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SWATCH21: A project for linking eco-hydrologic processes and services to aquatic biodiversity at river and catchment levels

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ABSTRACT

The objective of the SWATCH21 project is to improve our understanding of eco-hydrologic services at the catchment level, and biodiversity at the river scale. Six research questions are proposed: (i) How can we improve the access to input data for hydrological and ecological modeling? (ii) What is the role of glacier and snow in modifying the hydrological services? (iii) How can we best assess hydrologic services supplies and demands with the available data and tools? (iv) What will be the impact of the main hydrologic changes on species diversity in rivers? (v) Can we meet the targets of multi-sectorial river-related policies under different climate and landuse forecasting scenarios? (vi) How detailed do ES data and models need to be to answer relevant policy questions? The above questions are tackled through an integrated framework to access, share, process, model, and deliberate on hydrologic ecosystems services. State-of-the-art models have been selected, and will be compared and improved to model different ecosystems and their services. Initial results from a first SWAT model of Switzerland and Species Distribution Models are presented. Expected outputs from various climate and land use change scenarios include rivers' hydrology, predicted biodiversity, and the assessment of ecosystem services in terms of provisioning services (e.g. water resources), regulating services (e.g. nutrient, sediment and flood water retention), and cultural services (e.g. biodiversity, recreation). The expected outcome of the project is to improve integrated evidence-based water policy in the future through the analysis of tradeoffs and synergies between services.
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Abbreviations: API, Application Programming Interface; BDM, Swiss Biodiversity Monitoring Program; BRT, Boosted Regression Trees; CARET, Classification And REgression Training; CCDA, Critical Consecutive Days Analyzer; ES, Ecosystem Service; GAM, Generalized Additive Model; GBIF, Global Biodiversity Information Facility; GDM, Generalized Dissimilarity model; GEO-BON, Group on Earth Observations Biodiversity Observation Network; GEOSS, Global Earth Observation System of Systems; GERM, Glacier Evolution Runoff Model; GIS, Geographic Information System; GLM, Generalized Linear Model; GLMM, Generalized Linear Mixed Model; GRASP, Generalized Regression Analyses and Spatial Predictions; InVEST, Integrated Valuation of Ecosystem Services and Tradeoffs; IPBES, Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services; IPCC, Intergovernmental Panel on Climate Change; IUCN, International Union for the Conservation of Nature; MARS, Multivariate Additive Regression Splines; MEA, Millennium Ecosystem Assessment; NAWA, National Surface Water Quality Monitoring Programme; OGC, Open Geospatial Consortium; RF, Random Forest; SDI, Spatial Data Infrastructure; SWAT, Soil and Water Assessment Tool; SWAT-CUP, SWAT Calibration and Uncertainty Programs; SWATCH21, Soil and Water Assessment Tool project for Switzerland in the 21st century; WCMC, World Conservation Monitoring Center.

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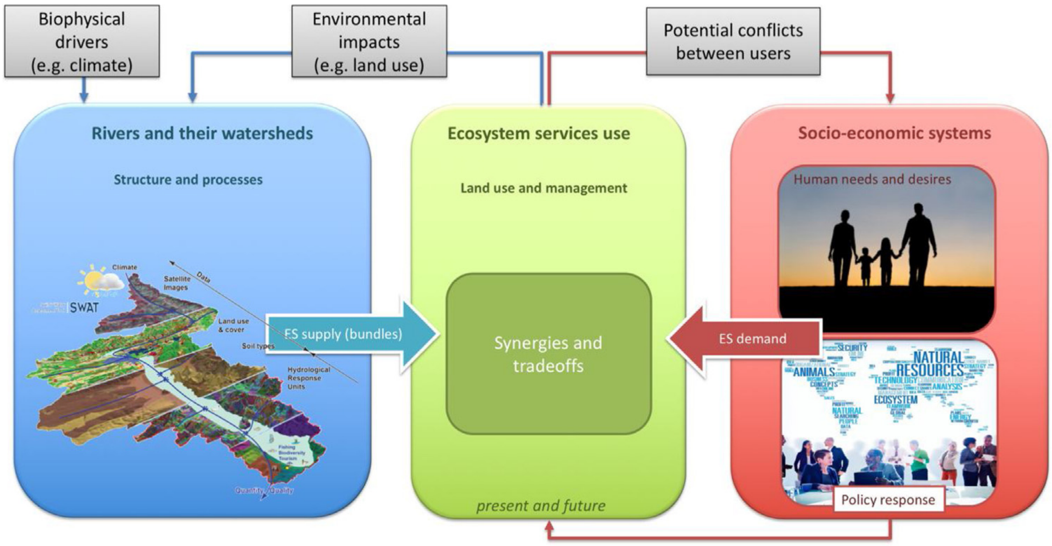

Fig. 1. Conceptual framework of the SWATCH21 on hydrological ecosystem services supplies and demands (inspired from Burkhard et al., 2012).

1. Introduction

The main objective of the SWATCH21 project is to improve our understanding of and to model hydrologic ecosystem services supplies and demands at the catchment level, as well as aquatic biodiversity at the river scale. The models are used to explore the outcomes of climate and landuse change forecasting scenarios on multiple policy targets and to explore the correlations between ecosystem services bundles (Fig. 1).

In 2016, the National Center for Climate Services and the Hydrology Division of the federal Office of the Environment has launched a new focus area “Climate Change and its consequences on Hydrology in Switzerland Hydro-CH2018” to establish a platform for knowledge sharing between researchers and end users in the area of climate change and hydrology.[1] This platform should provide up-to-date science-based information to assist decision makers on determining adaptation policies to climate changes. The SWATCH21 project will contribute to this science/policy interface effort by bringing new and original solutions to explore the impact of climate and landuse changes on eco-hydrologic services of Swiss rivers. Anticipating on some (not all) of the conclusions of this synthesis, the SWATCH21 project aims at filling some of the knowledge gaps:

1. Switzerland is a data-rich country but the data needed to assess hydrologic services and biodiversity is in long-term time series and difficult to gather;
2. The impact of glacier and snow melting on hydrological services is not well understood;
3. The provision of hydrologic services from river catchments has not been assessed across Switzerland;
4. The impacts of expected environmental changes on river species diversity and ecosystem services at the Swiss scale has not been explored;
5. The capacity to address multi-sectorial policy targets is weak; and
6. The desired level of model complexity to answer policy needs is unknown.

Theses research gaps led to the six research questions. In the first question (Q1) we explore how the access to input data for hydrological and ecological modeling can be improved. Hydrological and ecological modeling rely on accessing a large amount of high-quality heterogeneous data (e.g. weather, hydrology, hydropower, species, climate, landuse, and soil data). In order to improve the cycle of flow from raw observations to decision making, the initial time necessary to access and format the input data is often a limiting factor. Preparing a standard framework of essential data would greatly facilitate the cycle of decision making.

In the second question (Q2), we couple a glacier melt model with SWAT to better consider the future regime shifts. Indeed, less sustained summer flow and more concentrated spring melt flows might critically reduce the annual hydropower production due to intake of overflow during spring and reduced flow during summer (Schaefli et al., 2016). An increased seasonal melt coupled with rains will bring more intense floods. Because rain, rather than snow, falls on mountains in spring, river flows will peak earlier in the year, leaving summer months with increasingly drier conditions.

In question three (Q3), the aim is to assess hydrologic services supplies and demands with the available data and modeling tools. The assessment of hydrological ecosystem services necessitates the evaluation of both the supply and demand side of the services, increasing further the complexity of the data gathering and modeling effort.

