec les autres systèmes hydrologiques (rivières, lacs, cryosphère) et, (iii) garantir que tous les services liés aux eaux souterraines sont assurés. En outre, la protection des eaux souterraines est importante pour éviter que les ressources en eaux souterraines qui sont particulièrement résilientes au changement climatique ne deviennent inutilisables en raison de la pollution.

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1 Introduction

In Switzerland, about 80% of the drinking water originates from aquifers, with a comparable contribution of springs and pumping wells (SVGW, 2020). The stored groundwater volume amounts to about 150 km^3 of which more than 10% (about 18 km^3) is renewed annually .There is a growing interest to use groundwater also for irrigation (Sinreich et al., 2012). Aquifers play a buffering role in the hydrological cycle by temporarily storing water, a function that will become even more important in the context of CC with the expected more frequent extreme meteorological conditions (CH2018, 2018). Groundwater resources are generally less sensitive to extreme conditions than surface water. Nevertheless, groundwater volumes and fluxes might change due to CC. Such changes will especially affect the shallow groundwater systems that are commonly used for water supply in Switzerland. Given the importance of groundwater for water supply and ecological functions, there is need for understanding how CC might affect the groundwater dynamics and quality.

This report was realized in the context of the Hydro-CH2018 focus area of the NCCS. We summarize the current understanding of how CC might modify **groundwater resources** in Switzerland, and identifies knowledge gaps. We put an emphasis on groundwater resources that are particularly important for water supply. A major part of the report is dedicated to groundwater quantity, which has been investigated in more details so far, but effects on temperature and quality are covered as well.

To what extent **groundwater quantity** is modified depends foremost on the impact of CC on the way groundwater resources are replenished (**recharge**). Therefore, we discuss first the influence of CC on groundwater recharge in a general, which strongly depends on climatic conditions i.e. mainly on the amount, form (i.e. rain vs snow) and distribution of precipitation, and on temperature. Therefore, the section on recharge (chapter 2) is subdivided according climate into rain-dominated, snow-influenced and snow-dominated conditions.

Modifications of recharge pattern will have different implications on the groundwater dynamics and groundwater volumes (i.e. **discharge** and **storage**) depending on the aquifer type (unconsolidated, karst, fissured). Therefore, in chapter 3 expected changes will be discussed separately according to aquifer type, focussing on those that are particularly important for water supply and for which data on CC effects are available.

In chapter 4, we discuss CC effects on **groundwater temperature** before we address expected changes in **groundwater quality** as the groundwater temperature influences the rate of geochemical and microbial processes and thus groundwater quality. Groundwater quality and temperature must respect standards to ensure that it is suitable for water supply or for sustaining ecological services. Excesses in concentration of certain compounds in groundwater may have significant issues for public health or for natural ecosystems. The groundwater quality section puts an emphasis on anthropogenic compounds that are a common water quality concern and discusses in less detail how general hydrochemical and redox conditions might change.

The report focusses on Switzerland and is based on a review of the international scientific literature for similar climatic conditions. However, we also consider applied studies, typically carried out for public authorities and usually published as reports rather than scientific publications. They often provide the most region-specific information. Among the studies in the international scientific literature, only those from countries with similar predicated CC as for Switzerland were included. This strongly restricts the number of suitable studies, as from a CC point of view, Switzerland is located in a transition zone between the Mediterranean trend to significantly drier and the northern trend to more wet conditions. In addition to climatic conditions, it is also important that sites with comparable soil and geological conditions are considered. We integrate results from different types of studies: (i) studies that have evaluated the past response of aquifers to extreme meteorological conditions, (ii) studies that link aquifer responses to hydrogeological conditions, and (iii) impact studies based on coupled climate and hydrological models. Due to the limited amount of representative studies for Switzerland, for some situations, we formulate hypotheses how CC might influence groundwater resources rather than reporting published results. Such an approach requires a processes-oriented focus of the discussion as a basis to explore how CC might modify these processes. In addition, for the most fundamental question on how recharge might change, we specially carried out simulations using the recently published CH2018 climate scenarios.

While we acknowledge that the socio-economic development will modify groundwater ressources in addition to CC, and sometimes even more so, we do not cover this topic. We do however consider how different anthropogenic alterations of the landscape (e.g. land drainage, urbanization) influence the CC response of groundwater systems. We also consider feedbacks with other changes induced by CC, e.g. the shift of the tree line or changes in agricultural practice (e.g. irrigation, changes in cropping).

Generally, we discuss expected trends for lowland conditions in more detail than for higher altitudes for several reasons. There is already more information available for lowland sites, and generally, water needs are higher in these regions due to the higher population density. Furthermore, with increasing temperatures, these regions will experience climatic conditions that are unusual for Switzerland to date. In contrast, for higher altitude sites, climatic conditions will become more similar to current conditions at a lower elevation.

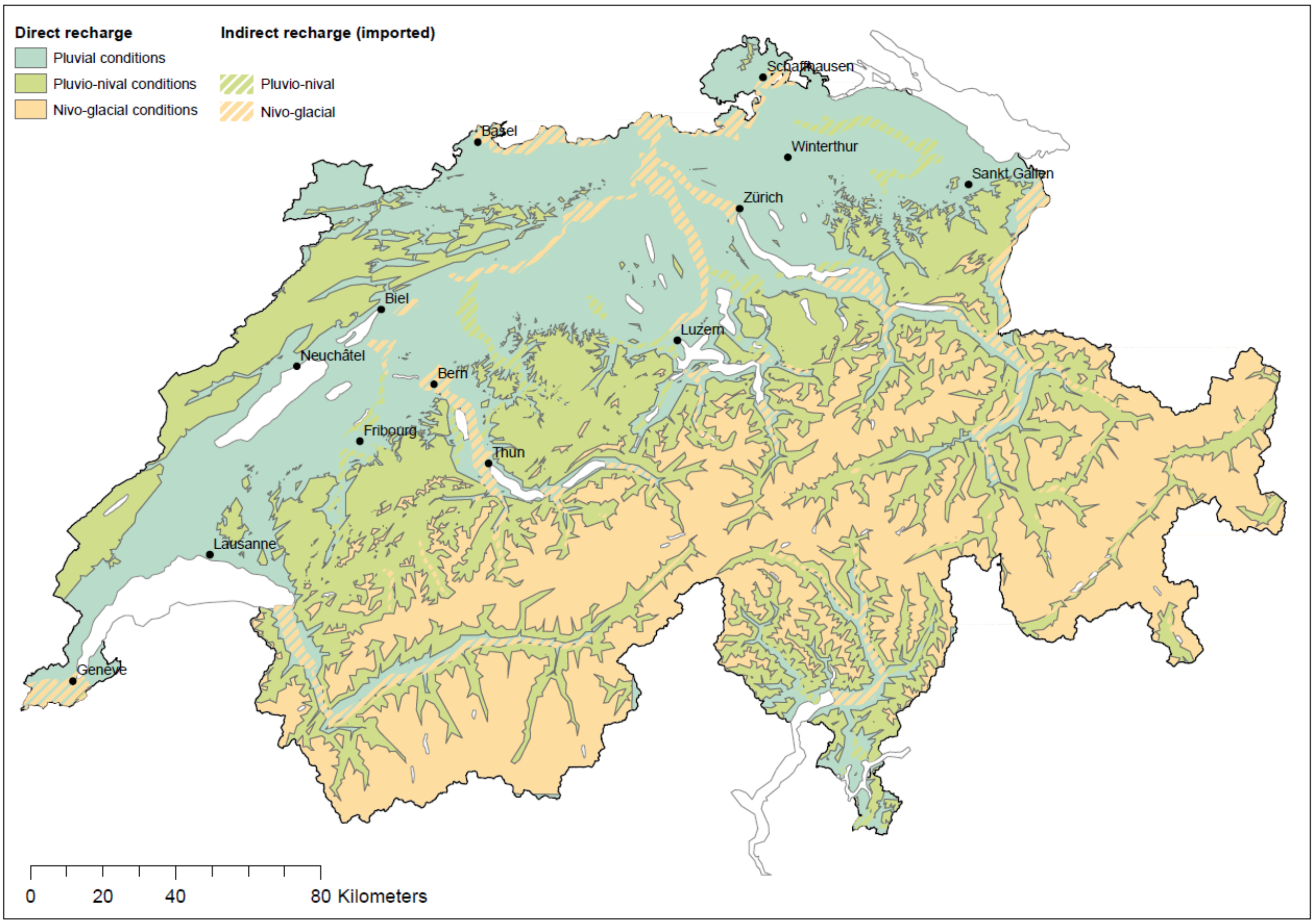
2 Expected changes in recharge

Groundwater recharge is controlled by hydro-climatic conditions, soils properties, vegetation and land use, but also depends to a smaller degree on aquifer type. Therefore, changes in recharge are discussed globally for all aquifers types. We here briefly summarize the expected changes in factors controlling the recharge. For a more thorough discussion of expected CC trends, the reader is referred to the CH2018 reports. We devote separate sections to the two main recharge mechanisms: 1) **direct recharge** by infiltration of precipitation and 2) **indirect recharge** by infiltration via surface water bodies (mainly rivers and lakes).

In both cases, recharge mechanisms depend on hydro-climatic conditions, which in turn are governed by elevation. For lowland aquifers (i.e. rain-dominated/pluvial conditions), vegetation and associated evapotranspiration plays an important role together with soil conditions. At higher altitude (snow-influenced/pluvio-nival and snow-dominated/nivo-glacial conditions), recharge by snowmelt becomes increasingly dominant. As soils are generally shallower or even absent, the geology and topography more strongly influence recharge. We therefore separate the discussion according to zones, proceeding from rain-dominated/pluvial zones (Swiss Plateau, < 800-1000 m), to snow-influenced/pluvio-nival zones (Jura / Prealps, 800-1000 < X <1800-2000 m) to snow-dominated/nivo-glacial ones (Alps, > 1800-2000 m).

2.1 Expected trends for factors influencing groundwater recharge

Climatic conditions (temperature and precipitation), as well as near-surface and surface factors, govern groundwater recharge (glaciers, snow, bedrock, soils, vegetation). Changes in these conditions and factors will thus induce a change in recharge.



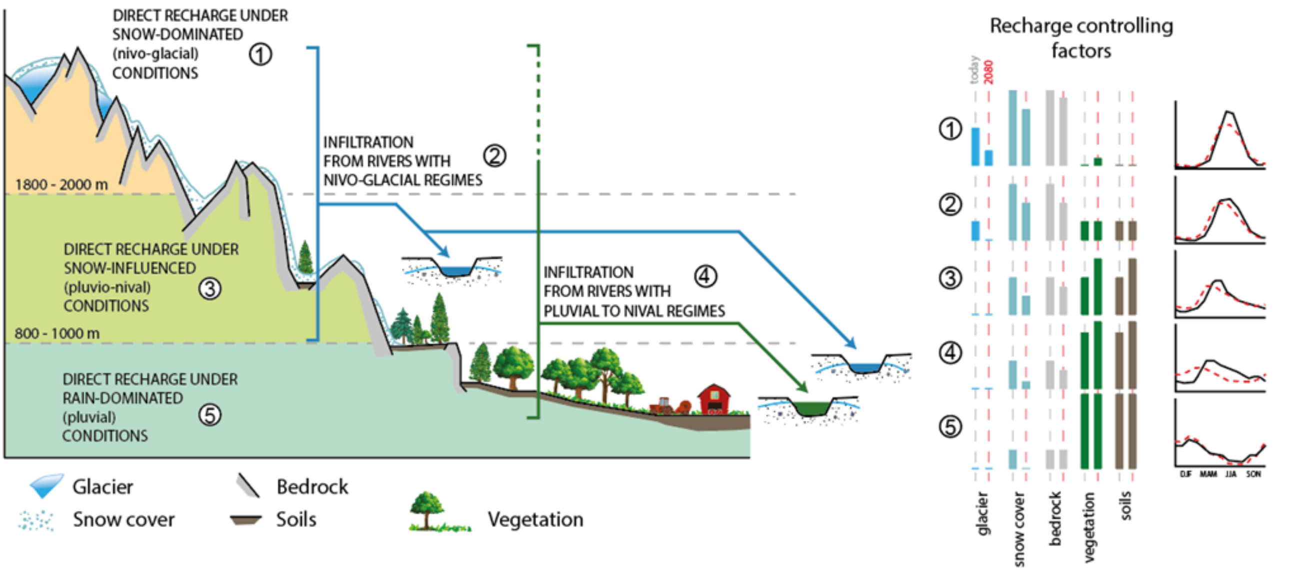


Figure 1. The relative importance of the main factors controlling recharge in Switzerland is governed by the elevation. Here, five recharge conditions are depicted; the direct recharge by infiltration in snow-dominated (1), snow-influenced (3) and rain dominated (5) conditions and the indirect recharge of alluvial aquifers by rivers infiltration in nivo-glacial regimes (2) and pluvial to nival regimes (4). All recharge conditions are strongly influenced by the evolution of precipitation and temperature as well as by a several near-surface and surface factors that are specific for each condition (presence of glaciers, presence and depth of snow cover, bedrocks, soils cover and vegetation). The relative weight of each factor in recharge processes is depicted on the right as well as the typical recharge regime under current and future conditions.

2.1.1 Hydro-climatic conditions

Predictions of temperature and precipitation are derived fromn recent climate models developed. The climate models are based on different scenrios for greenhouse gas emissions, which depend on underlying socio-economic trajectories. Earlier climate models often used the A1B emission scenario defined in the 4th assessment report of the IPCC which is based on business-as-usual characteristics but assumes technological progress that leads to emission reduction beyond 2050 (IPCC, 2007). The most recent climate model usually rely on the representative emission pathways (RCP) defined in the 5th assessment report of the IPCC (IPCC, 2014). In this report, results for two RCPs will be discussed, RCP2.6 and RCP8.5. RCP2.6 is based on effective climate protection with declining CO2 emissions from 2020 and the emissions reach zero by 2100. In reverse, RCP8.5 corresponds to no climate protection with a continuous rise of greenhouse gas emissions throughout the 21st century.

Temperature

The evolution of the temperature in Switzerland has been the focus of many studies and models. The last simulations for the more probable scenario indicate that about 66–77% of all days will exceed the local 75th percentile of today's daily maximum temperature (Keller et al., 2017). An increase of dry spell lengths in summer from +18% to +39% is expected especially for lowland regions (Beniston, 2007; Keller et al., 2017). For alpine regions, expected changes in the length of dry spells are smaller; from +7% to +17%. Zubler et al. (2014) worked on the expected evolution of different key climate indices for the temperature in Switzerland (number of summer days, of tropical nights, of frost days, etc.) for three distinct periods (2020–2049, 2045–2074 and 2070–2099). The authors indicate that global warming at the end of the century will reach up to 4°C in summer in most of Switzerland, leading to significant impact at the regional scale. The cumulated number of summer days per year (≥ 25°C) is roughly doubled compared to actual conditions (up to 100 days for lowland regions in southern Ticino), frost days decline by more than 50 days, and the amount of ice days even declines by about 90 days above 3000 m of elevation. The duration of growing season increases by about 50 days (extends from February to November in lowland regions).

Precipitation

Based on the results of the CH2011 project, Fischer et al. (2015) assess the coming changes in intensity and frequency of precipitation in Switzerland for the coming century. While uncertainties are large, they demonstrate that summer mean precipitation will significantly decrease because of a widespread reduction in the number of precipitation days (more than 17% in frequency for lowland regions and between 11-15% for alpine regions). Conversely, they project a higher mean precipitation intensity in spring and autumn north of the Alps as well as global precipitation increase for the winter season over all Switzerland and more particularly in the southern part.

In addition to changes in the amount of precipitation, changes in the intensity and distribution can also influence groundwater recharge for a given total amount. CC models (see Ban *et al.* [2015]) suggest that intense precipitation tends to become more common although predictions are uncertain.

Snow

In Switzerland, a substantial proportion of precipitation is temporally stored as snow (around 40%). Furthermore, for sites of higher elevation, the total amount of precipitation increases. Schmucki et al. (2015) assess the evolution of the winter snow water equivalent for three elevation ranges (<1000 m, 1000-1700 m and 2000-3000 m) and for three time periods of the century (2020–2049, 2045–2079 and 2070–2099). Their simulations show that the relative reductions in median snow depth decrease with the elevation corresponding to an upward snowline shift by 300 to 600 m (Gobiet et al., 2014). At the end of the century, relative reductions of snow depth would be about 35%, 85% and 95% at high-, mid- and low-elevations, respectively. These reductions are indicative but all simulations show that changes will accelerate after the second half of the century. For a site in Graubünden ranging from 500 to 3000 m, Bavay et al. (2013) predict a reduction of the snow water equivalent of 11 to 28% for the 2021-2050 period and of up to 67% for the 2070-2095. The end of snowmelt will shift form August to mid-June.

Glaciers

Glaciers of Greenland and of Central Europe show the faster retreat rate compared to other glaciers on the earth since the Little-Ice-Age (Zemp et al., 2015). Measurements show that the rate of the glaciological mass balances is actually significantly more negative than the average for the second half of the 20th century at the global scale.

Measurements and models indicate that almost 90% of the glacier volume in the Swiss Alps will melt before 2085. The main reason for this reduction is related to increasing temperatures, especially in spring and summer, which shorten the time period with a protecting snow cover. The ice exposed to the sun earlier in the season and longer in the year.

These glacier mass changes, as well as the reduction of the permafrost, have a significant impact on the dynamics of alpine aquifers as well as for all aquifers interacting with rivers with nivo-glacial to glacial regime (Evans *et al.* [2018]).

2.1.2 Vegetation

The soil moisture and recharge pattern are strongly influenced by the type and the density of vegetation. Vegetation in Switzerland may roughly be distinguished between forests, croplands and meadows. The distribution is controlled by climatic conditions but also depends on land uses. Land use changes with altitude, with a decrease in cropland and an increase in grassland and forests.

Changes for forests are expected. For lowland areas, coniferous are supposed to be progressively replaced by mixed deciduous trees. Climatic conditions on the Swiss Plateau will become unsuitable for the major species of Norway spruce and beech which are sensitive to summer droughts but suitable for more Mediterranean, drought-adapted species (holm oak, etc.). Due to higher temperature, the trees line is expected to move upward in the Alps and in the Jura leading to an increase in biomass locally. Growth conditions for the Norway spruce will improve in the Alps but over the long term, simulations show a global decrease in biomass. In details, impacts of CC on forests and dependent ecosystem services will strongly differ between sites. In parallel to CC, human practices (e.g. timber harvest) will also be part of the changes.

The utilisation of croplands will likely change in the coming decades due to CC and land use changes. The type and/or cultivar of crops might change as well as the intensity of crop rotations. Increasing temperature and content of atmospheric CO_2 would globally be beneficial for cereal crop. In the Alps, croplands will move upward in the alpine valleys with the increase of the temperature. Alpine meadows might transform partly to forests.

Accordingly, the CC effect on recharge is expected to be influenced by changes in vegetation as well, especially in rain-dominated environments where evapotranspiration strongly influences the amount of water available for recharge. Evapotranspiration might increase in alpine zones at the annual scale because of more trees and more crops but in counterpart, interception might decrease in winter when leaves of deciduous trees are off.

2.1.3 Soils

Soils play a significant role in the infiltration of groundwater. Soil properties change with altitude. At high altitudes, soils are generally shallower, less developed and have a lower water storage capacity. Especially at higher altitude, recharge then becomes more strongly influenced by the geological settings (permeability of lithologies) compared to lowland regions.

Soils in Switzerland are not expected to change with CC along the 21th century. However, agriculture, urbanization and land planning may have a significant impact on the infiltration properties – especially in lowland regions.

2.2 Direct groundwater recharge

Direct recharge consists of the local infiltration of precipitation and its percolation to the water table. In this paragraph, we will mainly focus on the initial infiltration step, which is decisive for the quantity of water that will recharge groundwater. The subsequent percolation through the vadose zone mainly controls the delay and temporal patterns of recharge, but not the overall quantity. From a recharge point of view, water that percolates below the root zone and is no longer within reach for plants is the most relevant.

2.2.1 Rain-dominated/pluvial conditions (Swiss Plateau and Tabular Jura)

Most lowland aquifers are governed by these conditions. The most common aquifers in this zone are the Molasse aquifers of the Swiss Plateau, the lowland karst aquifers of Northern Switzerland and aquifers in glacio-fluvial deposits. Some large alluvial valleys and plains at the foot of the Alps are also situated in zones with these conditions – although most of them might usually be governed by indirect recharge from rivers.

Whatever their type (unconsolidated, fissured, karst), lowland aquifers are the most exploited for irrigation and drinking water. Moreover, these aquifers are under increasing pressure from agriculture and urban developments as illustrated by the widespread occurrence of chlorothalonil metabolites.

Recharge mechanism

Under these conditions, recharge processes mainly depend on the vegetation and soil, which govern infiltration and evapotranspiration. Besides, the topography can play an important role by influencing the ratio between infiltration and runoff. Owing to the absence of snow, groundwater recharge mainly occurs in winter and in spring (November to April). In summer and in autumn, direct recharge of lowland aquifers is usually small or even absent because of low precipitation and high rate of evapotranspiration.

For understanding how CC might influence groundwater recharge, it is important to understand how precipitation partitions under current conditions among evapotranspiration, runoff and infiltration and how different factors influence the proportions among them. The following factors influence direct recharge:

- **Permeability of the top layer.** For soils with a low permeability, the precipitation rate can temporarily exceed the infiltration capacity and runoff occurs, especially for sloped terrain. Low permeability soils with a risk of water logging are generally drained in Switzerland. Thus, excess water beyond the infiltration capacity is rapidly evacuated via drainage pipes rather than runoff with a similar effect on the water balance.
- **Slope of terrain.** A steeper slope favours runoff versus infiltration.
- **Dynamic water storage capacity in the top layer.** Depending on its thickness and granulometry, the top layer can temporally store a considerable amount of water, typically in the range of 50-200 mm. This water remains available for subsequent evapotranspiration

rather than running off or infiltrating below the root-accessible zone. Hence, depending on the soil type, the threshold for the onset of recharge varies and thus different soils might react differently to changes in the precipitation and evapotranspiration regime.

- **Vegetation.** Vegetation has a strong influence on groundwater recharge as it controls interception processes, timing and extent of soil moisture depletion.
- **Controls on evapotranspiration.** In Switzerland, the amount of evapotranspiration is often limited by the available energy rather than the available quantify of water, i.e. the actual evapotranspiration is close to the potential one. However, already under current conditions in drier and warmer regions of Switzerland, evapotranspiration is water-limited during summer months. With the expected increasing temperatures and lower summer precipitations, water-limitation of evaporation will likely become more widespread.

Changes in direct recharge – Literature review

A growing number of studies have been published that investigate CC effects of groundwater recharge by coupling climate models with hydrological models and simulating future scenarios. We mainly considered studies from Switzerland, neighbouring countries and Europe in general. We evaluated the reported trends in groundwater recharge and the proposed mechanisms to explain the changes (Table 1). For studies in Switzerland and surrounding countries, a decrease in recharge is frequently reported and/or a modification of the seasonal distribution of recharge. However, some studies have also reported an increase in recharge or found that the direction and magnitude of change vary depending on the CC scenario.

For Switzerland, the CC effect on groundwater recharge was investigated in most detail for small aquifers in Wohlenschwil (**Case Study 1**), Canton Aargau (Moeck, 2014) and Baltenswil, Canton Zurich (Stoll et al., 2011). The two study sites are characterized by similar climatic conditions, but large differences in soil hydrological properties (Table 2). In both studies, the same emission scenario was used (A1B). The studies came to similar conclusions for recharge during summer (no change) and winter (increase). However, Stoll et al. (2011) did not observe a decrease of recharge in automn in contrast to Moeck (2014), likely due to the difference in soil type. The seasonal distribution of groundwater recharge varied depending on the method to simulate the local climatic conditions (downscaling method). The difference in recharge was a consequence of the difference in precipitation and evapotranspiration patterns predicted by the different model chains. Groundwater recharge strongly depends on the timing of precipitation within the year as winter precipitation is the most relevant contribution to recharge (Stoll et al., 2011).

Table 1: Summary of studies on climate change impact on direct recharge in international literature.

