Securing hydrological ecosystem services through catchment-wide land-use management

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Abstract

People rely on the integrity of ecosystems to provide essential hydrological ecosystem services such as drinking water, flood protection, recreation and hydropower to name a few. Human activities and global climate change are however increasingly jeopardizing the ability of ecosystems to deliver these services, which results in increasing economic costs. Besides a mitigation approach, this calls for adaptation measures related to ecosystem management in the entire catchment area. In this contribution, we present the approach taken in the Swiss National Research Project *HydroServ* for assessing the full value chain of hydrological ecosystem services provided by terrestrial ecosystems under climatic and socio-economic changes.

Keywords: hydrological ecosystem services, mountainous areas, integrated water management, valuation, GIS, land use change

1   Introduction

Global warming is expected to have strong impacts on the hydrological cycle and terrestrial ecosystems in the coming decades. Simultaneously, changes in political decision-making at different levels and in socio-economic boundary conditions are influencing land use and land cover in catchment areas. Both kinds of change undoubtedly influence water quantity, quality, location, timing of flow and related hydrological ecosystem services such as drinking water, flood protection, recreation and hydropower to name a few (Brauman et al. 2007). Hydrological ecosystem services (HES) are defined as the services produced by terrestrial ecosystem effects on freshwater and can be organized into three main categories (1) extractive and instream water supply (provisioning), (2) water damage mitigation (regulating), (3) maintenance of aquatic habitats (habitat) and (4) provision of water-related cultural services (cultural & amenity), analog to the categorization of Kumar (2010). Jeopardizing the ability of ecosystems to deliver HES results thus in increasing economic costs due to flooding, water scarcity or decreased water quality. Besides a mitigation approach, this calls for adaptation measures related to land-use management to foster the regulating and insurance services that ecosystems provide.

In view of these impending changes of climate, land use and land cover, there is a need for fostering our understanding of the full value chain of HES provided by terrestrial ecosystems. The vulnerability of HES depends, on the one hand, on their

sustainable supply and thus on the biophysical properties of terrestrial ecosystems and their relation to the quantity, quality, location and timing of water flow. On the other hand, it depends on the capacity of ecosystems and human societies to cope with the impacts of global change. With respect to climate change, regional actors will however only be able to react with adaptation strategies; in contrast they will potentially be able to mitigate negative trends in land use and land cover change. Projections of changing supply of different HES under shifting environmental variables (including climate), land use, land cover and socio-economic trends thus provides the basis to develop regional adaptation and mitigation strategies that (i) secure the life-supporting HES required for sustainable development and (ii) are economically and ecologically efficient as well as socially and politically feasible.

In this contribution, we present the inter- and transdisciplinary research project *HydroServ* funded by the Swiss National Research Programme 61, in which consequences of climate and socio-economic changes on water resources and on the related HES are assessed in an integrative manner. We focus in this contribution on introducing the methodological framework linking hydrological, ecological, and economical sub-models into a multi-period, spatially explicit Bayesian network (BN) that allows for feedback from changing socio-economic and political conditions to land-use and adaptation to climate change. The integrated assessment especially aims at assisting policy makers in their decision-making through the design of innovative instruments for the public and private sectors and institutional regulations, which will be required to respond to the anticipated changes while preserving a balance between demand and supply of HES. We discuss advantages and limitations of such an approach with respect to its value for suggesting adaptive landscape management practices.

2   Case study area

If the above issues are to attract the interest of stakeholders and carry momentum for real-world applications, they must be considered in a case study context. As case study, the project encompasses the catchment area of the river Kleine Emme in central Switzerland, a region which includes the UNESCO Biosphere Entlebuch (Figure 1). While there is a strong settlement pressure in the lowlands of the Kleine Emme, increasing abandonment of Alpine pastures as well as a the disappearance of high moorlands due to oxidation and vegetation regrowth characterize upstream areas.