In the fourth question (Q4), we explore the impacts of climate and landuse changes on species diversity in rivers. The question here is to test what the respective impacts of climate and landuse changes could be on species diversity at the river level. Are these impacts similar across the Swiss territory and according to different plausible forecasting scenarios?

[1] http://www.bafu.admin.ch/wasser/13472/16405/index.html?lang=en.

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For the fifth question (Q5), we explore the targets of multi-sectorial river-related policies (e.g. biodiversity, agriculture, flood) under different climate and landuse scenarios. With this question, we address the relationship between the value of ecosystems services on one hand, and multiple, often contradictory policies on the other hand. As environmental policies are often segmented, it is very difficult to assess whether multi-sectorial policy targets can be reached simultaneously. By using scenarios, we will explore plausible futures of hydrologic ES and biodiversity.

In the last question (Q6), we explore how detailed do ES and species distribution data and models need to be to answer relevant policy needs such as the national water, climate and biodiversity strategies. This final question concerns the level of details that needs to be obtained when modeling environmental systems providing ES in order to address policy relevant questions. By comparing several approaches to model the hydrology and biodiversity of Swiss rivers under different forecasting scenarios, we explore the impact of the related uncertainty on selected policy targets expressed as ES indicators. It is clear that scientists always try to improve their data and models but this often results in more complexity, extra costs, and longer analyses. Exploring the relationship between model complexity and their significance on decision making processes is crucial in order to reduce the gap between these two activities.

1.1. Soil and water assessment tool

Soil and water assessment tool (SWAT) (Arnold et al., 1998) is a continuous time, process based, semi-distributed, hydrologic model running on daily or sub-daily time steps. Although many hydrological models have been used in Switzerland such as: WaSim-ETH (Alaoui et al., 2014; Roessler et al., 2014), PREVAH (Antonetti et al., 2016), SEHR-ECHO (Schaefli et al., 2014), HBV (Finger et al., 2015), and Topkapi-ETH (Foglia et al., 2013) most suffer from various sources of limitations. These include suitability of application to mountainous regions only, lack of time continuity, lack of one or more essential components for our study such as: water quality, crop yield, agricultural management, and sediment transport, etc. In the light of anticipated changes stemming from climate/landuse change effects, we find it timely to build a comprehensive agro-hydro-meteorological model of the entire Switzerland and chose the model SWAT for the reasons outlined below.

Indeed, the SWAT model has been developed to quantify the impact of land management practices and climate on water, sediment, and agricultural chemical yields in large complex watersheds with varying soils, landuses, and management conditions over long periods of time. The program, therefore, lends itself easily to climate and landuse change analysis. SWAT is a valuable watershed-scale management tool and we chose this program for our purposes because: (i) it integrates many components such as hydrology, climate, nutrient, soil, sediment, crop, pesticide, bacteria, and agricultural management, (ii) it has been successfully applied worldwide in many different climate and landuse situations, (iii) the program is actively maintained and continuously updated with new and up-to-date knowledge of watershed processes, and (iv) many side programs are written for SWAT from calibration and uncertainty analysis to graphic packages for visualization and animation of the results. Hence, over time a universal consensus is built around the accuracy and usefulness of the program as there exist over 3000 scientific publications where SWAT has been used to address numerous watershed issues (Gassman et al., 2007; Gassman and Wang, 2015).

In SWAT, the spatial heterogeneity of the watershed is preserved by topographically dividing the basin into multiple subbasins, and further into hydrologic response units (HRU) based on soil, landuse, and slope characteristics. These subdivisions enable the model to reflect differences in evapotranspiration for various crops and soils. In each HRU and on each time step, the hydrologic and vegetation-growth processes are simulated based on the curve number or Green-Ampt rainfall-runoff partitioning and the heat unit phenological development method (Neitsch et al., 2011).

The SWAT model has been applied worldwide and its hydrologic components successfully tested, but the applications are mostly in areas where stream flows are predominantly generated from rainfall events (Arnold et al., 1998; Faramarzi et al., 2009; Rouholahnejad et al., 2014; Schuol et al., 2008a,b; Yang and Abbaspour, 2007). The model has less frequently been applied in mountainous watersheds and a few recent studies have shown model limitations in mountainous regions (Abbaspour et al., 2007, 2015; Fontaine et al., 2002; Qi and Grunwald, 2005; Rahman et al., 2013; Wang and Messe, 2005). Although there have been different experiments with snow/glacier melts and SWAT model, there is clearly a lack of formal methods of snow/glacier melt models coupled with the SWAT. Coupling a formal snow/glacier melt model to SWAT makes it more apt to Swiss hydrologic conditions allowing better predictions of river discharges and their impact on hydropower generation. This will, in general, enable us to more accurately use SWAT's capabilities to study the impacts of climate on water quantity and quality in the alpine regions and other glacier/snow dominated watersheds around the world.

1.2. Ecosystem services assessment and modeling

As early as 2005, the Millennium Ecosystem Assessment (MEA, 2005) used the ES approach to assess the consequences of ecosystem changes for human well-being. The aim was also to establish the scientific foundation to enhance the conservation policy and sustainable use of ecosystems at different scales and under different scenarios. The MEA approach provided strong support for the creation of the Intergovernmental Science-Policy Platform for Biodiversity and Ecosystem Services (IPBES, (Larigauderie and Mooney, 2010) emphasizing the importance of scientific information and its transparency (Vohland et al., 2011). The main challenge of IPBES remains to improve the science-based policy interface for BES at the international level at different temporal and spatial scales (Perrings et al., 2011).

At the national scale, the UK has published a spatially explicit assessment on the impact of landuse change on agricultural production, emissions and sequestration of greenhouse gases, recreational sites, urban green space, and biodiversity (Bateman et al., 2013). In Switzerland,

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several studies have been published assessing for example, the avalanche protection from forests on urban planning (Grêt-Regamey et al., 2008, 2013), or environmental policy in mountainous regions (Hirschi et al., 2013), but only few studies were carried out on hydrologic ecosystem services (Grêt-Regamey et al., 2011). Our project can however be seen as an extension of the PNR61 HydroServ[2] project that assess ecosystem services in the Emme valley to inform decision-makers. The impact of spatial scales on the quality of data available to assess ES supply and demand (Burkhard et al., 2012) was also investigated, suggesting a multi-scale approach when making decision based on ES, as well as the importance of the interface for stakeholder implications (Klein et al., 2015).

At a regional scale, Flanders in Belgium has produced a state-of-the-art assessment of ES (Stevens et al., 2015) by analyzing the relationships between the supply and demand side of the services, as well as on the impact of external drivers such as landuse and climate changes, and by presenting the results on very comprehensive dashboards. The tradeoffs (competition between services) and synergies (reinforcement of services) between supply, use and demand sides of services are also analyzed, demonstrating the need to assess ES cohesively.

Several important EU research projects are building on the concepts of ecosystem services and natural capitals as ways to improve the interface between scientific knowledge on one side and policy/decision making on the other side (e.g. Opera, OpenNESS, ESMERALDA, MARS, ECOPOTENTIAL). Two of these projects are sharing the development of a particularly interesting knowledge hub (www.oppla.eu) on Nature-Based solutions that was launched in September 2016. The OpenNESS project has reviewed the concept of ES bundles (Berry et al., 2016) as co-occurring services in space and time, tradeoffs and synergies (Turkelboom et al., 2016) as interacting services positively or negatively. A service can be used when it coincides between a supply and a demand.