Country	Reference	Type	scale	location	Period	Change in GW recharge	mechanism of change
Switzerland	Stoll et al. (2011)	Journal article	local	Baltenschwil, CH	transient until 2010	Tendency towards more recharge in winter and little change in summer, but strong dependant on downscaling method	increase in winter precipitation leads to more recharge, lower precipitation and higher temperature in summer have little effect as generally little recharge in this period
Switzerland	Moeck (2014)	PhD thesis	local	Wohlenschwil, CH	change by 2035 , 2060, 2085	changes by 2035 -0.2%, by 2060 -0.6%, by 2085 +2.6% compared to 1980-2001. Variability of recharge is strongly increasing	changes in precipitation and temperature lead to change in recharge regime, but little annual change. No signficant changes of GW levels or storage, changes in land use not considered.
Surrounding countries	Krüger et al. (2001))	Journal article	global	Nordrhein-Westfalen, D, and atlantic european region	change by 2100	mean decrease of around -20% for entire Europe	changes in precipitation and temperature, changes in land use NOT considered
Surrounding countries	Lischeid (2010)	Report	regional	Berlin-Brandenburg, D	changes in 1976-2005	overall reduction of recharge of 20-30 mm/a since 1980	increase in global radiation (and consequently, an increase in ET+T) versus constant precipitation lead to this decrease in effective recharge
Surrounding countries	Hattermann et al. (2011)	Journal article	regional	Sachsen-Anhalt, D	change by 2040, 2070, 2100	- 20-40%	shift in precipitation towards winter, increase in temperature (early snowmelt, higher ET+T), changes in land use NOT considered
Surrounding countries	Hattermann et al. (2011)	Journal article	regional	Sachsen-Anhalt, D	change by 2040, 2070, 2100	Increase by 20%	shift in precipitation towards winter, increase in temperature (early snowmelt, higher ET+T), changes in land use NOT considered
Surrounding countries	Barthel (2011)	Journal article	regional	Danube catchment, CH+AU+D	changes by 2060	overall reduction of recharge from 550 mm/a to 450 mm/a	slight reduction of precipitation and slight increase of evapotranspiration result in an overall reduction of recharge
Surrounding countries	Blomenhofer et al. (2012)	Report	regional	Baden-Württemberg, Bayern & Rheinland-Pfalz, D	change by 2050, 2100	between -10 and +10% short term, between - 30 and +30% long term	changes in precipitation (increase in lowlands, decrease in mountains), temperature increases lead to increased ET+T, changes in land use NOT considered
Surrounding countries	Baumeister et al. (2017)	Report	regional	Baden-Württemberg, Bayern, Rheinland-Pfalz & Hessen, D	change by 2050, 2100	overall -20% short term, overall -40% long term compared to 1980-2010	changes in precipitation (increase in lowlands, decrease in mountains), temperature increases lead to increased ET+T, changes in land use NOT considered
Surrounding countries	Kunstmann et al. (2017)	Book Chapter	regional	D	period 2011-2016 versus 1971-2000	reduction of recharge by 30% in the Elbe catchment, general reduction in the Upper Danube basin (until border of austria)	large uncertainties for hydrological impacts due to complex model chain with large intrinsic uncertainty and missing feedbacks. reduction of recharge due to lowering of anthropogenic lowering of water table much larger than climate change
elsewhere Europe	Holman et al. (2005) Holman (2006)	Journal article	regional	East Anglia, UK	change by 2050	-	hydrologically effective precipitation decrease, decrease in recharge period length, socio-economic use changes and soil degradation
elsewhere Europe	Woldeamlak et al. (2007)	Journal article	local	Grote-Neve, Belgium	change by 2100	wet scenario: overall increase of recharge up to +14%, dry scenario: overall decrease of recharge up to -40%	for a dry climate scenario, increase in temperature outweighs the increase in summer precipitation, which leads to smaller recharge. In wet climate scenario this effect is inverted, but not as strongly. changes in land use NOT considered
elsewhere Europe	Herrera-Pantoja and Hiscock (2008)	Journal article	regional	Great Britain	change by 2020, 2050, 2080	- 20-40%	decrease in hydrological excess water
elsewhere Europe	Pulido-Velazquez et al. (2017)	Journal article	regional	Spain	change in period 2011-2045 vs 1976-2005	recharge will decrease ,-12% overall in spain, with an increase in the interannual variability (the standard deviation) by 8%	changes in precipitation and temperature lead to decrease of recharge, changes in land use NOT considered
USA	Meixner et al. (2016)	Review article		catchments in the USA	-	various	mountain hydrology a key component also for lowland aquifers. A large uncertainty in precipitaiton frequency and intensity makes predictions in recharge highly uncertain
Global	Döll (2009)	Journal article	global	global	by 2050 and 2041-2070	± 10%	precipitation changes
Global	Green et al. (2011)	Review article			-	various	
Global	Taylor et al. (2013)	Review article			-	various	vegetation and land use more important than precip and temp. Precip and temp changes outweigh each other
Global	Smerdon (2017)	Review article				Mostly a decrease predicted in lowlands, regime change for mountains but no decrease	

Table 2: Climatic condition and soil type at study sites.

Site	Norm air temperature °C	Norm precipitation mm/y	Emission scenario	Soil type	Soil hydraulic conductivity m/s
Wohlenschwil	9.6	1080	A1B	Loamy soil	$1*10^{-3}$
Baltenswil	9.4	1140	A1B	Cambisol with high permeability	$3*10^{-6}$

Case Study 1: predicted changes in mean annual groundwater recharge for the Wohlenschwil lowland aquifer, AG

The Wohlenschwil site consists of a 2 m thick loamy cover layer overlying sandy to silty gravel. The simulations are based on meteorological data from the Buchs, AG MeteoSwiss station. Future climatic conditions were represented with a delta change approach for 10 CC model chains and three scenario periods using factors from the CH2011 database (CH2011, 2011). Depending on the CC model chain, an increase or decrease in the annual recharge is predicted within a range of about +/-15%, with an ensemble mean that is close to zero for all scenario periods (Table 2). While there is no clear trend on an annual scale, all model chains consistently predict changes in the seasonality of recharge (Hunkeler et al., 2014). In spring (MAM), recharge decreases for the first two scenario periods (2035 and 2060) due to higher temperatures favouring evapotranspiration. For the most distant period (2085), recharge is higher because increasing precipitation dominates over the temperature effect. During summer, changes are small despite the significantly higher temperature. This is not surprising as already under current conditions, a large fraction of water is lost to evapotranspiration and thus increasing temperatures have little effect. In contrast, in automn (SON), recharge tends to decrease due to a delayed effect of the soil moisture deficit that has accumulated during summer and higher evapotranspiration in automn. During winter, recharge tends to increase, mainly related to higher winter precipitation. The seasonality diagram also provides insight into why the annual average recharge does not tend to change. The decrease of recharge during automn associated with the delayed effect of higher evapotranspiration is compensated by more recharge during winter and early automn due to increased precipitation.

Percental (%) change in mean annual recharge			
Period	*2035*	*2060*	*2085*
ETH	-13.1	-14.5	-16.2
HC	-11.6	-11.1	-7.1
SMHI_Had	6.5	11.1	12.5
SMHI_ECH	5.4	3.4	9.1
MPI	0.3	-1.7	3.7
KNMI	1.7	2.8	11.9
ICTP	-0.3	-3.1	5.4
DMI	15.6	14.5	12.8
CNMR	-7.4	-16.5	-15.1
SMHI_B	1.1	8.8	8.8
Min	-13.1	-16.5	-16.2
Max	15.6	14.5	12.8
Mean	-0.2	-0.6	2.6

Table 3: Predicted changes in mean annual groundwater recharge for the Wohlenschwil site using 10 CC model chains for emission scenario A1B and three scenario periods: 2035 (2020-2044), 2060 (2045-2075) and 2085 (2075-2099). (Moeck, 2014).

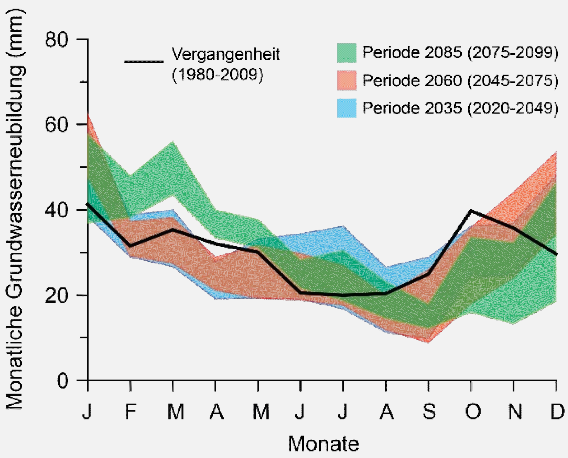


Figure 2: Monthly groundwater recharge simulated for three scenario periods. The bands correspond to the range of predictions obtained for 10 CC model chains (Hunkeler et al. (2014).

Actual observations and measurements for different sites in Switzerland over the last decades do not point out significant changes in the recharge processes yet. Measurements of the Milandrine underground rivers in the tabular Jura show that the annual groundwater recharge did not significantly change over the past 25 years with the increase of temperature (Jeannin et al., 2015). A slight decrease has been observed in the groundwater discharge (-0.26 L/s over 25 years) but this is negligible compared to the precision of the discharge measurement. Working on two springs of alpine karst aquifers in Ticino and Nidwalden with a ~20 years long dataset (1992-2010), Scheiwiller et al. (2013) came to similar conclusions. They do not find a significant trend for annual recharge amount and seasonality. The same observations have been made by Caballero et al. (2015) for two karst aquifers in southern France.

Changes in direct recharge – Calculations based on CH2018 climate scenarios

While these studies provide considerable insight into possible changes in recharge pattern, they did not systematically investigate the role of key controls on recharge i.e. soil type, topography or climatic conditions. Furthermore, new CC scenarios have become available (CH2018, 2018). We, therefore, carried out new simulations for this report. The new simulations aimed to investigate CC effects on recharge for typical Swiss conditions. In the simulations, we varied soil types, total precipitation amounts, slope angles and vegetation. To represent wetness gradients across the Swiss plateau, we used data from three MeteoSwiss meteorological stations (Payerne, Wynau, Wädenswil) with similar mean temperatures (Table 4) but varying norm precipitation (1981-2010). We considered soils with three different hydraulic conductivities and three slope angles. To identify more clearly the sensitivity of recharge to CC, we used the emission scenario 8.5. The calculations were performed for six general circulation models (ICHEC-EC-EARTH, MOHC-HadGEM2-ES, MPI-M-MPI-ESM-LR, MIROC-MIROC5, CCCma-CanESM2, CSIRO-QCCCE-CSIRO-Mk3-6-0) linked to the same regional circulation model (SMHI-RCA4). climate model chains. Groundwater recharge was simulated with a physically-based model (HydroGeoSphere) assuming homogenous soil conditions.

Table 4: Selected MeteoSwiss meteorological stations to simulate CC impact on recharge.

Meteosuisse Station	**Altitude**	**Norm Temperature (1981-2010)**	**Norm Precipitation (1981-2010)**
	masl	°C	mm/y
Payerne (PAY)	490	9.4	891
Wynau (WYN)	422	9.0	1129
Wädenswil (WAE)	485	9.5	1390

Table 5: Selected soil properties to simulate CC impact on recharge.

		Low	Medium	High
Soil hydrological conductivity	m/s	$5 \cdot 10^{-7}$	$5 \cdot 10^{-6}$	$5 \cdot 10^{-5}$
Slope ratio	-	0.005	0.04	0.085

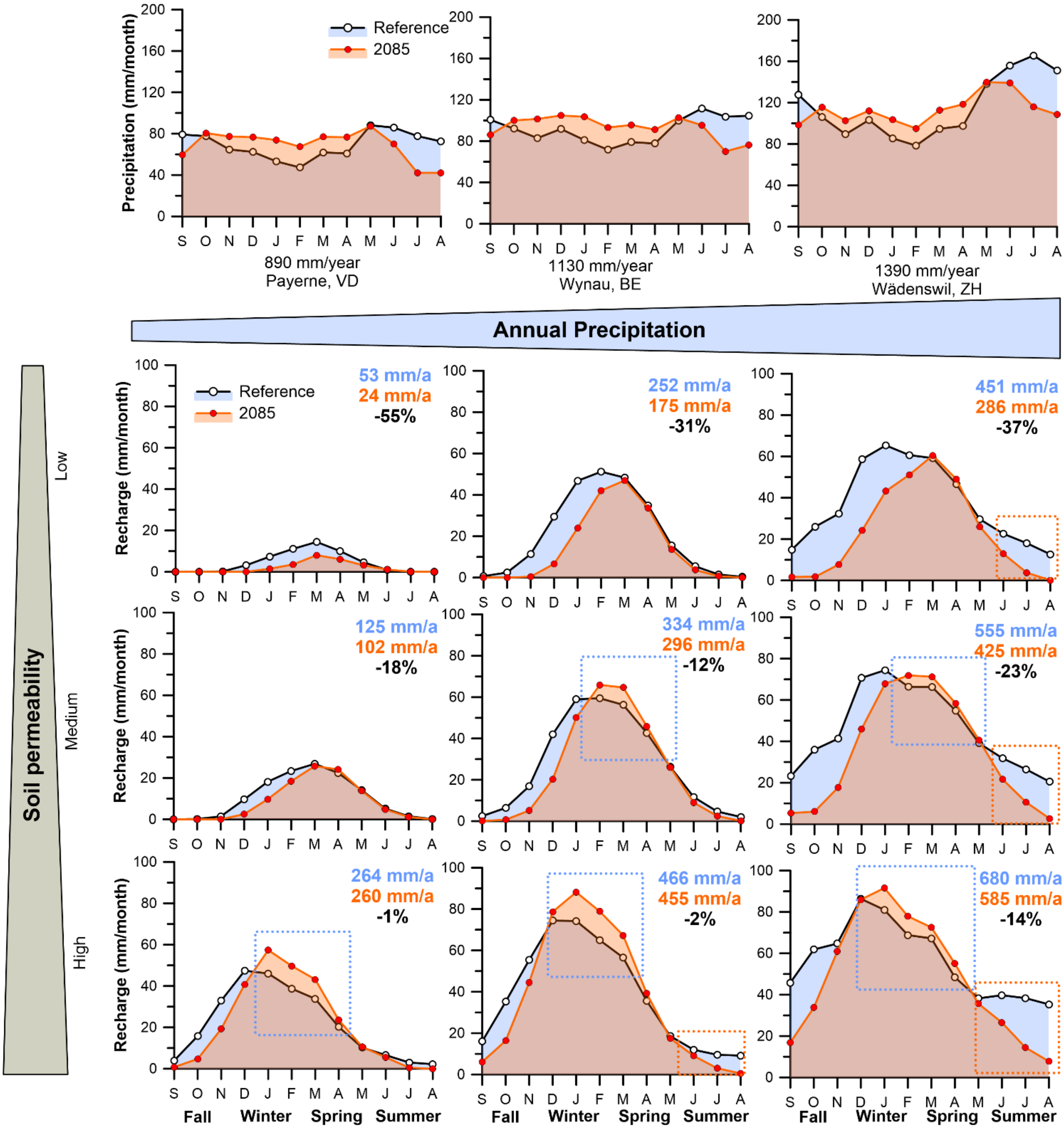


Figure 3: Simulated changes in recharge for three sites with a similar annual temperature but varying precipitation and three soils with a varying permeability (High, Medium, Low). Mean monthly recharge is compared between the reference (blue) and the 2085 period (red) for RCP8.5 and six climate change model chains.

Generally, the soil hydraulic conductivity had a much larger effect on recharge rates than the slope angle. Therefore, the effect of slope angle is not included in the graphs. Already under current conditions, large differences in the amount and timing of recharge can be observed as function of climatic conditions and soil hydraulic conductivity (Figure 3). The temporal distribution of recharge ranges from limited recharge in the winter half-year (for low permeability soils, lower precipitation) to recharge in all seasons (high permeability soils, elevated precipitation). As expected, the annual recharge rate increases with increasing total precipitation and with increasing soil permeability. For soils with lower permeability and drier conditions, recharge is small (upper left, Figure 3), as the water storage capacity of the soil is sufficient to retain most precipitation until it is lost to the atmosphere through evapotranspiration. For wetter conditions, the more abundant precipitation breaks through even for the lower permeability soil.

Under future conditions, the seasonal distribution and annual amount of recharge changes (Figure 3). In automn, recharge is smaller and/or the onset of recharge is delayed due to warmer temperatures and a higher soil water deficit that has to be compensated before recharge starts. The higher winter precipitation only leads to additional recharge for the wetter sites and/or for soils with a higher permeability (blue dashed boxes, Figure 3). At these sites, the higher winter precipitation breaks through the soil. At the drier sites and/or for lower permeability soils, the additional winter precipitation is stored in the soil and lost through evapotranspiration, favoured by the higher temperatures. In summer, recharge only decreases if precipitation is high and soil permeability elevated (red dashed boxes, Figure 3) corresponding to the site where summer recharge occurs under current conditions. Overall recharge becomes more strongly concentrated in the late winter/early spring period.

The net effect of these changes on annual recharge rates varies strongly among sites and soils from no change in annual recharge to a reduction by half (Figure 3). The changes in annual recharge tend to increase as a function of soil properties rather than of climatic conditions. The largest changes are observed for soils with a lower permeability, because the additional winter precipitation does not compensate the decrease in recharge in the other seasons. A decrease in annual recharge will likely be more critical for sites already showing low recharge under current conditions. The relative high decrease for the wettest site is likely less critical as recharge remains high.

Uncertainties of climate impact studies on recharge

Several studies have investigated uncertainties associated with modelling studies. Moeck et al. (2016) investigated the effect of simplification of the hydrological model on the predicted recharge rate. They observed that physically-based models performed better for conditions outside of the calibration space than simple bucket-type models. Simplified models showed an increasing bias for more distant scenario periods as climatic conditions increasingly deviated from the reference period used for model calibration. Nevertheless, uncertainties associated with CC models dominate over the uncertainties associated with the hydrological models, and lead to strongly varying predictions especially for more distant scenario periods (Moeck et al., 2016). In addition to the choice of the global circulation model, the downscaling method can introduce substantial uncertainty in the predicted recharge (Stoll et al., 2011).

2.2.2 Snow-influenced/pluvio-nival conditions (Jura, Prealps)

We mainly find two types of aquifers in these conditions; the fractured aquifers of mid-elevation massifs (south Ticino, etc.) and the karst aquifers of the folded Jura and the Prealps.

Recharge mechanisms

The temporal distribution of recharge at higher altitude is distinctly different from lowland sites. These regions are characterized by a pluvio-nival regime with a snowmelt period from March to May and a period with less recharge from June to October. Between October and December, these regions may experience a few weeks of significant rainfalls before the rain turns into snow for several months.

The highest recharge rate usually occurs during the snowmelt period. As snowmelt extends over a prolonged period, a higher fraction of the water can infiltrate than during periods with intense precipitation. Furthermore, during the period of snowmelt, evapotranspiration is usually low. The partitioning of meltwater among infiltration and runoff depends on geological and topographic conditions. Furthermore, for a given site, it also varies between years depending on whether or not the soil freezes before the first snowfall. In case of frozen soil, runoff is much larger during the snowmelt period than without freezing (Bayard et al., 2005).

Substantial recharge also occurs during summer and automn. Due to shallower soils and a lower air temperature, a substantial amount of precipitation may infiltrate during summer and automn. While recharge rates during summer and automn are smaller than during snowmelt, the recharge period is longer and thus recharge during summer/automn might be in some cases equally important as for the snowmelt period. These aquifers are actually less exposed to prolonged periods of droughts because recharge occurs in winter as well as in summer

Changes in direct recharge

With CC, aquifers under nival conditions will evolve towards more pluvial regimes. As long as the annual precipitation does not change significantly and the fraction of precipitation lost to evapotranspiration is smaller, the groundwater balance is not expected to change much on the annual scale but seasonal variations in the recharge pattern might occur. Predictions show that snowmelt periods will be shorter than today and more frequently disrupted by rainfall events – even in the middle of winter. Summer precipitations will slightly decrease and intense rainfall events are expected to be more frequent. As a consequence, the groundwater recharge will increase in winter and decrease earlier in spring due to the shortening of the snowmelt period. High-flows and periods of droughts will appear sooner than today (resp. early spring and late summer).

At mid-elevation sites (1000-2000 masl) marked changes in the snow dynamics during winter are already visible (Laternser and Schneebeli, 2003). In this altitude range, a permanent snow cover over several months during winter becomes increasingly rare and intra-winter melting periods more common. This has a strong effect on the temporal distribution of recharge, even if the precipitation distribution does not change (**Case Study 2**).

Case Study 2: Increase in recharge in the winter time for aquifers under snow-influenced conditions (Vers-Chez le Brand, NE)

Meeks (2018) investigated the effect of increasing air temperatures on snow accumulation and winter recharge for a site in the Jura Mountains (1'000 masl), while keeping precipitation fix. In the study, a combined snowmelt and soil water model was calibrated to past meteorological data and recharge rates measured in a cave. Then, the air temperature was successively increased in a range expected from CC models while maintaining the precipitation pattern. The author point out that an increase of 3ºC strongly reduces the maximum snow water equivalent and the duration when the snowpack is present (Figure 4). Recharge during the winter increases. For an extreme 5ºC increase, snow only accumulates transiently and the temporal recharge distribution is even more regular. Thus, for such mid-altitude sites, the pronounced minimum in groundwater recharge during winter will likely disappear and recharge patterns become similar to those of current lowland sites.

In reverse, during summer, recharge will likely decrease. Under current conditions, recharge during summer is more important than at lowland sites for several reasons (more precipitation, lower temperature, shallower soil, more grassland with less evapotranspiration). Hence, more evapotranspiration associated with higher temperatures will likely reduce recharge in summer, in contrast to lowland sites, where recharge tend to be low already under current conditions (Figure 3). In other words, due to colder conditions, evapotranspiration likely remains energy-limited even for higher temperature in the future. However, at a higher altitude, the summer minima will likely be less pronounced than the current minima in winter. Thus evaluating system behaviour during past winter minima is a good means to evaluate the reliability of the aquifer during summer minima.

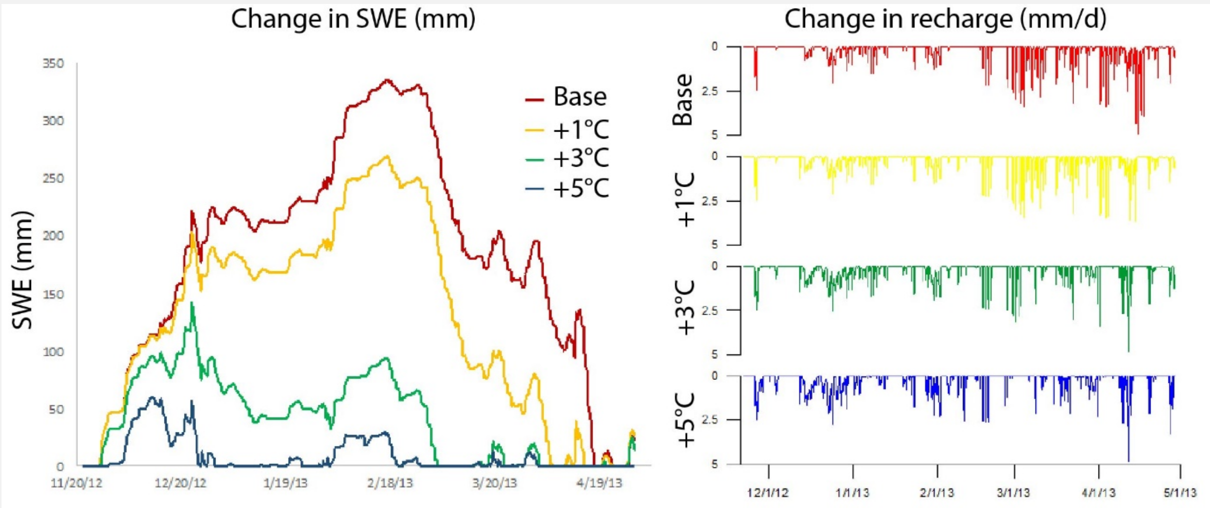


Figure 4: Effect of an air temperature increase on snow accumulation (left) and recharge (right) at a site in the Jura Mountains (Meeks (2018).

2.2.3 Snow and glacier-dominated/nivo-glacial (Alps) conditions

Recharge mechanisms

While in lowland settings, water storage in soils and evapotranspiration strongly influence recharge, at high altitude, the snowpack, topography and geology play an important role. In addition, permafrost can be another important limiting factor for water infiltration. At high altitude, groundwater recharge shows an uneven seasonal distribution with a long period with little recharge and a concentrated recharge period during snowmelt. The wider the altitude range of the recharge area, the longer is the recharge period by snowmelt. During the relatively short snow-free period, recharge by precipitation occurs as soils have generally a low water storage capacity and evapotranspiration is small because of low temperatures and associated vegetative community. Recharge is also influenced by the combined effect of topography and geology. Steeper slopes favour runoff over recharge while the common unconsolidated deposits (moraines, relict rock glaciers, talus) help to retain meltwater and precipitation (Arnoux et al., 2020b). In case of bedrock aquifers, which tend to have a lower permeability than the overburden, the recharge rate can be limited by the rock permeability rather than the available water given the general abundant precipitation at high altitude. The presence of glaciers can favour recharge by ice melt, either directly below the glacier, at the glacier margin, or through glacial lakes and streams (Saberi et al., 2019; Somers et al., 2019).

Changes in recharge patterns - Switzerland

With CC, actual alpine aquifers under snow/glacier-dominated conditions will move toward a more nival regime. Several studies indicated that the annual recharge will decrease: from -10% for a glacier-influenced aquifer in eastern Switzerland (Weber et al., 2012), and about -12% for a nival karst aquifers in the Austrian Alps for 2070 (Chen et al., 2017). Additionally, the seasonal variability will decrease.

In glaciated regions, the gradual melting glaciers might enhance the groundwater recharge in summer and early automn until the glaciers completely disappear. The glaciers melt will temporarily prevent aquifers from autumn droughts. This observation will only be valid for a few decades. Once most glaciers will be have disappeared (horizon 2085), aquifers will behave as nival ones, providing more water in winter time but turning to droughts in long dry summer and autumn period (Gremaud and Goldscheider, 2010). Melting permafrost and rock glacier could temporally provide some water. In addition, future summer droughts are expected to be less extreme than today's winter droughts. Perspectives for these regions are more site-specific than for other regions, especially because of the respective size and persistence of glaciers.

Ice melt goes along with the progressive thaw of frozen ground (permafrost). Evans et al. (2018) demonstrate that changes in frozen ground may also modify the quantity and timing of the available groundwater in high elevated aquifers. The thaw of frozen ground may lead to higher groundwater recharge as degradation of permafrost is expected to increase hydraulic conductivity of the soil and sub-surface (Evans et al., 2018; Rogger et al., 2017).

With warmer temperatures and longer snow free periods, evapotranspiration will increase in alpine regions (Arnoux et al., 2020a). Also, the vegetation type and coverage will change as cold-limited vegetation encroaches to higher elevations, increasing evapotranspiration, and decreasing recharge (Arnoux et al., 2020a; Goulden et al., 2012).

