13. Hydrology and Hydrogeology

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13.1
Quantification of fracture-matrix fluid exchange in fractured porous media PIV measurements

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Fluid exchange between fractures/free-flow and porous media is of crucial importance in various applications, such as geothermal energy, carbon dioxide sequestration, groundwater utilization, hydrometallurgical recovery, and infiltration/drying in fractured soil. However, it is still challenging to quantify fluid flow exchange between fractures/free-flow and porous media, particularly in fracture-dominated porous media.

Here, we use 3D-printing techniques to manufacture a well-structured, transparent porous medium, which consists of two low- and high-permeability matrices, each with one flow-through and one dead-end fracture. We conduct Particle Image Velocimetry (PIV) measurements in this 3D-printed medium (Ahkami et al., 2018) to determine the stress-jump (Saffman,1971) and velocity-slip (Beavers and Joseph, 1967) coefficients for characterizing fluid exchange at the fracture-matrix interfaces.

We further calculate the cross correlations between the aforementioned two coefficients and the velocities perpendicular to the fracture-matrix interface for all the interfaces of flow-through and dead-end fractures. The calculated correlation coefficients illustrate that the stress-jump and velocity-slip coefficients are incapable of quantifying fluid exchange across the current definition of physical fracture-matrix boundary. Using the PIV-measured velocities, we also discuss in detail the velocity-dependent boundary layer at the fracture-matrix interfaces for typical incoming and outgoing flow regions. Finally, we propose a new quantity to relate fluid shear rates inside the fractures and inside the matrices around the fracture-matrix interfaces. Our study provides insights into fluid exchange between fractures/free-flow and their surrounding matrix, which is crucial to characterize the associated mass and energy transport processes and to improve the efficiency and sustainability of the aforementioned applications.

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13.2
Improving hydrologic model realism by using stable water isotopes

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The last century of hydrological research has led to significant improvements in representing different hydrological processes in rainfall-runoff models. Despite this progress, most rainfall-runoff models are calibrated only against streamflow, which informs the celerity i.e. the fast response behavior of a catchment. Using environmental tracers such as stable water isotopes can help constrain the velocity aspect of the catchment. However, stable water isotopes have either been used qualitatively to learn more about the dominant hydrological processes or to calibrate a much more complex solute transport model, where the added benefit of using stable water isotope data is not entirely clear.

In this study, we use stable water isotopes to design a semi-distributed conceptual rainfall-runoff model for an Alpine catchment (Vallon de Nant), and incorporate information about pre-event water fraction in the stream within the rainfall-runoff model. Pre-event water fraction is estimated using stable water isotope data and a Bayesian mixing model, and is used to calibrate the rainfall-runoff model. This kind of a calibration scheme increases the representation of pre-event water fraction within the stream, thus making model simulations more realistic. We discuss the advantages and limitations of such a modeling approach and how it can be extended to other experimental catchments.

13.3
Modelling the impact of climate change on hydrological processes in the Volta river basin

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This study evaluates the impacts of climate change on water resources of the Volta River basin located in West Africa. In total, 43 combinations of global climate models (GCM) and five regional climate models (RCM) from CORDEX-Africa are considered under three representative concentration pathways (RCP2.6, RCP4.5 and RCP8.5). The R2D2 multivariate bias correction method is applied to the climate datasets before using them as input to the fully distributed Hydrologic Model (mHM) for hydrological projections over the twenty-first century. The mHM model is constrained with a novel multivariate calibration approach based on the spatial patterns of satellite remote sensing data (Dembélé et al., 2020).
Results reveal contrasting changes in the seasonality of precipitation depending on the RCPs and the future projection periods (2021-2050, 2051-2080 and 2071-2100) as compared to the historical period (1991-2020), while a clear increase in the seasonality of temperature is expected. A clear intensification of the hydrological cycle during the twenty-first century is expected only under the RCP8.5 scenario. In this case, an increase is foreseen for the long-term annual estimates of precipitation (+6.2%), average temperature (+9.5%) and potential evaporation (+5.0%). These changes in climatic variables will lead to changes in actual evaporation (+4.2%), surface runoff (+42%), streamflow (+84%), groundwater recharge (+37%), soil moisture (+2.3%) and terrestrial water storage (+3.2%). Consequently, recurrent floods and droughts could weaken the water-energy-food security nexus and amplify the vulnerability of the local population to climate change. These findings could serve as a guideline for decision makers, and contribute to the elaboration of adaptation and mitigation strategies to cope with dramatic consequences of climate change on various sectors including agriculture and hydroelectricity, and strengthen the regional socio-economic development.

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13.4
Climate change effects on groundwater recharge and temperatures - status and development for Swiss aquifers

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Climate change will have both quantitative and qualitative effects on groundwater resources. These impacts differ for aquifers in solid and unconsolidated rock, urban or rural locations and the principal processes of groundwater recharge. Knowledge of the intrinsic key parameters (aquifer geometries, storage properties, groundwater renewal rates, residence times, etc.) and the principal groundwater recharge processes as well as temperature imprinting enables a comparison and forecast of the sensitivity of individual aquifers to climate change.
The sensitivity of future groundwater temperature development for selected climate projections was investigated for representative Swiss unconsolidated rock groundwater resources on the Central Plateau, the Jura and the Alpine region. For non-urban and rural areas, climate change is expected to have a strong overall impact on groundwater temperatures. In urban areas, however, direct anthropogenic influences are likely to dominate. Increased thermal subsurface use and waste heat from underground structures as well as adaptation strategies to mitigate global warming result in increased groundwater temperatures. Likewise, measurements for the city of Basel show that groundwater temperatures increased by an average of 3.0 ± 0.7 °C in the period from 1993 to 2016 and can exceed 18 °C, especially in densely urbanized areas. Similarly, regarding shallow aquifers with low groundwater saturated zone thicknesses, such as in Davos (Canton Grisons), groundwater temperatures will strongly be influenced by changes in groundwater recharge regimes. In contrast, groundwater temperature changes within deep aquifers with large groundwater saturated zone thicknesses, such as in Biel (Canton Bern), or in some cases with large distances from the surface to the groundwater table and extended unsaturated zones, e.g. in Winterthur (Canton Zurich), are strongly attenuated and can only be expected over long time periods.
We show that seasonal shifts in groundwater recharge processes could be an important factor for the future development of groundwater temperatures. Moreover, the interaction with surface waters and increased groundwater recharge during high runoff periods are likely to have a strong influence on groundwater temperatures. Accordingly, a shift in precipitation and river flood events from summer to winter months is accompanied by an increase in groundwater recharge in comparatively cool seasons, which would be accompanied by a tendency for “cooling” groundwater.

