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Managing Catchments for Hydropower Services

Technical Report

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Wealth Accounting and the
Valuation of Ecosystem Services
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Abbreviations and Acronyms

CAT	Catchment Area Treatment (CAT)
DDF	Degree-Day-Factor
DEM	Digital Elevation Model (DEM)
GIS	geographic information system
HP	Himachal Pradesh
HRU	hydrologic response unit
InVEST	Integrated Valuation of Environmental Services and Tradeoffs
LULC	land use/land cover
PES	payments for ecosystem services
PET	potential evapotranspiration
RIOS	Resource Investment Optimization System
ROI	return on investment
SCS	Soil Conservation Service
SWAT	Soil and Water Assessment Tool
TNC	The Nature Conservancy
USDA	U. S. Department of Agriculture

Note: All dollar amounts are U.S. dollars unless otherwise indicated.

Executive Summary

Introduction

In recent years, natural resource managers and developers are moving toward integrating conservation and development goals. This shift is evidenced by novel policy mechanisms such as the establishment of schemes for natural capital accounting and other payments for ecosystem services (PES) programs. The state government of Himachal Pradesh has recognized the potential for these new policies to strengthen state resource development pathways and provide more balanced and sustainable trajectories for advancing both economic and environmental conditions. The state is currently developing a PES program around ecosystem services that support hydropower production, a major focus for green development. The first step in creating such a policy is to better understand the current status of ecosystem service provision and value in the State.

The objective of this project is to provide critical information on the relative value of different land management practices for maintaining critical services that support hydropower production, to assist in the development of an ecosystem service analysis and subsequent policy related to payments for ecosystem services (PES). This study presents the first phase of this analysis, focusing on targeting investments in soil and water conservation to support baseflow regulation and sediment retention in hydropower catchment facilities, and developing a framework for future work on economic valuation of these services.

Through a modeling analysis using open-source software tools developed by the Natural Capital Project (NCP), this study aims to achieve the following objectives:

1. Develop a methodology for improving targeting of soil and water conservation investments in forests in Himachal Pradesh;
2. Demonstrate the utility of the above method by applying it to identify priority areas for soil and water conservation investments to improve ecosystem services from landscapes (water yield and sediment retention);
3. Perform a conceptual comparison of two commonly used models for linking land management to water yield and sediment outcomes;
4. Provide a valuation framework and guidance on appropriate uses of these models for assessing ecosystem services and valuing their contribution to the hydropower sector; and
5. Develop capacity in state government for ecosystem service valuation.

Methodology

In this study, we apply a landscape screening model (RIOS) developed by NCP to identify cost-effective portfolios of investments in watershed services that minimize erosion and improve baseflow regulation in five pilot study areas in Himachal Pradesh. We then apply the InVEST sediment and water yield models (also developed by NCP) to estimate the relative change in annual water yield and sediment that could result from implementation of the recommended activities.

Wherever possible, local data on physical conditions and land management were collected to drive the models. Where local data are not available, published studies from the HP region, India, or global assessments were used to fill in gaps. The Catchment Area Treatment Plan for the Satluj Basin was used as a model to inform the selection of watershed management activities, feasibility, and costs. For each of the five study areas, activities portfolios were developed using RIOS at five budget levels, corresponding to activities covering 5 percent, 15 percent, 25 percent, 35 percent, and 45 percent of all available lands. For each budget level, we calculated the relative change in the total water yield and sediment that could results from implementation of those activities using the Integrated Valuation of Environmental Services and Tradeoffs (InVEST) models. A comparison was made between outputs of the InVEST water and sediment models for two study areas—Ghanvi and Baspa—to observed records from those sites in order to validate the modeling approach. We found that the models provided reasonable estimates of annual average water yield and sediment loads compared to recorded data, although model limitations imply that results should be interpreted in terms of relative changes only.

In addition, this study included a comparison of the strengths and weaknesses of InVEST and another widely used watershed model, the Soil and Water Assessment Tool (SWAT – developed by the United States Department of Agriculture [USDA] Agricultural Research Service) for hydropower-related ecosystem service valuation. We describe conceptual differences in the models and their data and capacity requirements. We then present a novel framework for combining hydrologic and economic modeling to estimate the value of water quantity and quality to hydropower production at HP facilities, using daily model outputs. Finally, the project includes several components of capacity building, including an initial training with HP government staff, iteration during the analysis phase with key staff in HP, and a final workshop and training to present the results and to build capacity for applying the RIOS and InVEST models locally.