Changes in recharge patterns – International literature

In a recent review of studies on CC effects in western US, the response of mountain system to CC was identified as a major knowledge gap due to a lack of process understanding (Meixner et al., 2016). Nevertheless, the authors formulated some general hypotheses on how CC could impact recharge rates. At high altitudes, snow will still play an important role in the water balance but the duration of the snowpack will decrease. While these changes will modify the seasonality of recharge, there is generally no agreement yet on how the annual recharge rates changes. Recharge could decrease because evapotranspiration and sublimation from the snowpack might increase due to the warmer air temperatures. However, in some regions, this decrease might be offset by higher winter precipitation. In mountainous areas, factors limiting recharge can be highly variable and as result the CC response.

In their recent review, Somers and McKenzie (2020) specified that groundwater recharge in several mountain regions is expected to decrease as the climate changes. In the western United States, a decrease in recharge to mountain aquifers is projected because of declining snowpack (Meixner et al., 2016). In addition to snowpack decrease, increasing temperatures and land cover evolution stimulate evapotranspiration and decrease groundwater recharge in high mountains (Goulden et al., 2012). Goulden and Bales (2014) projected a 28% increase in evapotranspiration across the entire King's River basin by 2100 in California's Sierra Nevada. The increase of groundwater age from 1997 to 2003 of spring water in the Sierra Nevada is also consistent with a decrease in groundwater recharge (Manning et al., 2012).

Take home message – Direct recharge by infiltration of precipitation

Pluvial/rain-dominated conditions

- The magnitude of change depends on soil properties and climate conditions, but especially on the amount of precipitation.
- Recharge tends to become more concentrated during a shorter period in winter/spring. In summer, recharge decreases for wetter conditions, especially if highly permeable soils are present. For other situations, recharge is already low under current conditions. In automn, recharge decreases and/or starts later for all conditions. In winter and spring, the more abundant precipitation only leads to an increase in recharge for sufficiently permeable soils and elevated amount of precipitation.
- The net effect on annual recharge depends on whether the increase of recharge in winter/spring is sufficient to compensate for the loss in automn and sometimes summer.

Snow-influenced/pluvio-nival conditions

- The seasonal distribution shifts. Recharge during winter becomes more common due to a shorter period with snow and melt events during the winter period. Inversely, less recharge occurs in summer and early automn due to a higher evapotranspiration and soil water deficit.
- As precipitations are generally higher at higher altitudes and evapotranspiration plays a smaller role in the water balance, the net changes on annual groundwater recharge is expected to be smaller compared to lower altitudes.

Snow and glacier-dominated/glavio-nival (Alpes) conditions

- The current winter period with nearly no recharge will become shorter and recharge by snowmelt will end earlier in the year. Recharge by rainfall increases but is associated with higheevapotranspiration.
- Recharge by glacier meltwater increases in the short term due to higher temperatures.

2.3 Indirect recharge by infiltration of river water

For unconsolidated aquifer in valleys, infiltration of river water is often the main recharge source. The infiltration rate is influenced by the hydraulic gradient across the streambed, which depends among other factors on the water level in the river. CC will alter river discharge regimes. Accordingly, the quantity and temporal dynamics of river water infiltration to aquifers is expected to change as well. In the following sections, the major mechanisms of river water infiltration are briefly summarized as a basis to discuss CC impacts. It has to be kept in mind that the effect of CC on the amount of groundwater in river-fed aquifers not only depends on how infiltration changes, but also how exfiltration is influenced.

2.3.1 Recharge mechanisms

Two major states of connection between rivers and aquifers can be identified: **connected** and **disconnected** (Figure 5). For connected conditions, a hydraulic continuum exists between the river and the aquifer (Figure 5a), while for disconnected conditions, an unsaturated zone forms below the streambed (Figure 5b and c). Disconnected does not mean that no infiltration occurs, but rather that infiltration happens via percolation through the unsaturated zone. Disconnected conditions can occur if the streambed has a smaller hydraulic conductivity compared to the underlying aquifer. This is often the case if colmation is present in the streambed. Especially in channelized rivers, the deeper part of the stabilized streambed is often more strongly clogged with very little infiltration. Infiltration mainly occurs at high discharge via the riverbanks (Figure 5c).

The state of connection determines how the infiltration rate varies as a function of groundwater depth and stream stage. The depth to groundwater has a different effect for the connected and disconnected case. In the connected case, the infiltration rate increases as the groundwater level drops, while in the disconnected case, it is independent of it for a given stream stage. In both cases, the infiltration rate increases with stream stage for two reasons: (1) the hydraulic gradient between the river and aquifer (connected case) or across the streambed (disconnected case) increases and (2) the wetted area across which infiltration occurs increases. The latter factor explains why the infiltration rate is expected to increase disproportionally with stream stage. For channelized conditions, a highly non-linear response is typical. At low stream stage, only minimal infiltration occurs while the infiltration rate rapidly increases once the stage exceeds threshold values. This behaviour is illustrated for a channelized section of the Venoge in the Canton of Vaud (**Case Study 3**).

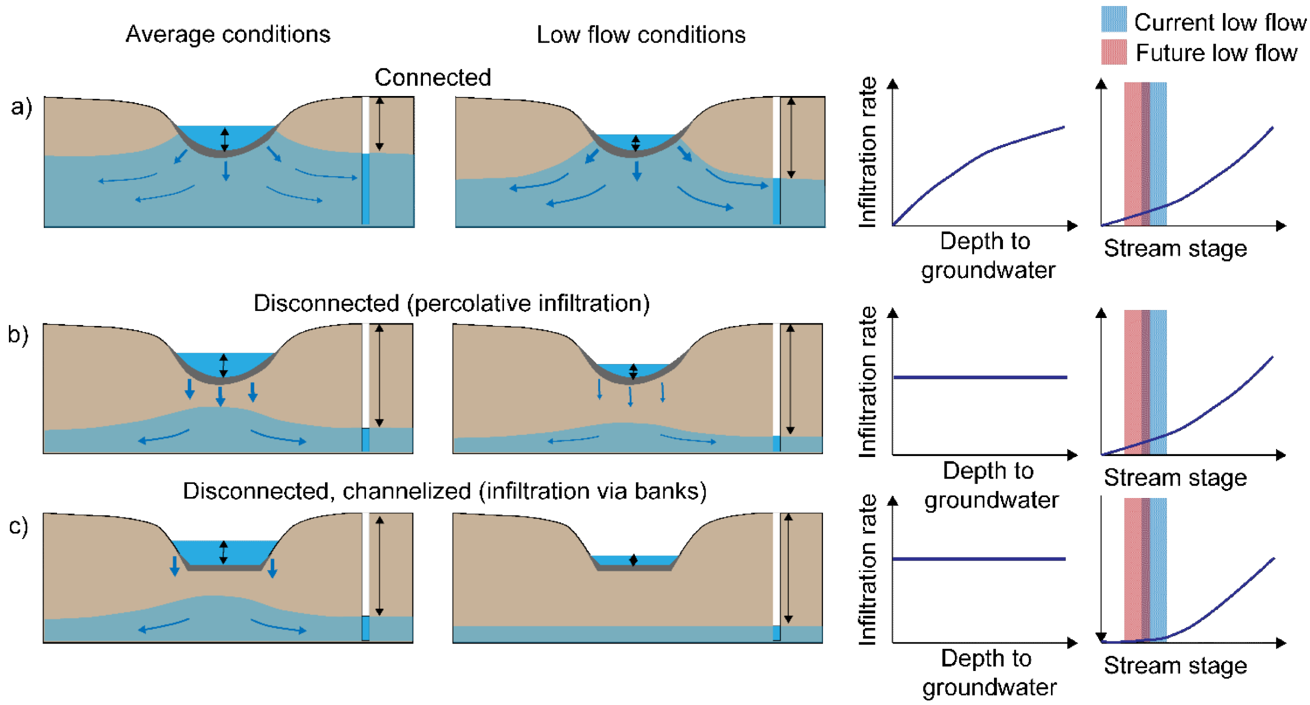


Figure 5: Schematic illustration of different states of connection between losing rivers and groundwater. Infiltration rate as a function of the depth to groundwater and stream stage.

Case Study 3: Effect of low flow conditions on groundwater recharge by infiltration of river water, example Venoge, Canton of Vaud.

For channelized rivers with colmated streambeds, infiltration of river water strongly depends on the stream stage as illustrated for channelized sections of the Venoge river in the Canton de Vaud for the drought year 2018. At this site, the electrical conductivity is a good tracer to demonstrate infiltration of river water. The river, which is mainly fed by karst springs, has an electrical conductivity of 300-400 µS/cm, while groundwater that infiltrates through agricultural soils has a value of 700-800 µS/cm. During the drought period from August to November 2018, the groundwater level steadily decreased and the electrical conductivity in piezometer adjacent to the river remained high, indicating that no infiltration of river water occurred. Once a threshold stream stage of 0.5 m is exceeded, the groundwater level rapidly increases and the electrical conductivity drops attesting infiltration of river water (Figure 6). The threshold elevation corresponds to the height where the highly fortified low flow channel overflows into the riverbanks suggesting that infiltration mainly occurs via the riverbanks.

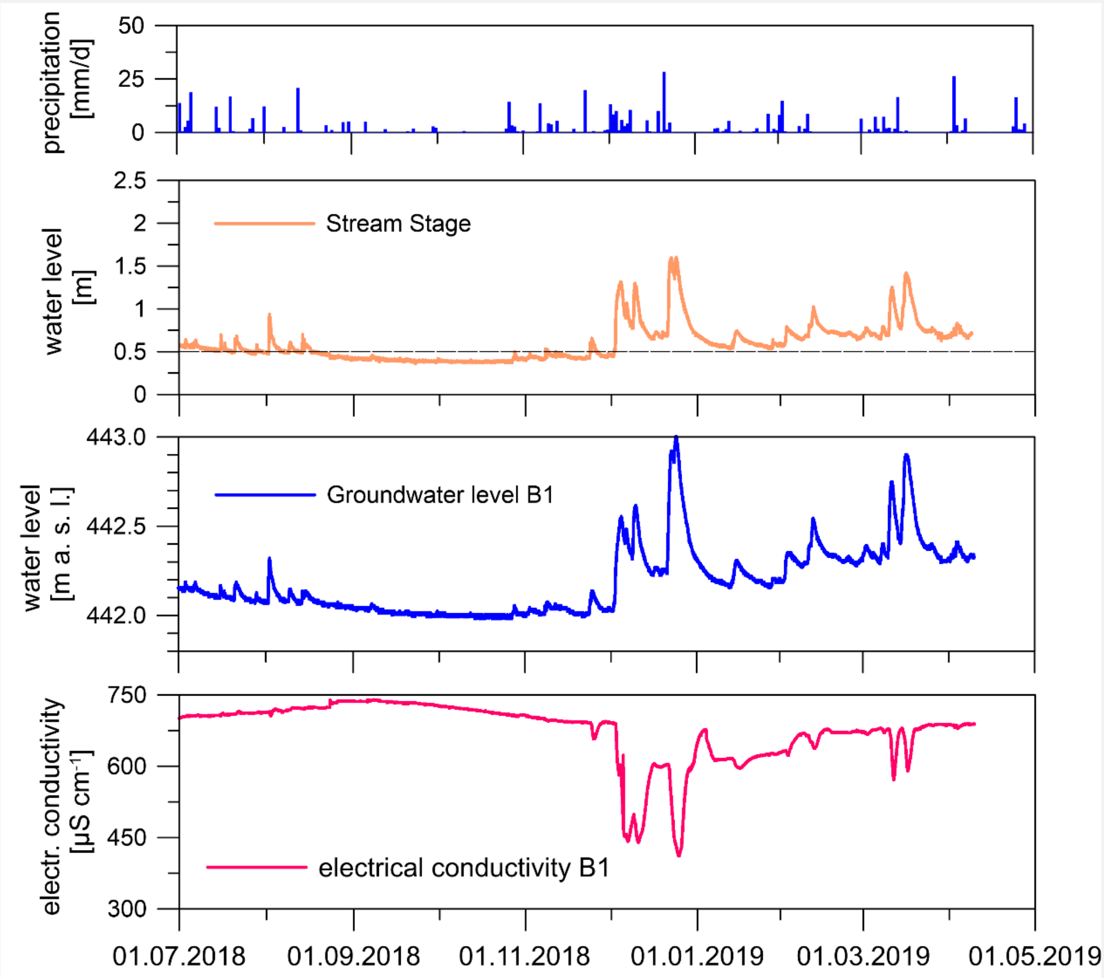


Figure 6: Groundwater level and electrical conductivity in piezometer close to the Venoge river (VD) and stream stage in the river.

2.3.2 Changes in river infiltration

CC can impact future river infiltration rates for several reasons: (1) modification of the river discharge regime, (2) modification of the streambed permeability due to changes in flood frequency and in biogeochemical processes that influence streambed clogging, and (3) modification of groundwater levels by other factors than river water infiltration, such as a change in direct recharge or increased pumping for water supply and irrigation.

Table 6: Effect of changes in river discharge and depth to groundwater due to climate change on groundwater recharge by river water infiltration.

State of connection	Changes in river stage/discharge and their effect on recharge			Changes in depth to groundwater and their effect on recharge	
	Higher winter discharge	Smaller summer low flow discharge	Prolonged low flow period	Decrease in winter due to more winter direct recharge	Increase due to more pumping or less summer direct recharge
Connected	More	Less	Less	Less	More
Disconnected - percolative	More	Less	Less	No change	No change
Disconnected - via banks	More	No change	Less	No change	No change

Modification of river discharge regime and depth to groundwater

The expected changes in river discharge regimes are discussed in detail in another HydroCH2018 report (Mülchi et al., 2020). For rivers with a pluvial regime, lower discharge is expected in late summer due to more evapotranspiration and decreasing summer precipitation. Summer discharge is expected to decrease also for rivers with pluvio-nival regime due to the earlier on-set of snowmelt. For rivers with nivo-glacial regime, discharge during summer will initially increase but then decrease as well in the far future due to the disappearance of glaciers. In return, for catchments at low and mid-altitude, discharge will increase in winter due to higher precipitation, a higher fraction of precipitation as rain and intra-winter melt events.

These changes in the discharge regime and depth to groundwater have a different effect for connected and disconnected rivers (Table 6). In the **connected case**, a higher river discharge will lead to more infiltration. In reverse, smaller low flow discharge and prolonged low flow periods lead to less recharge. However, the infiltration rate not only depends on the stream stage but also the groundwater level (see above), which change as well. If the groundwater level drops more strongly than the stream stage e.g. due to pumping or less direct recharge, the infiltration rate will increase despite a lower river discharge. This effect is illustrated in **Case Study 4** for the Bernese Seeland. In reverse, if the depth to groundwater decreases in winter due to more direct recharge or if the aquifer is saturated, river water infiltration might not increase despite the higher stream stage. In exceptional cases, the river can infiltrate completely. Then the recharge rate is controlled by the river discharge rather than hydraulic gradients and streambed permeability. Complete infiltration only occurs if the aquifer large and permeable to transmit the complete catchment outflow. Such a situation mainly occurs in the upgradient portion of catchments where catchment outflow is low, and the groundwater flux can be high due to coarse deposits and steep hydraulic gradients. Furthermore, in such zones, streambed sediments are often more permeable due to more frequent sediment transport favouring rapid infiltration.

Case Study 4: Interacting effects of CC on direct recharge and recharge by river water infiltration – Seeland case study

For the Seeland aquifer, the effect of CC on groundwater recharge and dynamics was simulated by combining a crop (CropSyst), a hydrological (WaSIM) and a hydrogeological (FEFLOW) model in the Agriadapt project. Here, the results of the simulations for groundwater recharge with constant land use and irrigation are shown. The infiltrating river water mainly originates from the Hagneck Canal. For representative emission pathway RCP2.6 (with climate protection), the discharge of the Hagneck Canal in the distant future (2070-2099) only shows minor changes. In contrast, for RCP8.5 (no climate protection), the discharge is considerably higher in January, February and March, due a higher proportion of precipitation as rain rather than snow, and lower from June to October due to a smaller amount of melt water.

Under current conditions, direct recharge occurs throughout the year. For RCP2.6, direct recharge does not change significantly, while for RCP8.5, it is higher in February to April due to higher precipitation, and very low from July to September. Lateral inflow shows a similar pattern with a delay of about 2 months. In contrast, the river water infiltration (indirect recharge) shows the opposite trend for RCP8.5, with a decrease in spring and increase in summer and automn despite the lower discharge. In summer/automn, hydraulic gradients between the river and aquifer increase due to less direct recharge and lateral inflow combined with more pumping, which enhances infiltration. Hence, the changes in direct recharge and lateral inflow are partly buffered by the changes in river water infiltration. This self-regulating mechanism helps to stabilize groundwater levels in the aquifer.

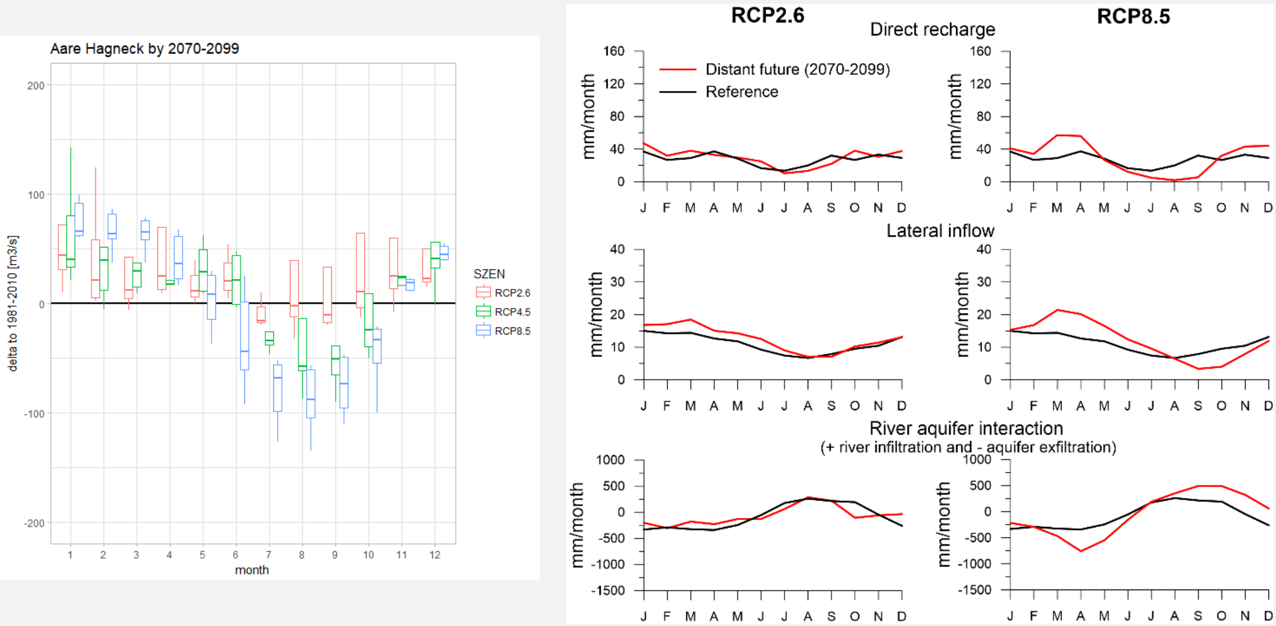


Figure 7: Effect of CC on Aare discharge at Hagneck and groundwater recharge in the Seeland for the distant future.

Under **disconnected conditions**, the effect of reduced low flow rates varies depending on how severely the streambed is clogged as illustrated in Figure 5. If significant infiltration occurs under current low flow conditions, a lower future stream stage will lead to smaller infiltration rates. However, if infiltration is already insignificant under current conditions, a future decrease in low flow rates will have a minimal effect on infiltration rates. CC will then mainly affect an extended duration of low flow periods. Hence, it can generally be expected that the amount of river water infiltration during summer decreases due to lower infiltrations rates and/or a longer duration of the period with no or only little infiltration. In reverse, during winter, the expected higher river discharge can lead to a higher infiltration rate especially considering that infiltration rates tend to increase disproportionally with stream stage (Figure 5).

Changes in the annual amount of infiltration will depend on the relative importance of the infiltration increase during winter and decrease during summer. In many cases, a change in the seasonal distribution will be expected to become more uneven similarly to direct recharge.

Modification of the streambed permeability

The more abundant winter precipitation and more frequent flood events can modify the sediment transport dynamics and thus the state of colmation, which strongly influences infiltration rates. Once a critical discharge rates is exceeded, sediment transport becomes sufficient to remove the colmation layer (Gianni et al., 2016; Partington et al., 2017). Such events might occur more frequently in the future and counterbalance the tendency to less infiltration due to more pronounced low flow conditions. This will tend to reduce flow-rates in rivers, leading to complete drying up of small rivers in some cases.

Take home message – Indirect recharge by infiltration of river water

- Infiltration can change due to changes in stream stage, groundwater levels or streambed permeability.
- More pronounced and longer low flow periods will lead in many cases to a decrease in groundwater recharge by river water infiltration during summer.
- The effect is expected to be more pronounced for rivers with percolative infiltration via the streambed or river-banks than for connected rivers. For hydraulically connected rivers, a drawdown of the water table e.g. due to enhanced pumping can even lead to an increase of infiltration despite a smaller discharge.
- On an annual scale, the effect of low flow conditions can be compensated by more infiltration during winter and/or more frequent removal of clogging layers due to more frequent and intense flood events.
- Overall, groundwater recharge by river water infiltration tends to become more irregular on a seasonal scale for lower altitude sites with a current summer minima. For higher altitudes with a current winter minima, groundwater recharge by river water infiltration becomes more regular.

3 Effects on groundwater storage and discharge

In this chapter, we discuss the consequences of changes in recharge patterns on the quantity of groundwater in aquifers and implications for (i) **groundwater services** and (ii) **risks** associated with groundwater. Among the groundwater services, not only water supply but also ecological services are considered. As discussed in chapter 2, CC is expected to modify the seasonal distribution of groundwater recharge and to some extent the annual amount. Especially under pluvial conditions, periods with no or only little recharge become longer and more frequent, while recharge tend to becomes more intense during winter. Extended periods without recharge potentially impact groundwater services, while periods with more intense recharge could trigger groundwater-related risks (i.e. floods, etc.). In the first case, a key question is how the effect of prolonged hot and dry periods propagate to groundwater. Two aspects play a role i.e. to what extent groundwater levels and fluxes decrease during such periods (**reliability**) and how quickly they recover again (**resilience**). It can generally be expected that such effects become dampened and delayed as they migrate into and through the subsurface (Figure 10). Thus, the effects of hotter and drier periods are expected to be less pronounced for groundwater than for surface water or for soil moisture. As a result, groundwater is a suitable resource to address soil moisture deficits by irrigation. Groundwater might be used to substitute surface water that is no longer accessible for irrigation to maintain minimal environmental flows. Thus, indirect effects, i.e. an increased use of groundwater due to drier summer conditions, needs to be considered in addition to direct effects.

The aquifer response to modified recharge regimes will strongly depend on the geological and hydrogeological conditions. Therefore, the CC effects on groundwater quantity will be discussed according to aquifer type as defined in Figure 8. We put the emphasis on the most important aquifer types for water supply in Switzerland i.e. porous and karstified aquifers. For porous aquifers, we do not differentiate into those in unconsolidated versus consolidated deposits as there is no fundamental difference in their hydrogeological behaviour. In the case of consolidated deposits, the aquifers can be partly fissured. However, we do not dedicate a separate chapter to fissured aquifers as their behaviour can strongly vary; they play a smaller role for water supply and little data CC impacts on such aquifers is available. For a given aquifer type, different responses are expected depending on the groundwater regime. In the discussion, we define groundwater regimes according to the typology shown in Figure 9, which includes pluvial, pluvio-nival and nivo-glacial groundwater regimes. These groundwater regimes can be site-specific or imported via rivers (Figure 9).

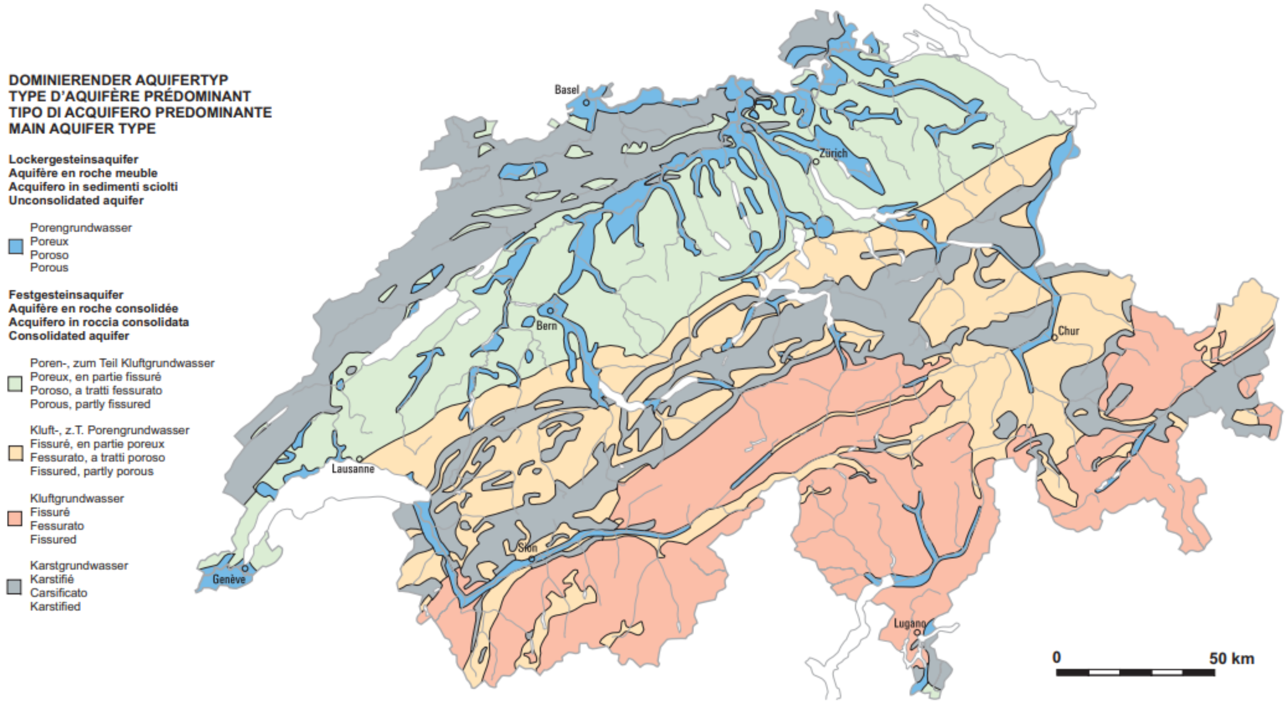


Figure 8: Hydrogeological sketch of Switzerland with the most important aquifer types (FOEN).

