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Projecting hydropower production under future climates: a guide for decision-makers and modellers to interpret and design climate change impact assessments

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Abstract

Hydropower is a key energy source in almost all world regions, it fuels social and economic development, ensures electricity security and is a pillar for renewable electricity production. But hydropower and its environmental impacts are vulnerable to climate change. This discussion of model-based climate change impact assessments and underlying modelling assumptions will help decision makers and scientists analyzing existing studies and identifying the most urgent open questions. Rooted in hydrological uncertainty analysis, this discussion focuses on the importance of local factors and on modelling uncertainties for a critical view on our ability to project future hydropower production in different world regions.

Keywords: hydropower, hydro-electricity, pump-storage, climate change, hydrology, water resources management, modelling uncertainty, climate-related renewable energy

Introduction

Hydropower is the most widely exploited renewable energy resource and plays a central role for socio-economic development around the globe. The World Energy Council mentions a deployment in more than 100 countries and estimates the 2011 total installed capacity worldwide to 0.95 TW and the hydropower production to 2767 TWh, which has contributed to around 15% of world-wide electricity production (Council, 2013, p. 17). Installed hydropower capacity continues to grow quickly and major projects are at the planning stage around the globe to increase energy security or to decrease carbon-based or nuclear power generation (Gullberg et al., 2014;IHA, 2013). Roughly one quarter of the installed power is located in China; the other major producers, the US, Brazil and Canada have around 8% of worldwide capacity each (Council, 2013). Most importantly, certain countries produce over 50% of their total annual electricity production through hydropower, for example Brazil, Canada, Mozambique, Norway or Switzerland (Council, 2013;Swiss Federal Office for Energy, 2014).

Hydropower production (HPP) systems generally have low operation costs but require a very high initial investment (Gaudard and Romerio, 2014). The investment horizon is typically of several decades, with water use concession duration strongly varying between countries (Gaudard et al., 2014;Glachant et al., 2014;Kumar et al., 2011). HPP projects of any size often experience significant public resistance. Albeit being a mostly non-consumptive water use (except from reservoir evaporation in warm climates), HPP systems have a considerable impact on the landscape and on human settlements; through water storage and diversions, they modify the natural water flow, the water temperature regime and the sediment transport. And HPP systems impact on the natural connectivity of river networks, laterally between the stream and its flooding area and longitudinally between up- and downstream habitats. Thereby, hydropower modifies and can endanger many freshwater ecosystems (Renofalt et al., 2010;Vorosmarty et al., 2010) (see also Sidebar 1 "Hydropower and ecosystem protection"). Large hydropower reservoirs can have an impact on the local climate but hydropower is generally assumed to be emission-free during the production stage. Locally, this might not entirely hold if considering hydro-chemical processes occurring due to land flooding and leading to emission of greenhouse gases (Chanudet et al., 2011;Hertwich, 2013;DelSontro et al., 2010). Finally, HPP systems can increase or decrease the flood risk downstream of water restitution points.

For any discussion of the potential vulnerability of hydropower production systems to climate change, it is important to point out that the potential effects of climate change will always superimpose onto other ongoing pressures on the considered water resources system, which might well largely outweigh any climate change effects (Koutsoyiannis et al., 2009;Carey et al., 2014;Destouni et al., 2013;Lettenmaier et al., 1999). We might in particular think of land use changes and increasing competition for water under demographic evolution, which both may also be related to climate change. Assessing the effect of climate change independently of other ongoing system changes might even be considered being a futile exercise. This motivated the international hydrological community through the International Association of Hydrological Sciences (IAHS) to focus their current research decade on change in hydrology and society ("PantaRhei") (Montanari et al., 2013;Ehret et al., 2014) and lead to the emergence of the field of socio-hydrology (Sivapalan et al., 2012).

In this context of sometimes passionate debates about what changes we can actually project (2014;Blöschl and Montanari, 2010;Koutsoyiannis, 2013), the purpose of the present review is to help the reader to critically analyze HPP climate change studies, to interpret their results and to identify open questions. Hereafter, I first discuss why and how HPP climate change assessment has to focus on individual case studies. I then provide an overview of the modelling components of state-of-the art impact assessments and of related uncertainties, followed by a discussion of selected case studies and of key open research questions.

Climate change impacts on HPP: dominance of local characteristics

To understand how HPP systems might undergo modifications due to climate change, we have to distinguish between production types and between scales of production. Hydropower is either produced in run-of-river plants with low hydraulic heads or from water stored in accumulation lakes with hydraulic heads up to several hundred meters, possibly with re-circulation of water between lower and higher level reservoirs in so-called pump-storage systems (Wagner and Mathur, 2011).

Run-of-river plants (also called river power plants) use the natural water flow of a river or of a diversion canal. Any change in the hydrologic regime, for example due to climate change, will thus have an immediate repercussion on the hydropower production. This makes such systems vulnerable in particular to a decrease of average flow or to an increase of low flow occurrence. This vulnerability can be illustrated based on the flow-duration curve (Figure 1), which is classically used to quantify the exploitable water volume for run-of- river plants. A change of the hydrologic regime (i.e. of the flow-duration curve) will either increase or decrease this exploitable volume (Figure 1).

Storage power plants, on the other hand, shift the power production from the moment of inflow occurrence to the moment of peak electricity demand (or peak market prices). Alpine storage systems are, for example, used for HPP during peak hours but also to shift production from summer inflow to winter when electricity demand is higher (Schaefli et al., 2007). This tendency might, however, currently be changing due to warmer winters and hotter summers, as visible for example in the Swiss electricity statistics (Swiss Federal Office for Energy, 2014). Additional storage flexibility is obtained with pump-storage HPP systems that produce electricity during periods of peak demand and re-pump water to the storage reservoir during off-peak periods, e.g. to absorb (nuclear) power or to maximize the economic benefit (Harby et al., 2013). More recently, hydropower storage plays an important role for the powergrid integration of intermittent renewable energy sources, namely wind and sun (Korpås et al., 2013;von Bremen, 2010).