HES and their benefits and beneficiaries considered in the study were identified in seven local expert interviews as well as with an analysis of local data and data from different river restoration projects. Table 1 provides a list of the HES considered in the study and classified according to the Millennium Ecosystem Assessment classification.

Figure 1: Case study area encompassing the catchment area of the river Kleine Emme in Switzerland. The region includes the UNESCO Biosphere Reserve Entlebuch.

Table 1: Selected hydrological ecosystem services considered in the study.

MA Services Classification	Hydrological ecosystem services	Benefits	Beneficiaries
provisioning services	capacity of ecosystems to produce biomass	food production	farmers local residents
regulating services	*water regulation:* a) capacity of terrestrial ecosystems to regulate peak flow and base flow of surface water	reduction in flooding	industrial companies municipalities local residents
	b) capacity of terrestrial ecosystems to recharge ground water	water supply	hydroelectric companies
	erosion regulation: capacity of ecosystems to stabilize soil and to prevent sediment accumulation downstream	erosion prevention	farmers water companies wastewater disposal
	water purification: chermical, physical and mechanical capacities to clean a polluted suspension	increased water quality	
cultural services	recreation	recreational activities	local residents tourists
supporting services	nutrient cycling, soil formation, photosynthesis	benefits already taken into account in other categories	

3   Hydrological ecosystem services assessment framework

We developed an integrative simulation framework to better understand the relationships and feedbacks between land use and land cover change, key hydrologic attributes and the related provision of HES to expected climatic and socio-economic

impacts (Figure 2). The framework is composed of two modules, the *system drivers* and the *system responses*, which are subdivided into several tasks described in more details in the following sections. Coupled within a spatially explicit multi-period BN, the framework allows simulating the full value chain of HES under conditions of uncertainty and incomplete information. The projections are run at ten years time steps up to the year 2050.

3.1   Bayesian Network Framework

BN are a kind of probabilistic graphical model having the advantages that (1) quantitative data and expert knowledge can be taken into account simultaneously, (2) uncertainty is fully accounted for, and (3) due to the explicit causal relationships between the variables of the models, the results can be intuitively communicated. Specifically, BN are directed acyclic graphs with nodes representing random variables, and arcs representing dependence relations among the variables. Thus they provide an intuitive representation of the joint probability distribution of a set of random variables (for a comprehensive summary see e.g. Jensen & Nielsen 2007). With their nodal form, BN support a structured and interactive approach to tasks requiring information from different specialist fields. Since BN are based on acyclic graphs, they provide a detailed evaluation of the joint influence of different input parameters and thus can be used to calculate risk.

The causal connections, the definition of the states as well as the filling of conditional probability tables (CPTs) are being done in an iterative process involving experts in interviews and methods for retrieving causality including impact matrices, experts and stakeholders questionnaires as well as available data from the case study region. In Figure 3, a preliminary Bayesian Network developed in the expert process
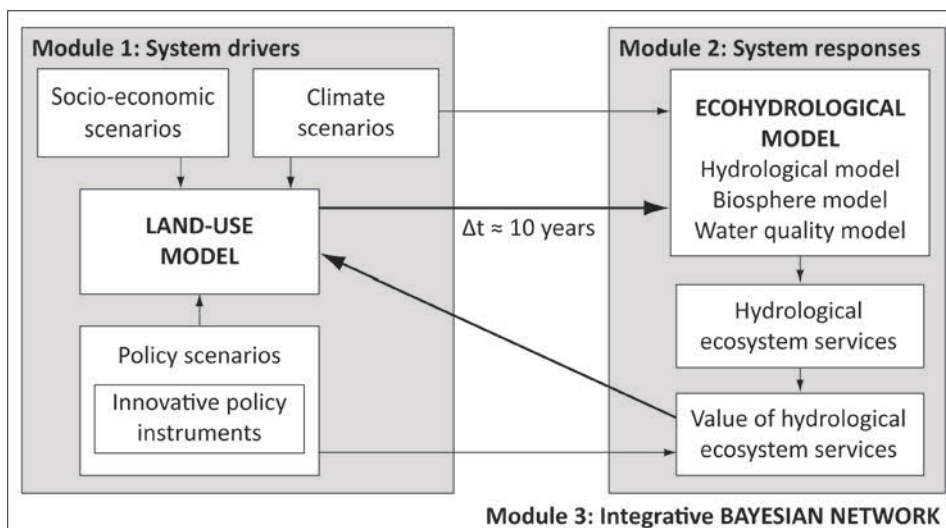