Figure 9: Typology of groundwater regimes in Switzerland (Schürch et al., 2010).

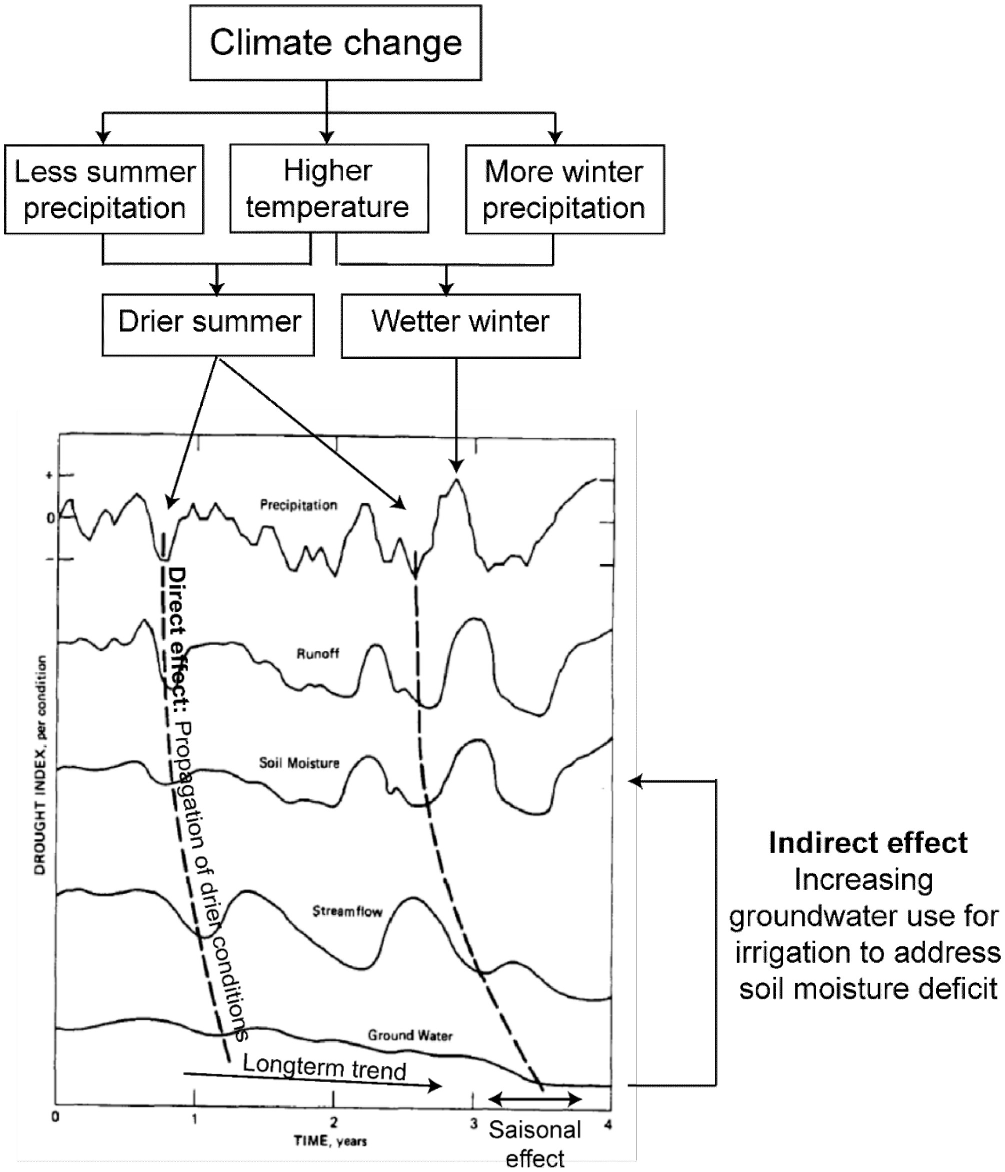


Figure 10: Schematic illustration of how the expected drier summer and wetter winter conditions propagate through different compartments of the hydrological systems (modified from Changnon (1987).

3.1 Porous aquifers

A comparison of the maps on aquifer types and groundwater regimes shows that porous aquifers are commonly located in zones with a site-specific pluvial groundwater regime. Therefore, porous aquifers with this regime are discussed with more details. Unconsolidated porous aquifers are often strongly influenced by river water infiltration and thus can have an imported groundwater regime. Although this chapter is mainly dedicated to porous aquifers in unconsolidated and consolidated deposits, some specific aspects related to fractured aquifers are discussed as well, especially for sites with several aquifer types.

3.1.1 Pluvial groundwater regime

As discussed in chapter 2, for sites with pluvial conditions, it is expected that groundwater recharge becomes more irregular on a seasonal basis with a longer period with little recharge in summer and more recharge in winter. Such a trend is expected for direct recharge and often also for recharge by river water infiltration. How directly this higher irregularity of water input influences groundwater level and groundwater services depends on the buffering effect of the unsaturated zone and aquifer properties. A thick unsaturated zone with a high water storage capacity can partly smooth out the irregularities of water input and delay the effect of low recharge in summer and automn. For a simple homogenous aquifer, the relationship between the change in input and change in discharge depends on the aquifer response time T, which is given by Peters et al. (2003):

$$T = \frac{S \cdot A}{K \cdot H}$$

Equation 1.

where: S is the storage coefficient (-), A is the area of the aquifer (m^2), K is the hydraulic conductivity (m/d) and H is the average saturated thickness (m). According to this equation, an aquifer has a long response time i.e. shows a highly inertial behaviour either if it is large (A), can release a lot of water per unit decline of hydraulic head (S) or if it has a low permeability K i.e. can retain the stored water well. In the following, we illustrate how aquifers with varying response time change according to a more irregular groundwater recharge regime. We consider an idealized annual recharge time series and evaluate how this time series propagates through the aquifer to a discharge zone. To reproduce future recharge conditions, we extend the period with little recharge by two months while keeping the annual recharge constant at 400 mm/year, thus increasing the recharge rate during winter. We consider three aquifer response times of 100, 300 and 1500 days. In case of a response time of 100 days, the longer period with little recharge leads to a significant decrease in the discharge in automn, while for larger response times, there is hardly any effect (Figure 11). Thus, aquifer with a longer response time show a high reliability, i.e. continue to supply a similar amount of water, despite of a substantially longer period without recharge. By considering equation 1, it can be seen that aquifers can be reliable for different reasons. Alluvial aquifer can be reliable despite their usual elevated hydraulic conductivity if they have a large spatial extent. In return, a sandstone aquifer in the Molasse can be reliable even if it has a limited extent as such aquifers tend to have a lower hydraulic conductivity. These conclusions are supported by a recent study on how hydrogeological conditions influence the low flow behaviour of rivers, which is dominated by groundwater processes. The study made use of numerical modelling (Carlier et al., 2019) and a statistical analysis of the relationship between (hydro)geological conditions and low flow rates (Carlier et al., 2018). The study demonstrated that extensive bedrock aquifers, typically sandstone units in the Molasse, are particularly important to sustain an elevated discharge during low flow periods (i.e. large A and moderate K).

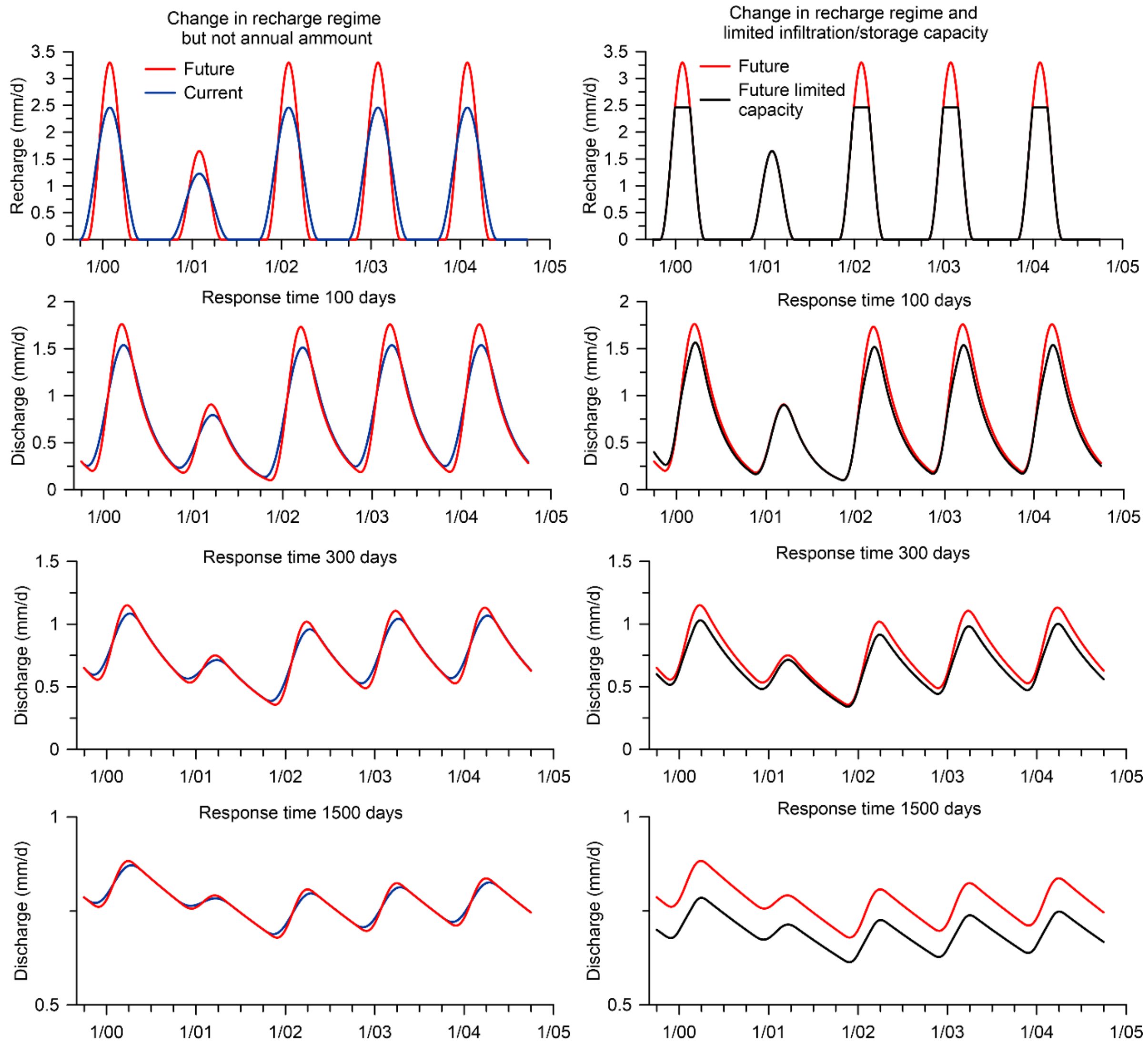


Figure 11: Effects of a change in groundwater recharge on groundwater discharge over a five years period. The left column corresponds to a more concentrated recharge in winter without changing the annual amount. In the right column a threshold for maximum winter recharge was added leading in addition to smaller annual amount. In addition to the change in recharge regime, the effect of a year with only half the average recharge is illustrated (1/01).

A different situation arises if in addition to the seasonal concentration of recharge also the annual amount of recharge changes. This occurs if the decreasing recharge in summer/automn is not compensated by more recharge in winter due to more runoff or soil storage followed by evapotranspiration of the additional winter precipitation in spring (see chapter 2.2). This is represented by setting an upper limit for the monthly recharge thus limiting the maximal recharge during the winter months (Figure 11). For aquifers with a short response time, the effect on the minimal summer/automn discharge is limited as it mainly depends on recharge during late spring and early summer (Figure 11). In contrast, for aquifers with a long response time, the entire discharge time series shifts to lower values as discharge mainly reflects the annual average recharge.

The response time also influences how quickly an aquifer recovers from recharge drought, i.e. a period with unusually low recharge. An aquifer with a low response time recovers almost instantly while for an aquifer with a long response time, discharge continues to drop even if the annual recharge increases again. It may take years until an average state is reached again. For systems with a long response time, the effect of multiple years with below average cumulates (Figure 11).

The effect of a more irregular recharge on the groundwater dynamics can also be evaluated by considering the effect of past drought periods, which can be considered as a proxy for future low flow conditions. The effect of the aquifer response time on the drought response is illustrated with data from two neighbouring unconsolidated aquifers in the Canton of Solothurn that have a different spatial extent (Figure 12). Aquifer 1 extents over 16 km in groundwater flow direction with an unsaturated zone of up 30 m thickness, while aquifer 2 covers only 3 km with shallow unsaturated zone. Thus aquifer 1 is expected to have longer response time than aquifer 2. The intensity of drought conditions was characterized by the Palmer Drought Severity Index (PDSI). The PDSI remained negative until 2005, though less strongly, and groundwater levels continued to decrease until the end of 2005 in aquifer 1. The lowest groundwater level in the displayed period was reached in 2011 after several years with below-average moisture conditions rather in 2003 during the most intense drought highlighting again the importance of cumulative effects over several years. Cumulative effects occur also in opposite direction. The aquifer maintains above-average groundwater storage levels over several years. In contrast, in aquifer 2, cumulative effects of drought periods are not observed and the aquifer recovers its average state quickly again. Similarly, excess storage dissipates quickly again.

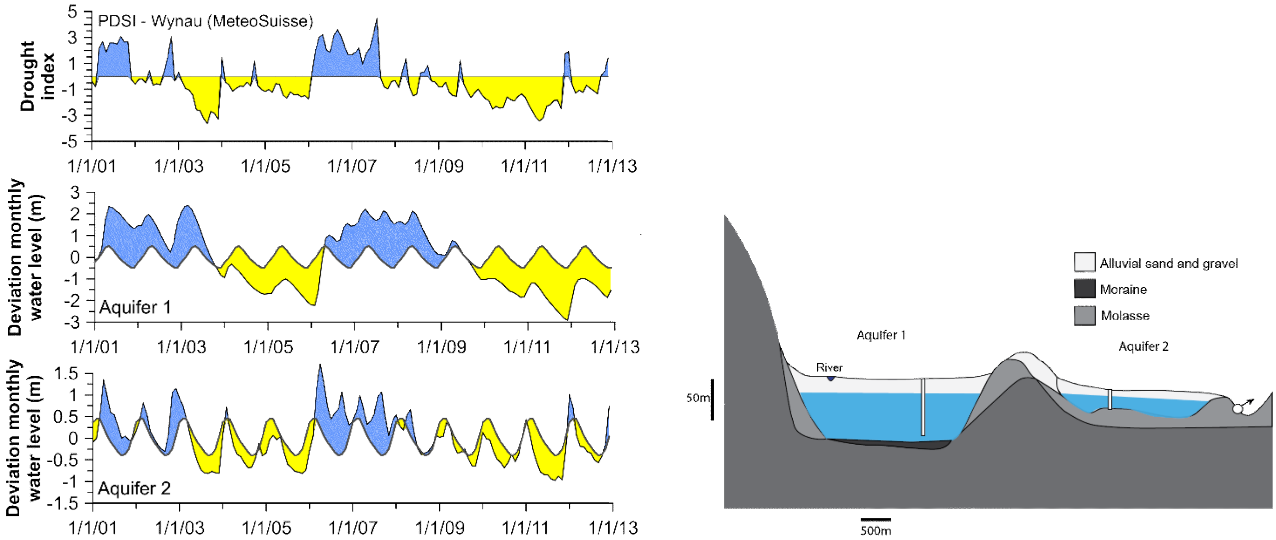


Figure 12: Left: Response of two unconsolidated aquifers of different size in the same region to past drought periods characterized by the Palmer Drought Severity Index (PDSI). Monthly mean groundwater levels and stream discharge are shown and their deviation from long-term monthly mean values is reported. All data are normalized to long-term mean values. Yellow: Monthly mean is below the long-term monthly mean value. Blue: Monthly mean is above it. Right: Cross-section illustrating the two aquifers. The groundwater flow direction of aquifer 1 is perpendicular to the section, while in aquifer 2 flow occurs parallel to the section.

In aquifers extending over a longer distance along the valley, such as in the Emmental (Figure 13), a characteristic upstream to downstream groundwater drought response occurred in 2003 and 2011. The strongest water table response occurred at the most upstream location (Figure 13, E1), while water tables remained stable further downstream (Figure 13, E2 and E4). The river dried out in some stretches in the upstream part of the catchment. As soon as stream water infiltration becomes low or ceases due to the low streamflow, groundwater levels dropped rapidly as groundwater drains out rapidly from the steeper aquifers. In the middle section of the Emmental aquifer (Figure 13, E2), groundwater levels were stable because streamflow remained high enough and streambeds are sufficiently permeable to maintain a high water table in the aquifer. Interestingly, a water table response can also be observed in its lower part (Figure 13, E3) despite stable conditions further upstream. In this zone, the river might be disconnected from the aquifer. The infiltration rate at low flow is no longer sufficient to sustain groundwater levels. Groundwater levels decline due to outflow of groundwater and to groundwater pumping.

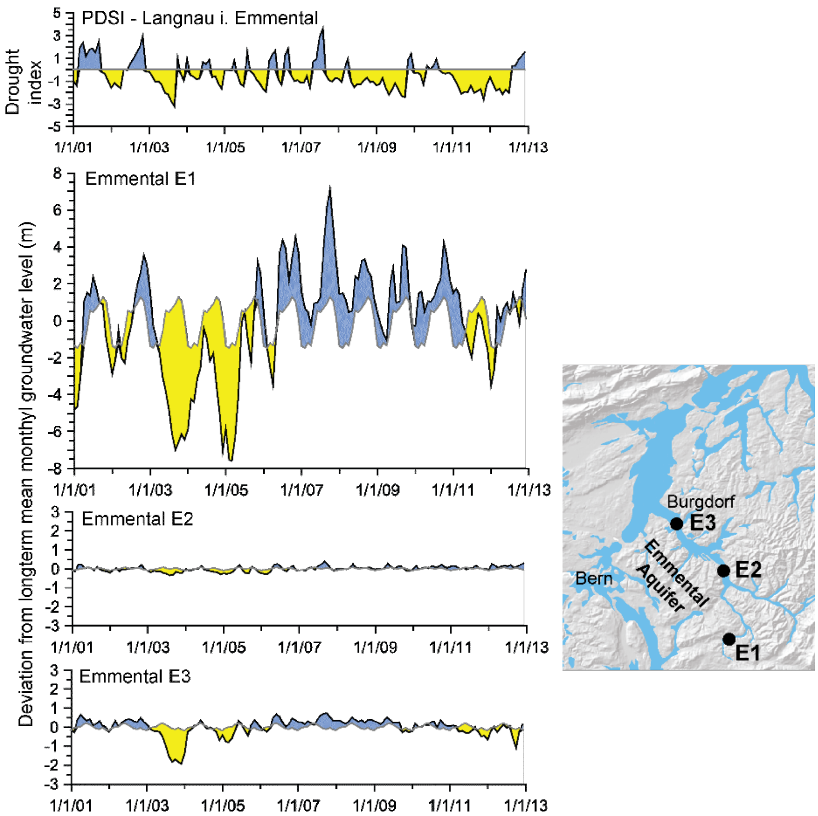


Figure 13: Difference in drought response for three locations along the alluvial Emmental aquifer. The drought intensity was characterized by the Palmer Drought Severity Index (PDSI). Monthly mean groundwater levels and stream discharge are shown and their deviation from long-term monthly mean values are reported. All data are normalized to long-term mean values. Yellow: Monthly mean is below the long-term monthly mean value. Blue: Monthly mean is above it.

As the upper Emmental, coincides with a major zone for water supply (zone between E1 and E2), the drought response of the site was further investigated during the 2011 drought period (Figure 14). Although the groundwater levels dropped by as much as 5 m within a few months, only about 5% of the stored groundwater volume in the alluvial aquifer was lost during the same period. It is also noteworthy that the aquifer recovered quickly again after the drought period.

Alluvial aquifers with recharge by river water often show a more rapid recovery from drought than aquifers that are fed by direct recharge only, as infiltration rates during high flow periods can become very high often supported by lateral inflow. For example, in the upper Tösstal, the groundwater level increased by 17 m within 16 days after the 2003 drought while only about 40 mm precipitation fell. Thus, for such highly dynamic systems consisting of very permeable aquifer in contact with rivers, it is not expected that successive droughts cumulate as it can be seen for example in the Gäu aquifer which is predominantly fed by precipitation (Figure 12).

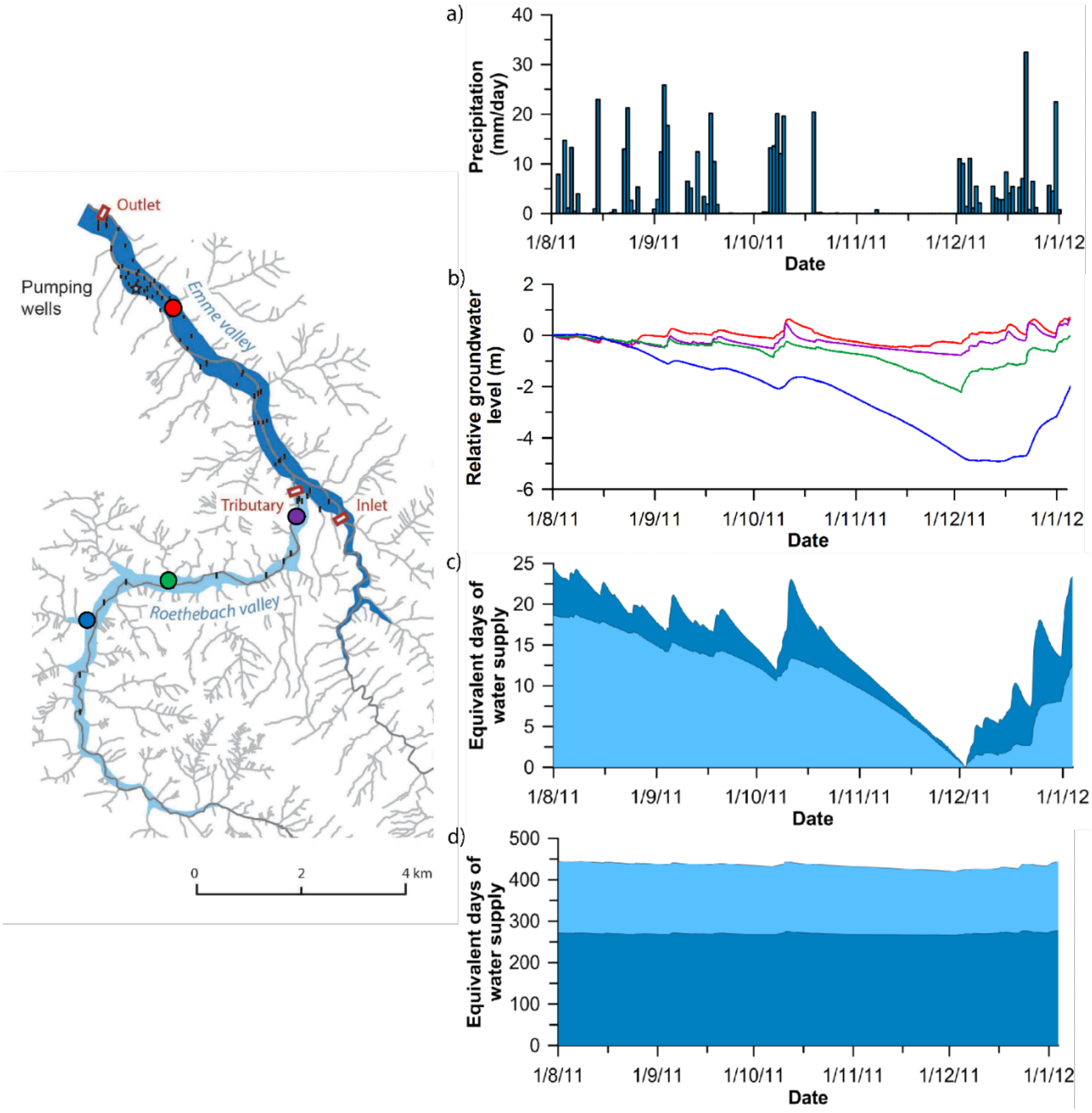


Figure 14: Response of the upper Emmental aquifer that is extensively used for drinking water supply to a drought period in 2011 (Kaser and Hunkeler, 2016). Relative change in groundwater levels along the valley (b). Change in groundwater storage in two parts of the alluvial aquifer relative to minimum during the period (c) and as a total volume (d). The storage volume is expressed as number of days of water reserves to sustain the average groundwater extraction rate.