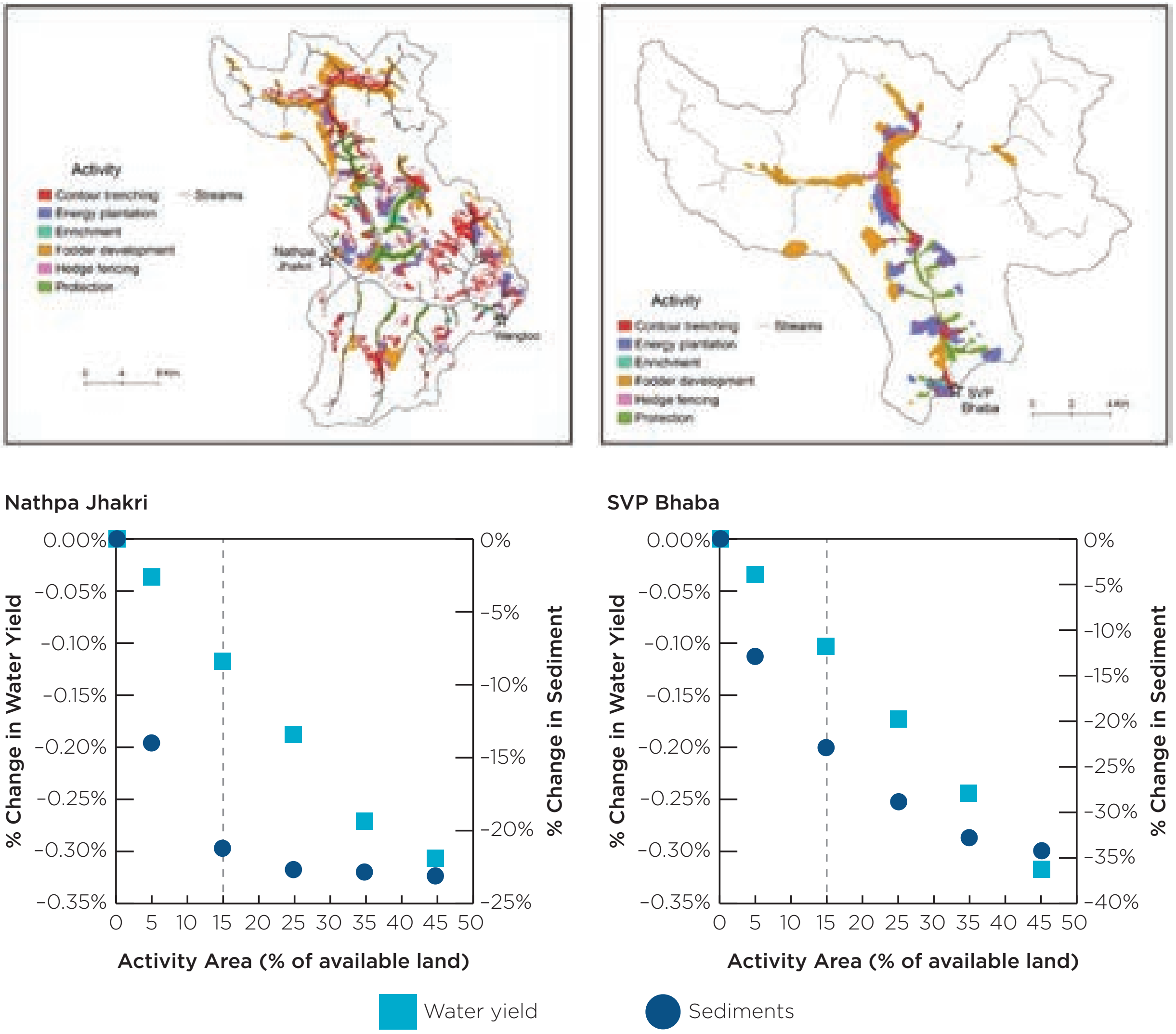
Results

The study areas differed widely in their potential for large-scale improvements from targeted activities. In some areas, such as Baspa and Ghanvi, there was little improvement at the watershed scale in erosion control, because there was little land available to implement activities (in Baspa the majority of land was already in agriculture, and in Ghanvi the majority was designated as healthy forest). In other study areas, such as Nathpa Jhakri and SVP Bhaba, the potential for improving sediment loads to streams is much greater (see Figure 1 below). Although in all cases the model results indicate a small decrease in water yield (on an annual average basis), the decrease is very small (typically <1 percent) and accompanied by significant decreases in sediment loads (up to 44 percent).

It is important to note that these model results show annual averages only. While small decreases in water yield on an annual basis are possible, it is important to understand seasonality of water flow in order to understand impacts on hydropower peak production and value. While the total amount of water yield during a year could decrease due to reforestation, the presence of better forest cover could help to capture water that would otherwise be lost during very wet periods, storing that water and releasing it during the dry season and thereby improving hydropower production during that time. The InVEST annual model is not able to demonstrate these important seasonal impacts that come from improved water storage and regulation capacity in the catchment area.

These results are useful for developing PES policies to target priority areas and setting targets for improvement in outcomes at the watershed scale. However, in order to accurately assign economic value to watershed services relative to run-of-river hydropower facilities common in HP, it is important to consider seasonal changes in water yield and even daily changes in

Figure 1: Recommended activities for two of the study area



Note: Nathpa Jhakri and SVP Bhaba—at a target of 15percent of available land (top). The graphs (bottom) show the change in water yield and sediment that results from implementing the activities across five budget levels, based on results from the InVEST model.

	SWAT	InVEST
Input and calibration data required	High	Med
Number of parameters required	High	Low
Ability to calibrate/validate	High	Low
Model complexity/ physical processes represented	High	Low
Time step	Daily	Annual
Technical capacity required for model set-up, validation and analysis	High	Med
Appropriate application in HP	Ecosystem service valuation	Relative change assessment

sediment loads. The InVEST model is not designed to produce this level of output, therefore another watershed model should be considered to provide detailed estimates of economic value (see Table above).

To address the question of valuation, we develop a framework for the economic valuation of services for the HP hydropower sector based on daily flow and sediment loads. However, we stop short of valuation at this stage, discussing how future work could fill this gap with further development of appropriate biophysical models. For example, SWAT is a complex watershed model that is capable of linking changes in land management with water and sediment in rivers on a daily basis.

Conclusions

If the HP government's plans to develop a system of natural capital accounts and a supporting PES scheme are to succeed, then a rigorous methodology for assessing the value of natural capital and ecosystem services is crucial. Such a method must be able to connect land conversion and land management with consequences for service delivery to different beneficiaries and different sectors. Beyond this longer-term goal, the outcomes of current efforts to implement soil and water conservation activities in HP could improve if activities were targeted at a landscape scale. Landscape level targeting could augment the current approach of identifying and mitigating problems at the local or point scale, providing a larger perspective and potentially reducing the overall cost and time needed to define optimal investment plans.

The work presented in this report demonstrates how biophysical and economic modeling may be combined to bring scientific information into the process of watershed management, and how impacts on the flows of ecosystem services could be quantified and valued for the hydropower sector. For this approach to be most effective, the choice of hydrologic model will be critical and must be driven by the level of detail deemed necessary for economic valuation and the available technical capacity.

Potential future work could incorporate sub-annual hydrologic models, such as SWAT, along with economic data on facilities costs and the price of hydropower, to evaluate returns on investment at a temporal scale appropriate for the run-of-river hydropower facilities common in HP. The valuation could be expressed in terms of the economic impact of improved ecosystem services on hydropower production during low flow season, as well as avoided costs for damage due to excess sediment. Such an analysis could provide a quantitative estimate of ecosystem services value for hydropower that can directly inform the development of natural capital accounts.

Two major challenges to the successful application of this approach in HP are identified:

1. The availability of high-quality, locally-vetted data and sharing of the same. The communication, curation, and integration of data across different departments and sources is needed for technical staff to understand what data are available and where. Continued support for improved data management, curation, and integration into shared data platforms would greatly help to lower this barrier.
2. The need to connect those with the required technical capacity in GIS with people possessing hydrologic and modeling expertise. Connecting the appropriate decision makers within the government departments to these working groups will enable them to interpret and apply the results in a real decision context.

1| Introduction

The state of Himachal Pradesh (HP) is currently developing a payment for ecosystem services (PES) program around ecosystem services that support hydropower production, a major focus for green development. Accounting to value forests and land management for maintaining and improving ecosystem services is also a major goal of the newly emerging system of natural capital accounts in HP. In this context, a well-designed PES scheme requires an understanding of the value of ecosystem services provided by the catchment area for different sectors (in this case hydropower facilities), the distribution of services, and their value in terms of how they contribute to efficient energy production. At the same time, several departments in HP—including forestry, rural development, and agriculture—are engaged in activities aimed at improving the condition of watersheds by implementing soil and water conservation practices.

Ecosystem services assessment can assist this effort by providing critical information to two main applications: identifying priority investment areas for enhancing and maintaining natural capital and ecosystem services; and providing information on value of services to different sectors to inform the development of a system of natural capital accounts.