Given that the storage volume is used to modify the natural water inflow regime and to maximize the economic gain, the hydrologic and economic vulnerability of (pump-)storage HPP systems to climate change depends on the particular setting and production strategy and cannot be directly deduced from hydrologic regime changes. These differences in operation strategies and in hydrologic-regime vulnerability of run-of-river and storage HPP are important to be kept in mind when interpreting hydropower production statistics in world regions with different hydro-climatic settings and electricity markets. (Council, 2013)

HPP systems are further categorized based on their installed production capacity (Wagner and Mathur, 2011, p. 12). Large HPP systems with possibly several interlinked hydropower plants and with up to several GW installed capacity produce electricity for ten thousands to millions of consumers. Small systems are typically in the order of magnitude of a few MW installed capacity and micro power plants with less than 100kW are installed for individual households. Small and micro power plants play a major role for rural electrification (Okot, 2013). The exact capacity-based categorization of HPP systems depends on world regions and countries but will generally determine what tax regime and legal constraints apply, in particular with respect to water resources and ecosystem protection laws. These aspects are of prime importance for climate change impact analyses that have operation strategies and economic considerations as endpoints (Gaudard et al., 2013).

For such end-to-end impact studies, from climate change scenarios to the simulation of hydropower production and economic gain, additional technological aspects might become relevant. In fact, the turbine types used for different HPP systems do not show the same sensitivity to sub-optimal flow conditions, i.e. each turbine type shows a typical decrease of efficiency if operated outside of the design flow range (Wagner and Mathur, 2011, p. 89). Another important technological and operational aspect is sediment management. Turbines generally suffer from abrasion due to

suspended sediments and sediments have to be managed to deal with the potential loss of storage volume (Palmieri et al., 2001).

The above considerations show that an assessment of climate change impacts on different HPP systems and in different climate regions requires an in-depth analysis of individual case studies. Given the dominance of local conditions, generalizations are difficult, sometimes even for small regions (Haenggi and Weingartner, 2012;Gaudard et al., 2014). Continental or global scale assessments of climate change impacts on hydropower (Lehner et al., 2005;Hamududu and Killingtveit, 2012;Strobl, 2014) have, thus, to be interpreted with care.

Case-study based climate change impact studies can provide only catchment-scale projections that, furthermore, have to be interpreted in light of all involved modelling uncertainties and in particular of the underlying climate change scenarios. Such case studies play nevertheless a key role to anticipate possible and plausible future situations (Ghile et al., 2014), for example for structural adaptations to possible climate change, for dam reoperation (Watts et al., 2011) or for dealing with dam safety in future climates (Chernet et al., 2014;Veijalainen and Vehvilainen, 2008).

From uncertain future climate to electricity production

Climate change impact analysis started in the early 1990ties in the context of the first IPCC assessment report (Intergovernamental Panel on Climate Change (IPCC), 1990). The earliest studies were essentially climate-sensitivity analyses that tried to quantify how arbitrary scenarios of air temperature increase and of precipitation increase or decrease impact the water balance and the hydrologic regime of individual catchments (Nash and Gleick, 1991). Such climate-sensitivity analyses are still in use but the vast majority of climate change impact analyses follows the classical modelling framework which uses climate model outputs as an input to a water resources system model and which emerged in the late 1990ties (Lettenmaier et al., 1999). This approach is exemplified in the most highly cited study in the field of HPP, the work of Christensen et al. (Christensen et al., 2004) on the Colorado River basin. Since then, similar studies have been completed around the world.

The core of climate-change impact studies is the comparison of an observed or simulated reference state (baseline) during a control period against one or several simulated future states (future scenarios). For hydropower production, this comparison is typically based on time series of streamflow and produced hydropower, which are compared using a series of system performance indicators including average yearly hydropower potential (in m^3 of available water or in GWh) or yearly hydropower production and economic gain.

These time series are obtained with an impact modelling chain (Bosshard et al., 2013) as illustrated in Figure 2, starting with a climate scenario, obtained from a global-circulation model (GCM) run, that is processed through a downscaling methodology to the scale of the case study (Maraun et al., 2010). This downscaled scenario is then injected into one or several HPP system models that simulate all natural and regulated water fluxes and possibly sediment fluxes within a hydropower production system. End-to-end studies include a HPP management model, possibly driven by outputs from an electricity market model (electricity prices) and by environmental constraints. If significant land use changes are to be expected between the control and the future period, this chain is completed with a land use evolution model, for example to account for vegetation evolution or for glacier retreat (Huss et al., 2010). Studies including ecosystem evolution models are extremely

rare; an example is the work of Sundt-Hansen et al. (Sundt-Hansen et al., 2014) on the impact of hydropower and climate change on Atlantic salmon with the ecosystem model presented in (Hedger et al., 2013).

A complete climate change impact assessment based on this modelling chain can be represented in three simulation phases and four analysis steps (Figure 3). The simulation phases include the model set-up phase where all models that require local calibration are identified and validated. This is followed by the control simulation phase where the models are used to complete a set of baseline simulations and by the scenario simulation phase where possible future projections are produced. In most studies, these control and scenario periods are around 30 years long, which probably represents a compromise between the cost of climate model runs and the length required to characterize average conditions (Jones et al., 1997).

To assess potential climate change impacts, the outcomes of these three simulation phases have to be analyzed and compared (Figure 3) to assess i) the model quality, ii) the natural variability, iii) the system changes and iv) the significance of system changes with respect to natural variability.

A fundamental problem of climate change impact assessments is the fact that it is not possible to attach a probability of occurrence to any climate scenario and the underlying greenhouse gas emission scenario (Koutsoyiannis et al., 2009;Shepherd, 2014). A similarly limiting problem arises from natural variability (also called internal variability, Lafaysse et al., 2014): any observed or simulated control state just represents a single realization under the conditions prevailing during the chosen control period. Whether the future climate actually induces a significant system modification requires understanding and quantifying the natural variability along the entire modelling chain (Addor et al., 2014;Lafaysse et al., 2014;Shepherd, 2014) and assessing whether the future situation exceeds this natural variability. This problem is well acknowledged for regions with strong climate patterns (e.g. the South American monsoon system Marengo et al., 2012) but few HPP climate change impact studies address it. An example is the study of Minville et al. (2010) for a HPP system in Quebec.