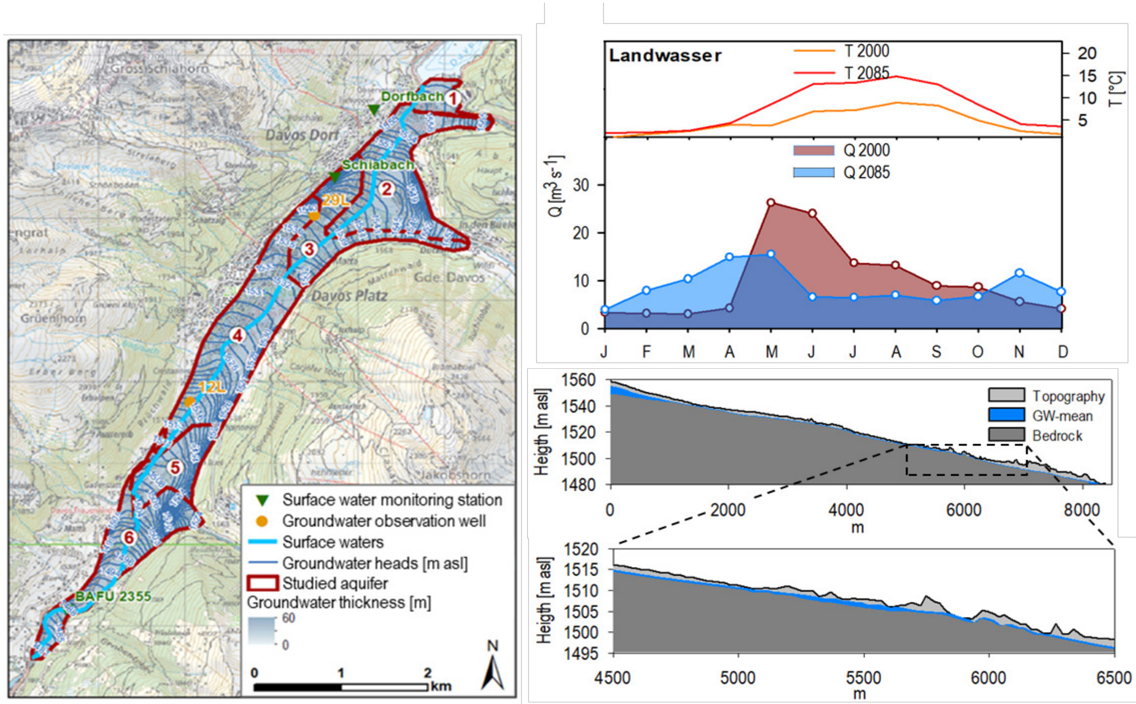

Figure 1. Left: Aquifer of Davos (Canton Grisons) illustrating groundwater head and thickness, including groundwater and surface water monitoring stations; for 6 subdomains groundwater flow length and times were evaluated. Upper right: Simulated emission scenario RCP85 and results for river discharge (Q) and temperature (T) for the reference state 2000 and for the year 2085. Lower right: Progression of the river Landwasser related to the bedrock and the surface topography for a mean groundwater head situation, including a zoom of the river section between 4500 and 6500 m where the river locally can be in contact with the groundwater table.

13.5
GRUN-ENSEMBLE: A multi-forcing observation-based global runoff reanalysis using machine learning

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Although river flow is the best-monitored variable of the terrestrial water cycle, the scarcity of available in situ observations in large portions of the world has until now hindered the development of consistent estimates with global coverage. Recently, fusing sparse in-situ river discharge observations with gridded precipitation and temperature using machine learning has shown great potential for developing continental (Gudmundsson & Seneviratne 2016) to global (Ghiggi et al., 2019) monthly runoff estimates. However, the accuracy of gridded precipitation and temperature products is variable and the corresponding uncertainty in the resulting runoff and river flow estimates is not yet quantified.

Here we present a multi-forcing global reanalysis of monthly runoff rates at a 0.5° resolution, named Global RUNoff ENSEMBLE (GRUN-ENSEMBLE) (Ghiggi et al., in preparation), composed of up to 525 runoff simulations. The GRUN-ENSEMBLE is based on 21 different atmospheric forcing datasets, overall spanning the period 1901-2019. The reconstructions are benchmarked against a comprehensive set of global-scale hydrological models (GHMs) simulations, using a large database of river discharge observations as a reference, which can serve as basis also for future GHMs intercomparison studies. Overall, the GRUN-ENSEMBLE shows higher accuracy than the GHMs, especially with respect to the reproduction of the dynamics and seasonality of monthly runoff rates. The accuracy of the reconstructions is dependent on the quality of the forcing data. However, we found the GRUN-ENSEMBLE to be less sensitive to forcing data compared to GHMs simulations. Potentially, this is because the employed ML algorithm is not impacted by the cumulative nature of errors and biases that affect dynamical models.
The uncertainty quantification related to the multi-forcing nature of the GRUN-ENSEMBLE paves the way for reliable and robust water resources assessments, hydro-climatic studies (Figure 1), climate change attribution, as well as evaluation, parameter calibration and refinement of GHMs.