To date, the focus of soil and water conservation activities undertaken in HP has been primarily to improve conditions at the site scale and reduce erosion and sedimentation into streams. Thus far the targeting and implementation of activities at local scales has not taken into account how these local changes may scale up to impact ecosystem services, nor how these activities in aggregate can contribute to achieving watershed conservation goals at larger scales. In order to develop a more effective PES policy and improve the larger-scale (that is, basinwide) returns from investments in soil and water conservation, it is important to understand how site-level activity impacts can scale up to changes in services delivered to a point of interest, such as a hydropower facility. Biophysical models may be used to identify how changes in landscape configuration impact service delivery.

Our analysis aims to demonstrate a methodology whereby biophysical models are applied to target activities that will ensure optimal ecosystem service returns. In addition, we demonstrate how ecosystem service models can offer estimates of the change in services resulting from ecosystem services targeting, providing the basis for valuation once economic models have been established to translate service flows into value for different sectors. Our methodology addresses PES design (application one above) with a prioritization model and relative impact assessment. To address application two, we develop a framework for the economic valuation of services for the HP hydropower sector. However, we stop short of valuation at this stage, discussing how future work could address this gap by further developing appropriate biophysical models.

Managers are often faced with a question of how best to preserve or enhance the supply of services, whether or not estimates of economic value are achievable. Even in cases in which economic valuation of services is not the immediate goal, it may still be highly desirable to understand where, and in what activities, managers can invest to achieve the greatest return on their investment in terms of improved watershed services. The Resource Investment

Optimization System (RIOS) software tool was developed to address this need by providing a free and open source landscape-level screening model to optimize improvements in ecosystem services from soil and water conservation activities.

With input from the HP Department of Forests, the RIOS model was applied to five hydropower catchments in HP, using activities that are currently included in the HP Catchment Area Treatment (CAT) Plan for the Satluj Basin (NERIL 2011). Portfolios of recommended activities resulting from the RIOS model were then analyzed with the Natural Capital Project's InVEST water yield and sediment retention models. These models quantify the change in services based on a baseline condition and various scenarios of land use and management. An overview of the models used in this analysis is given below, followed by a detailed description of data sources, site selection, and quantitative methods. Finally, we present the results of our analysis, including example activity portfolios for the study areas and results of the ecosystem services assessment.

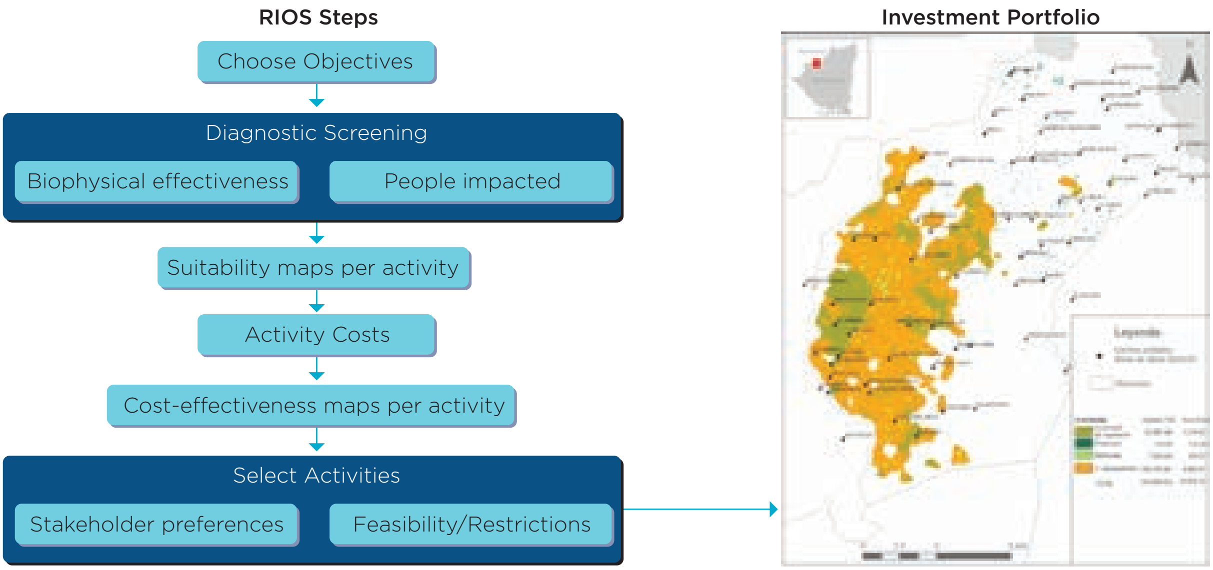
1.1| Overview of Models

RIOS

The RIOS model—developed by the Natural Capital Project and The Nature Conservancy (TNC)—is a software tool that enables more efficient watershed conservation investment design. It helps managers to understand what set of investments will give the greatest ecosystem service returns toward multiple objectives (Vogl et al. 2013). RIOS accomplishes this by combining biophysical information (such as soils, geology, or topography), social information describing feasible land use changes, stakeholder preferences for undertaking those activities, and economic data on their costs, as well as ecological projections of their impacts on different parts of a watershed (Figure 2). For more detailed information on the theory and application of RIOS, see the RIOS User Guide (Vogl et al. 2013).

RIOS can develop investment portfolios that target a range of different water resource objectives, including the following:

Figure 2: The RIOS Investment Portfolio Advisor



Note: The RIOS Investment Portfolio Advisor combines data on biophysical effectiveness, feasible activities, stakeholder preferences, activity costs, and budget to develop a portfolio of cost-effective investments.

- Groundwater recharge enhancement
- Maintenance of base flows
- Sediment retention
- Reduce nutrient loading (nitrogen and phosphorus)
- Flood mitigation
- Biodiversity

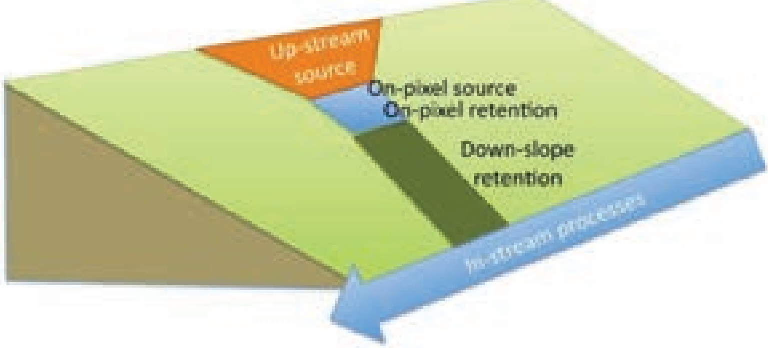
An example of applying RIOS for managing sediment retention in a watershed of the Cauca Valley near Cali, Colombia, shows that the RIOS optimized investment portfolio provided a five-time improved return on investment—as measured by percent sediment retention per cost—compared with an ad-hoc nonoptimized approach to investment planning.