Given the complexity of climate models (Knutti et al., 2013), discussions of their uncertainty are limited to their model structure and parameterizations (Murphy et al., 2004), of how they encode the thermodynamics and atmospheric circulation, as summarized in the recent discussion of climate model uncertainties provided by Shepherd (Shepherd, 2014).

To date, the only option to judge the plausibility of climate model outputs is to consider a multi-model ensemble of deterministic climate model simulations (such as ENSEMBLES (van der Linden and Mitchell, 2009) or CMIP5 (Knutti et al., 2013)) and to assume that the inter-model spread gives an indication of the output plausibility, i.e. to assume that smaller climatic differences between outputs of different climate models point towards plausible results. This inter-model comparison, together with physical reasoning, leads to the general agreement that air temperature is better simulated than precipitation, and that the reliability strongly varies between world regions (Shepherd, 2014).

Besides the fundamental sources of uncertainty related to the climate scenarios and to natural variability, the depicted simulation framework hides a wide range of additional uncertainties. In the hydrologic literature, there is an extensive discussion of how observational uncertainty, parameter

uncertainty and model structural uncertainty sum up to total modelling uncertainty (Beven, 2006;Clark et al., 2008;Gupta et al., 2012) even if there is no agreement on the methods to be used to quantify each of these uncertainties (Beven et al., 2012;Clark et al., 2011;Mantovan and Todini, 2006;Todini and Mantovan, 2007). A problem which is still waiting for innovative solutions is the fact that the hydrologic model is developed for an observed state and then applied to future states. These future states are likely to be significantly different from the reference state and, accordingly, the hydrological model cannot be validated for these future conditions, or only with differential split sample tests (Li et al., 2012). Furthermore, the model can often not account for potentially significant modifications of the hydrological system.

Another problematic issue is the use of hydrologic models that are calibrated on observed meteorological data with meteorological fields derived from climate models. These scenario fields, even if obtained with state-of-the art physical or statistical downscaling, have necessarily different stochastic properties than the observed fields; in particular regional climate model (RCM) outputs require a "statistical adaptation of model outputs" (Obled et al., 2002). The current solution is bias correction (Teutschbein and Seibert, 2012), which does, however, generally not capture potential co-variations between climate variables and is not necessarily valid for future scenarios.

At the bottom end of the modelling chain, the uncertainty of the water management model and possibly of the electricity market model can be assessed with stochastic tools as in the work of Schaefli et al. (2007) on hydropower in the Swiss Alps. A challenge is hereby to account for the feedback loop that might arise between large scale HPP and the electricity market or to account for policy-driven and societal changes affecting the electricity consumption and the market conditions.

Finally, any discussion of uncertainties arising from individual components of the climate change impact modelling chain falls short of accounting for the uncertainties arising from missing feedbacks between the different models. For large scale studies, feedbacks between climate and hydrology can be assumed to play a significant role. A possible way forward are fully-coupled land surface models (Larsen et al., 2014), but their ability to reliably simulate the hydrologic response at the catchment scale (and thus at the HPP plant scale) is under debate (Wood et al., 2011;Beven and Cloke, 2012). And there is the risk of producing, with overly complex models, simulation results that cannot be explained based on underlying hydrologic process assumptions (Blöschl and Montanari, 2010).

All these sources of uncertainties decrease the confidence in hydrological projections and in particular in extreme events (high flows and droughts), which are critical for hydropower management (Fatichi et al., 2013) and for dam safety (Chernet et al., 2014). And the vast majority of the hydrological and HPP climate change impact studies come to the conclusion that climate modelling accounts for far more uncertainty than the local-scale hydro-hydraulic modelling (Schaefli et al., 2007;Bosshard et al., 2013;Gosling et al., 2011). This conclusion has, however, to be critically analyzed in light of the fact that very few studies confront hydrological models that are fundamentally different (Addor et al., 2014;Kobierska et al., 2013) or study a wide enough range of land use scenarios as e.g. in the work of Finger et al. (2012), where the climate, the glacier retreat scenarios and the hydrological model are all deemed equivalent sources of uncertainty for HPP production.

Given the high number of involved models along the modelling chain and of underlying assumptions, the only solution to quantify projection uncertainty is to compile what is sometimes called *ensembles of opportunity* (Tebaldi and Knutti, 2007). This refers to the fact that they are assembled based on any model runs that are available within a given funding and computational context rather than based on scientific considerations of random or systematic sampling (Tebaldi and Knutti, 2007).

Such ensembles are typically composed of a set of climate model runs (of GCMs and RCMs) and, more rarely, of different downscaling methodologies (Stoll et al., 2011) and of different hydrological models (Bosshard et al., 2013) and land use scenarios (Finger et al., 2012). The members of such ensembles are, however, not statistically independent, in particular because the climate models are not (Knutti et al., 2013). Given, in addition, that it is not possible to attach probabilities of occurrence to climate simulations (Blöschl and Montanari, 2010;Shepherd, 2014), a formal statistical interpretation of simulated climate change impacts as proposed for example by Schaefli et al. (2007) is certainly not possible. The impossibility to assign probabilities to ensemble members explains why we should talk about *climate projections* rather than predictions (for a definition of forecast versus prediction or projection, see Table A.1 of the paper by Ehret et al. (2014)).

Ensemble-based climate change projections give, nevertheless, a view of the range of possible system outcomes for HPP management. An important question is, however, how to make use of ensemble simulations to assess dam safety in future climates. An interesting example is the guidance to dealing with potential flood hazard changes provided by the work of Lawrence and Hidal for Norway (Lawrence and Hisdal, 2011, chapter 8).