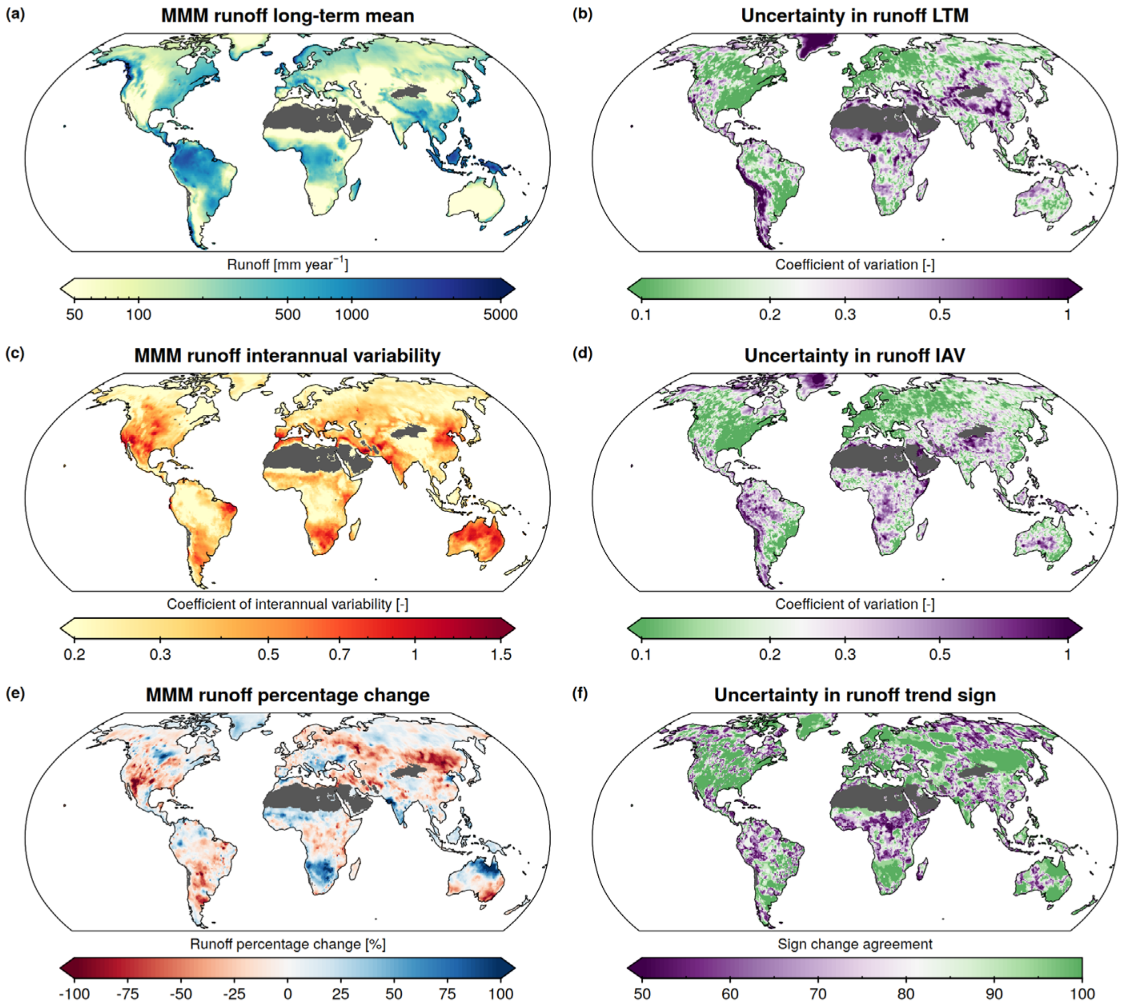

Figure 1. Climatological analysis based on the GRUN-ENSEMBLE for the period 1981-2010. Desert regions with long-term precipitation lower than 100 mm/year are masked. a) Multi-model median of the runoff long-term mean (LTM) computed for each GRUN-ENSEMBLE member. b) Coefficient of variation of the ensemble LTM statistics. c) Multi-model median of the runoff interannual variability (IAV) computed for each GRUN-ENSEMBLE member. d) Coefficient of variation of the ensemble IAV statistics e) Multi-model median (MMM) of changes in annual runoff rates, expressed in percentage change over the 30-year period, computed for each GRUN-ENSEMBLE member. f) Percentage agreement of the runoff trend sign across the 20 GRUN-ENSEMBLE members spanning the period 1981-2010.

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13.6 Assessment of methods to estimate bare soil evaporation based on lysimeter data

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Bare soil evaporation is a key component of the water balance and is influenced by numerous complex physical processes. While many empirical methods to estimate evaporation have been proposed, their performances under different hydrological conditions have not been assessed systematically. We evaluated four commonly used methods, namely the FAO-56 method with the skin evaporation enhancement (FAO-56 skin), the groundwater level fluctuation (GLF) method, Darcy's law method, as well as the Maximum Entropy Production (MEP) approach to estimate evaporation. The estimated evaporation rates were compared to evaporation rates measured by three lysimeters with different water table depths in the Guanzhong Basin, China. Our study includes conditions where the water table is above- as well as below the extinction depth of evaporation. The extinction depth is the critical depth below ground where groundwater no longer contributes to evaporation.

The results show that the position of the water table relative to the extinction depth is a useful first-order indicator of the performance of three methods (the Maximum Entropy Production method, the FAO-56 skin method, and the groundwater level fluctuation method). The MEP method provided the best results across all hydrogeological conditions. However, if the water table is below the extinction depth, significant biases can occur with the MEP approach. The FAO-56 skin method tended to overestimate the evaporation when the water table depth was larger than the extinction depth, and vice versa. The groundwater level fluctuation method, combined with the water balance method could reproduce the evaporation well. However, estimating evaporation using the groundwater level fluctuation method requires a falling water table in response to evaporation, which only can occur if the water table is above the extinction depth. In principle, Darcy's law can reproduce evaporation dynamics. A reliable estimation of the soil parameters is required and very difficult to obtain. The above results are significant to groundwater management and sustainable development in arid and semi-arid regions.