The underlying premise of the RIOS diagnostic screening approach is that a small set of biophysical and ecological factors determine the effectiveness of different conservation strategies in accomplishing different objectives. We defined a set of critical factors for each objective through careful literature review. From a review of experimental studies, review papers, and hydrologic model documentation, we identified the subset of factors that was most frequently identified as important for determining the magnitude of the source and effectiveness of activities that impact erosion control, nutrient retention, groundwater recharge, and so on.

Conditions on the surrounding landscape will determine much of the impact of activities. Therefore, RIOS relies on a set of four major components across its framework that captures the processes influencing these impacts and the effectiveness of activities: upslope source magnitude; on-pixel source; on-pixel retention; and downslope retention. Each component is represented by one or more factors within each objective.

As depicted in Figure 3, RIOS relies on four modeled processes on the landscape that impact the effectiveness of different conservation strategies in achieving objectives. All transitions will be more effective in places downstream of a large upstream source (whether it be sediment, nutrient, or runoff). This is because vegetation can trap more sediment or infiltrate more water if the amount of sediment and flow coming down from upstream is greater. Similarly, greater infiltration or groundwater recharge can happen if more water is flowing to the parcel from uphill. The opposite is true for the downslope condition. Transitions will be more effective when they are placed upstream of an area with low retention or infiltration. Local conditions also determine the effectiveness of activities, such that protecting native vegetation will have the biggest impact in

Figure 3: Four key processes used in the RIOS framework to account for the impact of a landscape change on objectives



places with low on-pixel sources and high on-pixel retention, while revegetation and improved management practices will have the biggest impacts in places with large sources and low retention.

RIOS calculates a score for each pixel on the landscape, indicating how effective an activity is expected to be for improving the desired objective, relative to other places. Factor weights balance the influence of each process on the overall score a pixel receives. The default factor weights in RIOS give equal influence to each process, but users can alter these weights if it is appropriate to the landscape or it suits the management goals. The RIOS tool then combines scores across objectives to give each pixel one score per activity, which reflects its ability to influence all objectives.

The size of the budget or the targets set by the user determine the number and extent of priority areas. The RIOS tool uses biophysical and social data inputs (described in Table 1 below) and calculates scores to identify which investments should be made first for a given budget level. Activity scores are divided by the activity cost to produce an ROI raster for each activity. Once the landscape and feasibility constraints are met, selection of priority areas is entirely driven by return on investment (ROI), where investments are represented by activity costs and returns are determined by relative rankings. RIOS selects priority areas by choosing the highest ROI parcels in order, until the defined budget is spent. The output of this diagnostic screening is the investment portfolio. More information on how RIOS calculates scores and uses budget and feasibility information to produce portfolios may be found in the online RIOS User's Guide (Vogl et al. 2013).

The RIOS approach requires typically readily available data and takes a rather simplified approach to diagnostic screening. However, it provides several important features. A ranking approach allows optimization over multiple objectives. It also identifies good places to invest in for each activity, combining the questions of "what" and "where" to invest. The ranking approach also includes factors that represent landscape context, providing a simple method to include some relatively complex and very important components of hydrological processes. This approach also develops ranks based on the change the water fund is trying to make, not only on the current condition of the watershed. Finally, the diagnostic screening approach in RIOS, though simple, provides considerably more transparency than using more sophisticated, process-based models would do.

RIOS-designed investment portfolios may be analyzed as scenarios of future land use change to determine the likely impacts that they will have on the watershed services of interest. RIOS incorporates the InVEST suite of models to estimate how much benefit one can expect to receive from making the recommended set of investments. If data are available to drive the InVEST economic models, then estimates of benefit can also be in monetary terms—for example, the change in dredging cost for reservoirs resulting from reduced sediment inputs. Because of the modular nature of RIOS, users are not limited to the ecosystem service models packaged with the software. For the current project, we use the InVEST models to estimate the relative change in annual water and sediment loading that could result from portfolio implementation.

InVEST

The Natural Capital Project (www.naturalcapitalproject.org) has developed an approach for valuing ecosystem services delivered from different configurations of land management to specific beneficiaries (such as a hydropower facility). The general approach combines ecological production functions with economic valuation approaches (such as market valuation, avoided costs, and production economics). The approach has been formalized into a free software tool called InVEST—Integrated Valuation of Environmental Services and Tradeoffs (Sharp et al. 2014).

InVEST models account for spatial heterogeneity in both the supply and demand for ecosystem services by modeling three steps in the supply chain from nature to people; supply, service, and value. First, the ecological production function, or the supply side of ecosystem services, is modeled based on biological, physical, geological, and other kinds of inputs, and draws heavily from well-vetted biophysical modeling approaches. The outputs from this step of modeling are in biophysical units and represent the level of supply of the ecosystem service provided by each part of the landscape.

The second step of modeling determines the amount of service actually delivered to specific beneficiaries. This step incorporates socio-economic, management, and other kinds of data on demand for ecosystem services with information on supply, because service is the level of supply that people actually demand in an area. In addition to mapping and quantifying supply and service steps, InVEST can estimate an economic value of services delivered, and these value estimates reflect social preferences for the amount of service delivered.

This study used the InVEST annual water yield and sediment models to estimate the potential impacts of the RIOS-designed portfolios for services relevant to hydropower production. These models are integrated catchment models developed to estimate hydropower ecosystem services and erosion control and produce outputs on an annual time step (Sharp et al. 2014). They predict the integrated catchment response based on large-scale (in both space and time) measurement of catchment characteristics and processes.

The InVEST annual water yield model uses a water balance approach to calculate evaporation and water yield based on the Budyko Curve framework (after Zhang et al. [2004]). The model considers annual average precipitation, soil water storage capacity, rooting depth, plant evapotranspiration rates, and other biophysical inputs. The model applies this calculation for each pixel, looking at the annual balance of precipitation and energy for evapotranspiration adjusted by a storage term. The pixel-level results reflect the spatial variability in land cover and management, and then the results are aggregated by sub-watershed to represent the integrated catchment response.

The InVEST annual sediment retention model uses the Universal Soil Loss Equation (USLE) and an iterative soil trapping scheme to estimate the amount of soil eroded from each pixel and the amount of sediment trapped by vegetation on each pixel. The USLE is a widely used, empirically-based model for erosion losses based on erosion experiments run in the United States. The method incorporates information on soil properties, land cover, and management to calculate soil loss on a per-pixel basis. The USLE provides an estimate of the erosion that occurs on a parcel of land. The model then implements an iterative soil trapping scheme to estimate the amount of soil trapped by vegetation downstream of soil erosion. The sediment is iteratively routed from the upstream-most pixels, with sediment coming from upstream pixels being trapped at a given efficiency rate, and the sediment going down-route being the combination of that sediment that is not trapped at an individual pixel and the sediment eroded from that pixel.