Selected HPP climate change studies

Considering the very high number of climate change impact studies, it might be surprising that for example a search on Web of Science (www.webofknowledge.com) provides only 218 results for a search with “hydropower”, “climate change” and “model”[1]. Besides a few early studies (Christensen et al., 2004;Mimikou and Baltas, 1997), almost all those papers, 193, have been published in the last 10 years (2005-2014) and a closer look shows that only roughly between 30 and 50 papers refer to model-based climate change impact projection on HPP. This relatively low number can at least partially be explained by the lack of tradition within the field of hydropower research to publish in peer-reviewed journals. Another factor might be the reluctance of HPP companies to share the hydro-meteorological data which is required to set-up and validate the local models.

Categorizing the existing HPP climate change impact studies is extremely challenging, above all due to the diversity of studied systems. Even within small regions, the interdependence of climate, hydrology and HPP might vary strongly. This is first of all due to large differences in seasonal water balance behaviour (Berghuijs et al., 2014), which gives rise to important hydrological regime differences (see e.g. the diversity of hydrological regimes within Switzerland, Horton et al., 2006). In addition, HPP infrastructure design and management strategies vary locally according to production and economic targets. And these operational details are often neither reported nor studied in detail.

[1] As of 01 December 2014

Accordingly, I do not attempt such a synthesis. Hereafter, I first discuss some selected examples for different world regions, followed by a more detailed discussion of climate change impact prediction on HPP in snow-dominated environments. This is completed with a table in the Appendix summarizing the methodological key choices of model-based climate change impact assessment, as a tool to assist the interpretation of additional case studies.

One of the most comprehensive studies is the climate change impact assessment of Christensen and Lettenmaier (Christensen and Lettenmaier, 2007) on the Colorado river basin that updates the results of an earlier study (Christensen et al., 2004). They project streamflow and water management for two emission scenarios and three future periods with eleven climate models, a single downscaling method and a distributed hydrologic model. Besides detailed results for consumptive water uses, their analysis suggests that HPP in this basin could decrease far more than streamflow (without giving, however, further details on the reasons). Their climate ensemble members show three typical results: i) All members show the same direction of change of air temperature; ii) the members do not agree neither on the direction of change of projected precipitation nor on its seasonality ; and iii) the difference between the ensemble members is higher than the projected annual precipitation change. Christensen and Lettenmaier (Christensen and Lettenmaier, 2007) discuss how increased winter precipitation counteracts the reduced streamflow due to decreased summer precipitation and due to warming-induced increased evapotranspiration. Furthermore, they emphasize that the studied basin shows already a large water storage to streamflow ratio, which suggests that increasing reservoir capacity or operation policy changes are not likely to be useful options for climate change mitigation. Overall, they conclude that their analysis is able "to evaluate the range of possible consequences as represented by the different models and emissions scenarios, including "consensus" (mean) results, and measures of variability" (Christensen and Lettenmaier, 2007).

As in the above study, it is often difficult to derive consistent conclusions from climate ensemble members for regions with hydrologic regimes that strongly depend on rainfall and its seasonality. Another example is the study of Manoha et al. (2008) that presents climate change projections for two French rivers with six different climate simulations from four GCMs, the delta change method to generate local-scale meteorological time series and a conceptual hydrological model. For the snow-influenced Isère catchment, the simulations coherently project an increase of winter flow, a shift of the melt peak and lower flow during autumn. For the Loire river as well as for the Rhone river, both showing a distinct summer low flow season, the ensemble members point towards a decrease of summer flows for the end of the century but the ensemble spread makes an interpretation of the results difficult and the authors explicitly acknowledge that their results just serve as a first guess for hydropower adaptation.

There are comparatively few studies on HPP in dry climates in the absence of snowmelt from upstream mountains. Here, the key issue is the frequency of critical low flow situations in conjunction with water use competition. Pereira-Cardenal et al. (2014) used for example a coupled hydrological and power market model to study the power system of the Iberian Peninsula with three RCMs (under a single emission scenario) and with the so-called delta change downscaling methodology. They highlight the fact that climate change also modifies the patterns of electricity and irrigation water demands, with all peaking during the summer months when water flow will be reduced.

It is also noteworthy that very few model-based climate change impact projections for HPP are available for Asia. Yu et al. (Yu et al., 2014) discuss the case of cascaded HPP within a basin providing 41% of Taiwan's HPP. The projections for 2020-2039 were obtained with two emission scenarios and seven GCMs, a stochastic weather generator (for downscaling), a conceptual hydrological model and HPP management rules that are transposed unchanged to the future period. Their results point, on average, towards decreased future inflows during the dry and the wet period but the ensemble members show a wide spread, leading to decreasing as well as slightly increasing future production.

For China, the only peer-reviewed HPP study I am aware of is the work of Wang et al. (Wang et al., 2014), who used, however, a regression method to predict the relationship between climate and hydropower, which does not allow a further interpretation of their results.

Finally, I would like to highlight the work of Ghile et al. (2014) for the Niger river basin. They argue that in this area, the climate projections are too uncertain for classical, model-based climate change impact assessment. Instead, they propose to first analyze the climate sensitivity of the considered water resources system (including hydropower), to identify climate-risks and to confront them with climate change projections only at a later stage (to estimate risk probabilities). They come to the conclusion that, even if the GCM projections disagree on the direction of precipitation changes, the risk for planned investments can be quantified. Such an approach is very promising to assess the robustness of HPP systems under uncertain climate projections and to communicate with stakeholders.

Snow-dominated environments

In strongly snow-influenced environments, robust climate change projections are possible, at least for some hydrological regime aspects that are key for HPP. This conclusion namely results from the numerous climate change impact studies on Alpine HPP (Alfieri et al., 2006;Gaudard et al., 2014;Haenggi and Weingartner, 2012;Manoha et al., 2008;Maran et al., 2014), and in particular in the Swiss Alps, where the high amount of glacier cover is assumed to increase the climate vulnerability of storage HPP (Fatichi et al., 2013;Finger et al., 2012;Rahman et al., 2013;Schaefli et al., 2007).