The EU Land and Ecosystem Accounts (EEA, 2006, 2011; Weber, 2007) provides a 1 km^2 grid account that can be scaled up to any administrative or ecosystem zoning (e.g., river basins, coastal zones or biogeographic regions). A more recent data and model driven methodology (Maes et al., 2013) was proposed to respond to Action 5 of the EU biodiversity strategy to produce ES indicators covering Europe. Another recent European effort proposes to map the potential of ecosystems to supply ES under the impact of landuse changes (Haines-Young et al., 2012). Finally, several global assessments were proposed including the economic valuation of 17 global ES (Costanza et al., 1997; Naidoo et al., 2008; Tallis et al., 2012; Turner et al., 2007), and the assessment of Sustainable Development Goals (Wood and DeClerck, 2015).

The growing interest for ES encouraged the development of an international classification (CICES) (Haines-Young and Potschin, 2013) based on the assumption that ES should be regarded as fundamentally dependent on living resources (e.g. not abiotic processes) and serving human well-being, either as ES, ecosystem goods, or ecosystem benefits. The last version of CICES proposes a hierarchical classification from three main branches of services (Provisioning, Regulation and Maintenance, Cultural) into a 3–4 digits' classification.

Several spatially-explicit tools have been developed and compared to assess ES (Bagstad et al., 2013). The integrative tools encompass all the steps of ES assessment from data access, to modeling, ES assessment and valuation (BSR, 2011). Popular applications include for INVEST (Kareiva et al., 2011; Tallis et al., 2008), SOLVES (Sherrouse et al., 2011) and ARIES (Villa et al., 2014) that are relying for the moment on relatively simple ecosystem models. More complex existing models can also be used to assess the different ES, however the scientific and human investments are often too large for the available resources to justify their implementation when assessing several ES in parallel.

In 2015, Brauman (2015) reviewed 381 papers on hydrological services and concluded that "the direct link from biophysical processes to human well-being makes hydrological services an appealing foundation for watershed management", leading to new research if we can overcome the interdisciplinary challenges and the conflicts on water needs. Brauman (2015) offers also a very useful framework linking ecohydrologic processes to hydrologic services.

In 2016, Francesconi et al. (2016) reviewed 44 papers on the use of SWAT to evaluate hydrological services. Indeed, recent papers based on SWAT outputs have started to establish some links between the evaluation of river ES and the nexus approach for instance in the Danube catchment (Karabulut et al., 2015). The authors have published a study proposing new standards to estimate water demands from SWAT outputs within a nexus framework, and taking into account upstream/downstream relationships in the Black Sea catchment (Fasel et al., 2016).

1.3. Species distribution modeling

Even though landuse is used to assess ES, ES depend rather on the distribution of biodiversity, expressed as species and/or ecosystems. Spatial predictions of species and ecosystem distribution have made huge advances in the last two decades by combining Geographic Information Systems with statistical modeling (Elith et al., 2006). Several tools have been developed to facilitate these analytical workflows for example: GRASP (Lehmann et al., 2002; Maggini et al., 2006), MAXENT (Elith et al., 2011), BIOMOD (Thuiller et al., 2009), CARET (Kuhn, 2008). Some of the main challenges have been to model species distribution from presence-only data (Elith et al., 2006; Phillips et al., 2009; Zaniewski et al., 2002), manage adequately spatial autocorrelation in species data (Crase et al., 2014), interactions between exploratory variables, as well as biotic interactions between species (de Araujo et al., 2014). Species distribution modeling are being used for informing several biodiversity conservation tools such as the assessment of species red list status (Fivaz and Gonseth, 2014), protected areas prioritization (Lehtomaki and Moilanen, 2013), species vulnerability to climate change (Maggini et al., 2014), or ecosystem restoration targets (Gaston et al., 2014).

[2] http://www.nrp61.ch/en/projects/project-hydroserv.

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While many different statistical approaches exist for species distribution modeling (Elith et al., 2006) (e.g. GLM, GAM, MARS, BRT, RF), the tendency has been to develop tools capable of building ensemble forecasting from several approaches at once (e.g. BIOMOD, CARET) while increasing the complexity and computing time of the statistical analyses, and decreasing the understanding of each separate statistical approaches by the user. For this reason, we suggest to focus on a reduced set of techniques with high predictive performance. Indeed, species distribution modeling is of limited value to conservation assessment when the overall diversity across large region depends more on differences in biological composition amongst locations (i.e. beta-diversity) than on site-level diversity (Ferrier et al., 2007). Thus, distance approaches like GDM can complement common alpha-diversity assessment and offers an insight into beta-diversity.

Species distribution modeling in river ecosystems is clearly lagging behind its terrestrial counterpart (Leathwick et al., 2006) with much less studies published. A recent example however has been published recently to model family and EPT richness at a landscape level across Switzerland (Kaelin and Altermatt, 2016). One of the challenges in aquatic macroinvertebrate distribution modeling is to consider the upstream–downstream relationship and the temporal variation of the hydrologic regimes. Advanced hydrological models like SWAT are therefore promising to translate landscape variables into biological conditions.

Several studies have already linked SWAT and aquatic biodiversity models (Wu et al., 2018; Kakouei et al., 2017), including some in the context of climate change (Guse et al., 2015; Woznicki et al., 2016). They used different response variables such as biotic indicators and species abundance, different modeling techniques, and as we intend to do in our project, they included hydrologic indices calculated from SWAT output time series as model predictors.

2. Material, methods and initial results

2.1. Choice of study site and biodiversity groups

In order to be able to address several possible contradictory river-related policies, we decided to concentrate on a single scale approach at a national level. As a data-rich country, Switzerland can serve as a laboratory to explore the level of complexity needed to better inform decision makers about ecosystems services worldwide. The workable solutions that we hope to find through this project will therefore be more easily generalized in other countries by adapting the policy context.

From the beginning of the 1970s, ‘ecosystem health’ was seen increasingly as valuable in many societies, and multiple approaches based on benthic macroinvertebrates have been developed to assess the ecological status of rivers and streams (Bonada et al., 2006). These organisms offer multiple advantages for biomonitoring as they are ubiquitous, they offer a large spectrum of responses to different stressors (high taxonomical and functional diversity), they are basically sedentary, which allow effective spatial analyses, they have a relatively long life cycle, they can easily be sampled, and keys to identification are available for many groups (Rosenberg and Vincent, 1993). All macroinvertebrate groups will be considered in our analyses, however we will specially focus on the Ephemeroptera, Plecoptera and Trichoptera (EPT), as they are commonly used for assessing river ecosystem and identified at the species level in several nationwide monitoring projects. Furthermore, a relatively recent red list (Lubini et al., 2012) has been published on these groups based on new data collections. We also consider a few emblematic fish species as an indication of their recreation use.

2.2. Analytical workflow

The general organization of the work program flows logically from the research gaps and questions starting with (1) the creation of a Spatial Data Infrastructure (SDI) and an Application Programming Interface (API) to facilitate the use and reuse of initial condition data, (2) into the integration of a glacier and snow melt model with the hydrologic Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) program, (3) followed by hydrologic ES modeling, and (4) river species distribution modeling, plus (5) the analyses of the impacts of climate and landuse forecasting scenarios on policy targets linked to specific ES and biodiversity indicators. Backcasting scenarios (Grêt-Regamey and Brunner, 2011) that would explore different pathways to selected policy targets are not considered in the first phase of the project but the proposed modeling framework should allow to explore these types of scenarios as well. Throughout the project, we carry out development of a second API, connecting the input data with the different pieces of software to automate the production of the SWATCH21 outputs (Fig. 2).