Both the InVEST water yield and sediment models also include several valuation steps. After the calculation of water yield, a hydropower valuation model can be applied to the water yield results. First water consumed upstream of the dam is subtracted from the water yield. Then the power produced is calculated based on an average annual flow rate and an average head drop across the turbine (supplied by the user), which is then adjusted by efficiencies of the turbine. The sediment model includes two options for valuation: one for water quality excluding sediment under an annual-accepted load and the other for avoided dredging for reservoirs excluding amounts that fill the engineered dead volume. Note that the valuation functions in the InVEST models were not applied in the current study.

See Appendix C and the model documentation (Sharp et al. 2014) for additional details on the InVEST models used in this study.

1.2| Data Acquisition

The initial phase of work began with the project team reviewing the available data. Much of these data were collected from local and national government agencies and academic institutions during and after a two-week visit to Shimla in June 2013. During this time, we obtained forest-related data from the HP Department of Forestry, hydropower site locations from the HP Directorate of Energy, land cover, soil, DEM and a variety of other layers from the Department of the Environment, microwatersheds from AGiSAC, and some observed discharge data from the Irrigation and Public Health Department. Mr.

Hemant Gupta (HP Forest Department) also arranged meetings with several people who provided additional background information about some of these layers (such as soil depth and land cover classes). We have been unsuccessful in our attempts to contact someone at the Department of Agriculture who could discuss local farming practices to assist with parameterizing land cover-based inputs, and observed data for validation and economic valuation are not available in some areas (Table 1).

Where local or national data were not available (either to be used as model inputs or to guide model parameterization), global databases and datasets were used. See Table 1 for a listing of data requirements for the InVEST and RIOS models, sources, and status of availability. Some data layers, such as soils, are available for Himachal Pradesh only in a form that is not optimal for modeling purposes, as they lack sufficient detail on measured soil characteristics. The information provided in these layers has been used to estimate necessary model parameters and the resulting parameters are provided in Appendix A. For climate inputs, precipitation data from the India Meteorological Department (IMD) were first considered for use. However, the available weather stations do not provide adequate coverage over the area of interest, having particularly poor coverage in higher elevation areas, and the associated high cost made this option less then optimal. Instead, we chose to use WorldClim, which incorporates major climate databases (including data made available by IMD), along with latitude, longitude, and elevation information to create interpolated global monthly precipitation grids that cover the entirety of our study areas and elevation ranges. These monthly grids were used to create the annual precipitation, actual and potential evapotranspiration, and rainfall erosivity model inputs.

Site Selection

During the data collection phase and initial visits to HP, we had multiple discussions with government staff to identify candidate study areas for application of our modeling approach. Through discussions concerning such factors as regional significance, hydropower significance, environmental and social variability, and data availability, our goal was to select locations important to current or future hydropower production and with adequate data to support our modeling efforts. We will also aimed to identify a suite of watersheds that capture a representative range of biophysical conditions (for example, high to low rainfall, steep to flat elevation, deep to shallow soils, and high to low temperatures) and social conditions (for example, a range of land uses such as urban, intensively farmed, small plot farms, natural areas, private and publicly owned lands, and low to high income areas). By doing so, we could be more confident that the suite of case study watersheds reflects the full range of conditions occurring in the state. In the end, the most important considerations for site selection turned out to be the importance of the facilities for power production and the availability of data that can inform our analysis.

After our initial visits to HP, the team reviewed the available data and narrowed down the selection to six candidate hydropower facilities and their associated catchment areas: Baspa II, Chaba, Sumej, Ghanvi I, SVP Bhaba, and the Nathpa Jhakri catchment area downstream of Wangtoo. The Sumej site was initially considered as a candidate site, but later it was determined that the catchment area is too small and there is not enough heterogeneity in land use, soils, and climate (at the resolution of available data) for our modeling approach to be informative there. Therefore, the current study will develop portfolios of priority investments and relative change in ecosystem services for the following hydropower facilities:

- Baspa II
- Chaba
- Ghanvi I
- SVP Bhaba
- Nathpa Jhakri catchment area (downstream of Wangtoo only)

Data Summary

Table 1 summarizes the data required to run the RIOS and InVEST water yield and sediment retention models in the four selected watersheds. These data allow priority areas to be identified for watershed investments that reduce erosion and improve seasonal flows to streams. In addition to geographic information, RIOS also requires socioeconomic data about feasible activities and budget allocations that are required inputs for the RIOS model to create realistic plans for watershed management interventions. Ideally, this information would be gathered in a stakeholder workshop in which local and regional authorities, landowners, and other experts are surveyed about the budgets available for soil and water conservation activities, which activities are feasible, how much they cost, and any preferences or restrictions on activities or where they can be implemented. For the current study, these inputs are derived from a review of the Satluj and Luhri Basin's Catchment Area Treatment (CAT) Plans (NERIL 2011) and from discussions with officials and experts during the data collection phase.

See Appendix A for maps of these data for the study watersheds, as well as details on nonspatial parameter data assigned for each land cover/land use class.

Figure 4 shows a schematic of how the data listed in Table 1 are included in the RIOS modeling process at each step.

Nonspatial data and assumptions

The following activities were chosen for use in the RIOS modeling, based on review of the Catchment Area Treatment Plan for the Satluj Basin (NERIL 2011) and from discussions with HP staff. Activity descriptions are taken from the CAT Plan. Assumptions about where the activities are allowed (based on the land use classification map) and costs are given in Table 2.

Energy plantation

Energy plantation schemes are essential in large scale for a continuous supply of fuel. Agricultural land should not be used for energy plantation. Instead, nonagricultural land, farm

Table 1: Summary of Data and Sources for Modeling

Data Layer	Source
Digital Elevation Model	USGS/NASA ASTER Global DEM (30m resolution)
Land Use/Land Cover	Soil and Land Use Survey of India (30m resolution)
Precipitation (monthly)	WorldClim (1km resolution)
Potential Evapotranspiration	Derived from WorldClim monthly precipitation, using the Modified Hargreaves Process (1km resolution)
Rainfall Erosivity	Estimated using WorldClim annual precipitation and annual erosivity equation for India from Singh et al. 1981
Soil Depth	Estimated from the Soil and Land Use Survey of India using class values from M.K. Gupta (pers. communication)
Soil Erodibility	Estimated from the Soil and Land Use Survey of India using Stewart et al. 1975 Erodibility factor mapping table
Soil Available Water Content	Estimated from the Soil and Land Use Survey of India using the USDA's Hydraulic Properties Calculator
Soil Texture	Estimated from the Soil and Land Use Survey of India using mappings from USDA texture classes to Laybe Run-Off coefficients
Hydropower Plant Locations	HP Directorate of Energy/AGiSAC
Hydropower Plant Watersheds	Created in GIS from Hydropower plant locations
Microwatersheds	AGiSAC
Village Locations and Population	Department of Census, Himachal Pradesh, 2001 census population data
Baseflow LULC Coefficients	RIOS general coefficients (global averages)
Sediment USLE C Coefficient	Average of several USLE studies in India, SWAT default values, NatCap database global averages, Wischmeier and Smith 1978
Sediment USLE P Coefficient	Tirkey et al. 2013; Wischmeier and Smith 1978
Water Yield Evapotranspiration Coefficient	Derived from AET/PET, averaged over each LULC
Water Yield Root Depth Coefficient	Schenk and Jackson 2002 and SWAT default values
Socioeconomic Data Required	
Restoration Activities to Consider	CAT report for Satluj, Luhri