All these studies on Alpine HPP show the now well known result that snow-influenced Alpine regimes will show higher winter low flow and earlier monthly peak flows; these regime changes are due to warming-induced earlier snow- and ice melt and to less streamflow during subsequent summer months (Horton et al., 2006;Huss et al., 2014;Beniston, 2011). The amount of reduction or increase (Huss et al., 2014) of annual streamflow depends, however, on the modelling assumptions and on the climate ensemble members. A particular challenge for HPP projection of this hydro-climatic region is the moment of peak water (see Sidebar 2 "Glacier runoff and hydropower").

The above conclusions on expected regime changes with higher winter low flows and earlier monthly peak flows can partially be transposed to other snow-influenced environments. Graham et al. (Graham et al., 2007) projected for a Swedish river with a strongly snow-influenced regime that the winter low flow will increase for the period 2071-2100 and spring peak will occur slightly earlier (they used 15 climate ensemble members). With a minimalistic correlation-based model, they conclude that hydropower potential will increase overall. They emphasize, however, that the projected seasonal dynamics strongly depend on the chosen method to produce local scale

meteorological time series. Using a climate ensemble with 13 members, Haguma et al., (2014) project similar shifts for a snow-influenced HPP catchment in Québec, accompanied with increased annual flow and hydropower production (simulated with a sampling stochastic dynamic programming approach).

The regime shift due to earlier snowmelt can, in fact, be expected around the world in environments where the snow accumulation season is out of phase of the melt season, such as e.g. in Norway (Chernet et al., 2013) or in Quebec (Minville et al., 2010), but not at places where sublimation is the dominant driver of snow and ice mass loss (as e.g. in the tropical Andes, Kaser et al., 2010) and not in the Himalaya, where accumulation and melt occur during the same (monsoon) season (Kaser et al., 2010). Here the hydrologic regime of downstream Asian rivers is not expected to experience a significant shift, as shown by the large-scale streamflow projections of Immerzeel et al. (2010) for the period 2046 to 2065. Their study, using a best guess glacier size scenario for 2050, five different GCMs and a simple snow- and ice melt formulation, does also not point towards a significant modification of flows during the winter low flow period (but given the melt model uncertainties discussed in their paper, this conclusion might not be robust).

In general, hydrological regime shifts that result from climate warming will have a much stronger impact on HPP in regions that, today, largely depend on the natural storage effect of the snowpack as e.g. the Western US (Mote et al., 2005;Madani and Lund, 2010), where, in addition, earlier snowmelt might come with more evaporation and, thus, considerable reduction of annual flow (Christensen et al., 2004). The importance of this natural storage effect is, however, sometimes overrated as pointed out by Immerzeel et al. (Immerzeel et al., 2010) for the Yellow river.

A crucial issue for high mountainous storage HPP, as well as for any storage HPP, is the role of the reservoirs for flood mitigation since they can potentially absorb high flow events (Bieri and Schleiss, 2013). In view of all involved modelling uncertainties, simulation-based projections of future flood events are, however, challenging. The reliability of such extreme event simulations is debated, as e.g. illustrated in the open peer-review of the work of Fatichi et al. (Fatichi et al., 2013). This also explains why analyses of intake overflow frequency (Finger et al., 2012), of spillway activation (Schaefli et al., 2007) or of future design floods (Chernet et al., 2014) have to be interpreted with care.

Another question that, to my knowledge, is largely absent from existing work on snow-influenced HPP is the question of how sediment loads impact on HPP, which is also highly related to extreme flow events. For examples of studies on glacier sediments and HPP in Norway, see , see the work of Bogen et al. in Norway (Bogen et al., 2012) or the work of Gardarsson and Eliasson in Iceland (Gardarsson and Eliasson, 2006).

Projecting future HPP management

A general challenge for HPP climate change impact analysis is the question of how to make reasonable assumptions about future HPP management. Most available studies transpose the current management rules unchanged to the future period (Fatichi et al., 2013;Finger et al., 2012;Schaefli et al., 2007), rather than to account for potential changes of production patterns, possibly due to climate change effects (Golombek et al., 2012). Such a “keep-as-is” approach might result in very unrealistic management rules for future scenarios. In particular in the context of multi-

purpose reservoirs, the analysis of alternative future operation strategies is essential, as e.g. in the work of Raje and Mujumdar (2010) that analyzed a reservoir on the Mahanadi river in Orissa (India) used for hydropower, flood protection and irrigation.

An example of how to account for possible electricity market evolutions is the work of Gaudard et al. (2013). They formulated a revenue optimization problem for the Swiss Mauvoisin storage HPP system. The electricity price is modelled as a function of electricity consumption, which in turn is modelled as a function of heating and cooling degree-days. Optimizing revenue for future climate scenarios, they come to the conclusion that HPP management (hydraulic head and turbine scheduling optimization) can at least partially mitigate HPP losses due to the on average 18% inflow reduction between 2001-2010 and 2091-2100. For another Swiss HPP system (Grimsel, a pump-storage system), Bieri et al. (2013) come to a similar conclusion. They study the effect of different electricity price scenarios on HPP revenue under climate change and conclude for a single emission scenario that HPP revenue losses due to the projected reduction of 25% of water inflow by the end of the century can largely be mitigated through HPP flexibility. Another interesting approach is the work of François et al. (2014) who propose to adapt HPP management rules to future conditions based on an analysis of the marginal value of stored water; with such an analysis, the best equilibrium between the water resources and electricity demand can be identified for future scenarios.

The wide-spread absence of projections of HPP management at the case study scale can certainly be explained by the fact that hydropower producers do not like to unravel their economic strategy or their data about past production. A possible way forward are joint academic-industrial research projects as for example the French RIWER2030 project (Hingray et al., 2013) or the Swiss Competence Centres on Energy research (Schleiss, 2014).

Other water-related climate change impacts on the energy sector

The above focus on the relation between climate, hydrology and HPP covers only one aspect of the interplay between river water and the energy sector. The role of water to store electricity for the grid integration of intermittent renewable energy sources has already been mentioned. How this integration might develop in the near future remains unclear (Beaudin et al., 2010;Yang and Jackson, 2011) especially in light of economic and environmental considerations (Gullberg et al., 2014;Kloess and Zach, 2014). Research into how the integration might be affected by the spatio-temporal variability of climate related energy (water, wind, sun) and by climate change is in its early stages (François et al., 2014), and much of this research is difficult to access, either in grey literature or in not publicly available reports (Engeland et al., 2014).