Figure 2: Modelling framework of HydroServ. The thick lines represent the main data flow between the tasks.

for assessing HES in the case study region is given. The variables are the output of the different tasks described below. To be a spatially explicit model, the BN communicates with ArcGIS® and runs the network for each cell.

3.2   Land-use decision model

Land users are actors who have immediate influence on the land use and land cover (like farmers, forest owners, or national park administration) and thus influence the supply of HES with their management decisions. In order to account for these key influence factors on hydrological attributes we set-up a spatially explicit BN model of the land use decision-making process for each parcel in the case study area.

Our decision-making model is based on the theory of planned behaviour developed by Ajzen (1991). Endogenous variables influencing the land use decision are cost-benefit expectations, subjective norms and behavioural constraints (financial, technical, legal and natural ones) the land user has. This model extends traditional decision models based on monetary costs and benefits, because it also includes subjective norms as independent variables in explaining land use behaviour. This allows taking into account the rationality of all types of actors ranging from private economically driven farmers to public land users with normative goals. Beliefs about environmental/climate factors, socio-economic factors and policy factors are modelled as exogenous drivers, which influence the decision-maker.
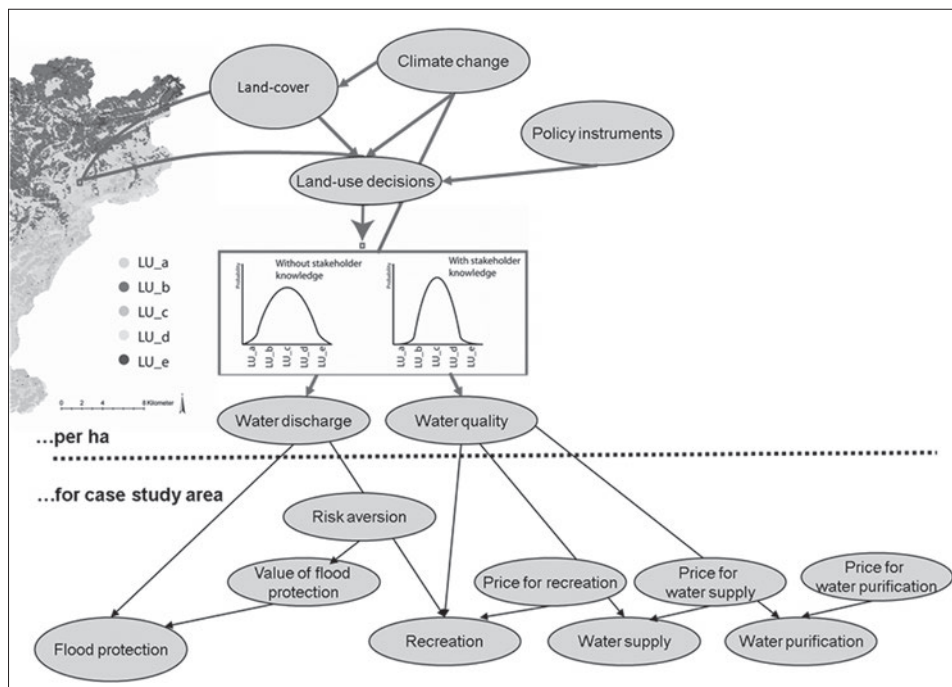

Figure 3: Bayesian Network for assessing hydrological ecosystem services. In the figure, only one time step is represented.