(*continued on next page*)

Table 1: Summary of Data and Sources for Modeling *(continued)*

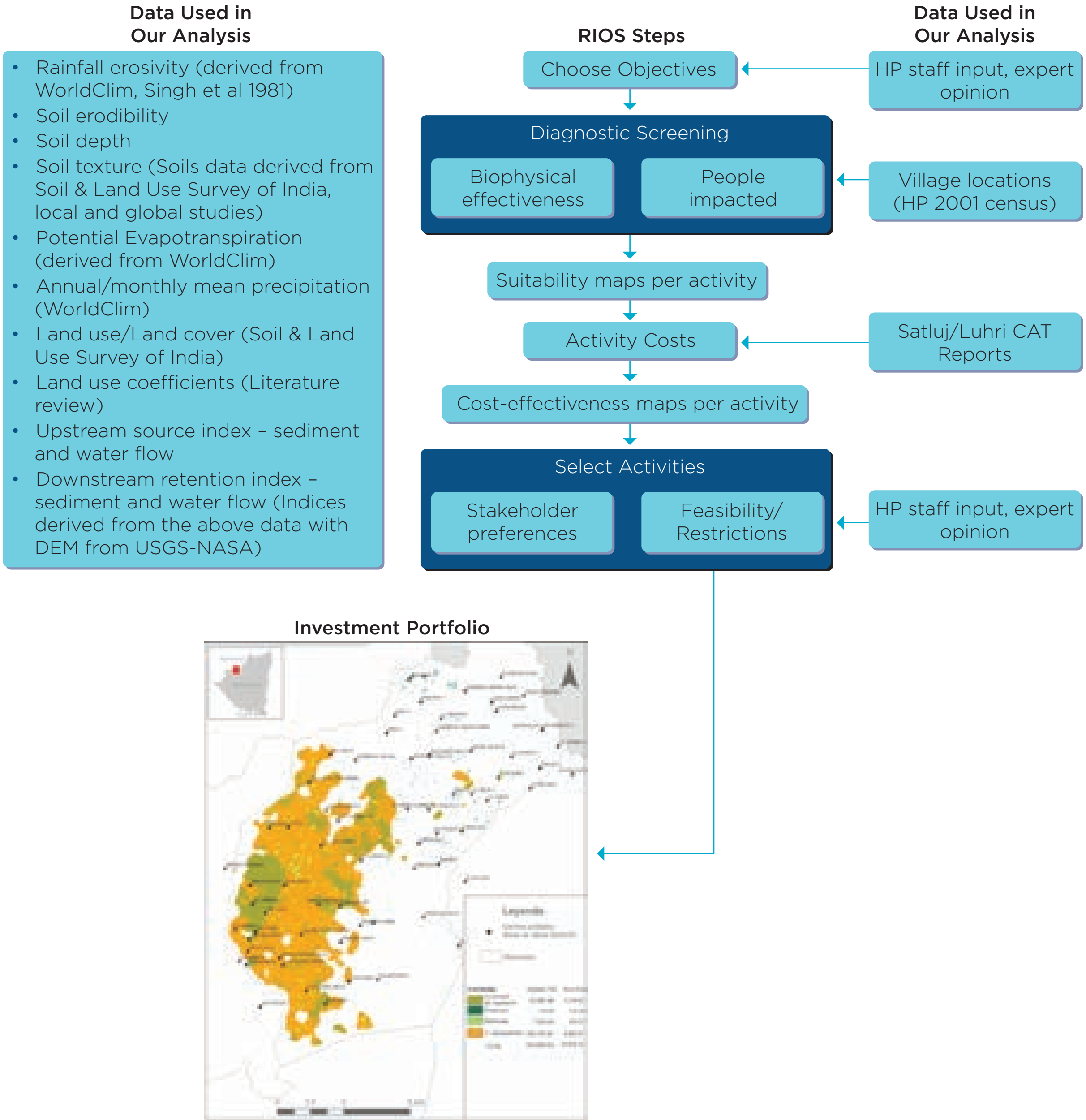
Data Layer	Source
Restoration Activity Costs	CAT reports for Satluj, Luhri
Budget Amount and Allocation	CAT reports for Satluj (will test a range of budgets)
Feasibility/ Restrictions	HP staff input (Mr. Anil Vaidya, pers. communication), expert opinion
Activity Preference Areas (Optional)	Not used in this study
Data Required for Economic Valuation	
Water Consumption (Annual Average)	Not available
Hydropower Facility Information	These data have been provided by the Directorate of Energy. *Specific data required:* • Turbine efficiency • Average head • Annual facility operating costs • Number of days per year shut down because of high sediment levels, plus the recorded sediment levels on the shut-down days (incomplete) • Threshold sediment level for safe operation of facilities • Average hydropower price (daily/annually—incomplete) • Remaining life of facility • Cost of existing investments in sediment abatement technologies (special coatings, settling ponds. and so on—incomplete)
Data Required for Model Validation	
Observed Stream Flow and Sediment Concentration	Daily discharge data: • Baspa II 2005–2013 • Ghanvi I 2003–2013 • SVP Bhaba (not available) • Nathpa Jhakri/Wangtoo 2005 – Nov 2009 Daily silt data: • Baspa II 2008–2013 • Ghanvi 2003–2013 • SVP Bhaba (not available) • Nathpa Jhakri/Wangtoo 2000–2013

wasteland, any land used for general purposes in the village, land on either side of nallas and roads, infertile forest lands, and waste lands are used for energy plantation.

Enrichment

The primary objective is to rehabilitate degraded forests, which improves, restores, and maintains the stock of desired species in the degraded forest areas, where natural regeneration is deficient or absent. Indigenous species or plants growing under similar habitat condition are preferred. A protective plantation in the form of the three-tier combination of grasses, shrubs, and trees is

Figure 4: Schematic of the RIOS model process



Note: Schematic of the RIOS model process and how the data collected to date will be leveraged to complete the analysis of priority areas for watershed protection activities that benefit hydropower production.

proposed. This keeps a check on soil erosion occurring because of tree felling and flowing water. This simultaneously promotes in-situ moisture conservation, improves soil fertility, increases productivity, and conserves biodiversity.

Fodder development

To reduce the dependency upon forests for fodder, such measures as the development and improvement of grazing lands by planting fodder species, seeds sowing of fodder grasses, eradication of weeds, and other measures are suggested. These conservation measures are area specific, need based, and unique for each microwatershed. Maximum importance is given to bio-engineering measures, which involve the use of local grasses, shrubs, and trees.