Besides direct use for power generation, river water plays an important role for thermoelectric power plant cooling, which might suffer from climate-related warming of river water and from more frequent power plant shut down during warm periods (Manoha et al., 2008;Rubbelke and Vogele, 2013;van Vliet et al., 2011). Furthermore, in many regions, thermoelectric plant cooling tends to be limited by high water temperatures during summer low flow when run-of-river HPP is also limited (Rubbelke and Vogele, 2013;van Vliet et al., 2013;Koch et al., 2014) and when electricity demand is highest (Pereira-Cardenal et al., 2014;Koch et al., 2014).

The need for cooling water furthermore exposes many nuclear power plants to river flood risks. In Switzerland, for example, the Federal Nuclear Safety Inspectorate required from all nuclear power plant operators a new deterministic assessment of the 10000 year flood after the Fukushima nuclear accident (Swiss Federal Nuclear Safety Inspectorate ENSI). Such extreme flood estimations play an essential role for engineering in view of safety regulations (Paquet et al., 2013), and probabilistic extreme flood estimation under nonstationary conditions is a currently emerging field (Obeysekera and Salas, 2014).

Finally, it is worth mentioning that climate change might adversely affect freshwater biodiversity (Heino et al., 2009), which in turn might further limit the development of hydropower infrastructure or require operation adaptation for existing HPP systems.

Conclusion

The planning horizon of major HPP infrastructure projects stretches over several decades and consideration of evolving boundary conditions might play an increasing role in the near future. The discussed multitude of uncertainties involved in climate change impact prediction underlines, however, that state-of-the-art hydro-climatic modelling is not likely to provide narrow enough water scenario ranges to be included into economic analyses for individual HPP case studies. Furthermore, not directly climate-related boundary conditions, such as economic growth, legal constraints, national subsidy frameworks or growing competition for water, can be expected to largely outweigh any climate change impacts from the HPP investor's viewpoint.

Accounting for possible future situations, derived from climate change impact projections, plays nevertheless a major role for climatically-robust design (Jeuland and Whittington, 2014) and to develop strategies to cope with uncertain change (Hallegatte, 2009) . An interesting approach might hereby be the focus on the *amount of acceptable change* to avoid tipping points (Werners et al., 2013). This holds in particular for possible changes of inflow seasonality, which can plausibly be anticipated in many world regions, albeit more qualitatively then quantitatively. What seems to be crucially lacking are joint scenarios of sediment loads, which could certainly be included in state-of-the-art hydrological models for HPP catchments.

The future probabilities of occurrence of extreme events will remain highly uncertain, in particular because it will never become possible to attach probabilities to different greenhouse gas emission scenarios or climate models. Rather than expecting breakthroughs in this field, decision-makers might want to invest into increasing the reliability of real-time forecasting systems to better cope with potential extreme events at various time scales, from hourly extreme streamflow to seasonal droughts. Anticipation of new HPP management strategies under future climates will hereby play a key role to identify future forecast needs, in particular for multipurpose dams.

Improved short-term hydrologic forecasts will also be a corner stone for a more reliable integration of climate-related energy sources and for power grid stability management, where hydropower storage and pump-storage HPP plays a crucial role to balance peak electricity production and peak demand. What is missing in this perspective are detailed analyses of co-variations among energy sources and hydropower storage potential (François et al., 2014).

In summary, end-to-end climate change impact assessments including electricity market models will continue to play a certain role to further understand local HPP conditions. But beyond producing scenarios of future water availability, hydrologic research could greatly enhance its relevance for hydropower production by changing its focus to the quantification of climate-vulnerability of HPP and power grid management and to addressing new hydrological forecasting needs under modified climates. Such work should in particular account for possible other changes of the boundary conditions, such as increased competition for water or legal constraints.

Sidebar I: Hydropower and ecosystem protection

Hydropower development is seen as a good carbon policy but it has important consequences for other natural capital (Agarwala et al., 2014) and these consequences might be exacerbated in growing competition for water resources under climate change. Structural ecosystem impacts arise from river damming, such as flooding of high value ecosystems, disrupted sediment regime or fish habitat fragmentation (Ziv et al., 2012;Nilsson et al., 2005). Non-structural impacts result from streamflow, sediment and water quality regime alterations downstream of HPP schemes. Run-of-river plants create non-natural above-average streamflow. Downstream of accumulation lakes, the streamflow remains exceptionally low with temporally variable sharp flow increases (hydropeaking), possibly accompanied by sharp water temperature in- or decreases (thermopeaking). Understanding and quantifying the connection between habitat viability and streamflow variability remains a research field of prime importance (Bunn and Arthington, 2002;Nilsson and Svedmark, 2002;Poff and Zimmerman, 2010;Ceola et al., 2013), in particular for the definition of new environmental flow policies (Arthington et al., 2006;Gorla and Perona, 2013;Tharme, 2003), for innovative methods for HPP maximization under environmental flow constraints (Renofalt et al., 2010;Watts et al., 2011) and to further quantify ecological risks resulting from direct anthropogenic impacts on streamflow (Doll and Zhang, 2010).