2.2.1. Data, spatial data infrastructure, and Application Program Interface

The aim of this first task is to gather all the necessary data for the project in a geospatial database (PostgreSQL with PostGIS) accessible through a Spatial Data Infrastructure (SDI) and via an Application Program Interface (API) in order to make them readily available as web services and in different programming environment such as in R for statistics and Python for GIS (Lehmann et al., 2017a).

Switzerland has several centralized geospatial database. The main abiotic data needed for this project is described in Table 1. The biotic data will focus on macroinvertebrate species and especially on the Ephemeroptera, Plecoptera and Trichoptera (EPT) groups. Most of the available data was collected as presence only data, but exhaustive standardized samplings were recently carried out within the framework of the Swiss Biodiversity Monitoring Program (BDM) and the National Surface Water Quality Monitoring Program (NAWA).

2.2.2. Glacier evolution runoff model

State-of-the-art glacier and snow melt models (Glacier Evolution Runoff Model (GERM) (Farinotti et al., 2012;

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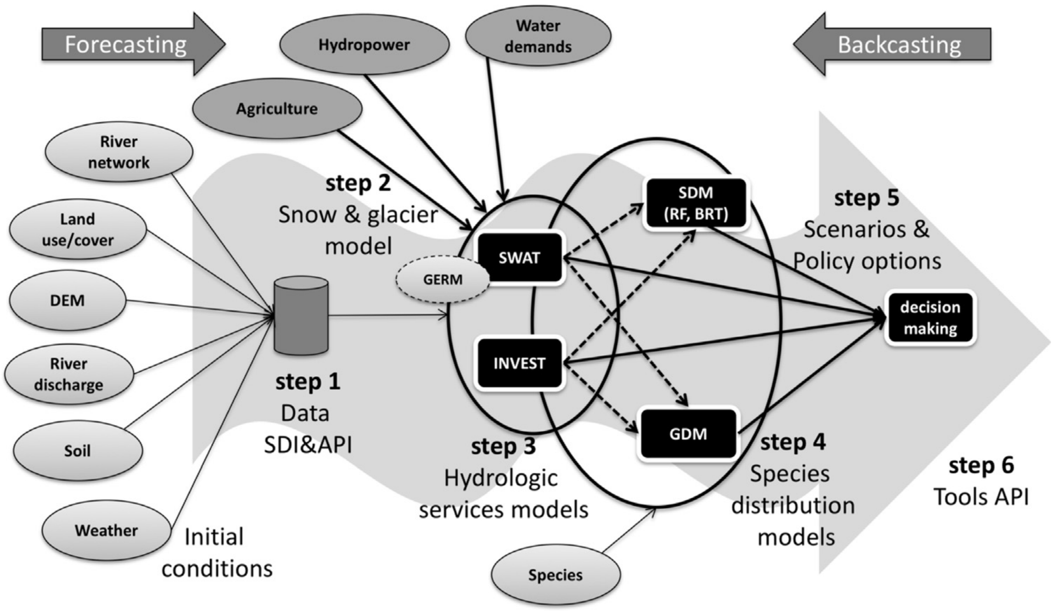

Fig. 2. Organistion of the work flow in six main steps.

Table 1
Main datasets and their sources that will be integrated in the SWATCH21 database and API.

Data type	Data sources	Resolution/scale	Description
DEM	Swisstopo	25 m	Elevation
Landuse	OFS	100 m	Classified landuse such as crop, urban forest water etc.
Downscaled landuse	OFS, UNIGE	25 m	A downscaled version of landuse
Human population	OFS	100 m	Population census
Soil suitability	Agroscope	1:200,000	Soil suitability types
Classified soil	UNIGE	1:200,000	Classified soil and physical properties such as sand/silt/clay, bulk density, $CaCo_3$ content
Hydrological network	Swisstopo	1:25,000	River network, lakes, reservoirs and derivations (GEWISS)
Weather	MeteoSwiss	Points	Daily precipitation, temperature, wind speed, solar radiation, relative humidity
River discharge/quality/temp./flood	FOEN	Points	Daily data from river gauges stations
Hydropower	Misc.	Points	Map of derivation, flow coming out of dams
Landuse scenarios	WSL (Bolliger et al., 2007)	100 m	Landuse change scenarios for Switzerland
Climate scenarios	CH2018	25 km	Climate change scenarios for Switzerland
Species occurrence	InfoFauna	340 points	Presence/absence data of Ephemeroptera, Plecoptera and Trichoptera (EPT)

Huss et al., 2008, 2014) will be coupled with SWAT to produce a transient dataset of runoff changes and variability from the recent past to the future. Using GERM, glacier surface mass balance and runoff are calculated in daily time-steps using a distributed temperature-index melt and accumulation model. Model components account for changes in glacier extent and surface elevation, evaporation and runoff routing. GERM includes components for snow accumulation distribution, snow and ice melt, 3D glacier geometry change, evapotranspiration, and runoff routing. The performance of the coupled SWAT-GERM models will be tested at in the Altesch catchment in the Rhone watershed.

2.2.3. *Modeling hydrologic ecosystem services: supply and demand*

In this task we will use two different hydrological models (SWAT[3] & InVEST[4]) to model water quantity and quality across the Swiss river network, and to quantify various ecosystem services.

SWAT is a complex hydrological model running on a daily basis using input from weather stations (rainfall, min and max temperature, solar radiation, wind), soil informa-

[3] http://swat.tamu.edu.
[4] http://www.naturalcapitalproject.org/InVEST.html.

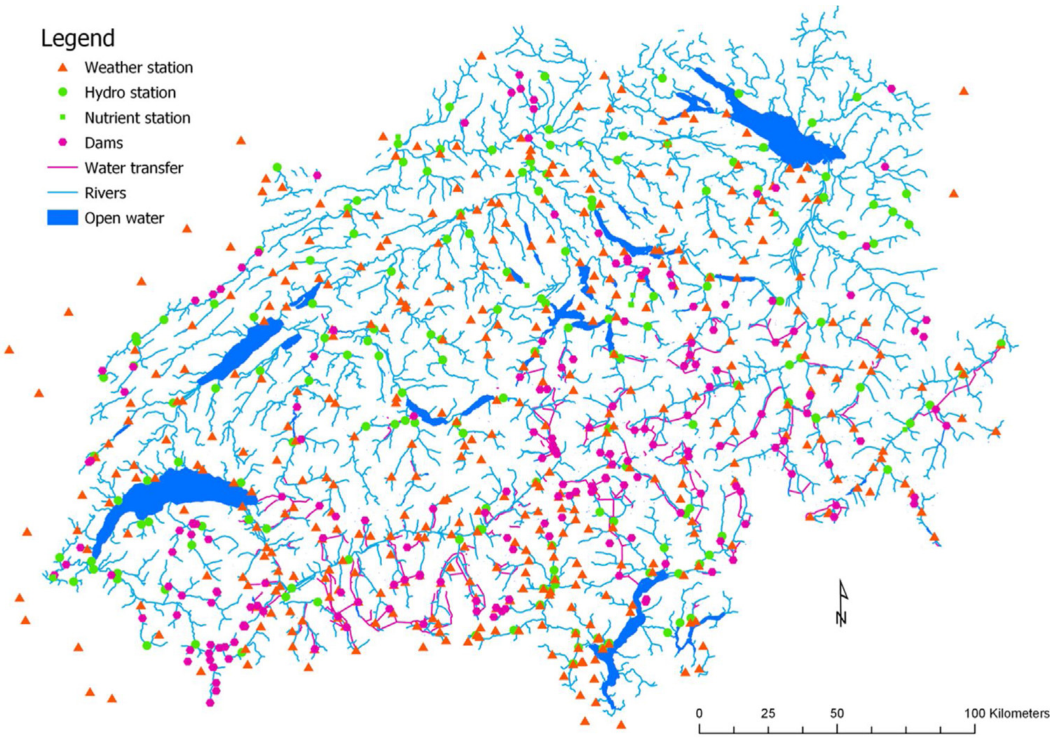

Fig. 3. Initial SWATCH national model with its measurement stations for weather, water quantity and quality, dams and derivations put in place.

