Why do we have so many different hydrological models? A review based on the case of Switzerland

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Abstract

Hydrology plays a central role in applied as well as fundamental environmental sciences, but it is well known to suffer from an overwhelming diversity of models, in particular to simulate streamflow. Based on Switzerland's example, we discuss here in detail how such diversity did arise even at the scale of such a small country. The case study's relevance stems from the fact that Switzerland shows a relatively high density of academic and research institutes active in the field of hydrology, which led to an evolution of hydrological models that stands exemplarily for the diversification that arose at a larger scale. Our analysis summarizes the main driving forces behind this evolution, discusses drawbacks and advantages of model diversity and depicts possible future evolutions. Although convenience seems to be the main driver so far, we see potential change in the future with the advent of facilitated collaboration through open sourcing and code sharing platforms. We anticipate that this review, in particular, helps researchers from other fields to understand better why hydrologists have so many different models.

1 Introduction

Hydrological models are essential tools for hydrologists, be it for operational flood forecasting, water resource management or the assessment of land use and climate change impacts. Since the advent of hydrological modelling, the number of models keeps increasing at a fast pace. It has become common to talk about the "plethora of hydrological models" (index term found more than 13'400 times in a Google search on 11 Jan 2021). Single models are branching out into numerous variants, such as the Hydrologiska Byråns Vattenbalansavdelning model (HBV; Bergström, 1976, 1992, 1995; Lindström et al., 1997) that exists in multiple versions nowadays. Some authors support the idea that there are too many hydrological models, which might lead to a waste of time and effort, and that the hydrological community should gather on a Community Hydrological Model (Weiler and Beven, 2015).

While any newcomer to hydrological modelling will easily find some guidance on navigating the sheer diversity of hydrological models, understanding the concepts and limitations (Beven and Young, 2013; Solomatine and Wagener, 2011; Kauffeldt et al., 2016), the question of how this diversity has emerged receives much less attention. Existing historical analyses of model diversity (Peel and McMahon, 2020) generally focus on the technical evolution of model types. According to our personal experience, much of the knowledge about why many similar models have emerged is transferred informally.

One of the key drivers for the pronounced model diversity in hydrology is certainly the wide range of model applications (Weiler and Beven, 2015) that all require *appropriate modelling*; this concept can be defined following Rosbjerg and Madsen (2005) as "the development or selection of a model with a degree of sophistication that reflects the actual needs for modelling results". Two well-accepted characteristics that models should exhibit are parsimony and adequacy to the problem at hand, i.e. a model should not be more complex than necessary and should be fit-for-purpose (Beven and Young, 2013). Indeed, a model developed for droughts cannot be blindly applied to the assessment of floods. Also, catchments with different properties or climatology may require different model structures (Kavetski and Fenicia, 2011a; van Esse et al., 2013). In other words, the hydrological model diversification is strongly driven by the modelling context and by what is now often called *uniqueness of place* (Beven, 2000).

However, the hydrologic literature also offers other explanations, ranging from legacy reasons for model selection (Addor and Melsen, 2019), to a lack of agreement on concepts for process representations and to the simple wish to try to do better with yet another model parameterization (Weiler and Beven, 2015).

We attempt here an analysis of what might explain the emergence of multiple hydrological models at a rather small scale, the scale of Switzerland, a country small enough to do an exhaustive analysis, but diverse enough to shed light on some of the most dominant drivers of model diversity. Despite Switzerland's small area (41285 km^2), numerous models are being developed and applied in the same contexts and often even for the same purpose and the same catchment.

Thus, this work aims to disentangle the motivations and reasons behind the choices that led to the current co-existence of a wide range of models. We focus this analysis on hydrological models (see Box 1) that simulate hydrological processes, including surface and subsurface flow, and the resulting streamflow at the catchment scale. Some of these models are classical rainfall-runoff models (Box 1), while others have more specific purposes. We exclude here models that simulate the water balance without providing streamflow at the catchment outlet. We first briefly present the different models used in Switzerland (Section 2), and attempt a classification according to types of application and research fields (Section 3), before presenting a synthesis of our findings on drivers of model diversity (Section 4) and conclusions (Section 5).

Box 1: What do we mean by hydrological model ?

A hydrological model is an input-output model that simulates the evolution of water storage, of water fluxes and potentially of associated chemical and physical properties at the Earth's surface and subsurface, based on the water balance equation. The term "rainfall-runoff model" is often used for hydrologic models that simulate streamflow at a catchment outlet based on input time series of rainfall. The term "rainfall-runoff" stems from the early times when such models simulated how much water of a rainfall event ran off to the stream (rather than being stored in the catchment), i.e. "runoff" designated the part of rainfall that appears as streamflow (WMO, 1992). Nowadays, rainfall-runoff models are continuous simulation tools that simulate all components of streamflow (including baseflow), and the term "runoff" now designates the lateral (as opposed to vertical) movement of water (at the surface or in the subsurface) towards a river (WMO, 2012). Modern rainfall-runoff models further transform simulated hillslope-scale runoff to catchment-scale streamflow; some of them include instream routing. Such models can be generalized to precipitation-runoff models in the presence of snowfall. The term "water balance model" is sometimes used as synonym for rainfall-runoff models (Boughton, 2004) . The correcter term "rainfall-streamflow" model appeared rather early (Young and Minchin, 1991) but is to date (12 Jan 2021) only used in 17 WebOfScience publications. Streamflow is in many papers called interchangeably "discharge" and sometimes even "runoff", which is a legacy effect.

2 Hydrological models developed and used in Switzerland

2.1 Preliminary remark

The information sources considered in this analysis are as far as possible peer-reviewed articles with applications to hydrology. The articles were retrieved based on searches by authors (hydrologists in Switzerland) and keywords. While we tried to search all applications as exhaustively as possible, biases in the search and citing network effects are possible if not likely. Where necessary, conference proceedings, PhD theses, research and government reports are also included. A few models are exclusively used or developed in engineering companies, and these are not included here. Furthermore, our analysis focuses on catchment-scale modelling and excludes studies that focus on hydrogeological modelling (Carlier et al., 2019) and those with a focus on urban hydrology (Peleg et al., 2017) or urban hydrogeology (Schirmer et al., 2013). All articles are not directly referenced in this paper, but a complete table is available in the supplementary material.

2.2 Model overview

There are several hydrological models that have been developed in Switzerland (Table 1), ranging from rainfall-runoff models (PREVAH, GSM-SOCONT, RS, SEHR-ECHO, WaSiM-ETH), to snow-based models (ALPINE3D), glacier-hydrology models (GERM) and water temperature models (StreamFlow). Some models (Table 1) have their roots outside Switzerland but are now actively being developed in Switzerland (HBV-light, TOPKAPI-ETH, SUPERFLEX) or were applied to Swiss case studies (CemaNeige-GR6J, LARSIM, VIC, SWAT, mHM).

All these models are briefly described in Appendix 1. Switzerland being an Alpine country, most of these models include a representation of snow accumulation and melt, some also include glacier-related processes.

Table 1. List of models (alphabetical order) applied in Switzerland; the fourth column indicates whether the model was originally developed (D) or further evolved (E) by teams active at Swiss universities or research institutes, or whether it is only applied to Swiss case studies, either by teams active in Switzerland (A-CH) or by teams active abroad (A). References are in the main text and Appendix 1.

Model name	Full name	Spatial structure	Type of use
ALPINE3D	ALPINE3D	distributed	D
CemaNeige-GR6J	CemaNeige - Genie Rural à 6 paramètres Journalier	lumped	A-CH
DECIPHeR	Dynamic fluxEs and ConnectIvity for Predictions of HydRology	HRU-based	E
GERM	Glacier Evolution Runoff Mode	distributed	D
GSM-SOCONT	Glacier and SnowMelt SOil CONTribution model	semi-distributed	D
HBV	Hydrologiska Byråns Vattenbalansavdelning	semi-distributed	A
HBV-light	Hydrologiska Byråns Vattenbalansavdelning - light	semi-distributed	E
HYPE	HYdrological Predictions for the Environment	semi-distributed	A
LISFLOOD	LISFLOOD	distributed	A
LARSIM	Large Area Runoff Simulation Model	semi-distributed	A
mHM	meso-scale hydrological model	distributed	A
PREVAH	Precipitation-Runoff-Evapotranspiration HRU Model	HRU-based & distributed	D
RS	Routing System	semi-distributed	D
SEHR-ECHO	Spatially Explicit Hydro. Response model for ecohydro. applic.	semi-distributed	D
StreamFlow	StreamFlow	distributed	D
SUPERFLEX	SUPERFLEX	(not fixed)	E
SWAT	Soil Water and Assessment Tool	semi-distributed	A-CH,A
TOPKAPI-ETH	TOPographic Kinematic APproximation and Integration - ETH	distributed	E
VIC	Variable Infiltration Capacity model	distributed	A
WaSiM-ETH	Water Flow and Balance Simulation Model - ETH	distributed	D
wflow	wflow	distributed	A

2.3 History of hydrological modelling in Switzerland

The early times of hydrological modelling in Switzerland can be situated in the years 1970 to 1990, when model diversity naturally emerged in response to modelling needs. From a hydrological processes perspective, a strong focus was on the simulation of snowmelt runoff (Braun and Lang, 1986) as well as on understanding the role of forests in the water cycle (Keller and Forster, 1991; Forster, 1989). Along with modelling studies in experimental catchments (Iorgulescu and Jordan, 1994), first model-based climate change (Bultot et al., 1992) and land-use change (Jordan et al., 1990) impact studies appeared. Quantitative real-time forecasts for water resources management (Lugiez et al., 1969) and hydropower production (Jensen and Lang, 1973) started being based on hydrologic models rather than statistical approaches.

It is worth noting that Naef (1977) presented already a first model intercomparison study, comparing complex and simple models. In fact, model diversity already started interpellating the research community in the late 1970ties and Naef (1981) notably asked: "But, given that the results are good, why do new models continue to be published?"