Sidebar 2: Glacier runoff and hydropower

Many HPP systems rely on water inflow from high altitude or high latitude catchments, i.e. on water from melt of seasonal snow covers and glaciers (Schaefli et al., 2007;Singh and Bengtsson, 2004;Paul and Andreassen, 2009;Chevallier et al., 2011). In such catchments, considerable adverse effects from global warming are often expected, due to a transition from snowfall to rainfall and due to glacier retreat. The climate-sensitivity of glacier-fed HPP systems depends on how strongly the production relies on the temporal streamflow delay resulting from the natural storage effect of snow and ice (Barnett et al., 2005;Sorg et al., 2012). Huss (2011) estimated the importance of Alpine glacier storage change for the streamflow of four major European streams (Rhine, Rhone, Po, Danube) and showed that glacier storage change has a non-negligible effect on summer runoff at much larger scales than what might be expected. However, the importance of glacier-fed streamflow strongly depends on the climate regime as demonstrated in the analysis of 18 major streams worldwide by Kaser et al. (2010). Their study pinpoints the importance of glacier melt for streams that enter seasonally arid regions. It should be kept in mind that such large-scale analyses based on

precipitation, discharge and glacier mass balance data strongly simplify the actual water balance and do not account for groundwater storage changes. The big open question for glacier-dependent HPP is the expected moment of peak water (Gleick and Palaniappan, 2010) and peak annual production due to streamflow from net glacier mass loss (Bolch et al., 2012;Huss et al., 2014). Locally, climate change impacts on glacial hazards (glacial lake outburst, Dussaillant et al., 2010) and on sediment delivery might outweigh the water availability question (Bolch et al., 2012;Gobiet et al., 2014).

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Figures

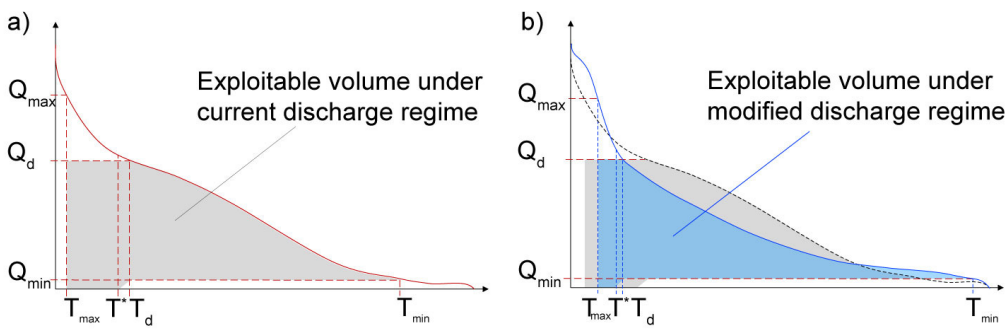

Figure 1: Sketch of the use of flow duration curves (Vogel and Fennessey, 1995) to assess the impact of hydrological regime changes on the hydropower production potential of run-of-river HPP (Haenggi and Weingartner, 2012;Basso and Botter, 2012); *Q* stands for discharge and *T* for the yearly time of exceedance (duration); Q_d: design discharge (nominal maximum discharge for the turbines), Q_{min}: minimum discharge imposed by the water use concession; Q_{max}: maximum flow constraint to protect turbines from sediments and floating material; *T is the duration beyond which the exploitable discharge is limited by Q_{min}.**

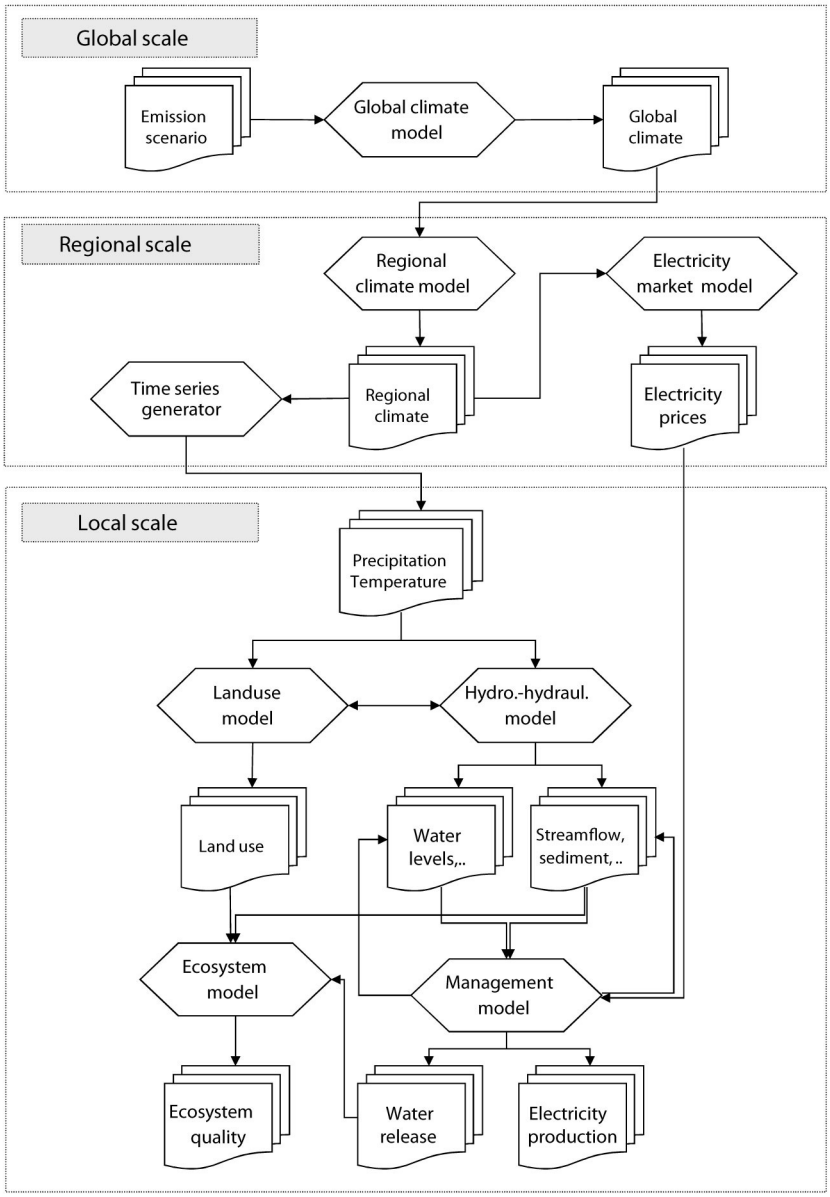

Figure 2:, Sketch of the model chain for climate change impact simulation. Many more feedback loops between the models could exist. A complete HPP management model includes HPP operation as well as maintenance work.