tion, landuse/landcover data, digital elevation map, and data from agricultural management practices. The multiple sensitive parameters of the model are calibrated from observation of water yield, sediment, and nutrient loads measured at river gauges (Fig. 3). The most commonly used tool for model calibration is SWAT-CUP (Arnold et al., 2012). SWAT has been used in most countries in the world, and so far few papers have been published, which included Swiss hydrology and water quality by the applicants (Abbaspour et al., 2007; Rahman et al., 2013). Once calibrated, SWAT model return tens of output variables on a daily, monthly or yearly basis such as water yield, sediment loads, and nitrogen and phosphorus and organic matter concentrations. These outputs are prepared at the subcatchment scale defined during the construction of the model and can vary from a few hectares to several thousands of square kilometers depending on the case study needs.

As SWAT was not particularly developed for mountainous regions, several improvements on its calibration are needed in a country like Switzerland (Fontaine et al., 2002; Rahman et al., 2013). For this reason, we introduced the GERM model in the previous task to incorporate into SWAT for more accurate snow and glacier melt inputs (Barnhart et al., 2014; Ficklin et al., 2012). With the expected SWAT improvements, this project will derive daily outputs at high spatial resolution for about 5000 sub-catchments in Switzerland for various hydrologic ecosystem services (e.g., water yield for hydropower, blue water available for agriculture or domestic uses, sediment, nutrient and flood water retention). Other river attributes will be calculated with a Geographic Information System such as river sinuosity, percent of forest and percent of agricultural and urban landcovers.

To test whether a simpler hydrological model can provide the necessary decision-making information, we will also use InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) that was develop as a suite of tools to spatially assess provisioning, regulating, and cultural ecosystem services (Haines-Young and Potschin, 2013). Indeed, InVEST was developed to bring simplified scientific information in the hands of decision makers to assess tradeoffs between policy and management options. The suite of tools includes sixteen InVEST models for terrestrial, freshwater, and marine ecosystems. The freshwater models presently include: Water Yield necessary for hydropower production and its potential value, but also its availability for other water uses (agriculture, domestic); Sediment retention; and Water purification that quantifies nutrient retention. Compared to SWAT, InVEST is based on much simpler models that run on a yearly basis and that depend on a reduced number of parameters, but the two models produce the same basic hydrological outputs that can be compared (Dennedy-Frank et al., 2016).

The outputs of SWAT concerns typically water quantity and quality and can be characterized by their spatial and temporal resolution. The highest possible temporal and spatial resolution will be selected while building the SWAT model in function of the tradeoffs between model complexity and the computing time needed to run a model, and therefore evaluate new scenarios. We typically expect to use SWAT output on a daily or monthly base with sub-catchments of about 10 km^2 (about 5000 sub-catchments for Switzerland). Many ecosystem services supplies can be derived relatively simply from SWAT or InVEST outputs; others will need additional analyses to assess for instance biodiversity support, recreational values, fishing potential, transportation and flood water retention (Fig. 4).

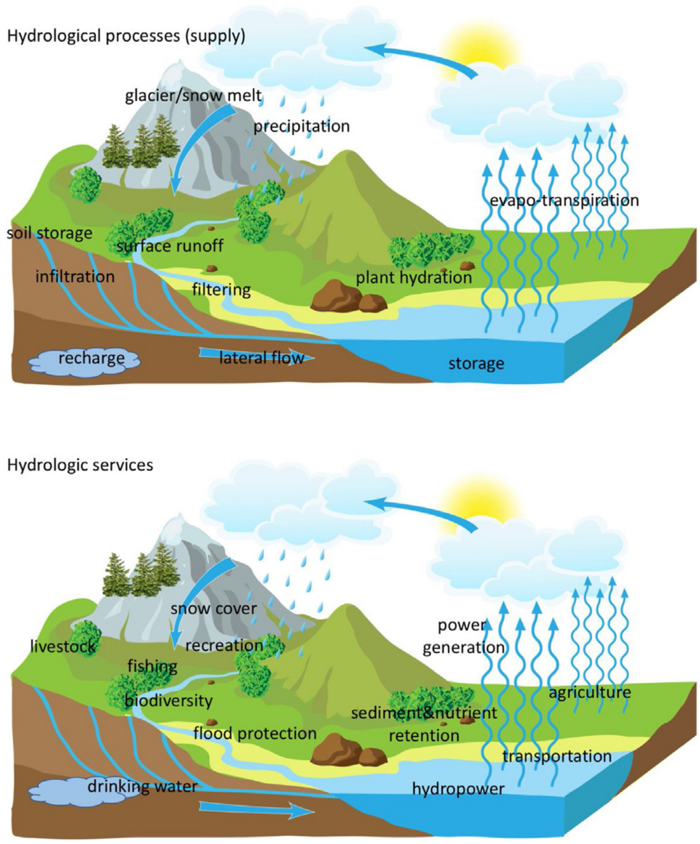

Fig. 4. Hydrologic processes (supply) and ecosystem services (derived from Brauman, 2015).

Below is the list of used services that we intend to model based on the classification proposed by Brauman (2015), as the result of the combination of the water services supplies modeled by SWAT and/or InVEST, and the methodology used in Fasel et al. (2016) to assess water demand in the Black Sea catchment:

- Diverted waters: (Provisioning services)
  - Agriculture: water used by crops will be directly derived from SWAT outputs. Irrigation demands are mapped in SWAT from available national data sources into agriculture management files.
  - Drinking water: the amount of blue water used for drinking will be assessed from the population distribution and statistics on the population water withdrawal intensity.
  - Livestock: blue water used by livestock will be estimated from the distribution of different types of livestocks.
  - Thermoelectric power generation: the amount of blue water used for cooling thermoelectric power plants will be assessed according to the generated electricity, type of fuel and cooling system used by the power plants. Detailed data will be obtained for the nuclear power plants.
- In situ water: (Provisioning services)
  - Hydropower: blue water transformed into energy by hydropower will be estimated using the distribution and size of existing dams. Evaporation from reservoirs will be estimated by using the SWAT outputs on potential evapotranspiration.
  - Transportation: the amount of water needed will be derived from navigable section locations on the Swiss river network.
- Water damage mitigation: (Regulating services)
  - Flood water retention: The Critical Consecutive Days Analyzer (CCDA) is a module of Climate Change Toolkit (CCT) which has been developed at Eawag (Vaghefi et al., 2017mm). It is used to analyze extreme events (dry and wet periods) and find the occurrences of past flooding patterns in the future data.
  - Nutrient and sediment retention will be directly derived from SWAT and InVEST outputs. They will be assessed by comparing the different landuse scenarios.
- Spiritual and esthetic: (Cultural services)
  - Fishing for recreation: this service will be assessed by modeling the species distribution of emblematic fish species such as trout using species distribution models.
  - Recreation: the recreational value of river beds will be assessed by a combination of GIS analyses of accessibility from roads and walking tracks, and the density of photos made available on Flickr.
  - Snow duration for skiing activities will be assessed from historical remote sensing classification of Landsat images with the Swiss Data Cube (Giuliani et al., 2017).
- Supporting: (Supporting services)
  - Biodiversity: Alpha- and beta-diversity of aquatic macroinvertebrates will be assessed by several modeling

techniques based on careful selection of hydrologic, topographic, climatic, geologic and land use explanatory variables derived from SWAT model and complementary GIS analyses at catchment and river reach levels.
- Environmental flow requirement for biodiversity: flow requirements will be estimated using a defined percentage of naturalized water flow allocated for preserving water ecosystems (e.g. Poff et al., 2010; Pastor et al., 2014; Overton et al., 2014).