From a historical analysis (see Supplementary Information), one interesting aspect can be retained: already in the early times of model development, part of the model diversity resulted from the work of geoscientists and engineers not directly specialized in catchment hydrology (Abednego et al., 1990; Baumgartner et al., 1986; Hager, 1984; Sautier and Delleur, 1980), which partly explains the parallel emergence of similar models.

Additional details on the emergence of hydrological modelling in Switzerland are given in the Supporting Information. For a more general dive into the history of modelling, the reader is referred to the work of Keith Beven (Beven, 2020b,a).

2.4 Model intercomparison

There are few model intercomparison studies in Switzerland, and none of them led to a preference of one model over the other, which is reflected in the fact that the recent re-evaluation of climate change impact on water resources involved all the major models developed in Switzerland (FOEN, 2021). The existing model intercomparison studies are classical studies on what we can gain from model complexity in terms of model performance; e.g. Gurtz et al. (2003) compared PREVAH to WaSiM-ETH, Orth et al. (2015) HBV-light to PREVAH and a simple water balance model, Kobierska et al. (2013) ALPINE3D to PREVAH and Andrianaki et al. (2019) SWAT to ALPINE3D and PREVAH.

3 Fields of model application and drivers of diversity

To structure the analysis of model diversity, we attempt here a clustering of modelling studies according to the underlying application. We propose a focus on the following categories of applications or research areas that have received signification attention in Switzerland (Fig. 1): hydrologic process research (Section 3.1), real-time forecasting (Section 3.2), characterization and quantification of floods (Section 3.3), climate change impact analysis (Section 3.4), ecohydrology and agricultural water use (Section 3.5), sediment production and transport (Section 3.6), analysis of model behaviour and uncertainty analysis (Section 3.7) and large scale modelling (Section 3.8).

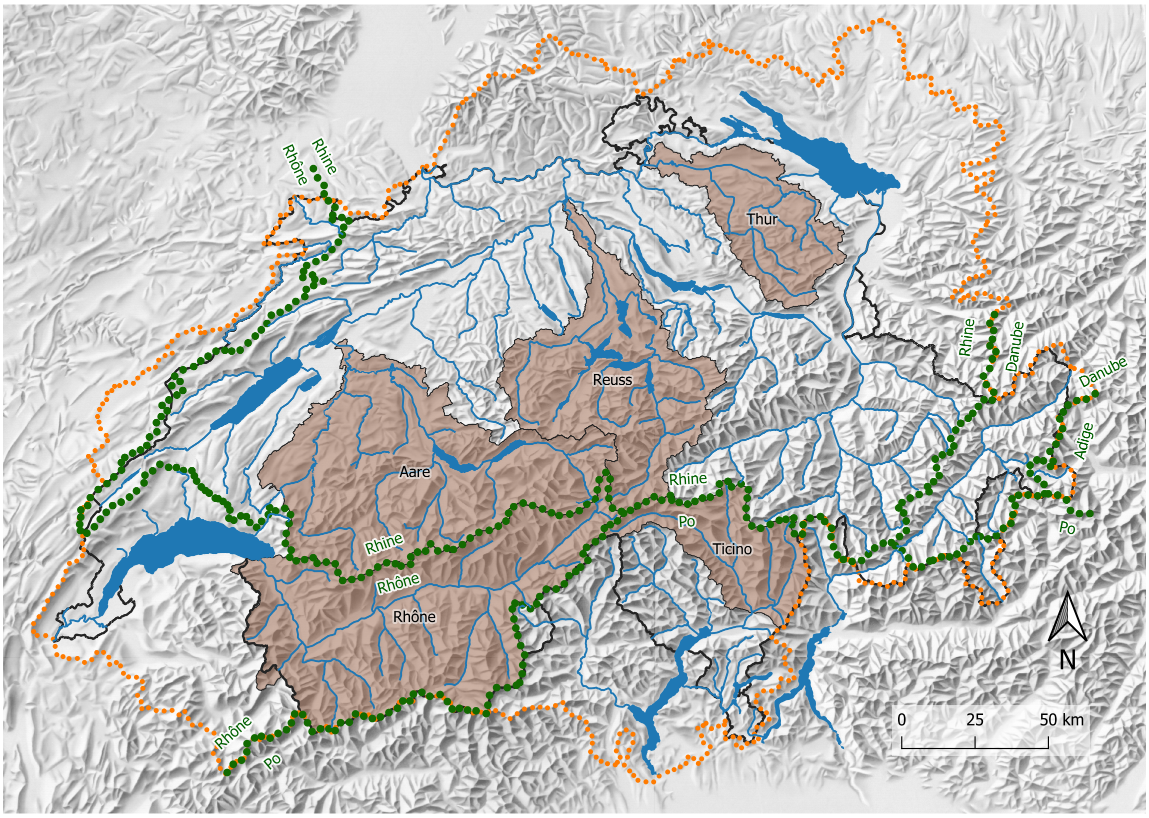

Figure 1 Map of Switzerland with its major drainage divides (green), the extent of the "hydrological Switzerland" (orange) and some catchments (brown) that are referenced in the text (Data: Federal Office of Topography swisstopo and Hydrological Atlas of Switzerland).

3.1 Hydrologic process research

Very few studies use catchment-scale hydrological models to assist hydrological process research and hypothesis testing within a hydrologic model development framework (Clark et al., 2016). This might be explained by the fact that it remains highly challenging to draw conclusions on hydrological processes based on model simulations at the catchment scale; corresponding work rather involves small scale modelling at the hillslope scale (e.g. the study of van den Heuvel et al. 2018 from the US).

One example is the work of Comola et al. (2015b) that analyzes how solar radiation patterns influence the snow-hydrologic response based on two models of different complexity (ALPINE3D and SEHR-ECHO). ALPINE3D was also used by Hindshaw et al. (2011) to attribute the origin of systematic seasonal and diurnal variations in glacial stream water chemistry, and by Brauchli et al. (2017) to assess the influence of small-scale snowmelt variations on the catchment-scale hydrologic response.

Another example of model-assisted process research is the analysis of Paschalis et al. (2014) with TOPKAPI-ETH on the interplay of rainfall's temporal variability and the clustering of saturated areas in flood generation.

Although there are currently few studies of this type, this topic holds potential for significant model diversification since hydrologic process analysis might require model structural changes to allow new hypotheses to be tested. An example is given by Dal Molin et al. (2020), who discusses, based on the SUPERFLEX framework, how to flexibly adapt the model structure to integrate new hypotheses about dominant hydrological processes.

3.2 Real-time forecasting

The ever increasing need for reliable real-time streamflow forecasts leads to a continuous evolution of the underlying hydro-meteorological modelling systems. Real-time forecasting started with deterministic forecasts from a single meteorological forecast applied to a single hydrological model; today, users expect full stochastic ensemble forecasts at hourly time scales, updated every few hours and with several stochastic meteorological inputs applied to different hydrological models (Karsten and Ebel, 2016). Coupled atmospheric–hydrologic ensemble prediction systems were proven to provide better forecasts than deterministic simulations (Verbunt et al., 2007; Zappa et al., 2008; Jaun et al., 2008; Liechti et al., 2013). These might also include data assimilation schemes (Jörg-Hess et al., 2015) or the assessment of hydrologic uncertainty related to meteorological forcings, model parameters and initial conditions (Zappa et al., 2011; Fundel and Zappa, 2011).

Such modern forecasting systems require hydrological models that provide forecasts at many locations in a stream network, that are fast to run, and that include the effect of hydraulic infrastructures (eg. of hydropower water intakes and accumulation lakes). Since the early times of flood forecasting, HBV and PREVAH were used in governmental offices (Karsten and Ebel, 2016) as well as in research institutes because of their relative simplicity and low computational costs (Verbunt et al., 2006; Addor et al., 2011; Murphy et al., 2019; Antonetti et al., 2019).

PREVAH also plays a prominent role in drought forecasting (Fundel et al., 2013; Jörg-Hess et al., 2015; Bogner et al., 2018a) and within the operational Swiss drought information platform (Stähli et al., 2013). Furthermore, it is to date the only model used for subseasonal streamflow forecasts (Monhart et al., 2019; Anghileri et al., 2019), which is still in its infancy in Switzerland.

Despite the dominance of HBV and PREVAH, the considerably more complex WaSiM-ETH model has, however, also been used for research studies on improving flood forecasting in mountainous areas (Jasper and Kaufmann, 2003; Ahrens et al., 2003; Jasper et al., 2002). Along with HBV, PREVAH and LARSIM, WaSim-ETH is today part of the Swiss operational ensemble forecasting system (Karsten and Ebel, 2016), which uses the FEWS platform (Flood Early Warning System; Werner et al., 2013) to provide forecasts for the cantonal authorities and the public (Swiss Federal Office for the Environment, 2019). A key advantage of the computationally intensive WaSiM-ETH model is the fact that it can explicitly account for lake regulations and hydropower operations (J. Schulla, personal communication, October 23, 2020).

In parallel to the above-mentioned models, RS MINERVE is being used as a specific flood forecasting tool for the upper Rhone river catchment, a large catchment (5220 km^2, see Fig. 1) strongly influenced by glacier melt and hydropower production (García Hernández et al., 2009b,a; Jordan et al., 2010). Before the recent implementation in WaSiM-ETH and in TOPKAPI-ETH, RS MINERVE was the only operational tool that explicitly modelled the effect of lakes and hydraulic infrastructures.

3.3 Characterization and quantification of floods and droughts

Infrastructure planning, water resources and natural risk management also heavily rely on probabilistic quantifications of extremes, i.e. an estimation of what could happen in terms of floods and droughts and their associated probabilities (called return periods in hydrology). Work in this field continues to be based on statistical analyses and extrapolation of observed streamflow time series (Brunner et al., 2018a; Asadi et al., 2018), but hydrological models play an ever-increasing role to complement missing or insufficient streamflow data.

Any model-based flood estimation method is computationally intensive since long model simulation runs are required at an hourly time step. Accordingly, simple models such as PREVAH (Viviroli et al., 2009c,a; Felder and Weingartner, 2017), HBV-light (Brunner and Sikorska-Senoner, 2019; Sikorska et al., 2017; Sikorska-Senoner et al., 2020) and RS (Zeimetz et al., 2018a, 2017; Bieri and Schleiss, 2013) dominate the Swiss literature on flood estimation; these models are all deemed to perform well enough for flood estimation in Swiss catchments by their respective authors and users.