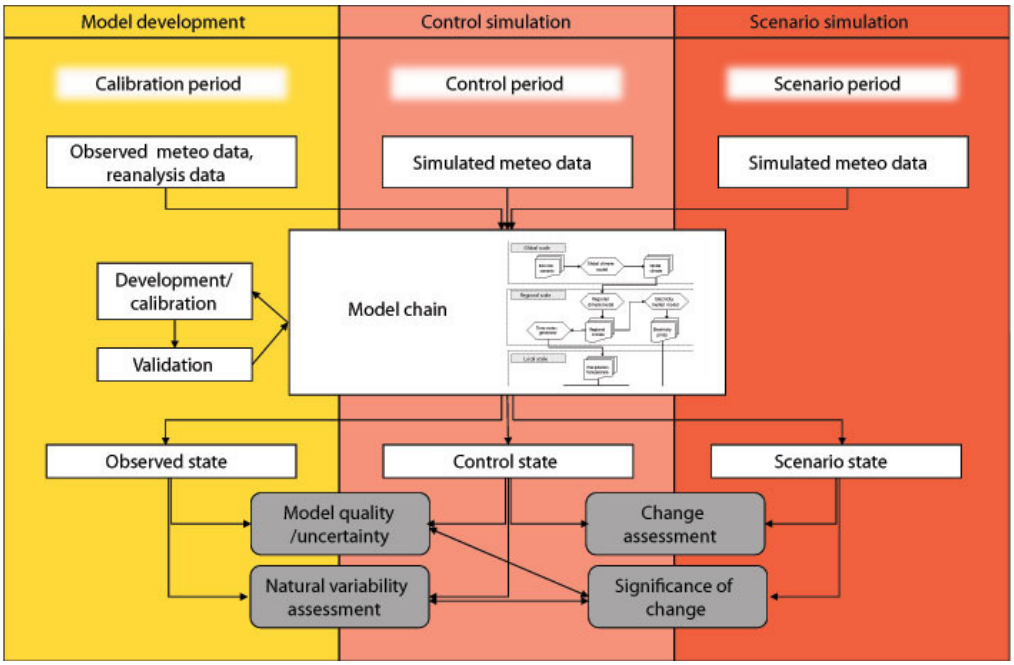

Figure 3: Sketch of the general framework of climate change impact assessment, composed of three simulation phases (colour boxes) and of four phases of output assessment (grey boxes).

Table A1: Assessment grid for HPP climate change impact studies. The analysis aspects are grouped into aspects of case study and endpoint selection, of model choices and of simulation assessment choices

Analysis aspect	Main options	Relevance
Geographic location	Region, country, river catchment.	Socio-economic and institutional water use context; legal constraints; climate region
Water management system type	Run-of-river, accumulation HPP, mixt, single / multipurpose dams	Relevance of results for similar HPP systems; relevance of water use competition; hydraulic and management model complexity
Scale	Small (few 100 km^2), meso (up to few 1000 km^2), large (>10000 km^2)	Choice of hydrological model; level of detail of hydraulic and management model; importance of expected land use changes; importance of feedbacks between hydrology / land use and climate; choice of climate downscaling methods
Hydrological key variables, time step	Daily, monthly or seasonal flows; including extremes or not; including sediment loads and water temperature or not	Relevance of simulations for everyday HPP, for risk management and infrastructure planning, for ecosystem impact assessment
Study end point	Hydrological regime and extremes, water management, economic performance	HPP plant specificity of obtained results; socio-economic relevance of obtained results (study of regime changes only versus full economic analysis)
Greenhouse gas emission scenarios	Latest IPCC scenarios / earlier IPCC assumptions / climate sensitivity analysis	Range of studied system outcomes; study of a potential pathway to the future (transient simulations) versus sensitivity analysis (simulation of future equilibrium situation)
Climate models and ensembles	Choice of GCMs / RCMs, type of used climate ensembles or not	Range of studied climate models (state-of-the-art or not, physical ensemble or not)
Downscaling method	Physical, stochastic or delta change method or ensemble of different methods	Probabilistic interpretation possible or not; detection of methodological scale mismatches
Analyzed climate variables	Precipitation, temperature, wind, etc.	Degree of dependence of HPP system simulation on climate; climate model reliability for analysed variables in studied region
Hydrological model	Conceptual vs. physical parameterization , widely applied versus tailor-made	Calibrated or physics-based parameters, associated methods of data / parameter uncertainty assessment; detection of mismatch between model use (present and future climate) and original model application domain
Land use evolution model	Coupled versus uncoupled to hydrological or climate model; physical / statistical / scenario-based	Joint plausibility of hydrology and land use under future climate, methods of uncertainty assessment
Water management model	Mechanistic or stochastic model; driven by observed or by optimized rules; model including	Relevance / realism of socio-economic study endpoints; study of adaption measures possible or not; importance of extreme hydrological event simulation and of water quality simulations for management system

	maintenance and emergency management or not	
Electricity demand model	(Supra-)regional market model versus local heuristic model	Relevance / realism of economic study endpoints; study of indirect climate change impacts on energy sector
Ecosystem model	Coupled versus uncoupled to hydrology / to land use; spatially-explicit or not	Relevance / realism of ecological study endpoints; study of adaptation measures possible or not; importance of extreme hydrological event simulation and of water quality simulations for ecosystem model
Natural variability assessment	Natural variability of relevant state variables acknowledged or not / discussed in detail / assessed	Assessment of climate change versus natural variability; relevance of obtained results for management and planning or for advancement of science; comparison of different studies
Uncertainty assessment I: level along the model chain	Sources of uncertainty acknowledged or not / discussed in detail / assessed	Assessment of climate change versus natural variability; relevance of obtained results for management and planning or for advancement of science; comparison of different studies
Uncertainty asses. II: models & scenarios	Which elements of the modelling chain are assessed with what type of method	As above, assessment of modelling quality at each modelling step
Change assessment	Comparison of hydro-climatic and HPP state variables or criteria-based	Level of detail of the results, in particular for study intercomparison
Level of significance assessment	Qualitatively discussed or formally assessed	Relevance of results for decision-makers; study and model intercomparison

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