This task should result in a new methodology to assess hydrologic ES in Switzerland that could be easily generalized in other countries or catchments. The chosen approach will be streamlined by code developed in the Python and/or R languages and make use of their geospatial and statistical libraries (task 6).

2.2.4. Modeling freshwater biodiversity along river networks and predicting possible future scenarios

The aim of task 4 is to model the distribution of species in order to estimate how different climate and landuse scenarios would affect alpha- and beta-diversity in Swiss rivers. Spatial pattern in aquatic macroinvertebrate will be modeled focusing on (1) discrete entities (species or community) and on (2) collective properties of biodiversity (differentiation diversity) (Ferrier, 2002). On one hand we will use species distribution modeling techniques (SDM) like Random Forest (Breiman, 2001) or Boosted Regression Trees (BRT) (Elith et al., 2008). According to our preliminary results, their predictive performance of these techniques was significantly superior to 6 other techniques (Fig. 5). For our tests, we used the R package 'biomod2' (Thuiller et al., 2009) and allowed level 1 interaction for Generalized Linear Model (GLM) and Multivariate Adaptive Regression Splines (MARS), and 3 dimensions for the Generalized Additive Model (GAM) smooth term. Otherwise, we used default parametrization (Fig. 5). SDM predictions will provide an assessment of environmental change impacts on individual species (Fig. 6), which can be used further to derive higher-level entities as community types.

On the other hand, we will use Generalized Dissimilarity Modeling (Ferrier et al., 2007) for assessing spatial patterns of turnover in community (beta-diversity). This

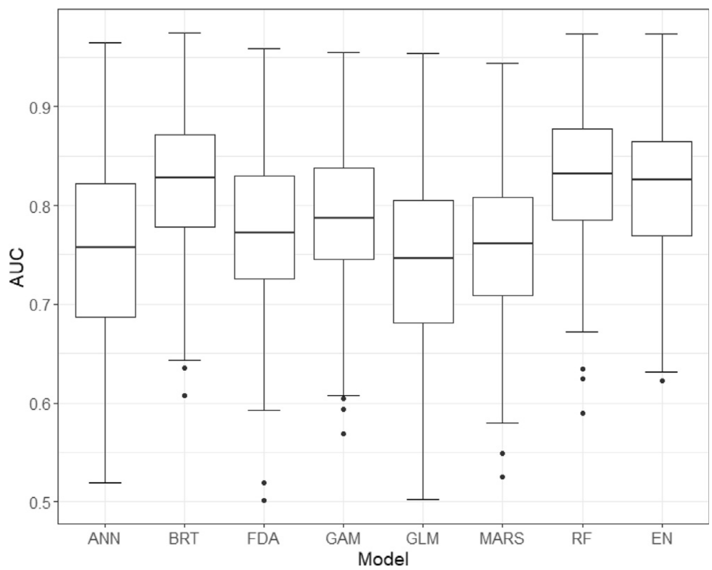

Fig. 5. Area under the curve (AUC) distribution (goodness-of-fit statistics for presence absence models) for 8 modeling techniques, based on 20 macroinvertebrate families and 8 sample splits for cross-validation (1280 models). The techniques were Artificial Neural Networks (ANN), Boosted Regression Trees (BRT), Flexible Discriminant Analysis (FDA), Generalized Additive Model (GAM), Generalized Linear Model (GLM), Multivariate Adaptive Regression Splines (MARS), Random Forest (RF) and Ensemble Model (EN), which combines the previous techniques and makes ensemble predictions.

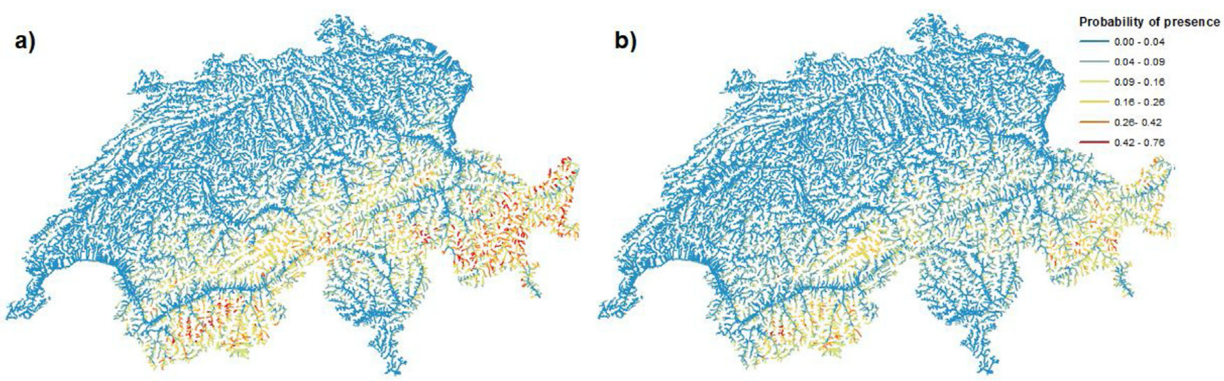

Fig. 6. Predicted distribution of *Rhithrogena nivata* with BRT based on (a) current temperature and (b) increased temperature (+3 °C). Presence probability represented by color, from blue (low) to red (high). (Preliminary results from SWATCH21 project).

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technique accommodates two types of nonlinearity common in ecological datasets: (1) the variation in the rate of compositional turnover along environmental gradients and (2) the curvilinear relationship between biological and ecological distance. The R package 'gdm' (Manion et al., 2018) allows to make predictions across time to estimate the magnitude of expected change in biological composition in response to environmental change (Fitzpatrick et al., 2011). Final sets of predictors will be based on stepwise selection of hydrologic, topographic, climatic, geologic and land use explanatory variables inspired from Kuemmerlen et al. (2014). Both complementary approaches will allow to estimate how different climate and land use scenarios would affect alpha- and beta-diversity in Swiss rivers.

2.2.5. Evaluating the relationship between Ecosystem Services bundles and multiple policy targets (agriculture, flood, energy, biodiversity) based on future plausible climate and landuse scenarios

First, analyzing the current Swiss policies and strategies for hydrology, flood, energy, biodiversity and agriculture will identify key environmental policy targets. The value of ES services is derived directly from the analyses presented at the end of Section 3) on Modeling hydrologic ecosystem services: supply and demand. The ES bundle analyses (Briner et al., 2013; Raudsepp-Hearne et al., 2010) will explore the combination of different climate (CH2018, 2018) and three landuse (WSL, Bolliger et al., 2007) scenarios on ES in relationship to key environmental policy targets (Grêt-Regamey and Brunner, 2011) (Fig. 7) .