A representative survey of the land users in the study region will give information to which degree the driving factors potentially influences their decisions. For the setup of the causal links between the variables in the BN, eight open-end expert interviews were first conducted. Based on the formulated relationships between the variables, six other experts filled the prior probability distributions of the variables in the BN. A questionnaire to update the probability distributions of the experts in the network was sent to 400 stakeholders in the case study region identified through cadastral registers the administration provides. The filled out questionnaires have not yet been evaluated but will serve to update the expert probabilities and thus decrease uncertainties in the expert evaluations based on local knowledge. A first draft of the spatially explicit model was implemented using Netica® and ArcGIS®. Modelled in a spatially explicit BN, the land use decision model thus provides probabilistic land use maps under different climate scenarios, socio-economic, and policy scenarios, which allows assessing the probability of land use change of each management unit over the modelled time steps.

3.3   Eco-hydrological model

For simulating changes of the hydrological response to land-use changes and climate change forcing, we set up an eco-hydrological model coupling a hydrological-, a water quality- and a vegetation- model. The modelling framework is based on the physically based distributed rainfall-runoff model TOPKAPI (Ciarapica & Todini 2002). This model, like others, is based on the landscape topographic index to identify saturation prone areas, an approach that has shown success even at global and regional scales.

The vegetation model LPJ-GUESS simulates how vegetation evolves in response to climate conditions (Wolf et al. 2008). This is a state-of-the-art model for representing primarily vegetation and forest dynamics at catchment scales, which had to be adapted in order to make possible the integration within TOPKAPI, and to avoid the risk of an overparameterized model, the computational requirements of which become too high for long-term simulations.

Because land uses and vegetation dynamics influence water quality, the eco-hydrological model is going to be interfaced with an approach describing the transport processes of the main nutrients and pollutants, which are associated with specific land uses and the dynamics of proxies for quantifying water quality related HES, e. g. toxicological criteria for fish and other aquatic biota. Modelling transport processes will be approached following the methodology proposed by Rinaldo et al. (2006). As indicators of water quality and proxy of ecosystem services, we will concentrate on nitrogen and phosphorous as main nutrients, and on pollutants that will be identified in relation to the effective land uses of the investigated areas. The coupling of the hydrological model and of the transport one will be initially implemented as one way and off-line modelling strategy. The implementation in TOPKAPI of the transport model will be, however, investigated.

3.4   Valuation of hydrological ecosystem services

Upstream and downstream areas are usually being managed independently without consideration of spatial trade-offs. Protection measures are taken without knowing to what extent they correspond to people's preferences. Taking into account people's preferences for HES and risk, while also considering spatial trade-offs, provides an important step towards sustainable integrated water management.

For assessing preferences for the selected HES in Table 1, an attribute-based choice experiment was set-up. In order to lift all participants to the same level of imagination, we generated 3D-visualizations showing changes in the landscape of the catchment area, the measures in the downstream area and the impacts of flood occurrences in the downstream area (Figure 4). In a first choice sequence, people's preferences for HES under different land use scenarios are assessed. Reconsideration of willingness-to-pay for land use management under changing climate conditions (i.e. changes in frequency of flood occurrence) and recreational preferences are enquired in the second choice sequence and give information about risk attitudes to changes in the availability of HES of the different stakeholder groups. The experiment includes a split sample with a short vs. comprehensive learning task about the influence of landscape composition land use and ground cover on water discharge. The survey set-up has been reviewed by four choice experiment experts and has been sent out to 800 inhabitants in the case study region. Filled out questionnaires have not yet been evaluated.

Figure 4: Excerpt of the attribute-based choice experiment with 3D-visualizations of upstream and downstream land-use changes.