However, given that all the above simple models rely on similar reservoir-based streamflow simulation methods, there is currently an important modelling effort by Kauzlaric (personal communication) to diversify flood estimation modelling for flood risk assessment, through the further development of the modular and open-source model DECIPHeR for Swiss catchments.

Other complex distributed models are to date only used to study specific flood types that involve a good physical parameterization of small scale processes, such as rain-on-snow flood events, as in the study by Rössler et al. (2014) with WaSiM-ETH.

In addition to the above studies, there are also applications aiming at the reconstruction and/or reproduction of historical floods dating further in the past. The effect of a major volcanic eruption in 1816 on the generation of floods in the upper Rhine basin (see Fig. 1) has been analysed by Rössler and Brönnimann (2018) using WaSiM-ETH. Stucki et al. (2018) reconstructed a large flood of the 19th Century in Ticino with PREVAH coupled with the routing part of RS (the model was chosen because it was already calibrated for the region by Andres et al. (2016)). Ancey et al. (2019) reconstructed the 1818 Giétro glacial lake outburst flood with GERM (which was also ready to use for this area). These examples show that models developed for current day conditions are transposed without further adaptation to historical conditions, similarly as they are transposed to future conditions (see the following section).

Work on droughts is much less abundant in Switzerland than work on floods, which is related to the fact that missing water was, in the past, not a hot topic in this country known as the water tower of Europe (Milano et al., 2015a). What can be highlighted here is that the same models are in use to assess droughts and floods, potentially with specific recalibration, but without modifying the model structure. This is motivated by the fact that existing models are deemed to reproduce well all dominant processes in the Swiss environment, as e.g. explicitly stated in the work of Zappa and Kan (2007) on quantifying the hydrological impact of the 2003 heatwave with a distributed version of PREVAH, later on used for additional drought analyses (Brunner et al., 2019a; Zappa et al., 2019). Similarly, HBV-light served in several drought studies (Staudinger et al., 2014; Staudinger and Seibert, 2014; Staudinger et al., 2015) and was used to assess low flow drivers in Alpine catchments (Arnoux et al., 2020).

However, significant efforts to improve the model representation of groundwater and the corresponding base-flow during droughts remain to be done in Switzerland, which will most probably lead to further model diversification.

3.4 Climate change impact analysis

Climate change impact studies emerged in Switzerland in the 1990s, including a large national research programme on climate change and natural hazards (snf, 2021). Since then, all model-based studies are mostly conducted with the models that established themselves in Switzerland, which have, however, not been specifically designed for climate change impact analysis; detailed assessments of how well these models can simulate future conditions are largely missing.

WaSiM-ETH was, for example, chosen by Jasper et al. (2004) to assess the effect of different regional climate scenarios in the Thur and the Ticino catchments (Fig. 1). The model choice is justified by the fact that "from the hydrological point of view of spatially distributed catchment modelling, this model represents the state-of-the-art" and that it "can be successfully applied to a wide range of scales". WaSiM-ETH has also been applied to assess future soil water patterns (Jasper et al., 2006; Rössler et al., 2012) and future summer evapotranspiration regimes (Calanca et al., 2006). It was even applied for the entire Rhine basin at a 1 km^2 resolution down to Rotterdam by Kleinn et al. (2005).

TOPKAPI-ETH, the other frequently used complex distributed model has also been used in several climate change impact applications (Fatichi et al., 2014, 2015b; Finger et al., 2012; Anghileri et al., 2018).

The most widely used models to study climate change impact on streamflow are to date however the reservoir-based models PREVAH (Köplin et al. 2012; Bosshard et al. 2013; Speich et al. 2015; Junker et al. 2015 and others; see Supplementary material) and HBV-light (Etter et al. 2017; Hakala et al. 2020; Brunner et al.

2018b; Jenicek et al. 2018 and others). In the western part of Switzerland, RS and GSM-SOCONT were used in the past, especially for high elevation sites (Horton et al., 2006; Uhlmann et al., 2012, 2013; Terrier et al., 2015).

The justification of these models for climate change impact assessments is well summarized by Köplin et al. (2010) who, for PREVAH, states that the model "has been developed especially to suit conditions in mountainous environments" and that it "has proved to be a reliable and flexible tool for various scopes of application and climate conditions ranging from drought analysis over water balance modelling to flood estimation and forecasting".

It is in the context of climate change impact studies that we see for the first time the use of an internationally well-established model, the SWAT model, with an application to the Upper Rhone river catchment (Rahman et al., 2014). SWAT was not specifically designed for Alpine environments, but it provides the interesting possibility to study the impact of vegetation-related land-use changes (Rahman et al., 2015). Later on, SWAT was also applied by Zarrineh et al. (2020) to an agricultural region in Western Switzerland to assess the impact of climate change on streamflow, erosion, and agriculture.

Overall, studies on the impact of vegetation changes remain extremely rare in Switzerland; examples include the analysis of forest change by Zierl and Bugmann (2005) with the ecohydrologic model RHESSys (not further used in Switzerland), by Köplin et al. (2013) and Schattan et al. (2013) with PREVAH and by Alaoui et al. (2014) with WaSiM-ETH. The work of Milano et al. (2015b) with PREVAH is to date the only study accounting also for anthropogenic effects on future water stress.

There is, however, an ample body of literature on the study of glacier retreat impacts on hydrology, which can be seen as a land-use change effect (Horton et al., 2006; Schaefli et al., 2007a; Finger et al., 2015; Etter et al., 2017; Addor et al., 2014; Junghans et al., 2011). This namely gave rise to the development of the GERM model (Huss et al., 2008; Junghans et al., 2011; Farinotti et al., 2012; Finger et al., 2013) and a new glacier retreat parameterization scheme widely applied internationally (Huss et al., 2010).

The question of how to model the effect of warming on snow accumulation and melt deserves special attention. Most hydrological models used in Switzerland rely on a simple temperature-index based snow routine. A more complex snow routine has been recently implemented in WaSiM-ETH (Thornton et al., 2019). ALPINE3D, which is built on the physically-based SNOWPACK model (Bartelt and Lehning 2002b,a,c; Lehning et al. 2002), has certainly the most complex representation of snow processes among Swiss models and has been used in several climate change impact applications (Bavay et al., 2009, 2013; Marty et al., 2017). However, detailed comparisons between simple snow routines and ALPINE3D have not been conclusive so far with respect to climate change applications (Kobierska et al., 2011; Shakoor et al., 2018). This long-standing question of how to model future snow will most likely see additional model diversification in the future.

In this context, we would like to stress here that there are still relatively few examples of hydrologic model ensembles (using several hydrologic models) for climate change impact assessment (Kobierska et al., 2011; Addor et al., 2014). The expectations in this regard might raise in the future, requiring the use of additional, and likely internationally widely applied, hydrological models.

3.5 Ecohydrology and agricultural water use

Ecohydrology studies the feedbacks between ecosystems, in particular with vegetation and the water cycle (Tague et al., 2020). To date, catchment-scale studies with ecohydrological models accounting for feedback with vegetation are scarce in Switzerland. An early example is a work of Zierl and Bugmann (2005), who used the model RHESSys to study climate and land-use change impacts on alpine streamflow in Switzerland.

This topic will gain importance in the future, e.g. to study transport phenomena of chemicals (Queloz et al., 2015), nutrient and pollutant cycling, $C0_2$ production or water temperature (Michel et al., 2020). In research, this might lead to increased use of complex, distributed models that can be coupled to ecosystem models, such a TOPKAPI-ETH (Pappas et al., 2015) or STREAMFLOW (Gallice et al., 2016).

Or, perhaps more likely, we will see the development of new models specifically targeted at vegetation-hydrology interactions, such as the one developed by Fatichi et al. (2012a,b) called Tethys-Chloris (T&C) and developed to simulate vegetation-hydrology interactions at large scales. It has been applied to catchments in Switzerland to study soil moisture spatiotemporal dynamics (Fatichi et al., 2015a), as well as to assess the vulnerability of Alpine ecosystems to climate change (Mastrotheodoros et al., 2019).

Similarly, there are very few studies on agricultural water use, a topic that will gain importance in the future, but that might not further drive model diversification. For example, WaSiM-ETH has already been shown to be suitable to study the demand and supply of water for agriculture, including irrigation (Fuhrer and Jasper, 2012). Besides, internationally widely used models might see more applications in Switzerland. One such example is SWAT (e.g. Abbaspour et al. 2007), which - given its user-friendliness - is likely to see more alpine applications despite not being specifically targeted to alpine environments (Andrianaki et al., 2019), but in exchange offers the option to study land management effects (Zarrineh et al., 2018).

3.6 Sediment production and transport

A special topic that deserves some focus is sediment transport modelling. The modelling of sediment sources, as well as transport capacity, requires models that yield reliable spatial patterns of hydrological processes, i.e. complex distributed models such as TOPKAPI-ETH, which is being extended for this purpose (Konz et al., 2011; Battista et al., 2020). Sediment management, for example in the context of hydropower production (Raymond Pralong et al., 2015; Gabbud and Lane, 2015), is constantly gaining importance in Alpine countries and will most likely drive the development of new modules to simulate the interplay of hydrological and geomorphological processes at the catchment scale.

3.7 Analysis of model behaviour and uncertainty analysis

A large body of hydrologic modelling literature focuses on a better understanding of model behaviour and in particular of model performance with respect to reproducing observed streamflow, e.g. as a function of model parameterizations, of spatio-temporal model resolution (Brunner et al., 2019c), of precipitation input data (Sikorska and Seibert, 2016; Müller-Thomy and Sikorska-Senoner, 2019), or of parameter estimation techniques (Foglia et al., 2009). In the context of model diversity, this field of research has overall little impact because most modelling groups who work on such theoretical aspects, simply use their in-house models for proofs of concepts or to actually improve their them (e.g. Schaefli et al. 2007b; Hingray et al. 2010).