Table 2. Activity costs and land classes where they may be considered

Land Cover/ Management Type	Activity (cost in Rs/ha)					
	Energy Plantation (138,000)	Enrichment (35,000)	Contour Trenching (90)	Live Hedge Fencing (960)	Fodder Development (27,000)	Protection (unknown)
Evergreen/ Semi-green Forest						Yes
Degraded Forest/Scrub Land	Yes	Yes	Yes (<65% slope)	Yes (≤30% slope)		
Land With or Without Scrub	Yes		Yes (<65% slope)	Yes (≤30% slope)	Yes	
Grass Land/ Grazing Land					Yes	
Gullied or Ravine Land						
Plantation						
Kharif						
Double Crop (K+R)						
Barren Rocky/ Stony Waste/ Sheet Rock Area						
Snow Covered/ Glacial Area						

Contour trenching

To improve the soil and moisture conservation in forests, contour trenches of size 1x 0.3x 0.3m are prescribed, keeping in view the slope, aspect, and moisture regime of the microwatershed. This method can be adopted in low rainfall area to high rainfall area up to 3200mm and from flat area to hilly area with up to 65 percent steep slope.

Live hedge fencing

Live hedge fencing is the use of live woody species, mostly shrubs, along with fence or on blank areas. It is usually in the form of densely planted shrubs. A quickset hedge is a type of hedge created by planting live, local, woody, thorny shrub cuttings, directly into the earth. Once planted, these cuttings root and form new plants, creating a dense barrier. Live hedge fencing can be done in lower hills where slopes are gentle and soil is not rocky. In this application, “gentle” slope was assumed to mean less than 30 percent slope. This number was derived by calculating the bottom quartile (25 percent) of slopes across the study area.

Protection

This activity is not prescribed in the CAT plan, but is included in RIOS modeling to represent situations in which protecting forests that are currently in good condition (not degraded) can benefit the provision of ecosystem services.

The following activities from the Satluj CAT Plan were ***not included*** in the RIOS modeling:

Brushwood check dams

Brushwood check dams are made up of posts in single or double rows and then brushwood is placed across the gully. The main objective of brushwood check dams is to hold fine material, carried by flowing water in the gully. Small gully heads, no deeper than one meter, can be stabilized by brushwood check dams. They are temporary structures and should not be used to treat ongoing problems, such as concentrated run-off from roads or cultivated fields. They are employed in connection with land use changes, such as reforestation or improved range management, until vegetative and slope treatment measures become effective.

Because the measures are applied at a very fine scale and are temporary, they are incompatible with the scale of RIOS application. In RIOS, the input data are at a 30x30m or greater resolution and the tool considers long-term changes in land cover and management. Furthermore, as check dams are applied as a best practice measure along with afforestation and fodder development, it is assumed that these would be utilized as necessary when these other two types of activities are recommended.

Civil structures

Engineering structures (that is, check dams, retaining walls, and others) are not considered in the RIOS modeling. The siting of these activities is based on highly localized conditions and engineering specifications that are outside the scope of this model.

1.3| Model Validation and Uncertainty Assessment

Overview

In this study, we use the InVEST water yield and sediment retention models to assess the potential change in ecosystem services resulting from the recommended watershed activities. Because the models produce long-term annual average outputs, calibration of model outputs to a time series is not possible. Comparison of model outputs against observed data is an important step to establish the accuracy of the results, quantify the uncertainty surrounding model inputs and parameters, and determine the best parameter values to use in future steps. Even without calibration against observational data, the model may be useful for understanding the relative change in service that can result from different management decisions and enable comparisons between alternative strategies.

In this section, we apply the InVEST water yield and sediment loading models to the Ghanvi and Baspa catchment study areas. These two catchments were chosen for two reasons: they had sufficient flow and sediment data readily available to support the analysis; and they represent complete catchment areas and so are hydrologically complete. Data on observed flow and sediment levels are not available for two of the other catchments (Sumej and Chaba), and the Nathpa Jhakri catchment below Wangtoo is not hydrologically complete, complicating the uncertainty assessment because uncertainty in inputs from the catchment area above Wangtoo would need to be quantified. Spatial data were not collected for the main Satluj River above Wangtoo. Therefore, model uncertainty is presented for the Ghanvi and Baspa catchments to give a sense of the general model performance and applicability in HP.

Model results are compared to observed flow and sediment data measured at the catchment outlets in order to validate the models' applicability in the study region. Uncertainty surrounding input data and parameter estimation are discussed, together with their implications in the context of model validation and uncertainty assessment.

For both the water yield and sediment models, we organize the analyses as follows:

- Summary of available data
- Model adaptation to glacier and snow-covered areas
- Sensitivity analyses and errors in input parameters
- Validation of the model results

Water Yield Model

Table 3 summarizes the available data used in our uncertainty assessment.

Model adaptation

The InVEST water yield model (Sharp et al. 2014) was not initially developed for landscapes with extensive snow-cover or glaciers. However, with reasonable assumptions it is possible to represent this particular landscape and validate the use of the model for estimating the water yield in areas partially covered by snow or glacier.

Table 3. Summary of water yield model inputs and their values (ranges for the raster data are the spatial minima and maxima)

Input	Type	Source[a]	Values	Estimated Error
Precipitation	Raster	WorldClim	G: [635; 1940] mm B: [597; 1014] mm	+/-10%, homogeneous
Reference Evapotrans-piration	Raster	WorldClim and Modified Hargreaves	G: [461; 911] mm B: [308; 869] mm	+/-10%, homogeneous
Depth to Root Restricting Layer	Raster	Soil and Land Use Survey of India	G: [100; 880] mm B: [0; 750] mm	[b]
PAWC	Raster	Soil and Land Use Survey of India	G: [0.02; 0.1] B: [0; 0.09]	[b]
K_C (Forest)	Coeff (LULC)	FAO 56	G and B: [1]	+/-20%,
K_C (Barren)	Coeff (LULC)	FAO 56	G and B: [0.3]	+/-20%,
K_C (Scrubland)	Coeff (LULC)	FAO 56	G and B: [0.6]	+/-20%,

(*continued on next page*)

Table 3. Summary of water yield model inputs and their values (ranges for the raster data are the spatial minima and maxima) *(continued)*

Input	Type	Source[a]	Values	Estimated Error
K_c (Snow/glacier)	Coeff (LULC)	Derived from AET/PET values from literature on glacier (see section below)	G and B: [0.2]	+/–50%,
Root Depths	Coeff (LULC)	Schenk and Jackson, 2002 and SWAT default values	G and B: [1; 2000] mm	[b]
Z	Decimal	InVEST User's Guide	5	Range [1; 25]
Observed Flow	Time series	Directorate of Energy, HP	Mean: G: 1598 mm/y B: 1190 mm/y	[b] +/–20%

Note: errors on LULC and DEM are not considered in this summary table.
Estimated errors are examined for their impact on model outputs relative to observed data (see details of error sources in section on sensitivity analyses). "G" and "B" stand for Ghanvi and Baspa watersheds, respectively.
[a] See main report for details on sources and data processing.
[b] Errors are not studied in the sensitivity analyses.