To estimate the impact of climate change on water resources of Switzerland, we will deploy the new CH2018 scenarios developed by a consortium consisting of MeteoSwiss, ETH Zurich, and the University of Bern (CH2018, 2018). CH2018 data is based on the latest set of European climate model simulations from the Coordinated Regional Climate Downscaling Experiment (CORDEX). In CORDEX, the global climate model simulations from the Coupled Model Intercomparison Project CMIP5 have been downscaled using regional climate models. CH2018 is bias-corrected for three emission scenarios namely RCP2.6, RCP4.5, and RCP8.5 for the time span 1981 to 2099. In this study we will use the median value of several RCMs for each RCP.

The landuse scenarios (Bolliger et al., 2007) are based on a business as-usual scenario that extrapolates trends observed between 1985 and 1997 into the future. A liberalization scenario was defined with limited regulation, while a lowered agricultural production scenario was created to foster conservation. Finally, in order to assess the impacts of climate and landuse scenarios of ES and related policy targets, we will follow an experimental design (Fig. 7) that will combine: 3 climate scenarios, 3 landuse scenarios, 2 hydrological models, 2 biodiversity models, leading to a total of 36 models (run with the SWATCH21 Tool API) that will be applied on all rivers of Switzerland. The experimental design will allow calculating the proportion of the 5000 subcatchments that reach the different policy targets in function of the different combination of climate and landuse change. It will also allow to compare the outcome of each scenario to the current situation, and to evaluate the differences between scenarios (Fig. 7). A Generalized Linear Mixed Model (GLMM) will allow also to explore which factor (choice of climate scenario, landuse scenario, hydrologic model and species distribution model) of the experimental design is more influencing the ES and biodiversity assessment.

2.2.6. SWATCH21-Tools API

The SWATCH21-Tools API connects different pieces of input data and software (SWAT, INVEST, BRT/RF, GDM) to automate the workflow for key ES variables. This allows information to be dynamically generated incorporating changes in or creating entirely new datasets, software, scenarios or policies, and helps to streamline the process of

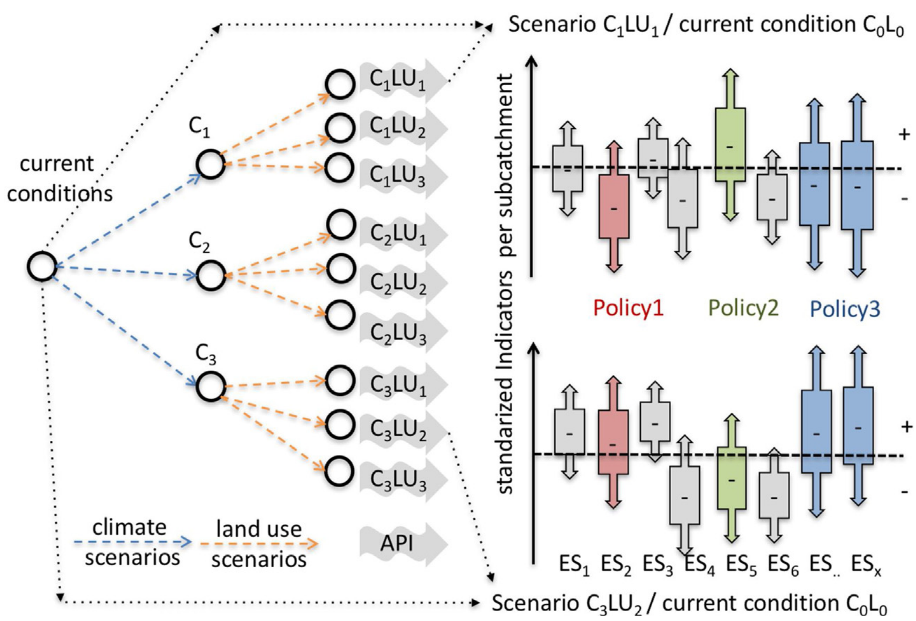

Fig. 7. Experimental design and bundles analysis.

Table 2
Main output datasets from the SWATCH21 project on all Swiss rivers.

Data type	Description
SWAT outputs	Daily, monthly and yearly water flow, nutrient and sediment loads
INVEST outputs	Yearly ES: water yield, sediment and nutrient retention
BRT/RF outputs	Species distribution predictions
GDM outputs	Beta-diversity prediction
Ecosystem services	Provisioning services: water for hydropower, water for domestic use, water for agriculture and livestock, water for power generation
	Regulating services: sediment retention, nutrient retention, flood water retention
	Cultural services: recreational value, recreational fishing value
	Supporting services: nutrient recycling, species diversity, environment flow requirements, transportation
Scenarios impacts	Impacts of climate and landuse forecasting scenarios on SWAT, INVEST, BRT/RF, GDM, ES outputs

going from data to decision making. This approach is reusable and portable creating a process for replicable results and verification, and a method that can be used to assess other environmental issues at different scales and locations by changing the input data and software components. For SWATCH21 this is being used to create a large ES dataset (see Table 2) for several scenarios and has great potential for reuse and interpretation as in Lehmann et al. (2017b).

This is achieved by creating middleware software to enable the models to interact via the Open Geospatial Consortium (OGC) Web Processing Service (WPS) (e.g. Giuliani et al., 2012), which provides an interoperable cloud-based protocol for the exchange and processing of data. This approach is inherently network based, supporting distributed computing, and is at the core of our framework for integrating heterogeneous processes. This gives the ability to integrate previously disjointed models into a single complex process and better utilize existing resources.

3. Discussion

3.1. Data sharing

SWATCH21 is promoting data sharing through web services as promulgated by the Open Geospatial Consortium (OGC, (Nogueras-Iso et al., 2005)). Indeed, policies are evolving toward making environmental data available with for instance the Open data policy in Switzerland,[5] the INSPIRE directive in Europe (Craglia, 2010) and the GEO data sharing principles at global level (Giuliani et al., 2011, 2016). However, the access to data needed for eco-hydrological modeling (meteorological, hydrological, biological and pedological data) remains limited by password protections, policy restrictions, and cost policies (Myroshnychenko et al., 2015). Web services and Application Programme Interface (API) allow direct exchanges between machines as needed in modern applications over the Internet (Lehmann et al., 2017a). These web based approach of data sharing in hydrology were reviewed in Lehmann et al. (2014) and are implemented in this project.

3.2. Model integration

SWATCH21 will provide an integrated solution for accessing and sharing inputs and outputs of models, as well as processing eco-hydrologic models. State-of-the-art models (GERM, SWAT, InVEST, BRT/RF, GDM) have been selected, and will be compared and improved to model different ecosystems and their services. The main outputs of the project will be new datasets made available to describe Swiss rivers hydrology, their predicted biodiversity and the related assessment of ecosystem services in terms of provisioning services (e.g. water resources), regulating services (e.g. nutrient and sediment retention, flood protection), and cultural services (e.g. biodiversity, recreation).

Such integration of models is necessary to be able to run and rerun a set of connected models under different environmental and/or socio-economic conditions according to different scenarios (Lehmann et al., 2014, 2017a). Furthermore, the capacity of rerunning more easily an entire modeling workflow contributes to the replicability of scientific analyses (McNutt, 2014; Ostermann and Grabell, 2017).

Several solutions allow to orchestrate complex workflows connecting several models. OpenMI (Gregersen et al., 2007; Moore and Tindall, 2005) has been developed in hydrology to link together models from different origins with different spatial and temporal scales. This approach has recently been proposed for integrated water resources modeling (Buahin and Horsburgh, 2018). With Web Processing Services (WPS) models themselves become OGC web services allowing to run workflows on the Internet (Castronova et al., 2013; Giuliani et al., 2012; Michaelis and Ames, 2009) and on different backends (Giuliani et al., 2012).