In addition to the direct effect of climate recharge via modified recharge processes, CC can also influence groundwater storage and discharge indirectly, by causing a change in groundwater use patterns, especially for irrigation. The effect of increased pumping for irrigation is illustrated for the Seeland case study (see **Case Study 4**) for different land use scenario with results from the HydroCH2018 project Agriadapt. For the moderate land use change scenario (-/+20% crop with irrigation), the average irrigation demand for the full season increases by 30% and 65%, respectively relative to the reference periods (Figure 15). In an extreme year, the demand increases by up to 200% (Figure 15). The groundwater level in automn is decreased by ~30 cm on average and by 100 cm in an extreme year, with little difference among land use scenarios. For the extreme land use changes, the drop in groundwater level is much stronger for the scenario with 100% irrigated vegetable, while the groundwater level for un-irrigated grassland corresponds to those in the reference period (Figure 16).

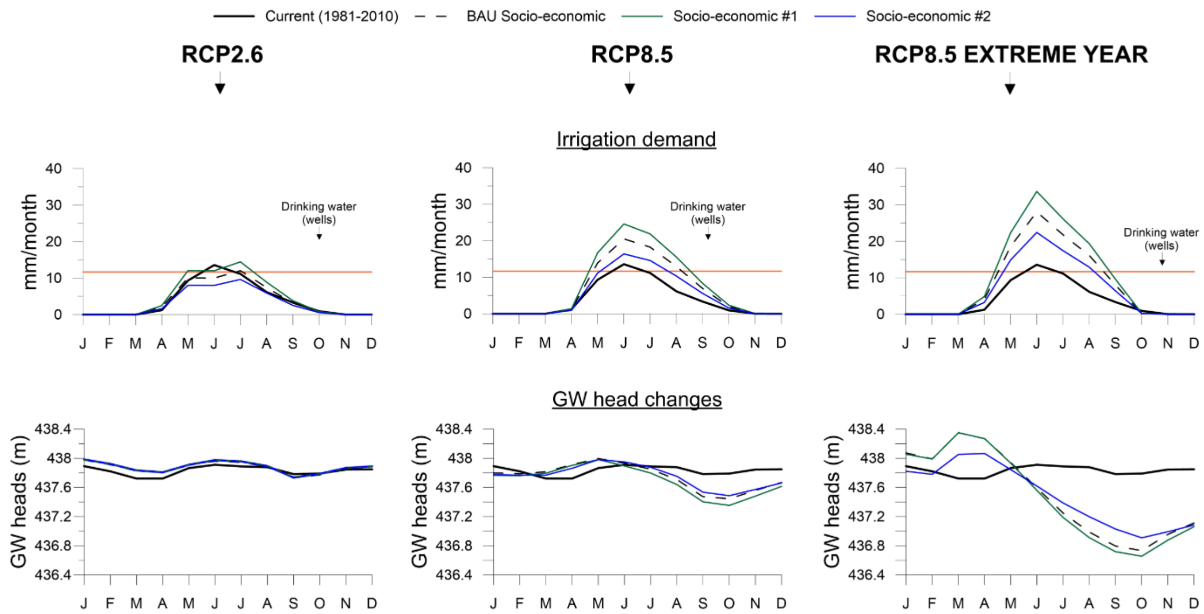


Figure 15: Direct and indirect effect of CC on groundwater levels in Seeland for unchanged land use (BAU) and moderate land use changes. The land use change involves a 20% decrease (#1) and increase (#2), respectively of crops requiring irrigation for the distant future (2070-2099). The average and extreme-year irrigation water demand is compared to current pumping for drinking water production.

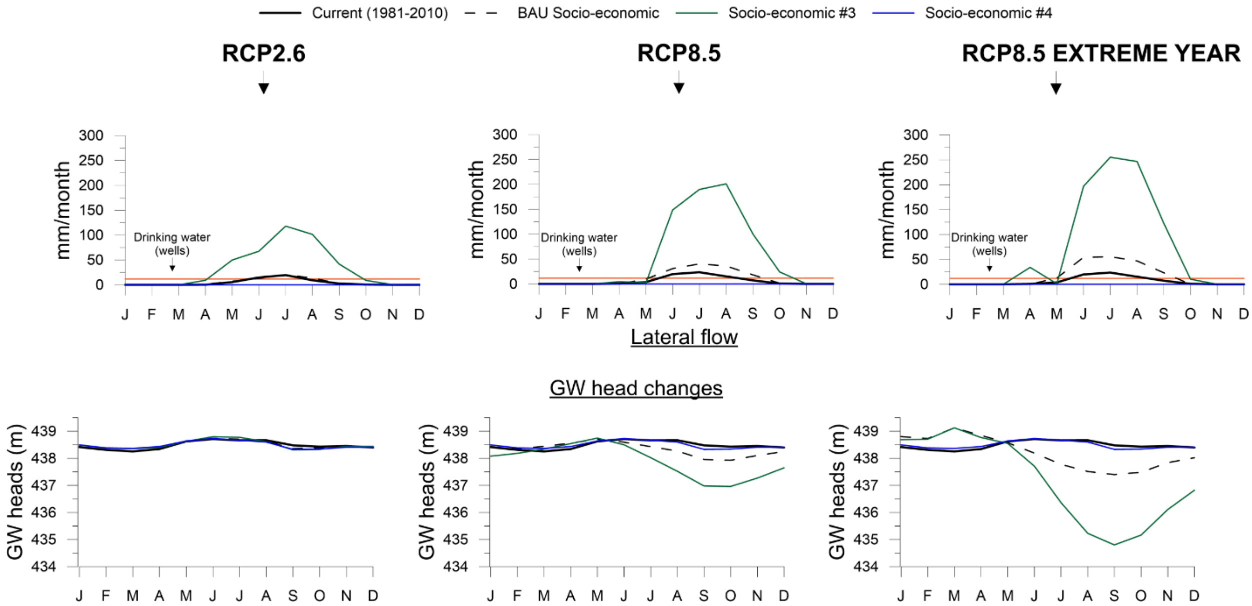


Figure 16: Direct and indirect effect of CC on groundwater levels in Seeland for unchanged land use (BAU) and extreme land use changes for the distant future (2070-2099). The extreme scenarios involve 100% irrigated vegetables (#3) and 100% non-irrigated grassland (#4), respectively. The average and extreme-year irrigation water demand is compared to current pumping for drinking water production.

3.1.2 Pluvio-nival to Nivo-glacial groundwater regime

CC will induce significant changes in the hydrology of regions with nivo-glacial regimes due to the disappearance of decreasing snowpack, glacier and permafrost degradation. While these trends are well-investigated for glaciers, snowpack and streamflow, so far only few studies have been carried out on the impacts on groundwater resources. Therefore, this topic was addressed in a Hydro-CH2018 project. The main objective was to investigate (i) how the groundwater dynamics is modified by CC, (ii) how the changes are related to geological and hydrogeological conditions, and (iii) what the impacts for streamflow are, in focussing on future low flow conditions during summer. The major findings are summarized here. More details can be found in the project report and related publications. The focus of this project was on small alpine catchments at high altitude, with no or negligible glacier cover. On this pilot catchment (Vallon de Rechy, VS), an integrated hydrological-hydrogeological model was established that explicitly simulates the groundwater dynamics and its implications on streamflow. For the others, a simplified conceptual modelling approach was used.

For the pilot catchment, the mean annual average water fluxes and states change systematically until 2100 (Figure 17). The mean annual snowpack, expressed as snow water equivalent decreases up to 50% with RCP 8.5 leading to a significantly lower input of meltwater. Evapotranspiration increases due to the prolongation of the snow-free period and higher temperatures and the stream discharge slightly decreases. The mean annual groundwater storage decreases due to a decrease of groundwater storage in the bedrock, which steadily declines over 100 years (Figure 18).

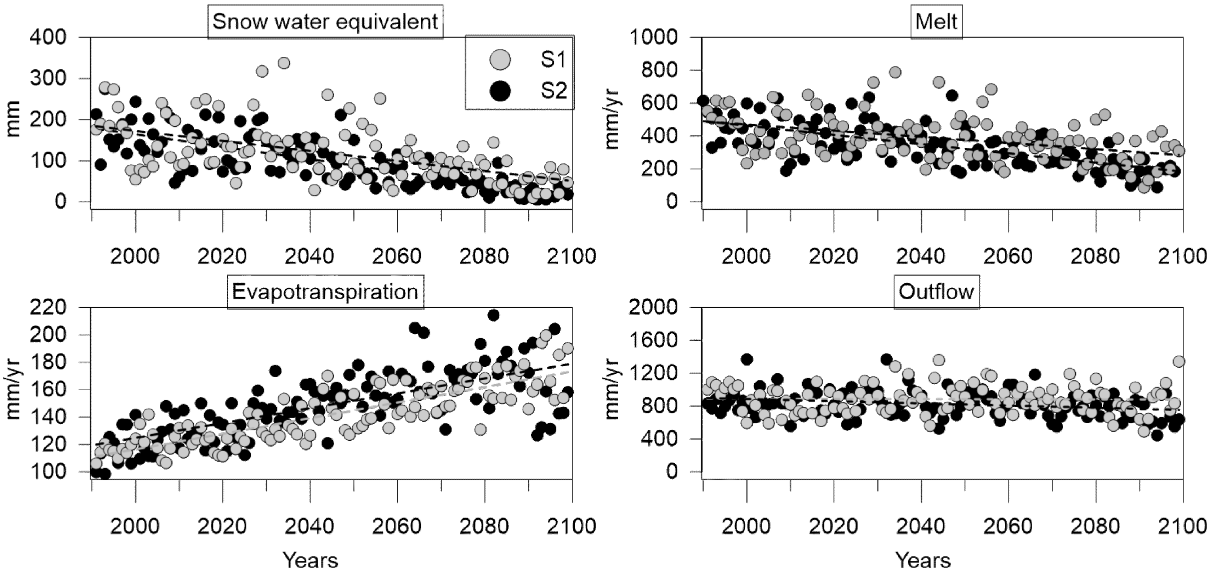


Figure 17: Annual averages of snow water equivalent, melting, evapotranspiration, flow at the catchment outlet of the Vallon de Rechy (VS) for two climate scenarios.

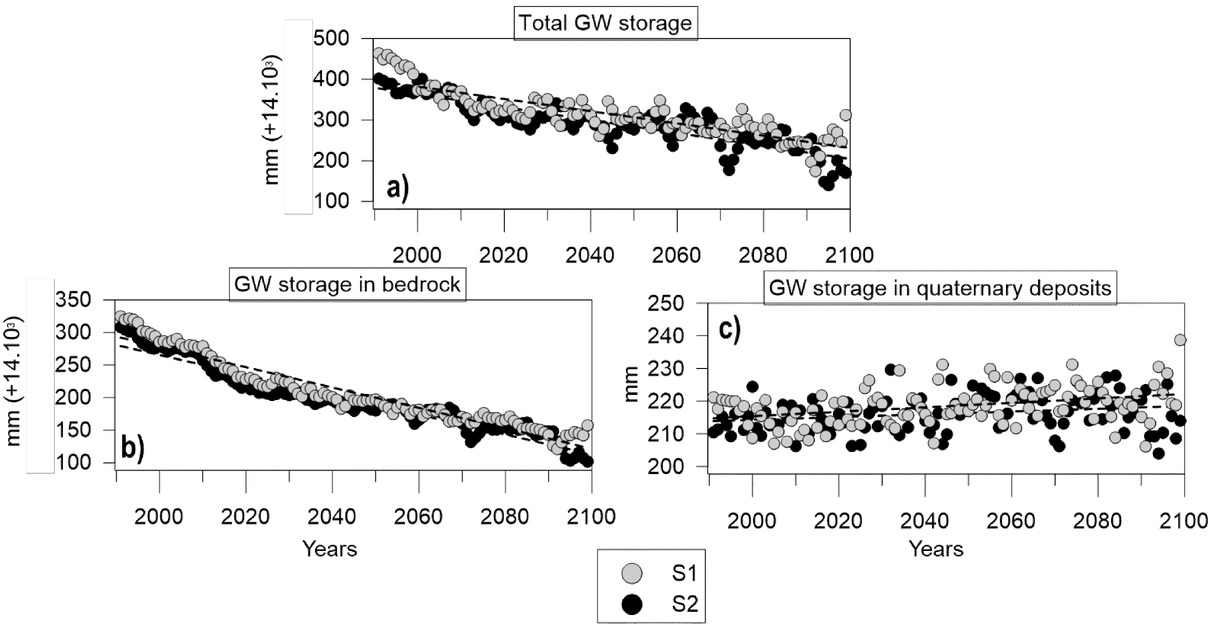


Figure 18: Annual averages of total groundwater storage, storage in low-permeable bedrock (basement) and storage in permeable quaternary unconsolidated deposits.

The large changes in snowpack dynamics and evaporation modify both the surface water and groundwater regimes. The maximum stream discharge diminishes and occurs early in the year. The stream discharge increases in winter and decreases in summer, leading to a transition of the minimal discharge from winter to summer. The groundwater regime changes as well, especially in the quaternary deposits, while the bedrock mainly shows a long-term trend. Groundwater storage increases in winter and decreases in summer leading to smaller annual amplitude. In relative change, groundwater storage is much smaller than the change in streamflow, highlighting the buffering effect of groundwater. These findings show that alpine catchments with high groundwater storage are more resilient to CC as they can store water during wetter periods and provide water during drier periods.

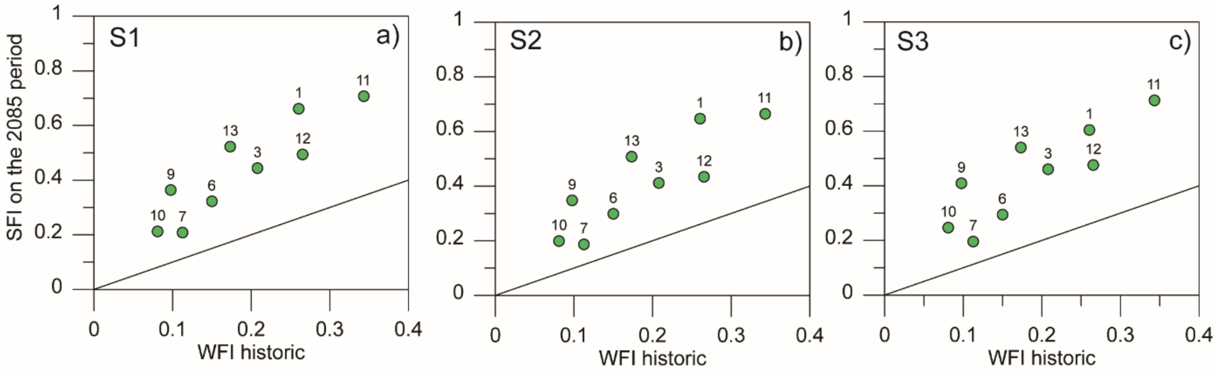


Figure 19: Comparison of future summer low flow rate (SFI) with historic winter low flow rates (WFI) for three CC models and different catchments at high altitude in the alpes (Arnoux et al., 2020a). The dimensionless low flow rates correspond to the minimum discharge over seven consecutive days during winter or summer divided by the mean discharge. The line illustrates a 1:1 relationship.

For water management, it is important to identify what environmental factors control the low flow rates. Our simulations suggest that future summer low flow rates will remain above current winter low flow rates by 2100, except for exceptionally dry years when they approach current winter flow rates (Figure 19). Catchments that have currently high winter low flow rates should also have high summer low flow rates in the future. An analysis of the relationship between geology/hydrogeology suggests that current winter low flow rates normalized by mean outflows are roughly correlated with areal extent of quaternary deposits that can act as storage volumes and/or favour recharge by retaining melt and rainwater. Thus, current winter low flow rate, or, in their absence, geological information can be used to appreciate summer low flow conditions under future climatic conditions. Regarding springs, the study suggests that varying effects can be expected with either a change in regime towards a more regular availability of groundwater and/or a long-term trend in discharge rates. However, these trends are so far only based on a limited amount of studies and have to be confirmed by additional studies.

The presence of glaciers and permafrost will influence groundwater response to CC in alpine areas. Glacier melt contribution to groundwater recharge is variable and poorly constrained as reviewed by (Somers and McKenzie, 2020). These authors found that, as the glaciers disappear, groundwater contribution to streamflow remains large and relatively consistent in the short term in a proglacial watershed of the Peruvian Andes. However, in the long term, evapotranspiration increases with temperature, decreasing groundwater recharge and exfiltration. The resulting dry-season streamflow is expected to decrease, as for lower alpine catchments with nival groundwater regime. However, in high catchments with extensive permafrost, its degradation will increase hydraulic conductivity of the soil and therefore will probably decrease peak flow and increase baseflow by increasing groundwater storage. Besides, changes in seasonal soil freezing are expected to influence both groundwater recharge and baseflow (Evans et al., 2018).

Take home message – Porous aquifers

- When evaluating the implications of CC on groundwater services, it is important to not only consider to what extent the services can be maintained (**reliability**), but also on how quickly they recover from considerable drawdowns (**resilience**).
- To what extent changes in groundwater recharge influence groundwater discharge dynamics depends on hydrogeological factors.
- Large aquifers with a low hydraulic conductivity, a high storage coefficient and/or an extensive unsaturated zone show a strongly buffered response to seasonal changes in recharge. However, they recover more slowly again from extreme periods. Examples for such systems are sandstone aquifer in the Molasse or extensive alluvial deposits with an extensive unsaturated zone.
- In reverse, small, superficial and/or very permeable aquifer that contribute to local water supply respond quickly to dry conditions but also recover quickly.
- In valleys with alluvial aquifers that extend from the mountainous zone to the plateau, the response to periods with diminished recharge strongly varies spatially. At upgradient locations, the groundwater level can drop rapidly over several meters, whereas further downgradient, groundwater levels remain stable.
- In alpine areas, extensive quarternary deposits covering the bedrock can buffer seasonal variability and stabilize stream discharge.

3.2 Karst aquifers

Karst aquifers cover ~20% of Switzerland under pluvial, pluvio-nival and nivo-glacial conditions. They differ from the other hydrogeological environments in three aspects mainly:

- The high rate of infiltration due to the relative absence of soils and the presence of open features (sinkholes, lapiaz, etc.) which favour the water to percolate deep through the ground. In certain regions, the infiltration rate may reach 100 mm/h. As i**nfiltration** in karst regions reaches 60 to 90% of total precipitation, the overall karst groundwater recharge represents nearly 40% of the total annual groundwater recharge in Switzerland. Malard et al. (2016) provide a benchmark for karst groundwater recharge in Switzerland with an estimated value of **8.4 km^3/yr, i.e. 20 to 46 L/s/km^2,** depending on the context (Tabular Jura, Folded Jura, Prealps, Helvetic Alps and Austroalpine domain), on hydrological years and on infiltration scenario (Figure 20).

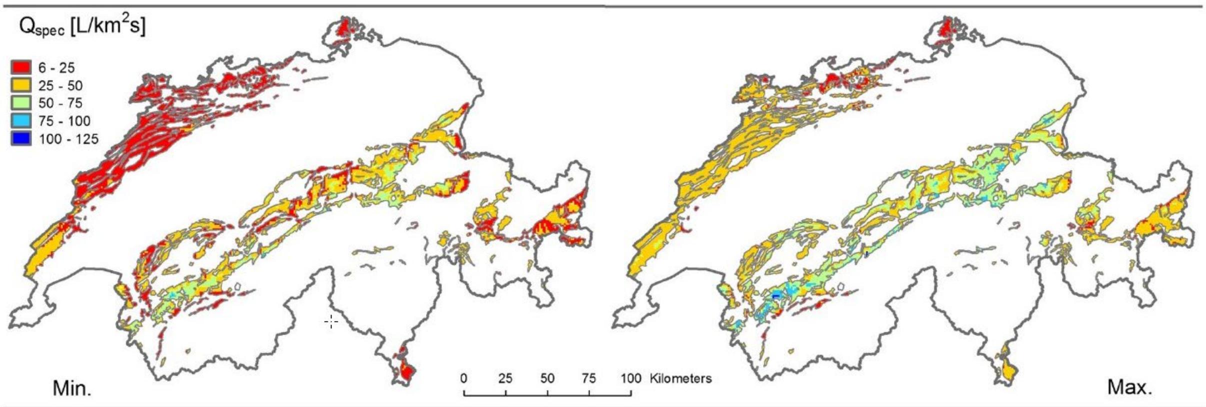


Figure 20. Annual recharge rates (in L/s/km^2) for minimum and maximum scenarios determined for all karst environments in Switzerland (Malard et al., 2016)

- The presence of a network of conduits connected to the spring, draining the surrounding volume of fissured rock. This implies the coexistence of a fast flow and a slow flow component: Groundwater flow-velocity in karst conduits may reach 1’000 m/h, while in low permeability volumes it does not exceed a few centimetres per hour.
- The high hydraulic conductivity of the conduit network induce very low gradients upstream from karst springs. As a consequence the unsaturated zone may be very thick in mountainous karst regions (up to 1’000 m).
- The thickness of the unsaturated zone combined with the heterogeneity of the hydraulic conductivities results in a cascade of temporary storages. Before reaching the spring, infiltration water may be stored successively in soils, in the epikarst, in some parts of the unsaturated zone and in the épiphreatic zone (Figure 21). Quick and slow flow components are present in all of these compartments leading to highly variable residence times; from a few hours up to several years, leading to huge effects on the flow dynamics at the springs.

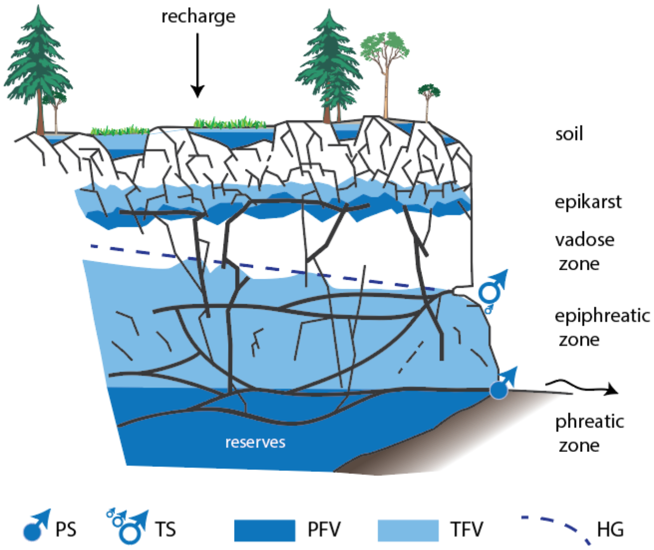


Figure 21. Location of the main storage compartments in a karst aquifer; PS: permanent spring, TS: temporary spring, PFV: permanently flooded volume, TFV: temporarily flooded volume, HG: hydraulic gradient in the main conduit network of the flow-system during flood events.

Two kinds of groundwater storages are usually distinguished in karst: groundwater **reserves** and groundwater **resources**.

Reserves refer to the volume of water enclosed in the carbonate rocks below the regional base level (usually the karst spring, located close to the level of the main valleys). In Switzerland reserves have been assessed to 120 km^3 until a maximal depth of 1,000 m below the ground surface (Jeannin et al., 2013). Reserves are usually not considered in the groundwater budget. Water is stored in the deep conduits and in the low permeability volumes of the phreatic zone.

Resources refer to the volume of groundwater located above the base-level, i.e. which could flow to the spring. Water can be stored in small conduits, fissures and rock matrix (low permeability volumes) within the epikarst (including soils), in the vadose zone and in the epiphreatic zone. Most of the storage is located in fissures and rock matrix (low permeability volumes). Conversely, conduits only account for a few percent of the storage capacity (Atkinson, 1977; Worthington et al., 2000).

The analysis of karst springs hydrographs usually shows at least two components in the discharge recession: a relatively “fast component”, which is assumed to results mainly from the storage in the “conduit network“, and a relatively “slow component” resulting mainly from storage in “low permeability volumes” (see Figure 22). The fast component provides the **seasonal storage** and it is seasonally replenished, while the slow component provides the **low flow storage**,which provides water at karst springs only for periods of drought.

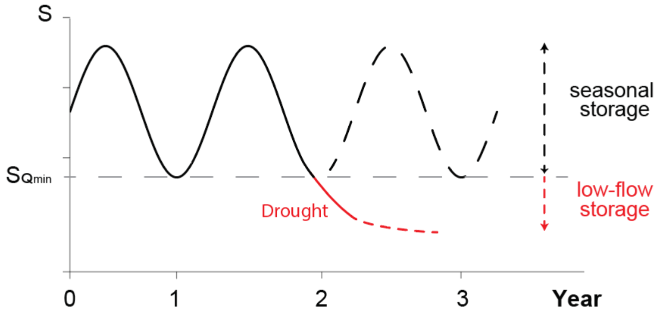


Figure 22. Difference between the seasonal and the low flow storage

Observations at various sites in Switzerland and analyses demonstrated that the low flow discharge of most karst springs can be well reproduced by the combination of two exponential curves with similar coefficients (ISSKA, 2019). This recession applies when discharge is not directly influenced by specific recharge events, i.e. below a certain value of discharge (~11.25 $L.s^{-1}.km^{-2}$). This value has been defined as the “debit d’entrée d’étiage”, and it surprisingly applies for most karst aquifers in Switzerland. The corresponding volume of storage is ~200 mm). It is expected to be the amount of water stored in the low permeability volumes of karst aquifers. This storage is recharged when heads inside the karst aquifer exceed a certain value. The aquifer remains in low flow conditions until recharge is sufficient to fill up the low-water storage to replenischment.An illustration is given in **Erreur ! Source du renvoi introuvable.** for the Areuse spring (NE). Green zones are periods of recharge with different intensities. Yellow zones reflect low-water conditions in the aquifer, turning to very low water (orange) and drought (red). Small recharge events during low water conditions are not sufficient to fully replenish the low flow storage (i.e. the “GW-Stock” does not increase to 1). Therefore, discharge rate goes back to low flow very soon after these short events.