13.7
Sustainable Use of an Overpumped Aquifer: Example the North China Plain

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The overpumping of aquifers is a non-sustainable practice, by which on average more water is abstracted from an aquifer than is recharged by seepage of rainwater or from surface water bodies. It is seen in many arid and semi-arid areas all over the world. The aquifer system of the North China Plain (NCP) is one of the most prominent examples for over-pumping.

Due to the increase of food demand of a growing population the irrigation agriculture in NCP was expanded significantly over the last 50 years. It is responsible for about 80% of water use. The over-pumping showed in a decline of groundwater tables by about 1 m per year, with consequences such as increased pumping cost, soil subsidence, drying up of wetlands, and sea water intrusion at the coast. At the same time the aquifer is losing its function as long-term reservoir, capable of buffering weather extremes such as multi-year droughts, which are expected to occur more frequently under climate change.
A prerequisite to maintaining an aquifer's drought mitigation capacity is sustainable groundwater use, which implies a long-term balance between recharge and abstraction. Sustainability can be enhanced by conjunctive use of surface water and artificial groundwater with excess surface water available outside of the irrigation season. Sustainable use requires management, based on quota and the red line concept.

The Sino-Swiss project developed such a system. It consists of 3 elements, which can be implemented with the presently available sensors and transmission techniques: A monitoring module recording groundwater levels and pumping rates, a data platform and modeling module, computing the allowable pumping rates under given sustainability goals, and a policy module implementing the required reductions in pumping.

The pilot site is Guantao County in NCP. The measurement of pumped volumes has been implemented using the electricity consumption of each well as a proxy. Pumping tests allow to convert the energy consumed into the water volume pumped. The dominant double cropping of winter wheat and summer maize in the region is the reason for over-pumping. A solution involves three elements: the reduction of winter wheat planting, increased surface water imports from the south and advanced water saving irrigation. Both a 2D groundwater model and a simple box model water balance sheet are used in the assessment of suggested scenarios. A decision support system has been set up, which determines the water requirements of the cropping system, the expected reaction of the groundwater levels and the amounts of fallowing and water imports needed to reach a target groundwater level in the next season, on average over the county. On the field implementation side, water quota and a water price have been defined by a ladder scheme, with water within quota being free of charge. A dry run of fee calculation - without farmers actually paying up to now - has been performed according to electricity consumption in 2018. A subsidy for fallowing of winter wheat has been introduced, for which villages can apply up to a number of hectares determined by the provincial government. Water saving irrigation is also subsidized but its potential is low. It will only increase when small family farms are merged to larger units practicing precision agriculture. For grain security reasons the over-pumping problem cannot be solved by fallowing of winter wheat alone. It has to be combined with more imports of surface water from the south. While progress has been made over the last 6 years, a final solution will still take a few years' work.

The Swiss partners in the project are ETH Zurich, hydrosolutions Ltd., Geopraevent Ltd. and the Zurich University of the Arts. The Chinese partners are the Water Resources Ministry's General Institute of Water Resources and Hydropower Planning and Design (GIWP), the China Institute of Geo-Environment Monitoring, the China Center for Agricultural Policy at Peking University, the Key Laboratory of Agricultural Water Resources of the Chinese Academy of Sciences in Shijiazhuang and the local Departments of Water Resources in Handan and Guantao.

13.8
From hydrological forecasts to adapted water management

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Hydro-CH2018, a major FOEN research project to be completed in 2020, also included several targeted literature studies. One of them focused on the use and management of Swiss water resources, and how its objectives are challenged by a changing climate.

To assess current and future water management in Switzerland, the sector was clustered into nine societal demands (see table 1). Some are of predominantly public interest (drinking water supply, waste water management, flood management, river and lake ecology), others are mainly commercial activities (thermal use, irrigation, tourism, industrial water use) or a combination of both (hydropower).

Table 1. Societal demands concerning water

Drinking water supply
Wastewater management
Industrial water use
Agricultural irrigation
Thermal use of water resources
Tourism
Hydropower
Flood protection
River and lake ecology

The literature study shows, that water resources in Switzerland are under pressure due to abstraction, pollution, encroachment of riparian areas, and hydro-morphological deficits. Recently introduced legislation on water protection aims to alleviate some of these pressures in the decades to come. The remaining pressures and climate change will exert a combined effect on water resources, to which water management will have to react.

Generally, the impact of socioeconomic change on water management is at least as important as that of climate change. This finding is in tune with earlier research projects such as the Swiss national research program on sustainable water management (NRP 61, 2010-2014).

In some sectors, adaptation of water management to climate change is likely to increase conflicts and environmental problems. This will be particularly the case in summer and fall when demand for water in agriculture and for cooling is heightened. Also, groundwater use for climate-neutral heating systems has increased pressure on underground water resources.

Drinking water supply
Switzerland obtains ca. 80% of its drinking water from underground aquifers. Much of the groundwater is abstracted in heavily utilized river plains where its quality is under pressure from agricultural activities, transportation, industry, and expanding residential areas. In many regions, virtually all groundwater is influenced by societal activities preventing the appropriate protection of drinking water quality. Combined with climate-induced reductions in available quantity, the lack of adequately protected groundwater resources is becoming a major challenge for future drinking water supply. Lately, wide-spread exceedances of the legal drinking water limit for pesticide residues in large parts of the country have confirmed the vulnerability of the system.