The HBV-light model is probably the most widely used with this respect; model performance studies range from the integration of glacier mass balance data (Finger et al., 2015; Schaefli and Huss, 2011), of snow data assimilation (Griessinger et al., 2016), accounting for streamflow observation uncertainty (Westerberg et al., 2020), the influence of spatial or temporal resolution of hydro-meteorological input (Girons Lopez and Seibert, 2016; Sikorska and Seibert, 2018), to the integration of citizen science data (Etter et al., 2020).

Similarly, there are several studies on model calibration and performance with PREVAH; examples include the study on error correction in forecasting chains by Bogner et al. (2018b), investigation of parameter regionalisation with little observed streamflow data by Viviroli and Seibert (2015) or the assessment of spatial pattern reproduction of soil moisture and evapotranspiration (Zappa and Gurtz, 2003) and of snow (Zappa, 2008).

More complex models are rarely used in this context due to computational constraints. Examples include the work of Cullmann et al. (2011), which used WaSiM-ETH to compare the efficiency of different methods for parameter estimation, or the work of Rössler et al. (2019), which also used WaSiM-ETH to compare various climate postprocessing methods and quantify their impact on different hydrological signatures.

Overall, there are only very few parameter regionalisation studies; one example is the work of Melsen et al. (2016), who applied the internationally used VIC model to the Thur catchment to assess the impact of parameter transfer over different temporal and spatial resolutions.

3.8 Large scale modelling

To complete the picture, we address here the application of some international hydrological models implemented for Europe or large European river basins such as the Rhine, and thus covering at least a major part of the hydrological domain of Switzerland. However, we restrict ourselves to those models whose code is publicly available and/or whose results are published and/or directly available for Swiss basins.

Kauffeldt et al. (2016) presented a technical review of large-scale hydrological models implemented in operational forecasting schemes on a continental level with regard to their suitability for the European Flood Awareness System (EFAS). Amongst the models evaluated in the study, three have been deployed specifically for Europe: LISFLOOD, HYPE and mHM (see Appendix 1).

While LISFLOOD and HYPE are already running operationally (see Appendix 1) at the European scale, mHM has only recently been applied for the development and evaluation of a pan-European multimodel seasonal hydrological forecasting system (Wanders et al., 2019). Rottler et al. (2020) applied it for assessing the potential future changes in flood seasonality in the Rhine River with a 500m spatial resolution.

Several other models have been applied specifically for the Rhine basin, mainly focusing either on forecasting discharge or climate change impact applications. Examples include the so-called wflow_hbv model (van Osnabrugge et al., 2017, van Osnabrugge et al., 2019 and van Osnabrugge 2020) for hourly/daily streamflow forecasting of the Rhine, allowing lake level data assimilation. Another example is the LARSIM model, which was implemented at a 1km^2 resolution in combination with HBV-light to assess the origin of streamflow components in a project of the International Commission for the Hydrology of the Rhine basin (KHR/CHR) in 2012 (Stahl et al., 2017). The major regulated and unregulated lakes were included in LARSIM, and also four of the most influent "clustered" hydropower reservoirs present on the upper Aare, upper Reuss, upper Rhine and in the Ill river catchment (Fig. 1).

In general, the skill of most large scale models is found to be inferior near the main Alpine ridge compared to mountainous or lowland areas. The high Alpine catchments have been identified early as posing a major challenge to large scale hydrological modelling (Kleinn et al., 2005). Besides larger errors in the meteorological variables (precipitation in particular), and the important effect of water management practices, the smaller the catchment area and the greater the elevation ranges, the more detailed the model structure and the spatial resolution need to be to achieve good model performances (Gurtz et al., 2003). While most likely being cancelled out downstream (Kleinn et al., 2005), these problems remain yet to be addressed in large scale modelling and certainly partly explain why specific Swiss-scale models continue to be extremely popular.

4 Disentangling the motivations behind the choices

In total, we reviewed 157 peer-reviewed journal articles on hydrological modelling in Swiss catchments (see Table 1 in the Supporting Information). Excluding the large scale applications (Section 3.8), a Swiss hydrological model (category D or E in Table 1) is selected in 93% of cases, leaving little room for international models. PREVAH takes the lion's share with about 30% of the applications, followed by HBV-light (16.5%) and WaSiM-ETH (14.6%). The most used international model is SWAT with a small 4% usage (7 cases), mainly related to research led from outside Switzerland. An analysis of the temporal evolution of model use (Fig. 2) suggests a small opening to international models. The relatively higher peak in 2003 is mainly due to articles related to the MAP project (Mesoscale Alpine Programme).

Addor and Melsen (2019) argue that the choice of a model is driven by legacy rather than adequacy, where they understand by legacy: "practicality, convenience, experience, and habit". This hypothesis implies that the hydrological model of choice depends on the one hand essentially on the experience available in the modelling group and on the other hand on the code and data availability.

In the articles analyzed here, about 25% of the authors specifically address the model's adequacy with the context or the landscape. However, this does not mean that adequacy has been formally tested or that it actually drove the choice of the model, but rather that it is argued as suitable to the intended application. About 53% of the articles do not provide any mention of adequacy. The rest provide some description of the model characteristics that might be interpreted as arguments for suitability to the case study. Furthermore, besides the hydrological processes studies (Section 3.1), there are no examples where the perceptual model, i.e. the modellers' perception of how nature works, is explicitly discussed, a shortcoming that is the rule rather than the exception in hydrological modelling works (Beven and Chappell, rev).

Some models are specialized for certain processes, such as ALPINE3D for snow and GERM for glaciers, and are thus proportionally more used in these contexts (Fig. 3). TOPKAPI-ETH tends to be more used for processes that need a physically-based representation or that need a gridded spatial structure to provide gridded output, e.g. in view of coupling to another model. RS specifically targets flood modelling and hydropower operations, as it was designed for operational flood mitigation with hydropower plants. The three most used models, i.e.

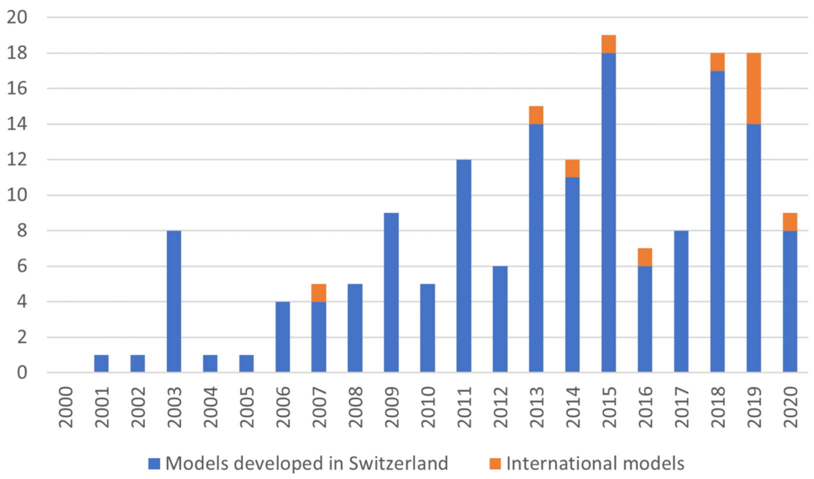

Figure 2 Number of articles reporting applications of hydrological models over the years with a distinction of the models developed in Switzerland and international models.

PREVAH, HBV-light and WaSiM-ETH, are general models and are applied to different topics, such as climate change impact studies, floods, droughts, cryosphere-related processes, and operational forecasting (Fig. 3).

One point to note is that the adequacy to climate change studies is generally not discussed. References to previous studies are sometimes provided, without the latter having addressed this point explicitly. While it is relatively easy to demonstrate a model's ability to reproduce floods or drought conditions, its transferability to other climate conditions is more difficult to prove directly.

One of the reasons driving the choice for one hydrological model, besides the adequacy, is reusing a model that is already set up for a catchment of interest, sometimes without the need to recalibrate it. About 20% of the articles explicitly state that the applied model comes from another study. Likely, this number should be higher as some authors publish multiple articles targeting different topics but on one model setup, without explicitly mentioning it.

Another reason is the selection of the model that is developed and used at the research institute. This is a strong driver, as for 66% of the articles the first author is affiliated with the institute where the model is being developed - which confirms a hypothesis that is indeed widespread in hydrology. The model at hand is thus well known, the code is available, and specialists are present to make necessary adaptations to it. Also, when the model is not one from the institute, collaborations are established with the developer or the lead researcher of the model, leading to the fact that for 72% of the articles, the model developer (or team leader) is co-authoring the paper. These three aspects - reuse of an existing setup, in-house knowledge and collaborations - have one common ground, which is convenience. Finally, the choice of the model might also be imposed by a project.

While we see an impressive model diversity at the single or few catchments scale, it is noteworthy that our review points towards an important national-scale shortcoming: while there are catchments that have been "over-modelled" (e.g. Thur, Dischma) - however with little model intercomparison - there is a clear lack of large scale or national studies. In particular, the few available studies often do not cross the Swiss national border, even though the "hydrological Switzerland" extends to its neighbouring countries (Fig. 1).

The absence of such larger scale studies might be explained by shortcomings and challenges more widely encountered in hydrological modelling over larger domains. These include differing quality and scales of input data and streamflow observations and large heterogeneity in hydrological behaviour (possibly requiring more than one specialized model). Yet, this heterogeneity may in fact provide us with the opportunity to improve our understanding of differences in model adequacy and model performance, and to draw most needed conclusions on the robustness of generalizations and on estimation uncertainty (Gupta et al., 2014; McMillan et al., 2016).