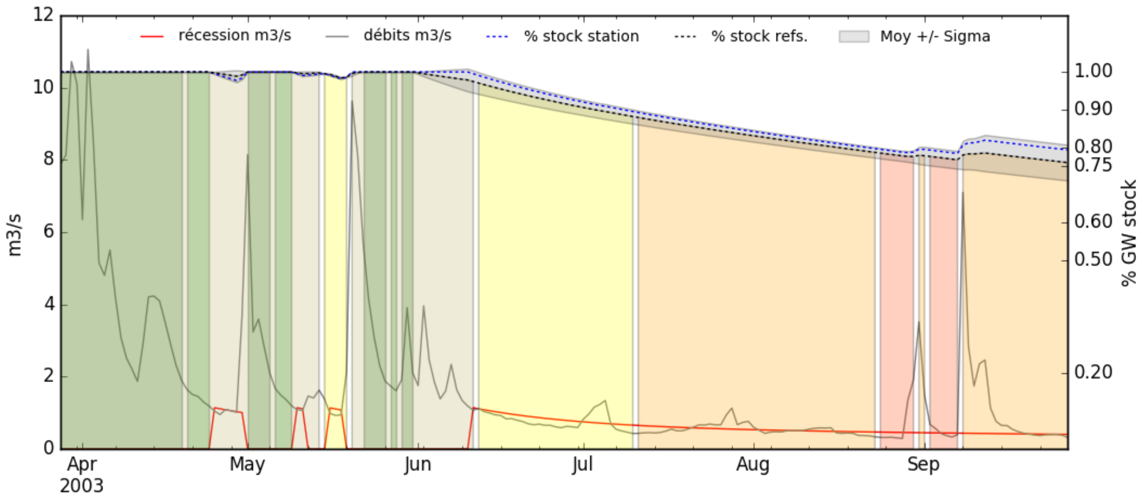


Figure 23. Application of the recession model on the discharge rates of the Areuse spring for April to October 2003. The grey line refers to the measured discharge at the NAQUA station; The dotted lines at the top refer to the let scale (% stock station) giving the state of replenishment of the low flow storage; and the red curve (recession) refers to simulated recessionsof the low flow discharge We can observe that periods of recession are well reproduced by the recession model. In September, in spite of significant flood events, the low flow storage is not significantly replenished and discharge rate quickly goes back to low flow rates.

Seasonal storage in karst aquifers ranges between 40 to 70 mm (see **Case Study 5** and (ISSKA, 2015)), i.e. from 0.3 to 0.5 km^3 (max 1 km^3) at the scale of Switzerland, including uncertainties and variations of hydrological conditions. It represents 3 to 10% of the annual recharge. These values are consistent with simulations made by Chen et al. (2017) for an Alpine karst aquifer in Austria. The authors found that the seasonal storage between high- and low flow periods is about 60 mm (i.e. 5% of the annual recharge).

Groundwater in karst aquifers is mainly discharged through concentrated springs, highly reactive and of relative high discharge rates. The mean groundwater discharge in the year from karst aquifers in Switzerland is about 270 m^3/s (Malard et al., 2016). Discharge rates at springs are characterized by large fluctuations between low- and high-flow periods (from 1 to 100, up to 1 to 1'000) reflecting the high drainage capacity of the aquifer. As an example, for the Areuse spring (NE), 50% of the annual flow is discharged in 50 days approximately, i.e. less than 20% of the year.

This means that for any karst flow-system, according to these criteria and knowing the dimension of the catchment area, it is possible to extrapolate the recession of the springs discharge over several months.

The typical shape of recession is given in Figure 24 and extrapolated over 12 months. This corresponds to an extreme situation where no recharge would take place over an entire year. This graph shows the expected evolution of groundwater storage for 1 km^2 of groundwater catchment in karst areas.

It is interesting to see that the discharge rate drops to 50% of its initial value after ~50 days of low flow conditions. After 12 months, the discharge rate is still 15% of the initial value. Regarding low flow storage, the curve shows that the storage decreases of about 10% in the first month. 50% of the initial storage is merely reached after 9 to 10 months.

Low flow duration and frequency have been assessed for two flow-systems over the last 30 years of records: the Areuse spring (NE) and the Milandre underground stream (JU). Observations show that drought may extend over 8 months once every 50 years at Areuse and once every 7 years at Milandre.

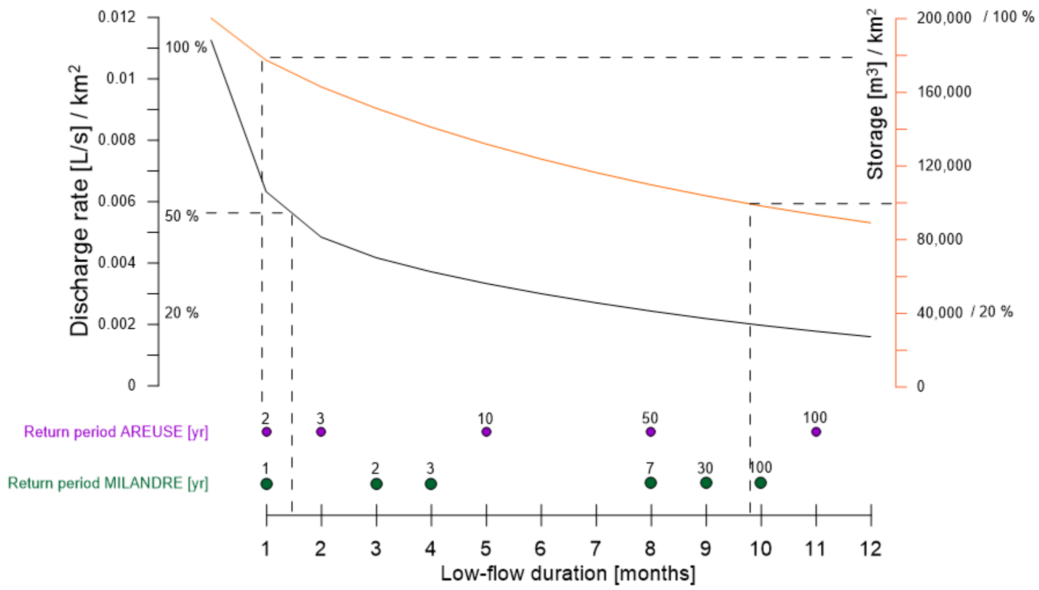


Figure 24. Top: evolution of discharge rates and groundwater storage during low flow conditions for a karst flow system (values are given per km² of catchment area). Bottom: return periods of low flow duration for Areuse spring and Milandre underground stream (in months).

Regarding winter droughts for high elevated catchments, observations show that for a nival-dominated aquifer (Schlichenden Brunnen, SZ), usual winter droughts are 4 months long while they may extend up to 7 months for nivo-glacial conditions (Tunnelquelle, Flims, GR). Statistically, it is interesting to observe that aquifers dominated by nivo-glacial conditions actually experience longer periods of drought (in winter) compared to lowland karst aquifers (in summer).

Case Study 5: seasonal storage in karst aquifers (Areuse, NE)

The Areuse karst aquifer has been described in several publications (Burger, 1959; Kiraly, 1973; Schürch et al., 2016; Tripet, 1972). The spring flows out from the Jurassic limestone in the western part of the folded Jura Mountain. The catchment area extends over 126 km^2 and is representative of snow-influenced conditions.

Simulations at the Areuse karst aquifer for a 15 years period (Figure 25) show that the mean seasonal storage is about 5 millions m^3, i.e. 3.5% of the mean annual recharge (~145 millions cbm). This represents about 40 mm of water which are seasonaly stored in the aquifer between low- and high-flow periods (cf. Figure 22). For extreme wet years (for instance 2000, 2002 and 2006), the seasonal storage exceeds 7 millions m^3, indicating that the seasonal storage capacity is a priori larger than 55 mm.

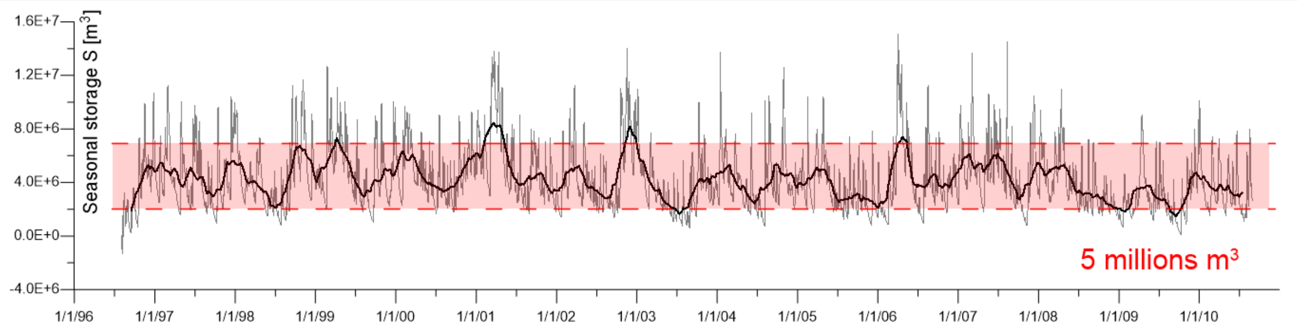


Figure 25. Variations of the seasonal storage for the Areuse test site based on the simulated discharge rates for the period 1996-2010 (daily timestep); the black curve refers to the 90 days running average (Malard et al. [2018])

The low flow storage and the discharge recession of the spring have been recently evaluated with the objective to understand and to reproduce the persistence and the rate of the spring discharge for summer droughts (ISSKA, 2019). Analyses of low flow periods (1996-2018) show that the low flow storage capacity of the aquifer is about 200 mm which reveals larger than the seasonal storage capacity.

The low flow reservoir is usually fully saturated at the end of the wet season. Depending on climatic conditions for the low-water period, this reservoir starts emptying and supports baseflow. Under current conditions, during significant droughts (e.g. 2018) the low flow storage may fall down to 70% (140 mm). Theoretically, the extrapolation of the recession tails show that karst springs may persist more than two years without any recharge.

Pluvial and pluvio-nival regime

In the perspective of CC, longer periods of droughts are expected for lowland to mid-elevated aquifers. If we suppose that return periods of drought are shortened by two, the expected duration of the recession will be 1 or 2 months longer. For instance, return periods of drought of 10 years for Areuse will move from 5 to ~6 months, and for Milandre will increase of a few days. In both cases, the expected decrease in discharge at the end of the recession will be significantly lower than 1 L/s/km^2: from 10 to 9 L/s at Milandre (4.5 km^2) and from 410 to 370 L/s at Areuse (120 km^2) The decrease in storage at the end of the recession will be less than 10% compared to current conditions. The decrease in resource does not seem significant. However, as water demands could increase in the meantime, e.g. for irrigation, cooling and other uses, frequent problems of supply may occur in late autumn. Adjustments in tapping strategies - such as a controlled overexploitation of groundwater reserves (groundwater volume located below the level of the springs) - may be required, especially for lowland karst aquifers (north-western part of Switzerland). This scenario can be applied as long as groundwater reserves are replenished during the recharge period. Such tapping strategy is called “active management” and is already frequent in various contexts, e.g. valley of Saint-Imier, BE (MFR, 1998) or in southern France (Fleury et al., 2008), etc. This strategy however lead to the drying up of karst springs, thus of surface streams for several months in autumn.

During recharge periods, effects of CC on karst groundwater are not supposed to be significant for lowland to mid-elevated aquifers. The surplus in recharge will not be stored in the low flow storage, and will mostly be flushed out at karst springs within a few days.

As noticed in Chapter 2.1, another consequence of CC would be the increase of extreme recharge events, which are expected to happen more frequently both in winter and summer. Expected variations with this respect are similar to those described for surface streams (FOEN, 2012): for snow and glacier-dominated conditions, potential flooding will follow the evolution of the snowmelt with an additional contribution of extreme rain events. The frequency of extreme recharge events is expected to increase in most regions. In karst regions, extreme flooding is controlled by storage conditions in the aquifer which are site-specific and non-linear processes. It may lead to unexcepted discharge rates at karst springs, or even to a reactivation of paleosprings, but it can also dampen the intensity of flood events. An example has been provided by (Malard et al., 2014) working on the floods of the Suze river in Biel, (see **Case Study 6**). Many other sites in Switzerland may be exposed to significant karst flooding, such as in Ajoie (Vouillamoz et al.), or in alpine valleys (Bättig and Wildberger, 2007).

Nivo-glacial regime

With the decreasing cover of glaciers the global discharge of alpine springs is increased by the melt water. This will change within the second half of the 21th century as most glaciers will have disappeared. The global recharge will thus decrease but it might be counterbalanced by a larger exposure of karst outcrops to direct infiltration via rainfall and snowmelt (less runoff). However, compared to current conditions, globally less recharge is expected for karst aquifers under nivo-glacial regimes.

As presented in chapter 2.2.2. actual winter droughts will progressively become shorter. Alpine springs will provide more water in spring and possibly late autumn. Droughts may appear in autumn before the first rainfalls occurring in November or December. They will however be less pronounced than actual winter droughts.

One of the direct effects of CC will be the increase of flood hazards for downstream valleys. As melt periods will become shorter and rainy, we might expect the melting rate being higher, especially over the short coming term, as long as glaciers contribute to melting.

Case Study 6: Does the karst aquifer enhance or dampen flood-peaks of the (example of the Suze river upstream the city of Biel, BE)?

The city of Bienne (BE) located downstream of the Suze River is exposed to flooding caused by the River overflows. Although the infrastructures were designed for a maximal discharge rate of 100 m^3/s (return period of 100 years), it appears that the river threatened to flood the city more than 6 times during the past century. The frequency analysis of the flood peaks shows an abrupt increase when the river discharge rate exceeds 75 m^3/s, On the other hand a plateau is observed at ~95 m^3/s, meaning that discharge rates for events with a return-period of 150 years are almost the same as those with a return period of 30 years! This mechanism is likely to result from significant storage processes taking place in karst aquifers upstream of the city, which smooth out extreme discharge peaks (Figure 26).

Temporary water storage in karst can be produced by the flooding of conduits (caves), which are reached by water only during high or very high flow conditions. This happens when the discharge capacity of the lower spring(s) is overpassed. Groundwater head rises then until it reaches another upper passage leading to the activation of overflow springs (b). If the storage volume between levels (a) and (b) is large, a significant plateau on the total hydrograph may be produced. If the flow capacity of level b is exceeded, heads may continue to rise until the water reaches a more elevated conduit level (overflows c).

In the present case the activation of spring c should lead to an new increase of the discharge for high return periods (Figure 26). In some cases spring (c) could be located in another valley than springs (a) and (b). Pateau (b) would then remain even for very high return periods.

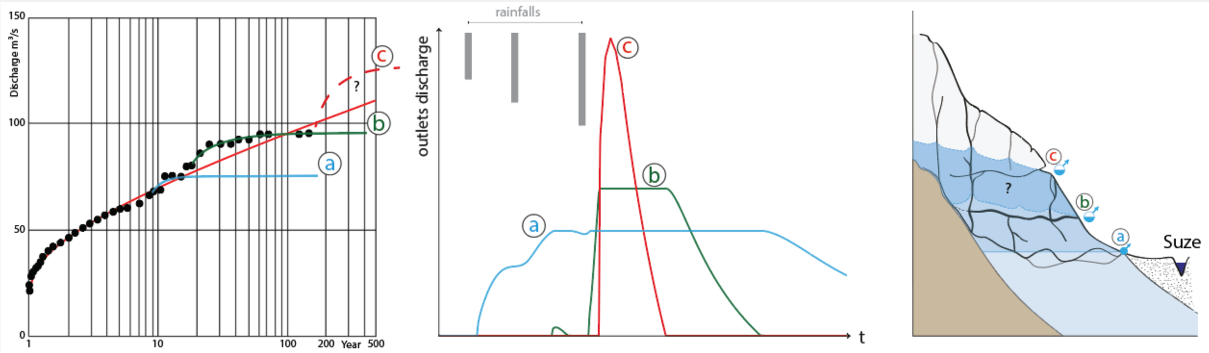


Figure 26.Non-linear evolution of flood peaksin karst regions: the successive activation of the (b) and (c) overflow springs will increase peak discharge of the flow-system (Malard et al., 2016)

In order to prevent disasters related to karst-enhanced floods, potentially exposed regions should therefore be investigated in details from the point of view of karst hydraulics. Forecasting models based on this knowledge and using groundwater measurements and meteorological predictions could then be proposed to predict risky situations.

Take home message – Karst aquifers

Aquifers of pluvial regime

- "Normal" periods of drought in summer will be 1 or 2 months longer than today and will extend later in autumn. The natural decrease in groundwater discharge will be clearly less than 1 L/s/km^2 at the end of the droughts compared to current conditions. The expected decrease in groundwater resources will probably not be significant compared to the expected demands from the users (irrigation especially). Ecological services may thus suffer from the deficit of karst groundwater, especially in wetlands or in downstream rivers.
- More groundwater recharge is expected in winter. This may compensate the observed deficit at the end of the drought period as the replenishment of karst aquifers is usually faster than for other aquifer types.
- Flood risks by groundwater uprising will increase in the summer time due to more intense precipitation (storms, etc.). This could be also the case during winter when groundwater storage is full and the excess water is drained by runoff.

Aquifers of pluvio-nival regime

- For catchments close to 1000 m a.s.l. drought periods in late summer will become longer than actual winter droughts.
- As for lowland aquifers, more groundwater recharge is expected in winter as snow accumulations may be frequently interrupted by rain events or short melting periods which enhance groundwater recharge.
- Flood risks may increase in winter – especially at the end – due to the conjunction of faster melting and rainfall events over fully saturated aquifers.

Aquifers of nivo-glacial regime

- For most aquifers of nivo-glacial regime, winter periods of drought will become shorter than today.
- In contrast, periods of drought may appear in late autumn, especially for aquifers which are not influenced by glaciers melt. In most cases periods of drought will remain shorter than current periods of drought in winter.
- Flood risks may be reinforced in spring by the conjunction of snow- and ice melt and intense rainfall events over fully saturated aquifers.

3.3 Implications for groundwater services

The implications of CC will likely vary depending on the groundwater service that is considered. Besides water supply groundwater also sustains ecosystems such as spring habitats, wetlands, alluvial forests or the hyporheic zone in streambeds. These ecosystems generally depend on the emergence of groundwater at land surface (springs, wetlands) or on groundwater levels close to the surface (alluvial forests, hyporheic zone). Due to this dependence on the near-surface presence of groundwater, ecosystems tend to be more sensitive to drought periods than water supply that can access deeper portions of stored groundwater.

The pressure on ecosystems can occur naturally or be accelerated by groundwater extraction for water supply as illustrated by both schematic examples given in Figure 27. The first case shows a multi-layered aquifer in fluvio-glacial deposits (Figure 27a). The upper aquifer supplies water to wetlands and a pond. Due to its shallow occurrence it will be very sensitive to climatic variations. The deeper aquifer is less sensitive to seasonal variations and its exploitation for water supply is not expected to influence ecological groundwater services. In the second example, a single aquifer is used for water supply and feeds a wetland and spring (Figure 27b). The deep pumping well has a low sensitivity to climatic variations. However, water extraction can negatively influence the groundwater discharge to the wetland and spring. In contrast to case 1, groundwater extraction for water supply competes with ecosystem service. In some cases, water supply systems themselves are sensitive to CC as they rely on the most superficial emergence of groundwater or only reach to a shallow depth. If groundwater reserves are overexploited beyond to what would naturally be discharged, it is important to ensure that the overall groundwater recharge is sufficiently effective to annually replenish the resource again.

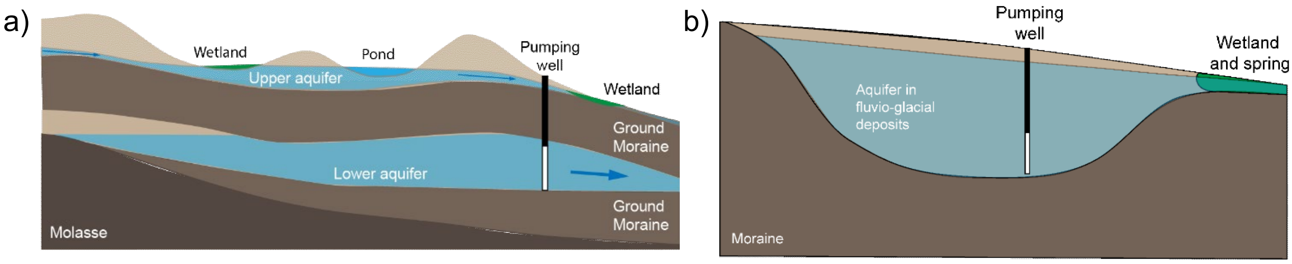


Figure 27: Illustration of the relationship between groundwater services for water supply and ecology and their sensitivity to drought and low flow conditions. (a) Two aquifer levels separated by till with groundwater pumping in lower aquifer. Wetlands and pond are sensitive to drought, but not pumping. (b) Single aquifer used for water supply and supplying a wetland and spring. Wetland and spring are sensitive to drought as well as water extraction by pumping.

4 Groundwater temperature and quality

Introduction

In this chapter, expected effects of CC on groundwater temperature and quality will be reviewed. These two topics are related as changes in groundwater temperature can indirectly modify the groundwater quality via its influence on the rate of biogeochemical processes, redox conditions or rate of inactivation of microbial contaminants.

4.1 Changes of groundwater temperature

The increasing air temperatures are expected to propagate to groundwater. In addition to this direct effect, the groundwater temperature will likely also be influenced by indirect effects, especially the more common use of groundwater for cooling as a consequence of CC. A cummulation of direct and indirect effects could likely lead to a particularly pronounced increase in groundwater temperature. In addition, other factors than CC influence the groundwater temperature as well such as urbanization or geothermal installations. For aquifers in unconsolidated deposits, seasonal temperature variations tend to vanish at distances of 10s to 100s of meter from the recharge zone, making it easier to track long-term temperature trends (Figure 28). In karst aquifers, temperature fluctuations can be propagated deeper into aquifers through preferential flow zones and hence temperatures are also influenced by the hydrological conditions.

Several studies have investigated instrumental records to explore relationships between air and groundwater temperatures in the past decades. A study based on data from the NAQUA National Groundwater Monitoring and long-term data records found contrasting temperature trends (Schürch et al., 2018). In nearly half of the locations covering various aquifer types, the temperature increased (>0.2°C/10 years) likely due to CC and/or urbanization. A decrease in temperature was observed for unconsolidated aquifers either due to geothermal use of groundwater or to more recharge during the winter season (Schürch et al., 2018). A more detailed modelling study for aquifers predominately fed by infiltrating river water confirmed that under future climate conditions, groundwater temperatures could decrease in such systems (Epting et al., 2020). The higher winter stream discharge due to more precipitation and a higher fractionation of rain leads to a higher fractionation of groundwater recharge during winter. Other studies have generally identified an increase in groundwater temperature in response to increasing air temperatures, once local effects have been considered such as changes in pumping regimes, land use changes or thermal use of groundwater (Benz et al., 2018; Figura et al., 2011; Menberg et al., 2014).

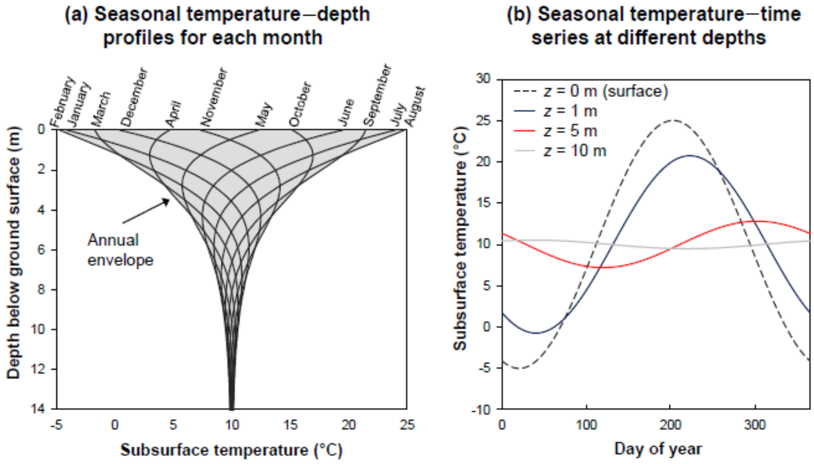


Figure 28: Propagation of seasonal temperature variations to groundwater as a function of the depth to the water table for a shallow sandy aquifer (Kurylyk et al., 2015).

The relationship between air and shallow groundwater temperatures has also been investigated systematically using analytical and numerical models (Figura et al., 2011; Kurylyk et al., 2015). These models have shown that the timing and magnitude of groundwater warming will depend on several factors including the rate of surface warming, subsurface thermal properties, aquifer depth and groundwater velocity (Kurylyk et al., 2015). As long as the surface temperature increases, the subsurface temperature will never reach an equilibrium with it and lag behind. However, the thermal sensitivity (i.e. the increase in groundwater temperature per degree in increase in air temperature) increases over time as the air temperature raises. For shallow groundwater, the increase in temperature is expected to become close to the increase in air temperature (Kurylyk et al., 2015) over longer time scales. The change in groundwater temperature will propagate all the way to groundwater discharge zones and influence stream water temperature. Studies have highlighted the need to consider the long-term groundwater temperature dynamics when predicting future stream-habitat temperatures (Snyder et al., 2015).