Industrial water use
Industry and business are major users of water in Switzerland. Their consumption exceeds household use of water by a factor of 2.5. Some 73% are obtained from private wells, 27% from public water supply. Up-to-date information on industrial water use is lacking, the most recent figures concern the year 2006. Abstracted quantities are published only by one canton, most other cantons do not require abstractions to be measured and there is no fee on water consumption (other than concession fees independent of actual abstraction).

Most industries and businesses discharge their wastewater via public treatment plants. To date, information about the chemicals contained in industrial wastewater are scarce. Their quantity is however significant: Chemicals from industry and business make up about a quarter of anthropogenic substances in the Rhine river at the border in Basel.

Wastewater

Wastewater management is among the sectors requiring major adjustments due to climate change. Reduced run-off in summer and fall result in an increase of wastewater concentrations in rivers. To make up for this, Switzerland will upgrade at least 130 strategically selected wastewater treatment plants with ozonization and/or active carbon filtration technology. This will markedly increase the quality of drinking water abstracted downstream of WWTPs. However, large parts of the Swiss river system will still receive wastewater from treatment plants without advanced technology.

A second challenge is that increasingly heavy storm water events are exceeding the capacity of sewage systems. To prevent untreated wastewater from overspilling into rivers, rain water is to be kept away from sewers by local infiltration and retention systems.

Agricultural irrigation

Agricultural irrigation is likely to become a key issue of water management in Switzerland. The area of crops requiring irrigation is rapidly increasing (+26% vegetable hectares 2010-2016). Extended additional irrigation infrastructures are currently being planned or implemented, usually with substantial public support. However, the additional water demand of these new projects is unclear. There is no policy of recording water abstractions of agriculture in Switzerland. As a result, authorities are often unable to assess the impact of irrigation on water resources. Conflicts with other water users and aquatic ecology are likely to increase.

The emphasis of public policies for adapting irrigation to climate change is on water use efficiency and a shift to less water-consuming crops or varieties. In practice, such demand management policies find little resonance. Almost all current irrigation development aims at increasing water availability. Hence, irrigation is a typical example for effects of societal change overriding those of climate change. In most areas, the extension of irrigated crop area has a larger impact on water consumption than rising temperatures.

One obvious solution to avoid increasing conflicts in times of water scarcity is a drought insurance. As soon as meteorological drought prevails, farmers are reimbursed for crop losses. Drought insurances also improve protection of rivers and groundwater from over-abstraction, as insured farmers will be obliged to stop abstracting water in times of low water tables.

Hydropower

Hydropower is expected to benefit from the general shift of runoff from summer to winter, as more water will be available in times of highest electricity demand. However, the effect of prolonged droughts could affect hydropower production also during winter. International political decisions and economic developments haven proven to substantially affect the demand for hydropower. Building hydropower infrastructure is expensive and time-consuming, and the general economic circumstances are unfavorable for further extensions. On the other hand, hydro-electricity is an important renewable energy source. Clearly, societal influences are much more important for the future of Swiss hydropower than hydrological changes brought about by climate change.

Outlook

Most societal activities concerning water are affected by both climate change and pre-existing pressures (abstraction, pollution, encroachment, infrastructure). Adaptation to climate change can only be successful if these pressures are also addressed. Quick and thorough implementation of existing legislation will make rivers, lakes and groundwater more resilient to the hydrological fall-out of climate change. At the same time, current water protection legislation ought to be assessed to make sure it is sufficient to safeguard future river and lake ecology.

13.9
Overland flow evolution on moraines in silicate and carbonate proglacial areas of the Swiss Alps

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In many areas of the world, the surface of the earth is changing rapidly. Overland flow is one of the processes that can dramatically modify the shape of our landscapes but is also affected by the land surface characteristics. However, our understanding of the evolution of overland flow characteristics and the feedback mechanisms between hydrological, pedological, biological and geormorphological processes that affect overland flow is limited.

We used a space-for-time approach (e.g. Lohse & Dietrich, 2005) and studied 3 plots (4m x 6m each) on four different aged moraines (several decades to ~13.500 years) on the Sustenpass near the Steinglacier and in the karstic glacier foreland of the Griessfirn near Klausenpass (total of 24 plots) to determine how overland flow generation changes during landscape evolution. We used artificial rainfall experiments with three different intensities to determine the overland flow ratio, peak flow rate, timing and duration of overland flow. The addition of tracers (2H and salt) to the sprinkling water and sampling of soil water allowed identification of the mixing of the water within the slopes and the interaction of overland flow pathways with the subsurface. In addition, the runoff samples and sensor-based turbidity measurements provide an estimate of the erosion rates during extreme events. In order to link the differences in overland flow generation with the pedological and biological characteristics of the slopes, soil and vegetation samples were taken on each plot to determine soil texture and root characteristics and the saturated hydraulic conductivity was measured in situ at three different depths (Maier, 2020).

The results show that the overland flow amount and related erosion rates, response times and mixing of overland flow and soil water change during landscape development and can largely be explained by related changes in soil surface and near surface characteristics. However, the rate of these changes during landscape evolution depends on the geology.

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13.10
PIV examinations on the flow-path evolution induced by shear displacements in rough-wall fractures

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Preferential flow-paths are well-known features in fractured rock masses, often allowing rapid movement of fluid and early breakthrough of solute and heat/cold in a small fraction of void space, compared to normal (unfractured) porous media. These preferential flow-paths can change as the configuration of fractures varies, due to, for example, shearing (Kluge et al., 2017; Yeo et al., 1998). Such changes could become particularly imporant for reservoir enhancement, such as hydraulic shearing stimulations. Although numerical studies have shed some light on such changes in flow-paths, experimental visualization and, more importantly, quantification of the flow-path evolution in fractures with rough walls still remain a challenge.