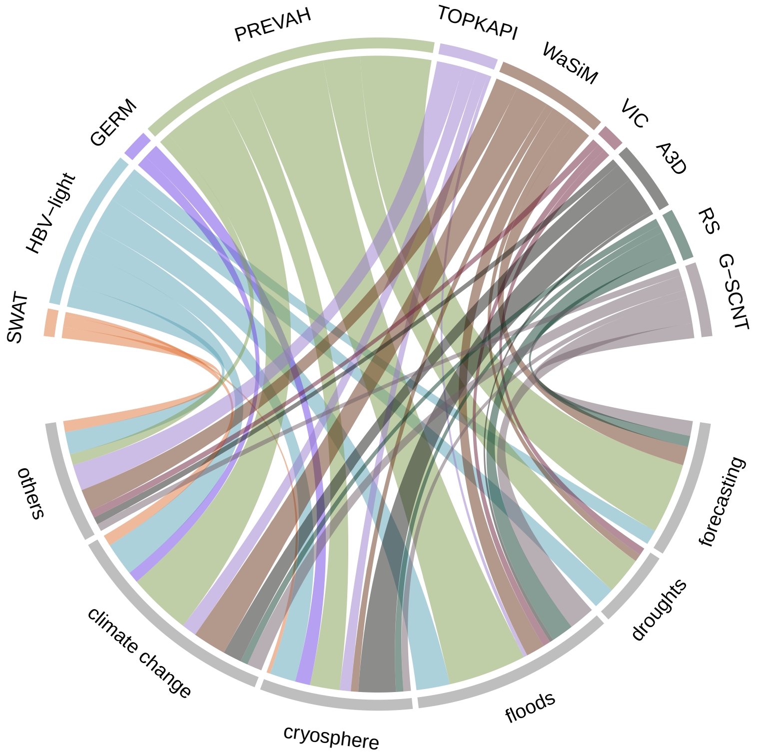

Figure 3 Hydrological models applied to different contexts in Switzerland. The importance of the link is proportional to the number of scientific articles. The importance of some models can be inflated by the fact that an article can address multiple contexts, such as floods and climate change. Models with too few use cases (less than three) are not included for the sake of clarity. A3D stands for ALPINE3D and G-SCNT for GSM-SOCONT.

5 Conclusion

Focusing on Switzerland, we carried out a comprehensive literature review on the hydrological models developed and applied in different contexts. The objective of this work was to disentangle the motivations and reasons behind the choices that led to the current co-existence of a wide range of streamflow models in a small country. To structure the analysis, we attempted a classification into eight fields of model application, ranging from hydrological process research to model uncertainty analysis and large scale modelling. For all reviewed studies, we examined the arguments that were explicitly put forward by the authors for model selection, as well as implicit aspects, such as the author's affiliation or co-authorships.

The model adequacy for the study context or the landscape is explicitly addressed by only 25% of the articles, while 53% make no mention of adequacy, neither provide any justification for the choice of the model. The models that have specifically been developed to represent specific processes, such as snow- or glacier melt or hydropower operations, are obviously mainly used in these contexts. However, the more general models, which are also the most used ones, are applied indifferently to various contexts and landscapes.

Not surprisingly, researchers active in Switzerland are very keen on using a model developed in Switzerland (93% of the case studies) or even at their own research institute (66% of the articles analysed), and possibly used on the same catchment previously (20%), which all in all underlines that convenience might be the foremost model selection driver. Moreover, this is likely to be the cause of the existence of so many hydrological models, as each research group develops its own tools.

Convenience certainly also explains that some catchments are used in numerous studies and that larger scale or multi-catchment studies on hydrological functioning and model behaviour are largely missing: both points might in fact be explained by how tedious it remains to gather all relevant data (Switzerland does not yet have a hydrological data portal). The absence of model intercomparison, in exchange, might at least partly be explained by the few open-source models used in Switzerland.

With ongoing climate change and ensuing challenges for water resources and water-related hazard management, hydrological modelling needs to evolve quickly. In Alpine environments, the most striking example is certainly the emergence of hydrological droughts (Loon, 2015) during summer and fall (Brunner et al., 2019b; Rigling and Stähli, 2020), which requires to understand the drivers of low flow (Arnoux et al., 2020) and the development of hydrological models that reliably represent groundwater recharge.

This component is, in fact, crudely parametrised in many streamflow models for alpine environments. Improved modelling of surface water-groundwater interactions is also a pre-condition for water temperature projections, agricultural water use and related water quality, drinking water management, and biodiversity assessment in ecosystems strongly influenced by river-groundwater interactions (Brunner et al., 2017).

Another key topic that will receive growing attention is the role of the vegetation in modulating climate extremes (Mastrotheodoros et al., 2020) and land-use changes induced by climate warming, calling thereby for improved representations of vegetation's role in hydrological models.

Accordingly, application-oriented as well as essentially research-oriented models can see further diversification in the near future. If model development continues the path taken so far, models will branch into sub-variants, and process-specific models will be created. However, we see two elements that might reverse the trend. The first element is the emergence of modular frameworks that allow creating a wide variety of model structures. While some specific topics might still need custom models tailored to certain applications, most hydrological models share similar principles and process representations. The creation of such flexible frameworks is strongly encouraged by Clark et al. (2011). Nowadays, different flexible frameworks exist, such as SUPERFLEX, FUSE (Clark et al., 2008), PERSiST (Futter et al., 2014), ECHSE (Kneis, 2015), MARRMoT (Knoben et al., 2019), Raven (Craig et al., 2020), and SUMMA (Clark et al., 2015). However, the flexibility provided by these frameworks likely comes with a counterpart, which is more code complexity. Most of these frameworks are relatively new and their adoption by a large community of modellers remains to be proven.

The second element is the growing adoption of version control systems that allow collaboration on open-source code with unprecedented ease. These code sharing platforms (code repositories) allow for anyone to suggest improvements (in a written form) to an open-source code or even to suggest changes to the code (e.g. pull requests) that will be reviewed by the developers of the model and merged to the main code base. As more models go open source, the need to create in-house versions to implement processes decreases. Hopefully, it should increase contributions to shared code bases and benefit a community-driven dynamic that would be beneficial for all, increasing thereby international collaborations.

Acknowledgements

We would like to thank various colleagues for their help on the history of hydrological modelling in Switzerland (see Supplementary Information) and Karsten Jasper for the insight on hydrological modelling at the Swiss Federal Office for the Environment (FOEN).

Appendix 1: Short model descriptions, alphabetical order

ALPINE3D (Lehning et al., 2006) is a model developed in Switzerland targeting surface processes in alpine environments, in particular snow processes, and is suitable for very steep terrain. It targets applications where the small-scale variability at the atmosphere-surface interface is important. Three-dimensional aspects relate to processes in the atmosphere, such as drifting snow. The snow-related processes are modelled by the physically-based SNOWPACK model (Bartelt and Lehning 2002b,a,c; Lehning et al. 2002). ALPINE3D has a built-in runoff module adapted from an early version of PREVAH (Lehning et al., 2006) and a runoff module that solves the Richards equations (Wever et al., 2017). It has been recently extended by a hydrological simulation tool for streamflow and water temperature prediction (Gallice et al., 2016).

CemaNeige-GR6J is the daily version of a lumped, bucket-type rainfall-runoff model with six free parameters (Pushpalatha et al., 2011), combined with the CemaNeige snow module (Valéry et al., 2014a,b), which is a routine for snow accumulation and melt based on a degree-day concept that introduces two additional free parameters. GR6J is an empirical model with a root zone storage and two routing routines: one for the slow (unit hydrograph) and one for the fast flow component (unit hydrograph, a non-linear and an exponential store). Both flow components interact with the groundwater through an exchange coefficient. It has seen one application in Switzerland for a climate change impact study (Keller et al., 2019).

DECIPHeR (Dynamic fluxEs and ConnectIvity for Predictions of HydRology; Coxon et al., 2019) is an open-source flexible model framework suited for different spatial scales. The model builds on the code and key concepts of Dynamic TOPMODEL (Beven and Freer, 2001), an improvement of the original TOPMODEL (TOPography based hydrological model; Beven and Kirkby, 1979). It can be run as a lumped model (1 HRU), as semi-distributed (multiple HRUs) or as fully distributed (HRU for every single grid cell). Each HRU is treated as a separate functional unit in the model and thus allows for different process conceptualizations and parameterizations across the catchment.

GERM (Glacier Evolution Runoff Model; Huss et al. 2008; Farinotti et al. 2012) consists of five different modules, which largely rely on existing approaches, dealing with snow accumulation, ablation, glacier evolution, evapotranspiration and runoff routing. It is a fully distributed, deterministic, conceptual model designed mainly for simulations at a daily resolution and a high spatial resolution. Glacier geometry is updated annually according to a non-parametric approach proposed by Huss et al. (2010). The hydrological module is based on the concept of linear reservoirs and distinguishes five surface types: ice, snow, rock, vegetation and open water.

GSM-SOCONT (Glacier and SnowMelt – SOil CONTribution model; Schaefli et al., 2005) is a semi-lumped conceptual glacio-hydrological model composed of the reservoir-based SOCONT model (consisting in a linear reservoir for the slow soil contribution and a non-linear reservoir for direct runoff) and the GSM model for the glacierized area. the SOCONT model was inspired by the GR3 model (Edijatno and Michel, 1989), which is part of the GR model family as is CemaNeige-GR6J (see above). It was developed at the Ecole Polytechnique Fédérale de Lausanne (EPFL). The model has a parsimonious structure and was initially developed for climate change impact studies. Catchments are subdivided first into ice-covered and ice-free parts and then in elevation bands. A version of GSM-SOCONT has been implemented into RS (see below) and modified for operational flood forecasting (Hamdi et al., 2005) and for design flood estimation (Zeimetz et al., 2018b).

HBV (Hydrologiska Byråns Vattenbalansavdelning model; Bergström, 1976, 1992, 1995; Lindström et al., 1997) is a rainfall-runoff model that focuses on runoff generation processes, including snowm, and is characterized, by its original developers (Bergström, 1992), as being very general and is thus applied in many different geographical and climatological conditions.

HBV-light (Seibert and Vis, 2012) is an implementation of the HBV model (see above) that is further developed at the University of Zurich. HBV-light corresponds to a simplified and userfriendly version of the original model.