3.3. Policy implications

By making available new datasets from the outputs of models and scenarios, SWATCH21 is addressing several policy needs in Switzerland, with a potential to be replicated in other regions. At the Swiss level, the new Biodiversity Strategy[6] integrates among its 10 strategic

[5] https://opendata.swiss.

[6] https://www.bafu.admin.ch/bafu/en/home/topics/biodiversity/publications-studies/publications/swiss-biodiversity-strategy.html.

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goals that by 2020 ecosystem services are recorded quantitatively and that sufficient knowledge is available for their consideration in decision-making. In order to reach this objective on river ecosystems much work is still needed as neither ecosystem services or biodiversity has been assessed and predicted across all rivers. The Swiss climate strategy for agriculture[7] explores ways to continue to ensure food supplies and provide social, economic and ecosystem services, agriculture and food production by adapting to climate change. This strategy should be a guiding light for agriculture and food production in Switzerland in their efforts to reduce greenhouse gas emissions and adapt to changing conditions. Agriculture is intimately linked to water resources and to water quality and this relationship is fully integrated in tools like SWAT. Another policy relevant topic is the vulnerability of Switzerland to flood,[8] which is increasing after a century in which only two major floods happened. Floods are the most economically damageable natural risk that concerns the most densely populated areas of Switzerland. SWATCH21 is bringing to these different policies new ways of assessing simultaneously the outcomes of scenarios on changes in ecosystem services that are themselves related to these policies, such as: water for hydropower, water for agriculture and livestock, water for power generation, sediment retention, nutrient retention, flood water retention, species diversity, environment flow requirements. By analyzing the synergies and tradeoffs between these services, policy makers will be able to understand the connection between various sectors when making decisions.

Another relevant aspect of SWATCH21 in the policy domain is related to so called Essential Water Variables (EWVs). EWVs are being defined by the GEO hydrology community as a minimum set of variables that are necessary to describe the water cycle (Lawford, 2013). Most of the EWVs are either inputs or outputs of a SWAT model, meaning than when a SWAT model is calibrated it links together though a hydrological framework almost the entire set of EWVs. This is particularly important to fully describe the water system and to inform different policy needs and indicators. Note that simultaneously, Essential Climate Variables (ECVs: (Bojinski et al., 2014)) and Essential Biodiversity Variables (EBVs: (Pereira et al., 2013)) have been defined. Essential Variables are the central concept of the European project GEOEssential that the first author of this article is coordinating.[9] Essential variables can be considered as an intermediate level of information between raw observations and policy indicators, as a minimum set of variables necessary to describe a system.

Finally, Brauman (2015) is demonstrating the concept of eco-hydrologic services that are modeled in SWATCH21 create a link between biophysical processes to human well-being and therefore provides the foundation of watershed management: assess conservation benefits, evaluate management practices, prioritize siting, account for externalities, and perform trade-off or cost-benefit analysis.

3.4. Future developments

Potentially conflicting policy targets exist such as safeguarding the level of biodiversity (Swiss biodiversity strategy), increasing sustainable hydropower energy production (Federal Council's energy strategy is banking primarily on increasing Switzerland's hydropower output by at least 10% by 2050) or the strategy for agriculture (maintain food security and reduce GHG emissions). These policy targets will be confronted to the related changes in estimated ES and biodiversity indicators bundles within the different landuse and climate scenarios. Possible tradeoffs between different bundles or types of services (provisioning, regulating, cultural, supporting) will be explored as in Raudsepp-Hearne et al. (2010). However, these policy implications are going beyond the scope of the SWATCH21 project.

Indeed, a second phase of the SWATCH21 project has already been submitted by four academic Swiss partners in 2018. It was given the title "Forming the science-policy interface for Switzerland's climate-water-energy nexus (NeXswiss)".

With climate change, scientists forecast a dramatic impact on the spatial and temporal distribution of water resources before the end of this century. In this context, water management will increasingly have to rely on an interdisciplinary approach which simultaneously considers climate, water, energy, and landuse. The NeXswiss project will bring a state-of-the-art integration of predictive modeling and stakeholder engagement. It will be the first allowing to weight the relationships between sectors relying on water use and gauging the impact of different scenarios or environmental policies on water resources. By building an innovative modeling framework, this project will allow to assess and compare the outcomes of existing or planned policies, and to explore plausible future scenarios. Through this "nexus" approach, a stronger integration will be possible between political sciences and scientific dynamic modeling to support decision-making. The expected changes in climate, landuse, hydrology and hydropower will undoubtedly impact the eco-hydrological services, and the NeXswiss project will assess and quantify them in terms of biodiversity support, agricultural productivity, sediment and nutrient retention, flood protection, and recreational value.

To give a few examples of concrete outputs, the NeXswiss project will enhance the implementation of the Swiss energy policy, considering the context of climate change and reinforced rivalries around rivers' ecosystems. The operation of existing hydropower plants, and planning of new ones, could also benefit from the NeXswiss project by considering other competing water usages. Changes in average and extreme climate changes, landuse changes and/or hydropower market conditions will greatly impact hydrological services depending on their upstream/downstream position. Finally, the impacts of changes in water quantity and quality on ecosystem services, could be

[7] http://www.fao.org/3/a-i3084e/i3084e24.pdf.
[8] http://www.climateadaptation.eu/switzerland/river-floods/.
[9] http://www.geoessential.eu.

predicted through the NeXswiss project, in a context of increasing and conflicting demands. As a first step, we will set up a national policy stakeholder group to guide the NeXswiss project and review its progresses. This stakeholder group will then guide the construction of a spatial data infrastructure to share the necessary input data sets among partners and identify the most useful outputs of the project. The next steps will involve the modeling of the hydropower potential for Switzerland, considering the European context and market. The energy market will in fact be factored in to predict water, glaciers dynamics, sediment transport, and inflow to hydropower reservoirs. Based on the outputs of this hydrological model, ecohydrological services will be assessed and predicted according to different climate, landuse and management scenarios. Finally, NeXswiss will promote the integration of its tools and outputs in environment policies by analyzing – at various decision scales – regulatory frameworks, horizontal institutional structures and informal agreements.

4. Conclusions

The main innovations proposed by this project are listed below:

- SWATCH21 will be a first attempt to model the full river network of Switzerland with the internationally used and recognized tool SWAT;
- It will integrate a proper glacier and snow model in the SWAT code which is greatly needed for all mountainous regions;
- SWATCH21 will allow to predict species diversity from river conditions across Swiss rivers for the first time;
- The project will improve and integrate software solutions (APIs) to bring ES into practice, by moving more easily from data acquisition, modeling, assessment, and visualization, into decision-making;
- The project will create a unique database of information on Swiss rivers containing variables on species potential distribution and richness, hydrological characteristics and ecosystem services;
- SWATCH21 will bring a solution to test the level of data and model complexity needed to address policy needs;
- The different climate and landuse scenarios will allow to test our capacity to meet multi-sectorial policy targets;
- The outputs from the entire project will be shared using a state-of-the-art spatial data infrastructure in order to be freely available for future researches; and
- The project will serve as a first stage of a more interdisciplinary and comprehensive project that will integrate also social, political and economic sciences to fully assess multi-sectorial policy needs.

Conflict of interest

None declared.

Ethical statement

Authors state that the research was conducted according to ethical standards.

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