Here, we report our experimental observations and quantitative analyses on flow-path evolution induced by fracture shearing. Fluid flow is introduced into a single rough-wall fracture, configured by the two inner surfaces of a base and a sliding cover. The two rough surfaces of the fracture are numerically generated using SynFrac. Both the base and the cover are 3D-printed with transparent materials. The sliding of the cover is precisely monitored by gauge meter to yield controllable shearing. A solution of mineral oil and anise oil is prepared to match the refractive index of the 3D-printed materials, and serves as the working fluid, seeded with nearly neutrally-buoyant fluorescent particles. Such an experimental setup allows us to implement the Particle Imaging Velocimetry (PIV) measurements, which still have rarely been applied in the geosciences (Ahkami et al., 2018; S.H. Lee et al., 2015). By acquiring the velocity fields of the fluid passing through the rough-wall fracture at different sheared positions, we are able to quantify the changes in the tortuosity and averaged flow rate of individual flow-paths. Our results provide important insights into the impact of shearing on fluid flow in fractures with rough walls.

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13.11
How many parameter sets are really needed for reliable simulation of extreme floods?

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Delivery of reliable extreme flood estimates with associated return periods along with uncertainties remains a major challenge in water resources management and safety-studies. In the absence of long discharge records, these estimates may be derived with a help of a hydrological model through a simulation-based study. Such a simulation-based approach is capable of generating very long pseudo-observed discharge time series based on meteorological inputs from a weather generator (Grimaldi et al. 2013). These pseudo-observed time series of discharge can be then used for frequency analysis. Yet, use of any hydrological model is linked with uncertainty that may arise from several sources and is often represented by the model parametric uncertainty (e.g. in a form of a probability distribution or multiple sets of equally probable parameters). To propagate this uncertainty on flood frequency estimates, multiple model runs are needed with these parameter sets. This increases however the computation requirements of model simulations, particularly if many different input scenarios or long time climatic series must be analysed.

An intelligent preselection of hydrologic model parameter sets is therefore desired. Sikorska-Senoner et al. (2020) have recently proposed a clustering of model parameter sets in frequency space to reduce the number of parameter sets to a smaller amount that could be easily dealt with within simulation frameworks. However, it is not clear how many parameter sets are really needed to reliable describe the full ensemble of hydrologic responses but with keeping the computational model efforts at a desired low level.

In this work, we analyse different number of parameter sets (between 1 and 1000) to describe the hydrologic responses ensemble in order to select an optimal number of parameter sets. Such an optimal number should maximize the information contained in the predictive intervals of flood frequency and minimize the computational efforts at the same time. A selection of these parameter sets is done through clustering of hydrological responses in flood frequency space. The approach is tested in a small Swiss catchment (Dünnern at Olten, 196 km^2) with 10’000 years of continuous daily pseudo-discharge simulations. These pseudo-observations are simulated with a hydrological model (HBV) fed with meteorological scenarios generated with the weather generator (Evin et al. 2018). The selection of the parameter sets is performed in the frequency space by analysing the variability of hydrologic responses through clustering of annual daily discharge maxima.

Our preliminary results illustrate that already 3 sets provide a good representation of the predictive intervals for flood flow frequency if only flow ranges are of interest. If one is interested in the inter-interval variability, 5 till 10 sets could be already sufficient to represent this variability of possible hydrological responses. Potential applications include different simulation studies of flow extremes or safety-studies for dams, bridges or hydropower.

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13.12
Dominant Factors Controlling Sub-Seasonal to Seasonal Hydrological Predictability in Switzerland

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Sub-seasonal to seasonal hydrological forecasts provide knowledge of hydrological variables (e.g. streamflow, soil moisture, snow depth, etc.) several weeks or months in advance (sub-seasonal to seasonal lead times, respectively), rendering them a powerful tool for decision-makers involved in early disaster recognition, management of hydropower plants and agriculture. The skill of such forecasts depends principally on two factors: knowledge of the land surface hydrological conditions (ICs) at the forecast start date and knowledge of the climate forcing (CF) during the forecast period. The common approach to the evaluation of the relative importance of the ICs and the CF is the Ensemble Streamflow Prediction (ESP)–reverse Ensemble Streamflow Prediction (revESP) framework (Wood & Lettenmaier, 2008) that contrasts the forecast skill originating from known ICs and an ensemble of historical climate traces with the forecast skill originating from an ensemble of historical ICs and known CF, respectively. Therefore, the skill of the ESP stems from perfect knowledge of antecedent moisture states (soil moisture, snow, groundwater), whereas the skill of the revESP stems from perfect knowledge of the meteorological variables (mainly temperature and precipitation). The impact of these two main predictability sources on sub-seasonal to seasonal hydrological predictions is highly dependent on the catchment location and elevation, the catchment properties and the season and lead time under consideration. This work aims at elucidating the role of ICs and CF for sub-seasonal to seasonal hydrological predictions in an ensemble of 307 catchments covering entire Switzerland. To this end, the hydrological model PREVAH was implemented to perform the ESP/revESP methodology for the period 2000–2018. The variable topographical, hydro-geological and meteorological characteristics of the catchments result in diverse hydrological regimes that lead to a different impact of the ICs and the CF on the (sub-) seasonal hydrological predictability and on the critical lead time (CLT), denoting the time after which the revESP skill surpasses the ESP skill.