HYPE (HYdrological Predictions for the Environment, Lindström et al., 2010) is a large-scale semi-distributed conceptual model, designed to simulate discharge and model flow paths of nutrients in the water, and was originally developed by the Swedish Meteorological and Hydrological Institute. In the model, the landscape is divided into classes according to the soil type, land use and altitude, and the parameters are either global or coupled to the soil type or land-use. The model can simulate natural hydrological processes of snow- and glacier melt, evapotranspiration, soil moisture, groundwater and routing through rivers and lakes, but also human-induced influences, such as regulated lakes and reservoirs, water abstractions and irrigation. HYPE is run operationally by SMHI for several purposes (e.g. flood forecasting or climate change impact assessments). The version covering the pan-European continent is referred to as E-HYPE, its application is entirely based on open and readily available data sources (Donnelly et al., 2015), including historical data (1981-2010), 1-10 day forecast, seasonal forecasts, climate change impact scenarios and actual model performance (`https://hypeweb.smhi.se/explore-water/geographical-domains/#europehype`).

LARSIM (Large Area Runoff Simulation Model; Ludwig and Bremicker, 2006) is a semi-distributed hydrological model, which describes continuous runoff processes in catchments and river networks. The model structure (subunit) can be grid-based or based on hydrologic subcatchments. While runoff generation (described with parallel linear storage reservoirs), routing (depending on channel geometries and roughness conditions) and flow retention are simulated at the subunit scale, snow storage, evapotranspiration, interception and soil storage are simulated at a subscale level according to land use classes. While it doesn't include a glacier melt component, LARSIM includes many features that were specifically designed for its operational use as a flood forecasting model, as well as offline applications (Stahl et al., 2017).

LISFLOOD is a GIS-based model for catchment-scale water balance simulation (Knijff et al., 2010). It has been specifically designed for large river catchments, and in particular, it makes use of data layers that are available for the Joint Research Center (JRC) at European scale, such as land use, soil type and texture, river network (Thielen et al., 2009). LISFLOOD is used by the European Flood Awareness System, EFAS, for medium- and seasonal-range forecasts with a 6-hourly and daily time step. Both historical river discharge time series (1991 to near real-time) and reforecasts (1999-2018) are available on the Climate Data Store of Copernicus (`https://cds.climate.copernicus.eu/`).

mHM (mesoscale Hydrological model; Samaniego et al. 2010; Kumar et al. 2013; Thober et al. 2019) is a distributed hydrological model, which has the particularity of using the multiscale parameter regionalization approach (MPR, Samaniego et al., 2010) for parameter identification. It has been specifically developed to not need recalibration when applied at different resolutions (Kauffeldt et al., 2016). It is driven by hourly or daily meteorological forcings and utilizes observable basin physical characteristics to infer the spatial variability of the required parameters. It is developed by the Umweltforschungszentrum Leipzig and has been successfully applied to catchments ranging from 4 km^2 and to beyond 500,000 km^2. To the best of our knowledge, it does not yet have a glacier melt component. The open-source code (Fortran) is available at `https://git.ufz.de`.

PREVAH (Precipitation-Runoff-Evapotranspiration HRU Model; Gurtz et al. 1999; Viviroli et al. 2009b) is a Swiss conceptual model that has been developed specifically for heterogeneous mountainous environments with highly spatially and temporally variable processes. It follows the HBV model structure, with numerous modifications, and was designed for studies in Alpine headwater basins (Orth et al., 2015). PREVAH branched out into different versions, two of which are mostly used: an HRU-based version that runs at an hourly time step and a fully distributed version (Zappa et al., 2012) that runs at a daily time step. The distributed version of PREVAH being the most used, any reference to PREVAH in this paper implies the distributed version if not stated otherwise.

RS (Routing System; Dubois and Boillat, 2000; García Hernández et al., 2007) has been developed at the Swiss Federal Institute of Technology in Lausanne (EPFL). The version that is freely available, and thus more used, is RS MINERVE, which was developed for operational flood forecasting in Valais (García Hernández et al., 2009b) and which is maintained by the CREALP (Centre de recherche sur l'environnement alpin). RS specifically targets hydropower systems by modelling the influence of regulated infrastructures and thus allows modelling complex hydrological and hydraulic networks with anthropogenic influences.

SEHR-ECHO (Spatially Explicit Hydrologic Response model for ecohydrologic applications; Schaefli et al., 2014) is an evolution of GSM-SOCONT that was developed at the Swiss Federal Institute of Technology in Lausanne (EPFL). The model aims at taking into account the spatial variability in the runoff generation. The catchment is divided into subcatchments connected to the river network in order to account for the origin of the different areal contributions and to route them in the river network.

StreamFlow is an extension of ALPINE3D (see above). It uses an explicit formulation of travel times (Comola et al., 2015a), as does SEHR-ECHO (see above).

SUPERFLEX (Fenicia et al., 2011; Kavetski and Fenicia, 2011b) is a flexible hydrological framework now developed at Eawag (the Swiss Federal Institute of Aquatic Science and Technology). It allows building hydrological models using generic components for hypothesis testing. The building blocks are reservoirs, lag functions, and connections. The models elaborated with SUPERFLEX can be lumped, semi-distributed (Fenicia et al., 2016) or fully distributed (Hostache et al., 2020). An open-source version written in Python is available (Molin et al., 2020).

SWAT (Soil Water and Assessment Tool; Arnold et al., 1998) is an open-source semi-distributed, process-based hydrological model. Besides hydrology, other SWAT components can simulate energy balance, soil temperature, mass transport and land management at the sub-basin and HRU levels. It is one of the most applied models worldwide probably because of the broad range of hydrologic and environmental problems that can be addressed with it.

TOPKAPI-ETH (Finger et al., 2011; Ragettli and Pellicciotti, 2012), developed at ETH Zurich, is a branch of the TOPKAPI model (TOPographic Kinematic APproximation and Integration; Todini, 1995; Todini and Ciarapica, 2002; Liu and Todini, 2002; Ciarapica and Todini, 2002). It is a fully distributed and physically-based model based on the spatial integration of the kinematic wave model over the pixels of the digital elevation model (DEM). TOPKAPI-ETH has been modified for application to mountain basins by adding a second soil layer and modules for snow, glaciers, reservoirs, water abstraction, and diversion, and a new evapotranspiration scheme (Finger et al., 2011, 2012; Fatichi et al., 2015c).

VIC (Variable Infiltration Capacity model; Liang et al., 1994) is an open-source grid-based land surface hydrological model. It is implemented so that grid cells with a resolution up to 1km are simulated independently of each other. Sub-grid heterogeneity introduced by different land-use types and elevation is handled via statistical distributions. Routing must be performed separately with an additional routine taking care of the water transport between cells.

WaSiM-ETH (Water Flow and Balance Simulation Model-ETH; Schulla and Jasper, 2007; Schulla, 2009) is a fully distributed hydrological model originally developed at ETH Zurich. It describes the water fluxes in the unsaturated soil using the 1D-Richards equation (Richards, 1931). The transfer function (runoff concentration) can be processed through a series of linear reservoirs or with the kinematic wave approach (from one cell to another). WaSiM-ETH covers a wide range of hydrological processes relevant for alpine environments, with different implemented variants.

wflow is the modular and distributed hydrological modelling platform of DELTARES (`https://www.deltares.nl/en/software/wflow-hydrology/`). *wflow_hbv* is a fully distributed version of the conceptual HBV model (Lindström et al., 1997) - applied on a grid basis - in the wflow framework with a kinematic wave as routing instead of the original triangular routing function; the model has an interception reservoir, snow module, root zone storage, fast runoff reservoir, and a groundwater reservoir (de Boer-Euser et al., 2017).

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Supplementary material to ”Why do we have so many different hydrological models? A review based on the case of Switzerland”

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Abstract

This supplementary material contains two parts: first an extended version of the history of hydrological modelling in Switzerland, and second a table listing all modelling papers for Section 3 of the main paper (related to applications of hydrological models in Switzerland).

1 History of hydrological modelling in Switzerland, extended version

1.1 Preliminary remark

There was a journal entitled ”Schweizerische Zeitschrift für Hydrologie” (Swiss journal for hydrology), published by Springer. The first issue of this journal was published in 1920 and called then ”Zeitschrift für Hydrologie” (journal of hydrology). The journal changed its name in 1949 to Swiss journal of hydrology. It became ”Aquatic sciences” in 1989 (Bossard, 1989) and is since then indexed on WebOfScience. The journal never had a particular focus on what we call hydrology today but was rooted in limnology and the hydrology of lakes (Tockner et al., 2009). The name was chosen in 1920 by the then called Swiss Hydrobiological Commission (Swiss Society for Hydrology and Limnology today) (Perret, 2001) despite of being strongly rooted in limnology at that time. Accordingly, the Swiss journal for hydrology does not appear here in this brief overview.

1.2 History of hydrological modelling in Switzerland

On WebOfScience, the very first hydrological modelling paper that refers to Switzerland (index search: hydrolog* and model* and Switzerland or Swiss) was published by Baumgartner et al. (1986) and was a proof of method for the use of remote sensing data for snow runoff modelling with the Snowmelt Runoff Model (SRM, Martinec, 1975). Journal of Hydrology has nevertheless published an earlier Swiss modelling paper, the work of Hager (1984), who used a no-name conceptual model to predict the effect of heavy rainfall on an 8 km2 catchment in the Swiss lowlands.

Digging into professional journals and doctoral theses and conducting personal enquiries revealed the early hydrological modelling work of Naef (1974) for engineering applications. The work of Naef in particular also includes a very early hydrological model intercomparison study (Naef, 1977) where the behaviour of several conceptual models have been tested for three small well-instrumented catchments to understand if complex models yield better results than very simple ones.

The above work on input-output models (the focus of the main paper) in the 1970-1980ies was preceded by regression-based methods for real-time forecasting, specifically for inflow to hydropower plants (Jensen and

Lang, 1973) and streamflow in the River Rhine (e.g. to predict downstream summer droughts, Lugiez et al., 1969).

Most of the early modelling work on streamflow with models representing hydrological processes (rather than purely statistical models) aimed at the development of operational forecast procedures and had a strong focus on snowmelt runoff and related streamflow, including in the lowland (Braun and Lang, 1986). Snowmelt modelling probably started with the work of Hoeck (1952), and modelling of snow runoff kept a strong influence on hydrological model development in the following decades (see main paper, Section 3).