In addition to long term temperature changes, short term effects during heat waves play a role in case of indirect recharge via the propagation of elevated river water temperatures into aquifers, especially for water close to the surface. Hence, in aquifer zones near streambeds i.e. the hyporheic zone, temperatures might increase more strongly in some periods than the change in the annual mean temperature. This more pronounced temperature increase can have a significant effect on the surface water quality and the quality of water recharging from rivers as both are influenced by processes in the hyporheic zone.

Take home message – Groundwater temperature

In areas dominated by direct recharge, the increase in air temperature is expected to propagate to groundwater. However, if river water infiltration is a dominant recharge mechanisms, the groundwater temperature can decrease due to higher fraction of recharge during winter.

In addition to climate change, other factors influence groundwater termperatures especially heat release from belowground infrastructure and geothermal energy use.

4.2 Changes in groundwater quality

Besides temperature CC can also influence groundwater quality for several further reasons. The composition of water that recharges aquifers might change as CC can influence the composition of direct recharge through soils as well as of infiltrating river water. The relative contribution of different recharge sources changes and thus the mixing ratios between these waters in the aquifer. Because different recharge sources often have a different chemical composition, changes in mixing ratios will modify the resulting chemistry. This mechanism can lead to a change in the groundwater composition even if the composition of each recharge source remains unchanged. Finally, processes within the aquifer might be altered if the groundwater dynamics or physico-chemical conditions such as temperatures change. In the following, these mechanisms are reviewed in more detail.

4.3 Modifications of the composition of recharge water – Direct recharge

CC can influence the composition of recharge waters directly under constant land use or indirectly via land use changes that are triggered by CC. In the discussion, the emphasis lies on direct effects as indirect effects are difficult to predict. We mainly focus on agricultural lands as agriculture often strongly influences the chemical composition of recharge waters. Numerous studies have investigated the CC effects on nitrate leaching, as nitrate is a very widespread groundwater quality problem. Fewer studies were dedicated to other compounds such as pesticides or microbial groundwater quality.

4.3.1 Nitrate leaching

Different methodological approaches were used to investigate CC effects on nitrate leaching (Table 7). This includes the analysis of nitrate leaching during past extreme conditions, lysimeter experiments reproducing future climatic conditions, and modelling studies. The modelling studies generally made use of models that integrate crop grows, soil water dynamics and soil nitrogen/carbon dynamics. The emphasis of these models is often on the effect of cropping systems and nutrient cycles while the soil hydrology is strongly simplified and associated uncertainties are not considered. CC effects are evaluated with different levels of complexity. In some studies, the sensitivity of the system to changes in temperature and precipitation is evaluated by applying increments of change to past data series. In others, meteorological input data are generated using one or several climate model chains.

Agricultural studies generally express nitrate leaching in terms of nitrate fluxes in kgN/ha transported below the root zone. How changes in nitrate fluxes translate into concentration changes depends on the CC effect on recharge rates, which is often not presented.

Table 7: Overview of research approaches to investigate the effect of CC on nitrate leaching

Experimental approach	Description	Examples
Data-based evaluation of sensitivity to temperature and precipitation	Nitrate leaching under past extreme meteorological conditions (dry/wet periods, elevated temperatures) is evaluated.	(Jabloun et al., 2015)
Lysimeter experiments	Future climatic conditions are simulated by modifying precipitation frequency and intensity in covered lysimeter facilities, and by soil heating.	(Patil et al., 2012)
Model-based analysis of sensitivity to temperature and precipitation	Models are calibrated to past data series. Precipitation and temperature are modified in increments covering a likely range of change based on climate models.	(Patil et al., 2012)
Coupling of CC with agricultural/soil models	Meteorological data time series are generated with climate model chains and used as input parameters in agricultural/soil models.	(Doltra et al., 2014; He et al., 2018)

The current mechanisms of nitrate leaching are well understood: Leaching occurs due to mismatch between N supply and N crop demand leading to an accumulation of N in form of nitrate in soils that is at risk of leaching to groundwater. The amount and timing of nitrate leaching are strongly influenced by soil hydrological processes, but also depend on the biogeochemical N turnover in soils and on the dynamics of crop growth, which are all sensitive to meteorological parameters. The leached N mainly originates from N-mineralization rather than from direct leaching of fertilizer especially in countries having optimized N fertilization.

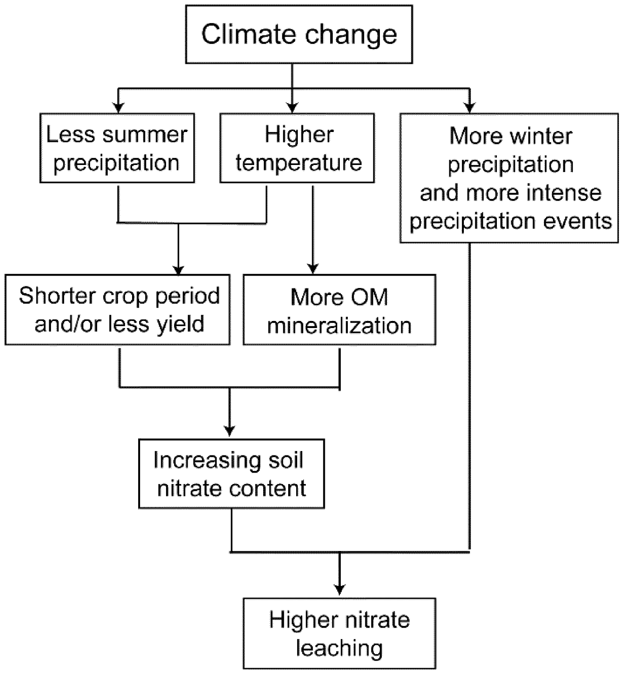


Figure 29: Mechanisms that lead to increased nitrate leaching due to CC.

Under constant land use, studies generally suggest that CC will lead to an increase in nitrate leaching (Bowles et al., 2018; Stuart et al., 2011). The main mechanisms leading to an increase in nitrate leaching are summarized in Figure 29. Under more variable climate conditions with more frequent extremes, it becomes more challenging to synchronize N supply and demand. Several mechanisms can modify nitrate leaching depending on the season (Table 8). During spring, there is generally a risk of a mismatch between N availability and N demand i.e. if fertilizer is already in place, but plant growth is delayed due to adverse weather conditions. More variable weather conditions and especially the greater frequency of larger and/or more intense precipitation events could lead to more frequent nitrate leaching (Congreves et al., 2016). During summer, changes in temperature and precipitation influence plant growth and the rate of N mineralization, in addition to soil hydrology. In years with favourable moisture conditions, higher temperatures can accelerate plant growth, partly to avoid heat stress (phenological escape) and the harvest occurs earlier (Doltra et al., 2014; He et al., 2018; Patil et al., 2012). The faster crop development is often associated with a smaller crop yield and correspondingly lower N uptake, as plants have less time to intercept radiation, which is necessary to produce biomass (Doltra et al., 2014; He et al., 2018; Patil et al., 2012; Rezaei et al., 2015). Thus, a higher amount of N remains in soil. After the harvest, the N mineralization under warmer conditions remains high while the N demand has dropped, further increasing the risk for leaching. In years with warm but dry conditions, the crop growth and accordingly nutrient update is restricted by drought stress. Higher unused N residuals remain in the soil that can be subject to leaching. Some studies suggest that N-mineralization is less influenced by drought stress than plant growth, further contributing to an excess of mobile N.

The effect of hot and dry summers on groundwater nitrate concentrations is well documented for past events, as illustrated with data from a case study in the Canton of Aargau (Baillieux et al., 2014) and from the NAQUA National Groundwater Monitoring network (Figure 30). In the case study, the nitrate concentration increased after drier summers of 2003, 2004 and 2005 with a delay that is related to the travel time through the hydrogeological system. The increase is however much smaller than the previous decrease due to the transformation of cropland to prairies. Increased nitrate leaching after dry periods seems to be widespread as indicated by the NAQUA data (Figure 30, right). After 2003, the 25 mg/L concentration limit is exceeded in a larger proportion of monitoring wells with capture zones dominated by cropland. In a lysimeter study carried out by Agroscope in Reckenholz (ZH), an increase of nitrate concentrations after dry summer conditions was also observed (Vögeli Albisser and Prasuhn, 2013). Changes in nitrate leaching are also caused by modified climatic conditions in automn and winter, when generally a major part of nitrate leaching occurs. For soils with a higher water storage capacity, higher winter precipitation can lead to a larger fraction of leaching of the stored nitrate, while for soils that can store less water already under current conditions most nitrate is lost. The amount of nitrate leaching can further increase due to higher N mineralization related to warmer automn and winter temperatures. However, the higher N availability can be offset by a higher crop N uptake by the winter cover (catch or winter crop).

In addition to changing meteorological conditions, CC can influence the crop dynamics also via a CO_2 fertilization effect by the higher atmospheric CO_2. Increased CO_2 reduces stomatal conductance. This could theoretically conserve soil moisture as less water is transpired. However, drought stress limits the CO_2 fertilization effect.

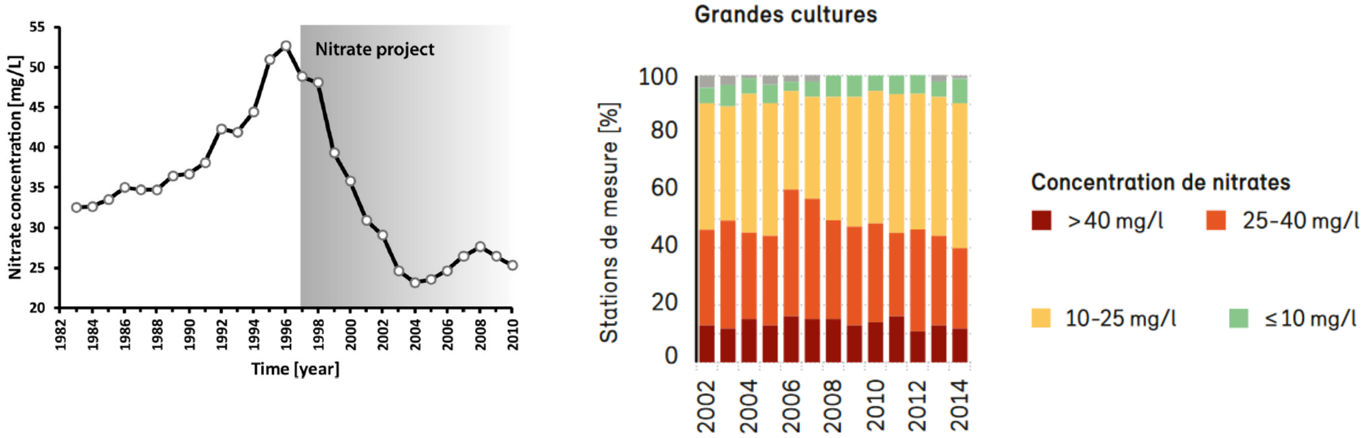


Figure 30: Influence of the 2003 dry and hot period on nitrate concentrations. Left: Data from pumping well where cropland was transformed into meadows to lower nitrate concentrations (Baillieux et al., 2015). After the hot and dry period, nitrate concentrations increased again temporarly. Right: Nitrate concentrations for 93 monitoring sites with predominantly croplands in their capture zone (FOEN, 2019).

Some studies have also investigated interactions between CC and land management. In one modelling study, the effect of climate variability was compared for conventional and best management practices for the same main crops (no till, fertilization based on soil testing, catch crops). For moderate

CC, nitrate leaching was less sensitive to climate variability under best management than conventional practise. However, for more extreme conditions, the effectiveness of best management procedures decreased (Congreves et al., 2016) because nitrate leaching more frequently occurred during the main crop growth period when soil nitrate concentrations tend to be higher also under best management practise. Some studies indicate the effect of CC on nitrate leaching to be smaller than the effect of improved management practises (Congreves et al., 2016), while other studies observed the inverse (Doltra et al., 2014). However, there is a general consensus that best management practices are even more important under more variable climate conditions, to minimize periods with a high amount of leachable N in soils.

Table 8: Overview of mechanisms that modify nitrate leaching due to CC. While climate models consistently predict higher temperatures, the effect on precipitation (especially summer precipitation) is less certain. Thus, warmer summer conditions might be associated with or without less precipitation, and thus both combinations are considered.

Period	**Climate change feature**	**Consequences on nitrogen cycling and nitrate leaching**	**References**
Spring	Intense precipitation	Leaching of fertilizer before plant uptake	(Congreves et al., 2016)
Summer	Warmer and moist conditions	More rapid crop growth leads to smaller N uptake and longer subsequent periods with N-mineralization but little uptake. Higher risk of N leaching.	(Doltra et al., 2014; Patil et al., 2012)
Summer	Warmer and dry conditions	Reduced plant growth and N uptake leads to higher a soil nitrate that is subject to leaching.	(He et al., 2018)
Automn and winter	Warmer and more humid conditions	Higher N mineralization due to higher temperature and higher potential for leaching. However, better growth conditions for catch or winter crops can increase N uptake	(Patil et al., 2010)

Farmers will likely adjust their practices to CC, which was not taken into account in most of the studies discussed above. Such changes can be considered as indirect consequences of climate on nitrate leaching. Farmers might plant different crops, for example, more winter crops or other intermediate crops to fill gaps in the crop sequence due to more rapid crop growth. In addition, different versions of the same crop (cultivars) might be used that have a longer growth period and/or are more adapted to heat/drought stress. Such adaptations will reduce periods with no vegetation cover and thus likely reduce nitrate leaching. Another expected adaptation is irrigation. With irrigation, crop growth and N uptake continues during drought periods decreasing the potential for nitrate leaching of unused N as long as over-irrigation is avoided (Vögeli Albisser and Prasuhn, 2013). However, even under optimized periods, in open field agriculture, periods with elevated soil nitrate concentrations will persist in the future. To limit nitrate leaching under more variable and extreme conditions, best management practices will become even more important

4.3.2 Pesticide leaching

For predicting the CC effects on pesticide leaching, the main mechanisms leading to pesticide leaching to groundwater need to be considered. Pesticide leaching mainly occurs through preferential flow triggered by abundant precipitation. The risk of preferential flow depends on the soil structure and is usually higher for clay and loam rich soils than for sandy soils. Compound properties play an important role too. The more rapidly a compound degraded, the more strongly it is adsorbed to the soil matrix and the more rapidly it diffuses into soil aggregates, the lower is the risk for pesticide leaching. Most of these processes are sensitive to precipitation and/or temperature and thus pesticide leaching might be modified by CC (Table 9). Similarly, to nitrate leaching indirect effects will play a role too. These include shifts in land use and crop patterns, and a possible higher use of pesticides due to higher pressure by weeds and plant diseases.

The following discussion of CC effects on pesticide leaching is mainly based on studies from Scandinavia, where the topic has received a particular attention. In a study in Sweden, the changes in amount of pesticide leaching was investigated for a silty clay soil cultivated by no-tillage practise, which can be considered as a worst-case soil for pesticide leaching due to the stable aggregate structure and abundant earthworm hole (Steffens et al., 2013). The authors considered three compounds with a small, moderate or large tendency to sorb, and simulated pesticide leaching with a numerical model that takes into account preferential flow (MACRO). While higher precipitation generally increases the risk of pesticide leaching, temperature has a competing effect. Higher temperatures increase degradation and diffusion, thus reducing the risk of pesticide leaching while it leads to weaker sorption, thus increasing leaching. Using a single CC scenario, the authors concluded that leaching of weakly and moderately sorbing pesticides applied in spring should decrease due to the dominant effect of faster degradation due to higher temperature. In contrast, for automn application, the effect of increased precipitation dominates over temperature effects and pesticide leaching is likely to increase (Steffens et al., 2013).

The scope of the study was then expanded from a single site to cover the entire south of Sweden. Direct (changing climate) and indirect effects (changing pesticide use due to CC) were considered (Steffens et al., 2015). Indirect effects included change in land use from grassland to maize, shifts from summer to winter crops, and an increased use of pesticides to address a higher weed pressure. Among the 37 simulated herbicides, only 7 gave simulated concentration above 0.01 ug/L, and total leaching concentration was dominated by 4 compounds (clopyralid, bentazone, metamitron, metazachlor). Leaching was higher for soils with a lower organic carbon content and a higher clay content. Direct CC effects on pesticide leaching were minimal with a slight decrease in leaching because enhanced degradation due to higher temperature and changes in precipitation that promotes leaching cancel each other out. In contrast, indirect effects lead to significant increase of pesticide leaching, which is consistent among all five CC models.

Although the expected CC patterns are somewhat different in Scandinavia from Switzerland, the results can be extrapolated to Switzerland. While in Scandinavia precipitations are also expected to increase in summer, in Switzerland they are expected to remain stable or to slightly decrease. Based on the Swedish modelling study, this should lead to a more pronounced decrease in pesticide leaching as the temperature effect dominates over the precipitation effect. However, there are still major uncertainties regarding changes in the frequency and intensity of precipitation that could modify leaching patterns. Nevertheless, similarly to Sweden, it can be expected that also in Switzerland, direct effects are smaller than indirect effects, which in turn are strongly influenced by agricultural policy.

Table 9: Overview of mechanisms by which CC modifies the risk of pesticide leaching. After Steffens et al. (2013)

Climate change effect	**Effect on pesticide behaviour in soils**	**Effect on pesticide leaching**
Increasing temperature	More rapid degradation	Decrease
	Higher diffusion rate	Decrease, due to more diffusion into aggregates reducing the risk for leaching through preferential flow paths
	Lower sorption (for the more commonly exothermic reactions)	Increase, as a larger fraction of compound remains dissolved in water and is available for leaching
Decreasing summer precipitation	Lower soil moisture, leading to slower degradation	Increase leaching during subsequent precipitation events
Increasing winter precipitation	More frequent preferential flow	Increased leaching, especially for pesticides applied in automn

4.3.3 Dissolved mineral compounds in recharge water

The total solute content of recharging water is usually dominated by products of dissolution of carbonate minerals, i.e. Ca^{2+}, HCO_3^- and to a smaller extent Mg^{2+}, leading to an increase in hardness, in electrical conductivity and a decrease in pH. Dissolution of carbonate minerals is controlled by the CO_2 content in soils and vadose zone, which depends on soil biological processes, which in turn are controlled by climate. A longer vegetation period together with an enhanced mineralization of soil organic matter due to higher temperatures is expected to increase soil and vadose zone CO_2 concentrations and according the concentrations of solutes from carbonate mineral dissolution, as long as carbonate minerals are present in soil.

A few studies have addressed the issue of changes in groundwater composition with CC. Calmels et al. (2014) observed the effect of the vegetation and of biochemical soil processes to the carbonate weathering in the Jura Mountains. They suggest that recent modifications in land use and climate for the past century already changed the groundwater mineralization. This process has been studied at a larger scale by Gaillardet et al. (2019) who confirmed that the increase of soil CO_2 with increasing temperature and soil moisture dominated over the decrease of the carbonate solubility with temperature.

Working on a long-term hydrochemical datasets (1978-2018) of a karst spring in southern France, Ulloa-Cedamanos et al. (2020) observed an increase in Ca^{2+} and Mg^{2+} (+0.12 mg/l per year) and HCO_3^- (+0.73 mg/L per year) over the 40 years period together with temperature as well as a significant decrease in SO_4^{2-} (-0.08 mg/L per year). While the increase in Ca^{2+}, Mg^{2+} and HCO_3^- result from an increase in carbonate dissolution due to a boost of microbiological activities in soils, the decrease in SO_4^{2-} may be related to less sulfuric acid inputs due to the observed reduction of atmospheric pollution since the mid-eighties.

Regarding Switzerland, water analyses for different springs and wells in the Jura Mountains between 1990 and 2012 (Jeannin et al., 2015) also point out a clear increase of water mineralization (Figure 31). The increase in bicarbonates is about 5%, i.e. +16 mg/L over the observation period and it is accompanied by a decrease in pH of about ~0.01 pH units per year. Considering the largely accepted fact that carbonate dissolution acts as carbon sink for the atmosphere, it can be postulated that the observed increase could act as a negative feedback mechanism, tending to slowdown the atmospheric increase in CO_2.

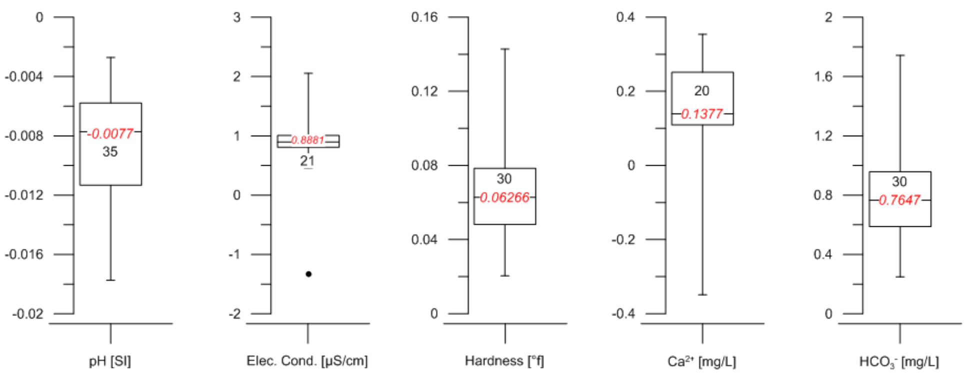


Figure 31: Whisker–Box plots of statistic trends for the main parameters related to the carbonate dissolution which have been analysed in water emerging from 40 springs or wells in Ajoie (JU); plain values refer to the numbers of stations where the statistic trend was identified, italic value gives the estimated rate of change (/year). No global trend could be identified for Mg2+ which is not represented here (Jeannin et al., 2015).

Significant changes for compounds related to human practices have been demonstrated too: decrease in K^+, Cl^-, SO_4^{2-} and increase in Na^+ (Figure 32). Changes of these compounds with CC is not proved. The decrease of K^+ is related to fewer inputs of potassium-based fertilizers while the decrease of SO_4^{2-} might be related to the reduction of atmospheric pollution as discussed by Binet et al. (2020).

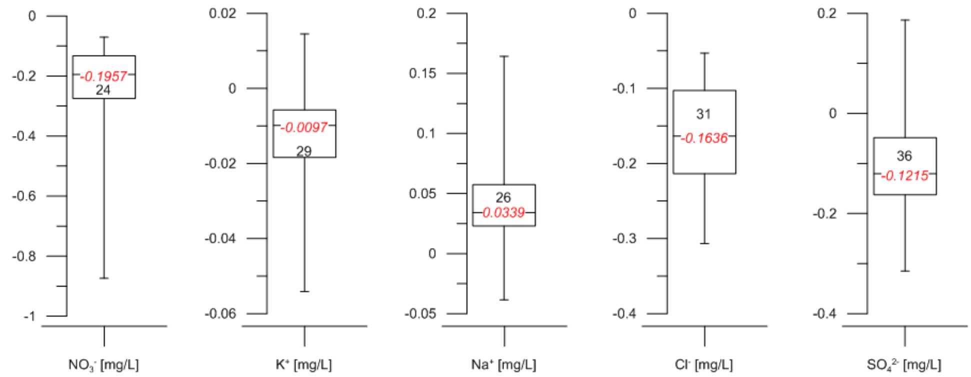


Figure 32: Whisker–Box plots of statistic trends for parameters that are not directly related to the carbonate dissolution but also showing a meaningful trend; plain values refer to the numbers of stations where the trend was identified, italic value gives the estimated yearly rate of change (Jeannin et al., 2015).

4.4 Modifications of the composition of recharge water – River water infiltration

CC can modify the composition of water that infiltrates from rivers into aquifers for two main reasons: On the one hand, the chemical composition of river water changes (Table 10), and on the other hand, removal processes in the streambed and adjacent zones are altered due to modifications of temperature and/or residence time of water in this zone (Table 11). Effects of hot and dry periods leading to hydrological droughts as well as the effect of intense precipitation events changing flood frequencies have both to be considered. However, anthropogenic effects will likely have a stronger impact on future quality of infiltrating river water such as modification of streambed conditions, especially in the context of river revitalisation, upgrading of waste water treatment plants and changes in use of agrochemicals.

4.4.1 Modification in river water composition

During drought events, the proportion of water from different sources changes and accordingly river water composition (Mosley, 2015). For rivers in non-glaciated catchments, the proportion of water from point sources, especially wastewater treatment plants, and deeper groundwater flow systems increases during droughts while the contribution of shallow flow paths through soils and superficial aquifers diminishes. Whether the concentration of a compound increases, decreases or remains unchanged depends on its predominant origin (Mosley, 2015). The concentration of micropollutants from wastewater treatment plants tend to increase during dry period as less dilution occurs. In reverse, the concentration of pesticides, some nutrients (e.g. phosphorous) and sometimes DOC tend to decrease as they reach rivers mainly via shallow flow paths that are no longer active. Mixed and counteracting drought responses were found to be relatively common (Mosley, 2015). For example, DOC concentrations may remain stable because the effect of an increasing proportion of water from wastewater treatment plant (higher DOC) and deeper groundwater flow systems (lower DOC) can cancel each other. In addition to the changing proportions of water types in rivers, hot and dry periods influence in-stream processes. Nutrient uptake by algae and macrophytes can increase due to enhanced growth at higher temperatures, denitrification can increase due to longer residence times, or photodegradation of micropollutants increases due to the higher exposure to sunlight. While concentrations effects can vary among substances, a pronounced increase in the river water temperature occurs during hotter and drier periods.

During intense precipitation events, shallow flow paths are activated leading to the flushing out of various substances (DOC, nutrients, pesticides) and microorganisms depending on land use. Cycles of drought and wet periods can lead to increasing concentrations as substances become concentrated during drought periods and are then flushed out rapidly (Burt and Worrall, 2009; Jarvie et al., 2003; Morecroft et al., 2000).

Table 10: CC effects on stream water quality that are relevant for groundwater recharge by river water infiltration.