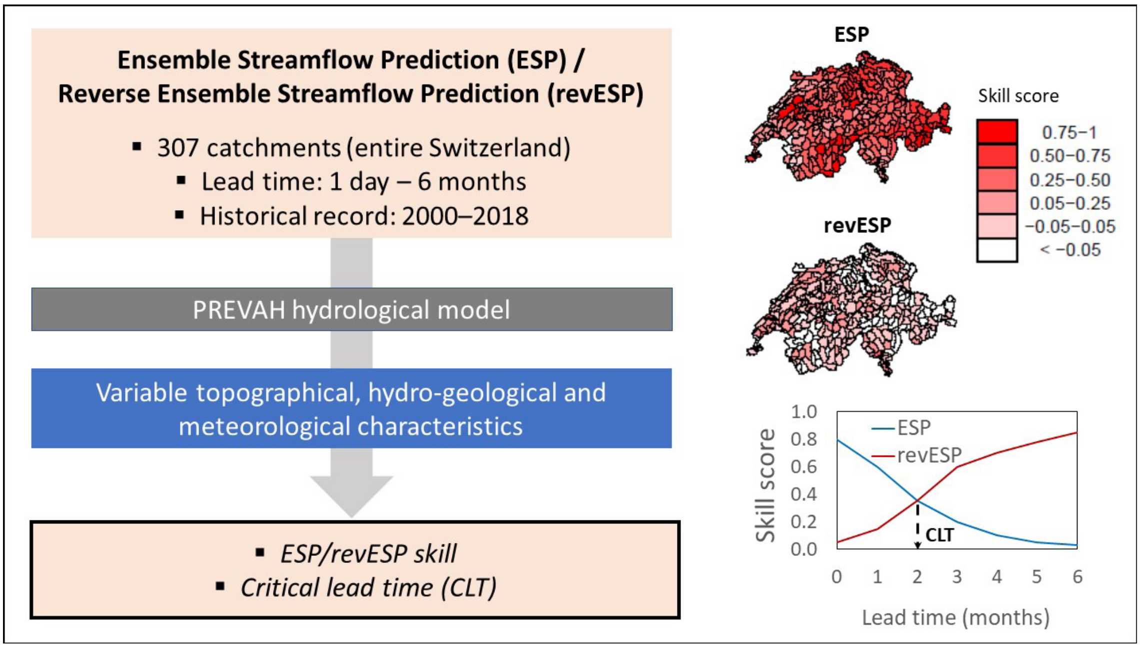

Figure 1. Graphical illustration of experimental procedure

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13.13
Fully-integrated surface-subsurface hydrological modelling in steep, snow-dominated, geologically complex Alpine terrain

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Most hydrological climate change impact assessments in Alpine areas continue to be underpinned by simple conceptual hydrological models. However, such models have numerous limitations that may ultimately affect the reliability of predictions generated using them. For instance, spatial variability in surface and subsurface material properties is often lumped together, empirical snow modelling approaches prevail, and the potential hydrological impacts of contemporaneous changes in other environmental system components such as vegetation and permafrost tend to be overlooked. Considerably more sophisticated physically-based, spatially explicit codes which are capable of simulating 2D surface flows, 3D variably-saturated subsurface flows, and evapotranspiration in a fully-integrated fashion appear to have great potential with respect to the simulation of mountainous hydrological processes. However, integrated models have not yet been applied in real steep, snow-dominated, geologically complex Alpine catchments. This presentation therefore describes the development, automated calibration, and application of a fully-integrated model of two adjacent headwaters in the western Swiss Alps under both historical and plausible future climatic, vegetation, and permafrost conditions. The model incorporates both a detailed representation of the 3D geological structures encountered in the study region and a sophisticated, energy balance-based snow modelling routine that additionally accounts for the gravitational redistribution of snow from steep slopes and was conditioned on two types of complementary snow observations. The results indicate that, for a moderate warming scenario towards the end of the century, "direct" climatic changes are found to dominate the impacts upon key hydrological variables such as streamflows and groundwater levels, whilst "indirect" forest expansion is likely to have a more modest modulating effect via enhanced evapotranspiration. Overall, the work attests to the potential of integrated models to provide a physically sound and internally coherent representation of hydrological dynamics in even the most complex of Alpine settings. That said, the amount and diversity of the data required, as well as long execution times, mean that such an approach is presently only recommendable in exceptionally important or ecologically sensitive catchments.

13.14
Elevated concentrations of toxic elements in high-alpine streams of the Eastern Alps: a manifestation of climate change?

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In the Eastern Alps, there are several high-alpine streams with distinctivley white-colored streambeds (Fig. 1). The white color originates from the precipitation of nanocrystalline basaluminite [$Al_4OH_{10}(SO_4)\cdot(H_2O)_3$] sticking to the bedload of the streams (Wanner et al., 2018). The phenomenon is triggered at the origin of the streams where the oxidation of pyrite leads to the production of sulfuric acid and the subsequent dissolution of aluminum from the host rock. Owing to its strong *pH*-dependent solubility, precipitation of basaluminite eventually occurs when the acidic and aluminum-rich streams are neutralized along their flow paths.

For this contribution, we present chemical water analyses for seven high-alpine streams with clearly visible basaluminite precipitates. The streams are all located in the canton of Grisons. Geologically, the catchments are located within the crystalline basement of the Australpine nappes and the exposed host-rock is dominated by pyrite-bearing mica-schists. All streams show low *pH* conditions (<5) and elevated total dissolved solid concentrations up to 2000 mg/L. The lowest *pH* and highest element concentrations are observed at the origin of the streams where streamwater temperatures are below 2 °C. Beside their low *pH*, the streamwaters do not meet Swiss drinking water quality with respect to their As, Ni, F, Al, and Mn concentrations. Moreover, in most streams the concentrations of As, Mn and F even exceed the Swiss regulatory limits for contaminated sites. The mobilization of toxic As is further manifested by elevated As concentrations in basaluminite precipitates collected along the streams, reaching values up to 1400 µg/g

In a preliminary study, we have shown that slow moving groundwater flow is required to promote pyrite oxidation and the subsequent mobilization of toxic elements in such high-alpine settings (Wanner et al., 2018). The observation that the minimum temperature of all seven acidic streams is very close to the melting point of ice now suggests that rock glaciers (i.e. permafrost) occurs at the origin of the streams and that these form little aquifers with sufficiently high groundwater residence times to produce sulfuric acid from pyrite oxidation. The presence of rock glaciers is also consistent with geomorphologic observations, the high altitude of the catchment origins (>2700 m a.s.l.), and their generally north-facing orientation.