The work of Braun and Lang (1986) combined the well-known temperature-index snow model (underlying also the SRM model; Martinec, 1975) to the simplest possible streamflow transformation model, which assumes that half of the snowmelt during a given time step reaches the stream directly and the other half reaches it following a linear recession. This simplified approach (compared to more recent runoff transformation routines that use a recession coefficient as in SRM), dates back to the work of Martinec (1970) on snowmelt runoff modelling, which is thus probably the earliest runoff modelling study in Switzerland.

Early modelling work also included glacier-melt runoff simulation (Braun and Aellen, 1990, who used a model called HBV3-ETH, not in use anymore). Braun and Renner (1992) completed first attempts of parameter regionalization, i.e. the transfer of model parameters from one catchment to another, based on catchment characteristics. The work of Hottelet et al. (1993) is an early example of model adaptation to a specific catchment; they added three parameters to HBV-ETH to account for aspect dependent snowmelt and karst runoff for the Thur catchment. During the same period, one of the very first climate change impact prediction studies in Switzerland was the work of Bultot et al. (1992), who applied a conceptual hydrological model called IRMB on a 212 km2 lowland catchment. Jordan (1990) completed one of the first land-use change impact studies on streamflow in mountainous regions, using Topmodel.

Hydrologic process studies in experimental catchments started early on, with a focus on the role of forests on water quality and streamflow in the Alptal catchment (Keller, 1970, 1989) and a focus on rural runoff generation processes (Jaton, 1982).

Early attempts to use models for hypothesis testing and process understanding in experimental catchments (Jordan, 1990) were undertaken with Topmodel by Iorgulescu and Jordan (1994), with SHE by Jordan et al. (1987) and with OTTHYMO by Wisner and Jordan (1983).

In parallel to the work on streamflow quantity, Keller and Forster (1991) published an application of a model, called Brook, developed by Fédérer and Lash (1978) to assess the influence of streamflow sources on stream water chemistry; the model used was initially designed to assess the effect of forests on the water cycle and streamflow (Forster, 1989), a key topic (besides snow) during the early hydrologic model development phase (Keller, 1979; Hegg et al., 2006). Forest hydrology can in fact be considered as the very foundation of hydrologic research in Switzerland, initiated after the first Swiss federal law on forest protection 1867 (Keller, 1985; Hegg et al., 2006).

Finally, it is important to point out that the above overview lacks reference to a strong driver of hydrologic prediction methods: the development of hydropower in Switzerland, which was very pronounced in the early 20th century (Jeger, 1942). The design and management needs of hydropower certainly had a strong push on the development of hydrological models, but early documents are hard to find nowadays. It also drove the development of prediction methods for ungauged catchments during the early development phase (Bruschin and North, 1977), and later on, motivated the development of a large body of detailed climate change impact studies on hydropower and high Alpine streamflow regimes (Westaway, 2000; Schaefli, 2015).

2 Hydrological model uses

Reference	Model(s)	Field of application	Location	Ade-quacy	Reuse	Affilia-tion	Co-auth.
Middelkoop et al. (2001)	WaSIM	climate change, floods, droughts	Rhine	N	N	*	Y
Jasper et al. (2002)	WaSIM	forecasting, floods	Ticino, Verzasca, Maggia	Y	N	Y	Y
Ahrens et al. (2003)	WaSIM	forecasting	Ticino, Verzasca, Maggia	N	N	N	Y
Ahrens (2003a)	WaSIM	forecasting	Ticino, Verzasca, Maggia	N	Y	N	N
Ahrens (2003b)	WaSIM	forecasting	Ticino, Verzasca, Maggia	+−	N	N	N
Gurtz et al. (2003)	PREVAH, WaSiM	others	Dischmabach, Rietholzbach	*	N	Y	Y
Jasper and Kaufmann (2003)	WaSIM	forecasting	Ticino, Verzasca, Maggia	Y	N	Y	Y
Verbunt et al. (2003)	WaSIM	cryosphere	Massa, Rhone, Dischmabach	+−	N	Y	Y
Zappa and Gurtz (2003)	PREVAH	others	Ticino	*	N	Y	Y
Jasper et al. (2004)	WaSIM	climate change	Thur, Ticino	+−	N	Y	Y
Kleinn et al. (2005)	WaSIM	climate change	Rhine	*	*	*	*
Verbunt et al. (2005)	WaSIM	others	Swiss Alpine Rhine basin	+−	N	Y	Y
Zierl and Bugmann (2005)	RHESSys	climate change	Alptal, Saltina, Verzasca, Dischma	Y	N	N	N
Calanca et al. (2006)	WaSIM	climate change	Thur, Ticino, Rhone	+−	N	Y	Y
Horton et al. (2006)	GSM-SOCONT	climate change	11 catchments	N	N	Y	Y
Jasper et al. (2006)	WaSIM	climate change	Thur	Y	N	Y	Y
Verbunt et al. (2006)	PREVAH	forecasting, floods	Upper Rhine basin	Y	N	N	Y
Abbaspour et al. (2007)	SWAT	others	Thur	N	N	N	Y
Schaefli et al. (2007b)	GSM-SOCONT	others	Mauvoisin	N	N	Y	Y
Schaefli et al. (2007a)	GSM-SOCONT	climate change	Mauvoisin	N	N	Y	Y
Verbunt et al. (2007)	PREVAH	forecasting, floods	Almost countrywide	+−	Y	N	N
Zappa and Kan (2007)	PREVAH	cryosphere, droughts	Thur, Rhone, Lütschine	+−	N	Y	Y
Cullmann and Wriedt (2008)	WaSIM	others	Rietholzbach	N	N	N	N
Jaun et al. (2008)	PREVAH	forecasting, floods	Almost countrywide	N	N	N	N

Zappa (2008)	PREVAH	cryosphere	Whole Switzerland	*	N	Y	Y
Zappa et al. (2008)	PREVAH, HBV	forecasting, floods	Verzasca, Kleine Emme	*	*	Y	Y
Bavay et al. (2009)	ALPINE3D	climate change, cryosphere	Dischma, Inn	Y	N	Y	Y
Foglia et al. (2009a)	TOPKAPI	others	Maggia valley	+−	N	N	N
Foglia et al. (2009b)	TOPKAPI	others	Maggia valley	Y	N	N	N
García Hernández et al. (2009)	GSM-SOCONT, RS	forecasting, floods	Rhone	N	N	Y	Y
Jaun and Ahrens (2009)	PREVAH	forecasting	Upper Rhine basin	N	N	Y	N
Schaefli and Zehe (2009)	GSM-SOCONT	others	Rhone	N	N	Y	Y
Thielen et al. (2009)	LISFLOOD	forecasting, floods	European scale	*	*	*	*
Viviroli et al. (2009b)	PREVAH	floods	Countrywide	Y	N	Y	Y
Viviroli et al. (2009a)	PREVAH	floods	Upper Rhine basin	Y	N	Y	Y
Hingray et al. (2010)	GSM-SOCONT	floods	Rhone	N	N	Y	Y
Jordan et al. (2010)	GSM-SOCONT, RS	forecasting, floods	Rhone	N	N	Y	Y
Köplin et al. (2010)	PREVAH	climate change, floods	Countrywide	Y	N	Y	Y
Rößler and Löffler (2010)	WaSIM	others	Lonza (Lötschental valley)	*	N	N	N
Addor et al. (2011)	PREVAH	forecasting, floods	Sihl catchment	N	Y	Y	Y
Cullmann et al. (2011)	WaSIM	others	Thur	N	Y	N	N
Finger et al. (2011)	TOPKAPI	cryosphere	Rhonegletscher	N	N	Y	Y
Fundel and Zappa (2011)	PREVAH	forecasting	Thur, Alp, Verzasca	Y	N	Y	Y
Hindshaw et al. (2011)	ALPINE3D	cryosphere, others	Damma glacier	+−	Y	N	N
Junghans et al. (2011)	HBV, GERM	climate change, cryosphere	Upper Rhine basin	+−	N	N	Y
Kobierska et al. (2011)	PREVAH, ALPINE3D	climate change, cryosphere	Damma glacier	N	N	Y	*
Konz et al. (2011)	TOPKAPI	others	Chiene catchment	+−	N	Y	Y
Schaefli and Huss (2011)	GSM-SOCONT	cryosphere	Rhonegletscher	+−	N	Y	Y
Tobin et al. (2011)	GSM-SOCONT	forecasting	Visp, Dranse	N	Y	Y	N
Zappa et al. (2011)	PREVAH	forecasting, floods	Verzasca	Y	N	Y	Y

Farinotti et al. (2012)	GERM	climate change, cryosphere	9 catchments	*	N	N	Y
Finger et al. (2012)	TOPKAPI	climate change, cryosphere	Vispa	N	N	Y	Y
Fuhrer and Jasper (2012)	WaSIM	others	6 catchments	Y	N	Y	Y
Köplin et al. (2012)	PREVAH	climate change	Whole Switzerland	N	N	Y	Y
Rössler et al. (2012)	WaSIM	climate change, droughts	Lonza (Lötschental valley)	+−	Y	N	N
Tobin et al. (2012)	GSM-SOCONT	forecasting	Rhone	N	N	Y	Y
Bavay et al. (2013)	ALPINE3D	climate change, cryosphere	Grisons	Y	N	Y	Y
Bieri and Schleiss (2013)	GSM-SOCONT, RS	floods	Aare	N	N	Y	N
Bosshard et al. (2013)	PREVAH, HBV	climate change	Alpine Rhine	N	Y	N	Y
Finger et al. (2013)	GERM	climate change, cryosphere	Glacier de la Plaine Morte	+−	N	N	Y
Foglia et al. (2013)	TOPKAPI	others	Maggia valley	N	N	N	N
Fundel et al. (2013)	PREVAH	forecasting, droughts	Thur	N	Y	Y	Y
Kobierska et al. (2013)	PREVAH, ALPINE3D	climate change, cryosphere	Göscheralpsee	Y	Y	Y	Y
Köplin et al. (2013)	PREVAH	climate change, cryosphere	Whole Switzerland	Y	Y	Y	Y
Liechti et al. (2013)	PREVAH	forecasting, floods	Verzasca, Pincascia	N	N	Y	Y
Rahman et al. (2013)	SWAT	others	Rhone	*	N	N	?
Uhlmann et al. (2013)	GSM-SOCONT, RS	climate change, cryosphere	Findelen basin	+−	N	N	Y
Addor et al. (2014)	HBV-light, PREVAH, WaSiM	climate change	6 catchments	*	*	*	*
Alaoui et al. (2014)	WaSIM	climate change	Ursern Valley	+−	N	N	Y
Bosshard et al. (2014)	PREVAH	climate change	Rhine	*	*	*	*
Fatichi et al. (2014)	TOPKAPI	climate change	Rhone	Y	N	Y	Y
Köplin et al. (2014b)	PREVAH	climate change, floods	Whole Switzerland	N	N	Y	Y