3.5   Climate and socio-economic scenarios

According to Graham et al. (2007), climate change may cause an increase in river flow, earlier spring peak flows due to shift in snowmelt and an increase in hydro-power potential. However, predicting the effects at the catchment scale requires the use of climate scenarios that match the basin scale. Thus, in addition to the political, economical and social forcings that drive the land use model, we also consider the effects of climate change by means of local scenarios generated through a stochastic downscaling procedure (see e.g. Burlando & Rosso 1991, 2002). In the case of precipitation, we will generate synthetic hourly precipitation series using the generalized Neyman-Scott Rectangular Pulses Model (Burton et al. 2008), properly reparameterized to be statistically consistent with the projected climate conditions (Bordoy & Burlando 2011b). Local temperature scenarios will be obtained by means of a Markovian model, which will be used to reproduce the high frequency stochastic fluctuations and the seasonal oscillation after being reparameterized on the basis of Regional Circulation Model (RCM) simulations. This approach, though simple, allows simulating temperature series at hourly resolution being consistent in mean and variance with the projected climate projections. The forcing RCM used for the reparameterization is RegCM3 (Im et al. 2010a, b), which is debiased according to Bordoy & Burlando (2011a).

Our policy and market scenarios were based on storylines based on three IPCC scenarios (A1B, A2, and B1), developed for mountainous regions in Switzerland (Walz et al. 2010). The importance of the variables in the storylines for the case study region was assessed in five local expert interviews and used to develop new storylines for the case study region. Furthermore, the storylines were expanded with further details on future governance mechanisms shaping the inter-resource regimes relevant for the maintenance, improvement, and degradation of the HES in the case study region. The literature on coordination mechanisms both in land use planning and building permits, in real estate registers, in agricultural policy output, infrastructural supply concessions and contracts between several use right owners was analyzed and complemented with input from five experts interviews. Based on developed for were then downscaled to our study regions and expanded by further assumptions with respect to the management of ecosystem services in focus.

4   Discussion

We present the work flow of the approach taken by the Swiss National Research Project *HydroServ* for assessing the full value chain of HES provided by terrestrial ecosystems under climatic and socio-economic changes. A focus on HES makes it possible to concentrate a large amount of physical and ecological data into a limited number of variables that are directly relevant to policy (de Groot 1992) and that can be readily communicated to diverse stakeholders (Rapport et al. 1998; Norberg 1999).

While each task of the *HydroServ* project provides currently new knowledge in its discipline from the coupled hydrological model to the HES valuation, the multi-pe-

riod Bayesian network provides an integrated framework for assisting decision-makers in developing new suitable institutional arrangements to secure the provision of HES. The generic approach permits an evaluation of a range of policy alternatives, which will be the base for policy recommendations and a practice-oriented step-by-step methodological "design of institutional arrangements for HES" provided to the stakeholder at the end of the project in 2013. A transfer of the quantitative results of the study to other case studies can however only be conducted, if the catchment area is similar in terms of land-use, land-cover, political decision-making, and climate forcing.

One of the key advantages of the BN is that it allows unifying human expertise and quantitative knowledge in a coherent framework, in which the opinions of decision-makers can easily be integrated and thus transferred to other case study areas. Integrating the different points of view of stakeholders regarding the situation of the catchment area supports the establishment of alliances with groups of policy-makers (federal and cantonal) and practitioners (e. g. hydropower generation) in order to support the use of the project results. Such an approach however requires a careful stakeholder process from the beginning of the project, and is thus time intensive.

Notwithstanding the lack of complete scientific information about the future supply of and demand for HES coupled with the increased variability of the potential spatial impacts of global change and regional socio-economic developments, the presented approach linking hydrological, ecological, and economical models and allowing for feedback from changing socio-economic and political conditions to land-use and adaptation to climate change provides an important step towards sustainable integrated water management. In summary, the project offers several innovative aspects including:
1. Closing the feedback loop between supply and demand for HES with new institutional approaches.
2. Integration of participatory approaches into numeric simulation for securing the provision of HES patterns at a regional scale.
3. Identification and evaluation of the effects of mitigation and adaptation strategies on the provision of HES.
4. Synthesis of research results to support decision-making processes and policy innovation for sustainable economic development.

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