Climate change feature	**Mechanism of change**	**Implications for water quality**
More frequent hydrological drought	Less dilution of water from point sources, mainly waste water treatment plants	Increasing concentrations of compounds from points sources (e.g. bacteria/microbial, micropollutants)
	Lower contribution from shallow flow paths	Lower concentration of substances that are leached from soils with especially agricultural land use
	Higher proportion of deeper groundwater components	Increase in mineralization and nutrients
More frequent intense precipitation events	Flushing out of accumulated solutes and microorganisms from soils and shallow flow paths	Higher concentrations of DOC, nutrients, pesticides, and microorganisms

4.4.2 Modification of processes in the infiltration zone

Processes in the streambed and near-stream aquifer zone have usually a strong effect on chemical and microbial composition of recharging water. In this zone, biogeochemical processes are usually faster than in the aquifer due to the nutrient supply from the river (Hiscock and Grischek, 2002). Furthermore, external and internal colmation enhances the filtration of microorganisms and particles. Increasing stream temperatures during summer and more frequent flood events can modify the efficiency of contaminant removal processes. In addition, increasing temperatures can potentially accelerate redox processes leading to release of manganese and iron from sediments, which are a concern for drinking water supply. The mechanism by which CC can impact these processes is summarized in Figure 33.

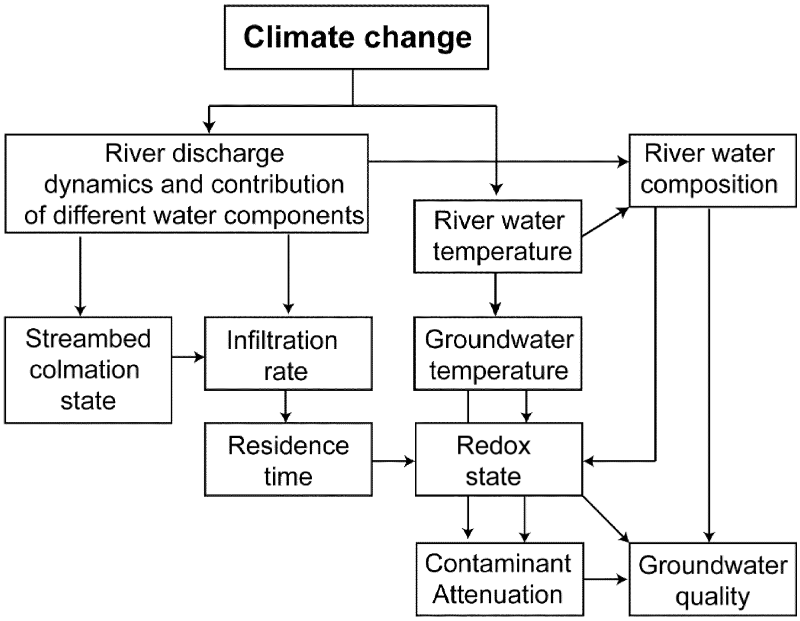


Figure 33: Mechanisms by which CC can impact the quality of infiltrating river water.

During heat waves, the higher river water temperatures can propagate into groundwater. The effect will be most notable in the near stream zone, influencing biogeochemical turnover, and become increasingly attenuated further away from rivers. The influence of higher temperatures and sometimes longer residence times on contaminant attenuation is well known from studies at riverbank filtration sites (Burke et al., 2014; de Wilt et al., 2018; Massmann et al., 2006; Sprenger et al., 2011). Two factors have to be taken into account: (i) Higher turnover rates due to higher temperatures and (ii) a tendency towards more reducing conditions with increasing temperature and residence time. However, in some studies, counterintuitive effects were observed i.e. a tendency to more reducing conditions during flood events with shorter residence times (Diem et al., 2013a; Diem et al., 2013b). In this case, not the residence time but rather the availability of labile organic carbon was the limiting factor for biogeochemical turnover and its supply was enhanced during flood events. The overall effect of increasing temperature on contaminant attenuation depends on whether oxygen becomes completely depleted and whether compounds are preferentially degraded under oxic or anoxic conditions. Micropollutants tend to be degraded preferentially and more rapidly under oxic conditions (de Wilt et al., 2018). As long as some oxygen remains in the infiltrating water, higher temperatures tend to increase removal rates, while a transition to anoxic conditions inhibits it. For some micropollutants and nitrate, the transition to anoxic conditions enhances their removal. For pharmaceuticals, some studies have suggested that strongly reducing conditions are required (de Wilt et al., 2018). While several studies at bank filtration sites have demonstrated a transition to anoxic conditions during drought conditions (Sprenger et al., 2011), the general risk is probably smaller in Switzerland as streambeds tend to be coarser, organic carbons contents lower and residence times shorter than at lowland sites. Furthermore, nitrate in streams can buffer the redox conditions and prevent the release of manganese and iron (Diem et al., 2013b; von Rohr et al., 2014). Regarding microbial contaminants, for viruses, inactivation rates tend to be higher at temperatures above 20°C, while the temperature dependence is less clear for bacteria (John and Rose, 2005). In principle, bacteria of faecal sources could multiply in the environment at warmer temperatures if sufficient nutrients are available. However, their survival is strongly influenced by other factors such as competition with natural organisms and predation, redox conditions or nutrient availability. These factors are themselves temperature dependent, and can lead to a decreasing survival of faecal bacteria with increasing temperature.

Flood events, which may become more frequent in the future, can remove the colmation layer, leading to a decrease of the efficiency of chemical and microbial contaminant attenuation (Ascott et al., 2016). In addition, in periods with intense precipitation, contaminants can be leached from soils and vadose zone to groundwater (Ascott et al., 2016; Schürch et al., 2008). As a beneficial side effect, the supply with dissolved oxygen can improve and thus the risk of release of iron and manganese during hot and dry periods is reduced. A perturbation of the colmation layer can lead to a rapid increase of groundwater levels and the mobilisation of contaminants from the vadose zone, e.g. present at contaminated sites.

Table 11: CC effects on contaminant attenuation processes in the river infiltration zone.

Climate change feature	Mechanism of change	Implications for water quality
Higher river temperature in summer	Increase in rate of biogeochemical processes while redox conditions remain oxic	More rapid removal of micropollutants
	Increase in rate of biogeochemical processes with shift to reducing conditions	Inhibition of micropollutant degradation. Release of dissolved manganese and iron.
	Increased rate of inactivation of microorganisms	Lower risk of microbial contamination.
More frequent intense precipitation events	Removal of colmation layer and higher infiltration rate	Less effective filtration of microorganisms
		Improved oxygenation of aquifer
	Increase of groundwater level	Mobilisation of contaminants from the vadose zone

4.5 Modification of mixing ratios in aquifers

Many aquifers are often recharged by several sources of water e.g. infiltrating river water and direct recharge. Water that is captured in springs or pumping wells usually represents a mixture of different water types with a varying chemistry. In Switzerland, pumping stations are often located in proximity to rivers and pump a large portion of infiltrating river water. As larger rivers originate from mountain areas with less intense land use, infiltrated river water has often a high quality.

During more extreme climatic conditions, the mixing ratios in captured water can change, leading to a modification in its chemical composition. The direction of changes depends on the predominant origin of a substance. For solutes from agriculture, infiltration of water from pre-alpine and alpine rivers often leads to a dilution effect (Baillieux et al., 2014). During low flow conditions, infiltration rates decrease and pumping wells draw more water from the land-side leading to increased concentrations of solutes that reach groundwater via direct recharge.

Springs often represent a mix of groundwater from shallower more variable and deeper more stable flow paths. During long recession period in drought periods, deeper components increasingly predominate and can be associated with higher content of dissolved minerals and sometimes more reducing conditions.

4.6 Changes within aquifer processes

The chemical composition of groundwater can potentially also change due to processes within aquifers, especially influenced by changes in groundwater temperature. Several studies have investigated how increasing aquifer temperature influence the groundwater chemistry in context of subsurface heat storage projects. The effect of an increase of the temperature on concentrations of compounds originating from rock-water interactions is usually only small. If sufficient organic carbon is available, the rate of redox processes can increase with a shift to more reducing conditions. However, in higher energy fluvio-glacial deposits, which are common in Switzerland, the availability of labile organic carbon is often limiting redox processes, and thus an increase in temperature by a few degrees should only have a limited effect on redox conditions. Degradation rates of contaminants and inactivation rates of microbial contaminants, especially viruses, should increase.

Take home message – Groundwater quality

Changes in groundwater quality due to CC are already observed, especially in lowland areas, both for aquifers fed by river infiltration and by direct recharge. The range of possible changes is large and each case must be investigated individually.

CC can influence groundwater quality by modifying the composition of recharge water and/or altering mixing ratios of water with a different composition (e.g. due to modification of the amount of infiltrating river water).

There is a risk for increasing nitrate leaching after dry and warm periods and/or periods with abundant precipitation. During dry periods, the nutrient uptake is smaller. Furthermore, elevated temperature can increase mineralization of organic matter as long as sufficient moisture is available. To limit nitrate leaching under more variable climate conditions, measures to increase the nurtrient use efficiency become even more important.

Indirect effect of climate change can potentially influence the groundwater quality as well such as shifts from summer to winter crops with an increase herbicide use in autumn when leaching risks are higher or an increased use of pesticides to address a higher weed pressure.

Increasing irrigation can modify the composition of recharge water in a positive direction (improved update of nutrients in dry periods) or negative direction (increasing leaching of pollutants). Controlled irrigation is essential to limit negative effects.

5 Summary

This chapter discussed the expected effects of climate change on groundwater quantity, quality and temperature in Switzerland for the 21th Century.

When evaluating the effect of **climate change on groundwater quantity**, a key question is whether the **rate of replenishment of aquifers** (i.e. groundwater recharge) will change, as other changes will depend on it. Therefore, a considerable part of this chapter is dedicated to recharge and new simulations of groundwater recharge were carried out specifically using CH2018 climate scenarios. The current seasonal dynamics and future trends strongly depends on the fraction of precipitation that falls as rain versus snow. Therefore, the discussion of climate change impacts on recharge differentiates among pluvial, pluvio-nival and nivo-glacial conditions. Pluvial conditions were treated in more detail as they have received more attention so far.

Under **pluvial conditions**, groundwater recharge predominantly occurs through the infiltration of rainwater across soil (direct recharge) and through the infiltration of river water (indirect recharge). **Direct recharge** will tend to become more concentrated during a shorter period in winter/spring. In summer, recharge will decrease and become unsignificant (unless it is already low under current conditions). In automn, recharge will decrease and/or start later due to higher summer soil water deficit and higher evapotranspiration. In winter and spring, increasing precipitation will only lead to an increase in recharge for sufficiently permeable soils and sufficiently wet conditions. The net effect on annual recharge will depend on whether the increase of recharge in winter/spring is sufficient to compensate for the loss in automn and sometimes summer. For **infiltration of river water**, climate change effects are expected to be more varied as they strongly depend on the state of hydraulic connection between a river and an aquifer, in addition to future rivers stages. For rivers that are hydraulically connected to aquifers, the infiltration rate is influenced by the depth to groundwater (in addition to the river stage). If the groundwater level drops e.g. due to lower direct recharge or more pumping, the infiltration rate can increase due to a higher gradient. This will have a stabilizing effect on the groundwater level. For hydraulically disconnected rivers where infiltration occurs via percolation through an unsaturated zone below the streambed, a lower river stage will result in smaller infiltration rates. However, the expected more frequent, intense precipitation events and higher precipitation during winter might replenish aquifers by rapid infiltration via riverbanks thus again compensating for infiltration loss during more pronounced low flow periods. Large discharge events can have even a more pronounced effect by removing colmation layers and modifying the state of connection. In the upgradient section of river reaches flowing over very permeable material rivers can completely infiltrate, and recharge will be limited by the residual river discharge. Under **pluvio-nival conditions**, under actual conditions groundwater recharge by snowmelt plays an important role. During winter a prolonged period without recharge usually occurs. For such conditions, increasing temperatures will lead to a more regular temporal distribution of recharge as the period with snow cover will become shorter and intra-winter melt events more frequent. Furthermore, direct recharge might increase due to the thawing of permafrost and, for a limited period of time, due to the increased infiltration along rivers related to glacier melt. Earlier snowmelt and higher temperatures, will lead to lower recharge during summer and fall.

For groundwater management, an important question is how the changes in recharge influence the **groundwater storage in aquifers** and **groundwater services or risks** associated with it. Groundwater services not only include the provision of water for households, industry and irrigation but also ecological services, which might be affected to a different degree by CC. Prolonged periods with limited recharge are particularily challenging with this respect. The questions arise whether aquifers will be able to provide the expected groundwater services (**reliability**) or in case of failure, how quickly they recover again (**resilience**). The effect of hotter and potentially drier summers is expected to be more moderate for groundwater than for other hydrological systems such as soil moisture or stream discharge. Owing to the important storage capacity of aquifers, the opposite trends of less water in summer/automn and more in winter/spring could compensate each other with little net effect. This is for example not the case for soil moisture, where additional winter precipitation cannot prevent a severe soil moisture deficit in summer. However, the more uneven water input can also propagate to groundwater to some degree, depending on hydrogeological properties of aquifers. Aquifers that can store less water and/or have a high permeability leading to a rapid dissipation of storage, are expected to show a more pronounced drop in groundwater levels and discharge in the future. In many cases, ecological services will probably be more affected than water supply: The former often relies on the uppermost part of stored groundwater, for example, to maintain water levels in a wetland or an alluvial forest, while water supply can access deeper parts of aquifers via boreholes or drainage galleries, and is thus less sensitive to a drop in groundwater level and storage. Some water works have already started to capture groundwater in deep zones in order to reduce their exposure to extended hot and dry periods. Aquifers that are more prone to “fail” tend to recover more rapidly again (i.e. are more resilient) often on a seasonal scale, while larger aquifers or those with a lower permeability are less impacted by a longer absence of recharge, but also take longer to recover and have a tendency for multiple years with water deficits to cumulate (i.e. less resilient). The generally high availability of groundwater makes it an attractive resource to cover additional future water needs, e.g. during hot and dry periods, especially for irrigation. Therefore, CC can indirectly influence groundwater levels more strongly than directly.

While the effect of hotter and drier summer conditions on groundwater services has been studied in quite some detail, the question of increased **groundwater risks** due to more abundant winter precipitation has received less attention so far. During prolonged periods with intense precipitation, groundwater levels can increase affecting groundwater infrastructure from below or leading to local flooding. New flow paths can potentially be activated that can trigger mass movement. Little is known how widespread these risks are.

For **groundwater quality,** a fundamental question is whether the composition of recharging water changes due to CC. For **direct recharge,** the leaching of nitrate and pesticides are in the foreground. Studies on **nitrate** tend to agree that under future climate conditions, nitrate leaching will increase if no adaptions in agriculture are implemented. Faster or reduced plant growth during summer in combination with increased mineralization of organic nitrogen due to higher temperature will lead to higher soil nitrate contents that are more vulnerable to leaching during intense precipitation event or more abundant automn/winter precipitation. This is consistent with observed increases in nitrate concentrations during past hot and dry summers, especially 2003. The effect can be reduced by adapted irrigation and choice of cultivars with longer growth periods. Furthermore, best management practices will become even more important to limit periods with excess soil nitrate. For **pesticides**, no significant increase in leaching is expected according to modelling studies. While more frequent intense precipitation will increase the risk of leaching, the fraction of pesticides available for leaching will drop due to a more rapid degradation at higher temperatures and more rapid sequestration into microporosity. Indirect effects are expected to be much more singificant, such as a higher pesticide use due to a higher weed pressure, more frequent crop rotations, an extension of crop areas or more frequent use of pesticides in automn for winter crops when the leaching risk is higher. For **indirect recharge**, the expected effects are again more varied and more difficult to predict. The quality of infiltrating water depends on changes in the composition of river water and modifications of filtration and degradation processes during infiltration. Depending on the source of a compound, its concentration in river water might go up, down or stay constant during more pronounced low flow periods. Higher stream water temperatures will propagate to groundwater and increase the rate of contaminant degradation, but can also lead to anoxic conditions that can make pollutants more recalcitrant and release **manganese and iron**. In the Swiss context, the latter will likely be less common as coarse streambeds and surrounding sediments often contain less organic matter (an important driver of redox processes), and nitrate can buffer the redox potential. It is unlikely that higher groundwater temperatures alone will lead to a more frequent occurrence of microbial pathogenes in groundwater. For viruses, the inactivation rate is more elevated at higher temperatures and for pathogenic bacteria, temperature is only one among several factors that influence their survival. Other factors than temperature will likely have a more significant controlling effect such as the composition of stream water or the degree of colmation of streambeds. Besides changes in the composition of recharge water, the groundwater quality can also change due to modifications of mixing ratios of water of different origins, which will be highly site specific.

For **groundwater temperature**, changes can go in opposite directions. In areas dominated with infiltrating precipitation, the increase in air temperature is expected to propagate to groundwater. However, especially in urban areas, other factors can dominate over climate change such as heat release from below ground infrastructure and geothermal energy use.

6 Recommendations

In this chapter, we outline possible adaptation strategies based on the identified changes. Three major themes that are particularly relevant for water resources in Switzerland are to be distinguished: 1) more pronounced low flow periods in summer due to higher temperatures and likely less precipitation, 2) more frequent intense and abundant precipitation, and 3) a shift from nival to pluvial conditions at mid altitude and earlier snowmelt at higher altitude. For each of them, the expected changes, impacts and adaptation options are presented in Table 12. We also make some recommendations for groundwater monitoring in the context of climate change (Table 13). Finally, adaptation strategies require additional hydrogeological characterization of aquifer systems. In Table 14 we attempted to list needs with this respect, focussing on processes that are particularly important under extreme conditions.

As this section focusses on possible adaptation strategies, challenges related to groundwater are in the foreground that call for adaptation. However, it has to be kept in mind that groundwater generally plays a buffering role in the water cycle and thus will contribute to dampening the effects of more frequent extreme conditions both wet and dry. Excess water is stored in the subsurface, diminishing the effect of abundant precipitation, and in reverse the stored water diminishes the effect of dry and/or hot period. It is generally important to identify when these dampening mechanisms contribute to the resilience of the hydrological systems or when their buffering capacity is exceeded. In the latter case adaptation strategies have to be applied.

Table 12: Major expected changes concerning groundwater due to three main evolutions (a b c) of CC in Switzerland. The main related impacts and adaptation strategies are given for each of the identified changes.

a) Longer hot and/or dry periods (<1000 m a.s.l.)

Changes	Impacts	Adaptation strategies
Lower GW levels and smaller fluxes especially under pluvial conditions.	• Lower GW availability for water supply, especially for small and shallow groundwater resources	• Jointly manage groundwater resources with different drought sensitivity at regional level • Active management of groundwater resources making use of the significant storage volumes in the subsurface • Enhance groundwater recharge in periods of high water availability (artifical recharge, river revitalisation, retention/infiltration in urban water management) • Enforce groundwater protection to maintain water quality of the available GW resources • Summer pumping of GW reserves with potential artificial recharge in winter
	• Decreasing water availability for groundwater dependant ecosystems	• Incorporate ecological services in groundwater management strategies • Implement strategies to balance groundwater availability with changes in ecosystems, e.g. through adequate revitalisation projects.
Decreasing groundwater exfiltration feeding surface water bodies	• Decreasing stream discharge	• Measures to increase groundwater storage during wet periods (artificial recharge, river revitalisation) in order to sustain streamflow during drought periods • Manage groundwater extraction near streams that are sensitive to drought
	• Reduced buffering of surface water temperature dynamics	• River revitalisation measures to reduce temperature (e.g. shading) and increase habitat diversity
	• Higher proportion of treated wastewater with implications for the surface water quality	• Enhanced / improved waste water treatment
Increasing soil moisture deficit and higher soil temperature	• Increasing water demand for irrigation	• Reduce water demanding crops • Adjust cultivation time in the year • Improve irrigation effciency • Use alternative water resources that are not in competition with drinking water supply • Implement GW monitoring and management strategies to find a balance between all GW uses (ecological services, drinking water, agriculture…)
	• Increasing concentrations of dissolved compounds in soil solution due to lower nutrient consumption during drought and enhanced biogeochemical processes (N, C mineralisation) leading to higher leaching potential to groundwater	• Avoid nutrient excess by optimizing timing and amount of fertilizer application • Controlled irrigation to avoid excessive nutrient residues due to poor crop growth in hot periods • Increased irrigation efficiency

b) More frequent intense and abundant precipitation (all regions)

Changes	Impact	Adaptation strategies
Periods with intense groundwater recharge	• Activation of additional groundwater discharge zones, periodically very high degree of soil moisture (temporary wetlands)	• Integration of groundwater in flood risk concepts • Adjustment of land use • Adjustment of agriculture practices
	• Increasing groundwater levels impacting infrastructure (e.g. basements)	• Integration of groundwater in flood risk concepts
	• Rapid leaching of substances from soil during periods of high water table	• Best management practices to limit accumulation of leachable compounds in soils and in the unsaturated zone
	• Increasing landslides due to extreme GW-levels (pressure)	• Monitoring & dedicated regional studies

c) Rising snowline (> 1000 m a.s.l.)

Changes	Impact	Adaptation strategies
Period of minimal GW storage and stream discharge shifts from winter to summer	• Increased water availability in winter, decreased availability at the end of summer	• Improved understanding of groundwater storage dynamics in alpine region as a basis for water management. The role of bedrock formations in storage dynamics remains poorly understood. • Water management plans to adjust water needs and exploitation to resource evolution

Table 13: Groundwater monitoring needs in the context of climate change

Objective	**Explanation**	**Approach**
Monitor changes in groundwater quantity, quality and temperature at locations with limited and/or stable anthropogenic influence to disentangle the effect of climate change from other changes	Currently, monitoring stations tend to focus on areas with intense water use and pressures, which makes it difficult to differentiate climate vs other anthropogenic influences. This makes it more difficult to understand and anticipate the impacts of climate change.	Evaluate to what extent existing monitoring networks are suitable to track climate change impacts unobscured by other factors. Complement network if needed.
Improve the reliability of methods for monitoring water fluxes at springs and in streams/rivers during low water periods taking into account groundwater.	Current monitoring systems are often optimized for average to high flow, but generally show a large uncertainty for low flow conditions. Outflow via the subsurface is not considered.	Redesign gauging stations (double-profiles thresholds) and/or complete the low flow monitoring by additional indicators including groundwater.
Complement and coordinate surface water monitoring stations with groundwater monitoring	To appreciate the relative effect of droughts on surface and groundwater and interactions among the two, both systems have to be monitored at representative locations	Analyze existing monitoring networks for their suitability for integrated water monitoring (for both subsurface and surface water components), and suggest adjustment of groundwater monitoring
Verify that current groundwater monitoring locations are suitable to capture effects of extreme conditions, both effects of dry periods and abundant precipitation.	Current monitoring networks might prioritize areas with more intense groundwater use or target average groundwater conditions. They might not capture extremes during drier and wetter conditions.	Identify zones where climate change might lead to particularly pronounced changes and verify if these zones are covered by current networks.
Monitor changes of alpine groundwater systems due to higher temperatures (earlier snowmelt, the disappearance of glaciers).	Currently, there is very limited monitoring data available for alpine groundwater systems, which makes it difficult to understand and predict how such systems change.	Complement existing monitoring networks with locations at higher altitudes outside of the major alpine valleys in combination with precipitation and surface discharge monitoring.
Monitoring and forecasting of groundwater recharge at the national scale (including groundwater recharge from snow) to anticipate the evolution of groundwater reserves during drought periods	For groundwater management, it is important to know how quickly groundwater reserves recover after drought periods, which critically depends on groundwater recharge.	Combined monitoring and modelling approach to quantify and forecast groundwater recharge. Integration of climate, soil moisture and lysimeter data. Existing models need reliable and adequate field data to be validated. Establish groundwater recharge maps for different climate scenarios using models.

Table 14: Needs for improved hydrogeological characterization as a basis for adaptation measures

Objective	Approach
Improved understanding of the contribution of bedrock aquifers to stream discharge during low flow periods	Geological and hydrogeological characterization of bedrock aquifers with a focus on more permeable units (e.g. sandstone)
Improved understanding of groundwater storage in alpine areas and its contribution to low flow discharge	Geological and hydrogeological characterization of alpine aquifers
Improved understanding of the state of connection between SW and GW, and its temporal dynamics in response to changing discharge regimes (e.g. more frequent/intense flood events)	Integration of knowledge on streambeds at the scale of aquifer systems
Characterizing GW direct recharge under variable conditions including extreme ones (drought to storm)	Monitoring and field experiments in order to characterize the whole range of potential conditions and the thresholds in changes between recharge/runoff ratio.
Improved understanding of low flow catchment discharge via subsurface pathways to better appreciate low flow water fluxes in catchments as a basis for water management.	Hydrogeological characterization of aquifer conditions especially at the location of gauging stations and quantification of water fluxes.
Improved knowledge of the potential of deeper, potentially less drought-sensitive aquifers for water supply	Establishment of large scale geological models combined with better characterization of the deeper aquifers via boreholes and geophysical methods. Evaluate hydrochemical state of deeper aquifer.
Better assessment of the potential of artificial recharge for increasing groundwater storage to support water supply during drought periods	Identification of favourable conditions for artificial recharge combined with pilot studies in promising areas
Identification of river stretches that will dry out more frequently in the future due to complete infiltration of streamflow into the subsurface.	Development of a conceptual framework and model for mapping the concerned river stretches and testing at selected field sites.

Take home message

Integrated Groundwater Management (IGM) is a wide domain, which is not well developed yet in Switzerland due to the high water availability. Most countries which already suffer dryer conditions than Switzerland have developed IGMs for addressing their increasing water needs with limited resources. These techniques are available and should be progressively deployed in our country. A dedicated documentation of our water resources and aquifer characteristics needs to be established for the future management of surface and groundwater in Switzerland.

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