Köplin et al. (2014a)	PREVAH	climate change, cryosphere	Whole Switzerland	N	Y	Y	N
Paschalis et al. (2014)	TOPKAPI	floods	Kleine Emme	Y	N	Y	Y
Rahman et al. (2014)	SWAT	climate change	Rhone	+−	N	N	N
Rössler et al. (2014)	WaSIM	floods	Lonza (Lötschental valley)	Y	Y	N	N
Staudinger and Seibert (2014)	HBV-light	forecasting, droughts	21 catchments	N	N	Y	Y
Staudinger et al. (2014)	HBV-light	droughts, cryosphere	7 catchements	N	N	Y	Y
Comola et al. (2015a)	ALPINE3D	others	Dischma	N	N	Y	Y
Comola et al. (2015b)	ALPINE3D	cryosphere	Dischma	Y	N	Y	Y
Fatichi et al. (2015)	TOPKAPI	climate change	Rhone	Y	N	Y	Y
Finger et al. (2015)	HBV-light	cryosphere	Rhone, Hinterrhein, Landquart	+−	N	Y	Y
Jörg-Hess et al. (2015b)	PREVAH	forecasting, droughts	Landquart, Thur	N	Y	Y	Y
Jörg-Hess et al. (2015a)	PREVAH	forecasting, cryosphere	Thur, Rhine, Hinter Rhine, Vorder Rhine, Vorarlberg, Landquart Plessur	N	Y	Y	Y
Junker et al. (2015)	PREVAH	climate change	Kleine Emme	+−	Y	N	Y
Milano et al. (2015b)	PREVAH	climate change, droughts	9 catchments	N	N	N	N
Milano et al. (2015a)	PREVAH	climate change	9 catchments in VD	Y	N	N	N
Orth et al. (2015)	PREVAH, HBV	floods, droughts	Ergolz, Murg, Broye, Langeten, Cassarate, Sense, Emme, Dischma	+−	N	N	Y
Pappas et al. (2015)	TOPKAPI	others	Kleine Emme	+−	N	Y	Y
Rahman et al. (2015)	SWAT	climate change	Rhone	+−	Y	N	?
Raymond Pralong et al. (2015)	PREVAH	climate change	66 small catchments	+−	N	Y	Y
Speich et al. (2015)	PREVAH	climate change, cryosphere	Countrywide	N	N	Y	Y
Staudinger et al. (2015)	HBV-light	droughts	24 catchments	N	N	Y	Y
Terrier et al. (2015)	GSM-SOCONT, RS	climate change	Aare	+−	Y	Y	Y
Viviroli and Seibert (2015)	PREVAH	others	49 catchments	Y	N	Y	Y

Andres et al. (2016)	PREVAH, RS	forecasting, floods	Canton Ticino	+−	Y	Y	Y
Donnelly et al. (2016)	HYPE	others	European scale	*	*	*	*
Girons Lopez and Seibert (2016)	HBV-light	others	Thur	Y	N	Y	Y
Griessinger et al. (2016)	HBV-light	forecasting, cryosphere	20 catchments	N	N	Y	Y
Melsen et al. (2016)	VIC	others	Thur	+−	N	N	N
Schaefli (2016)	SEHR-ECHO	cryosphere	Dischma	N	N	Y	Y
Sikorska and Seibert (2016)	HBV-light	forecasting, floods	Plessur	N	N	Y	Y
Brauchli et al. (2017)	ALPINE3D	cryosphere	Dischma	Y	N	Y	Y
Etter et al. (2017)	HBV-light	climate change, cryosphere	Gigerwaldsee	N	N	Y	N
Felder and Weingartner (2017)	PREVAH	floods	Aare	Y	N	Y	N
Marty et al. (2017)	ALPINE3D	climate change, cryosphere	Aare, Grisons	N	N	Y	Y
Sikorska et al. (2017)	HBV-light	floods	9 catchments	N	N	Y	Y
Staudinger et al. (2017)	HBV-light	others	21 catchments	N	N	Y	Y
van Osnabrugge et al. (2017)	wflow_hbv	forecasting	Rhine	*	*	*	*
Wever et al. (2017)	ALPINE3D	cryosphere, floods	Dischma	Y	N	Y	Y
Zeimetz et al. (2017)	GSM-SOCONT	floods	Mattmark	N	N	Y	Y
Anghileri et al. (2018)	TOPKAPI	climate change, cryosphere	Visp	Y	N	Y	N
Bogner et al. (2018b)	PREVAH	forecasting, floods	Sihl catchment	N	Y	Y	Y
Bogner et al. (2018a)	PREVAH	forecasting, droughts	Countrywide	N	N	Y	Y
Brunner et al. (2018)	HBV-light	climate change, floods	8 catchments	+−	N	Y	Y
Etter et al. (2018)	HBV-light	others	6 catchments	N	N	Y	Y
Hakala et al. (2018)	HBV-light	climate change	10 catchments	N	N	Y	Y
Jenicek et al. (2018)	HBV-light	climate change, droughts, cryosphere	14 catchments	N	N	N	Y
Meyer et al. (2019)	HBV-light	climate change, cryosphere	Hinterrhein, Schwarze Lütschine	+−	N	N	Y
Rössler and Brönnimann (2018)	WaSIM	floods	Rhine	N	N	N	N

Shakoor et al. (2018)	ALPINE3D	cryosphere	Damma, Arolla	Y	N	Y	Y
Sikorska and Seibert (2018)	HBV-light	others	13 catchments	N	N	Y	Y
Stucki et al. (2018)	PREVAH, RS	floods	Lago Maggiore	N	Y	N	N
Zarrineh et al. (2018)	SWAT	others	Broye	+−	N	N	N
Zeimetz et al. (2018b)	GSM-SOCONT	floods	Mattmark	N	Y	Y	Y
Zeimetz et al. (2018a)	GSM-SOCONT, RS	floods, cryosphere	Mattmark Dam	N	N	Y	Y
Zischg et al. (2018)	PREVAH	floods	Aare	N	Y	Y	N
Ancey et al. (2019)	GERM	cryosphere	Giétro	N	N	N	Y
Andrianaki et al. (2019)	SWAT	cryosphere	Damma glacier watershed	*	N	N	N
Anghileri et al. (2019)	PREVAH	forecasting	Verzasca	Y	Y	N	Y
Antonetti et al. (2019)	PREVAH	forecasting, floods	Emme	N	N	Y	Y
Brunner et al. (2019e)	PREVAH	droughts	Countrywide	N	N	Y	Y
Brunner et al. (2019a)	PREVAH	climate change, droughts	Countrywide	Y	N	Y	Y
Brunner and Sikorska-Senoner (2019)	HBV-light	floods	9 catchments	N	N	N	N
Brunner et al. (2019b)	PREVAH	climate change, floods, droughts	19 regions	N	Y	Y	Y
Brunner et al. (2019c)	PREVAH	climate change, floods	Countrywide	Y	N	Y	Y
Brunner et al. (2019d)	PREVAH	droughts	Countrywide	Y	Y	Y	Y
Keller et al. (2019b)	GR6J	climate change, floods	Emme	N	N	N	N
Keller et al. (2019a)	WaSIM	climate change, floods	Thur	N	N	N	N
Mastrotheodoros et al. (2019)	VIC	floods, droughts	Thur	+−	N	N	N
Melsen et al. (2019)	VIC	others, floods, droughts	Thur	N	Y	N	N
Monhart et al. (2019)	PREVAH	forecasting	Verzasca, Thur, Klöntal	N	N	Y	Y
Müller-Thomy and Sikorska-Senoner (2019)	HBV-light	floods	9 catchments	N	N	N	N
Rössler et al. (2019)	WaSIM	climate change	Thur	N	N	N	N
Thornton et al. (2019)	WaSIM	cryosphere	Vallon de Nant	Y	N	N	N
Van Osnabrugge et al. (2019)	wflow_hbv	forecasting	Rhine	*	*	*	*
Wanders et al. (2019)	mHM	forecasting	European scale	*	*	*	*
Battista et al. (2020b)	TOPKAPI	others	Kleine Emme	Y	N	Y	N

Battista et al. (2020a)	TOPKAPI	others	Kleine Emme	Y	N	Y	N
Dal Molin et al. (2020)	SUPERFLEX	others	Thur	*	N	Y	Y
Etter et al. (2020)	HBV-light	others	Murg, Guerbe, Mentue, Verzasca	N	N	Y	Y
Giordani et al. (2020)	PREVAH	forecasting, floods	Verzasca	N	Y	N	Y
Hakala et al. (2020)	HBV-light	climate change, floods, droughts	Montsalvens, Vernex	N	N	Y	Y
Rottler et al. (2020)	mHM	climate change, floods	Rhine	*	*	*	*
Sikorska-Senoner et al. (2020)	HBV	floods	Dünnern at Olten	+−	N	Y	Y
Westerberg et al. (2020)	HBV-light	others	Kander, Broye, Wigger	N	N	N	Y
Zarrineh et al. (2020)	SWAT	climate change	Broye	N	Y	N	N

* not relevant or not analysed

Table 1: List of reviewed modelling papers ordered by dates and author names. Adequacy: the adequacy of the model with the landscape or use case has been justified; Reuse: the model set up has been explicitly reused from previous work; Affiliation: the first author is affiliated with the institute where the model is being developed; Co-auth.: the model developer or its lead scientist is co-authoring the paper.

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