The apparent importance of permafrost in generating low streamwater *pH* values and elevated toxic element concentrations implies that the impact of climate change on the water quality of such high-alpine streams should be assessed. A likely scenario is that the ongoing permafrost retreat will expose more pyrite-bearing bedrock to aerobic waters and that the production of sulfuric acid and mobilization of toxic elements will increase in the future. This scenario is supported by a long-term monitoring study performed in a smilar setting in the Rocky Mountains, demonstrating that the concentrations of sulfate and Zn strongly increased over the past 40 years (Todd et al., 2012). Moreover, the importance of climate change in adversely affecting the water quality of high-alpine streams is also demonstrated at one of the investigated catchments in the Eastern Alps. There, from aerial photographs it can be inferred that the onset of basaluminite formation only dates back to the year 2000, implying that the phenomonon is relatively new. In conclusion, we propose to initiate a long-term water quality monitoring of the affected high-alpine streams in the Eastern Alps to assess the future impact of climate change on these particular water ressources.

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Figure 1. Photograph of basaluminite precipitation occurring along “Ova Lavirun”, a high-alpine stream in the Engadin area. The white arrow marks the onset of precipitation, which is triggerd by the neutralization of Ova Lavirun by a circumneutral tributary merging from the upper left.

13.15
CH2018 projections for Run-of-River power production

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Around 57 % of electricity in Switzerland is generated by hydropower (HP), whereof around 25 % are produced by Run-of-River (RoR) power plants.
In the context of the Swiss energy strategy 2050, an attempt is made to increase this share by about 10 % (in total 38'600 GWh/a). But, growing energy demand coupled to growing ecological awareness is catapulting hydropower into a position of great expectation and responsibility. In this context, the present research proposes to compare climate change impact on RoR production with the potential increase by optimizing the design discharge or to losses due to environmental flow requirements.

To assess climate change impact, daily runoff until the end of the century was simulated with the hydrological model PREVAH, using a total of 26 climate model chains from the new Climate Change Scenarios CH2018, corresponding to the two different CO_2 emission scenarios RCP2.6 and RCP8.5. Changes in HP production under climate change are estimated for eleven RoR power plants based on differences in the flow duration curves (FDCs) between the reference period (1981-2010) and the future periods (2045–2074 and 2070–2099), assuming unchanged installed machinery and environmental flow requirements.

The changes in RoR power production are due to changes in precipitation, temperature and evaporation, which in turn have a strong impact on the dominant hydrological processes (snow accumulation and melt, glacier melt and runoff production), and show important spatial and temporal differences (Figure 1). By mid-century (2045–2074) and under concerted mitigation efforts (RCP2.6), annual production will remain roughly the same as during the reference period. Production will decrease slightly (about -3 %) without climate change mitigation (RCP8.5). Exceptions are power plants that are strongly influenced by melt processes. Due to reduced snowfall and increased winter precipitation and ensuing higher winter streamflows, winter production will increase at almost all RoR power plants considered in this study by mid-century, by about 5 % on average.
By the end of the century (2070–2099), a slight decline of the annual production (-1.5 %) is to be expected under RCP2.6. Without climate change mitigation (RCP8.5), annual production will fall further (-7 %). Winter production will increase at virtually all studied RoR power plants. Depending on the emission scenario, the average winter production increase will be between 5 % (RCP2.6) and 10 % (RCP8.5). However, this increase in winter production will not be sufficient to prevent annual production decline.

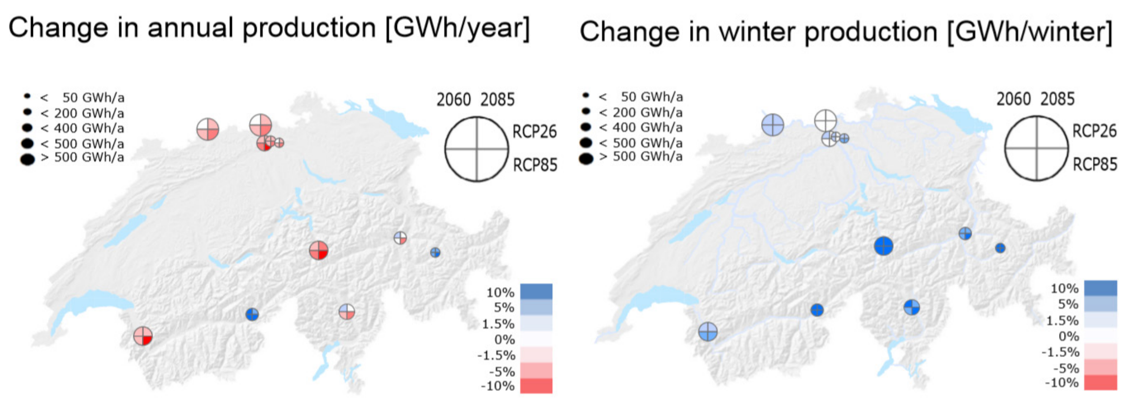

Figure 1. Expected changes in annual (left) and winter (right) production of eleven selected Swiss Run-of-River power plants for the periods 2060 (mid-century, 2045–2074) and 2085 (end of century, 2070–2099). The calculations are based on the most recent Climate Change Scenarios CH2018 established by MeteoSwiss (26 climate models; two emission scenarios: with concerted mitigation efforts RCP2.6 and no climate change mitigation RCP8.5) and a state-of-the-art hydrological model (PREVAH), taking into account unchanged installed machinery and environmental flow requirements (SCCER-SoE 2019).

These climate change induced reductions of annual HP can be put into context by comparing the potential production losses that result from environmental flow requirements or production increases through optimizing the design discharge. For the eleven RoR power plants under current hydrological conditions, the potential that could be achieved by optimizing the design discharge is an increase of 6% in production. Compliance with legal constraints on environmental flow rates, compared to no residual flow, means a decrease of 4% in production.

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