The modeling approach relies on a simple water balance of the snow-covered or glacier areas at an annual time scale. We assume that the water yield from these areas is given by:

$$Y = P - E + M,$$

where Y is water yield, P is precipitation (rainfall), E is evapotranspiration, and M is glacier and snowmelt, all expressed in mm.

Annual rainfall precipitation is obtained from the WorldClim database (Hijmans et al. 2005). Significant knowledge gaps remain around the partitioning of rainfall between evaporation and percolation in cold climate (Berthier et al. 2007). Evaporation strongly depends on the surface cover, either bare ice or covered with debris (Kayastha 2000). Much finer temporal and spatial data, added to field knowledge, would thus be needed to refine the evaporation estimate. Since this is beyond the scope of this study, we favor a simple partitioning based on a study by Sakai et al. (2003), which suggests that 25 percent of the rain is evaporated during the melting season. Since evaporation is negligible over the cold months, we assume an average evaporation of 20 percent (+/–10 percent) annually.

The contribution of glacier and snow-covered area to the water yield is generally obtained by mass balance, since direct measurements of snowfall are rare in the area (Singh and Jain 2002). Glacier melt alone is a significant component of the water balance, as suggested by the State of the Environment Report on Himachal Pradesh (2009). For example, in the Baspa Basin, stream runoff has increased by 75 percent during the last 30 years because of glacier retreat. According to one of the most comprehensive study undertaken in the area (Berthier et al. 2007), the mass balance of glaciers approximates 800 mm/year, which represents a significant contribution to the water yield.

However, quantifying the additional contribution of snow to the water yield is challenging in our study because of the lack of detailed data on the extent of snow-covered area, inter- and intra-annual variations in the same, and measured snowfall depths. Further investigations should be conducted to estimate the intra-annual variation in snow cover, typically between March/April (maximum cover) and September/October (minimum cover). Since this option, which relies on analysis of satellite imagery at different times of the year, was outside the scope of the analyses, we used the findings from Singh and Jain (2002) to estimate the *total* glacier and snowmelt contribution. In the Sutlej Basin, the researchers reported an annual contribution from snow and glacier melt of 60 percent of the total water yield (or 300 mm from the whole basin). Since the Sutlej Basin contains the Ghanvi and Baspa catchments and presents a similar land cover distribution (snow covered area averaging 43 percent, compared to 44 percent in Ghanvi, and 65 percent in Baspa), it constitutes a relevant reference for our study. Other studies confirm these estimates, reporting a contribution of snow and glacial melt ranging from 35 to 60 percent of streamflow (Kumar et al. 2007; Singh et al. 2000).

Practical implementation

The InVEST model allows the actual evapotranspiration to be set as an input for any LULC (in practice, this is done by setting the parameter LULC veg to 0 and Kc to the ratio between actual and reference evapotranspiration). Based on the study by Sakai et al. (2003), we simply set K_c-glacier to 0.2. K_c for the snow-free forest land use class is set to 1, following the literature on the energy-water balance (Zhang et al. 2001).

As detailed above, glacier and snow melt are assumed to contribute 60 percent of total flow. The InVEST water yield model provides an estimate of streamflow that is 40 percent of predicted value when the precipitation (rainfall) input is used without considering snowfall. This allows estimating the volume contributed by the snow and glacier melt, normalized by area (value in mm). For spatial representation, a raster with glacier and snow melt can be overlaid to the InVEST map of water yield (the sum of which provides a spatial representation of total water yield). The value of the raster is set to the modeled melt, in mm, for glacier areas and 0 for other areas. The modeled glacier and snow melt M, in mm, is:

$$M = 0.6\ Y \frac{A_{tot}}{A_g},$$

where Y (mm) is the water yield predicted by the InVEST model (excluding snow and glacier melt), and (km^2) is the catchment area and (km^2) is the glacier LULC area.

Methodological notes

The main assumptions in our approach are summarized as follows:

- The LULC's map is static and supposedly accounts for the intra-annual and inter-annual variation of snow covered areas, that is, it represents an average condition across multiple years. In our approach, inter-annual variations resulting from glacier retreat are captured in the glacier melt component. Intra-annual variations are captured through the evaporation coefficient (Kc) that accounts for larger evaporation from snow-free areas during summer.
- Precipitation is rainfall only (from WorldClim's weather station network). Most of the rainfall occurs during July-August (Singh and Jain 2002) and contributes to snow melt.
- Snow and glacier melt are subject to large uncertainties: in particular, the context of climate change makes it difficult to make long-term assessments, since the glacier melt component of the water balance is largely unknown. The value of glacier melt derived by Berthier et al.

(2007) for the 1999–2004 period can be used as a reference, but it does not include the contribution of snowmelt in nonglacier areas.

Finally, we note that with additional data an alternative method could be used relying on a simple water/energy balance. The method consists of three steps: estimating the annual amount of precipitation as snow from the literature; calculating the average annual snowmelt from the daily time series of temperature (DDF, or Degree-Day-Factor approach) (Hock 2003); deriving the annual water yield, as the sum of snow melt and rainfall minus the snowfall. This approach accounts for glacier melt since the DDF can be applied to ice areas. However this method does not allow for an examination of spatial variation in the land cover and management characteristics that may contribute to spatial variations in water yield from different areas of the catchment.

Sensitivity analyses and errors in input parameters

The estimate of the total annual flow strongly relies on the assumptions of glacier and snow melt contribution. However, in our situation, we performed simple sensitivity analyses of the InVEST model, aiming to estimate the uncertainties on the rainfall contribution to flow.

Following Sanchez-Canales et al. (in review), we limited the sensitivity analyses to the following inputs: precipitation (P), potential evapotranspiration (PET), Z coefficient, and the crop coefficients K_c for the dominant LULC. Estimates of uncertainty bounds for each input are given below and in Table 3:

- For P and PET, the errors were estimated from a study by Hijmans et al. (2005), which provided an order of magnitudes for precipitation and temperature errors in the WorldClim dataset.
- For the Z coefficient, capturing the local precipitation pattern and additional hydrogeological characteristics, we acknowledged the large uncertainties present in the literature (Sharp et al. 2014) and assumed a possible range from 1 to 25.
- For K_c, we only investigated the dominant land use classes within each study watershed. For Ghanvi, forest and snow/glacier dominate the watershed (50 percent and 44 percent, respectively). For Baspa, scrubland, barren, and snow/glacier dominate the watershed (13 percent, 12 percent, and 65 percent, respectively).
- Errors for forest and scrubland/barren were estimated from studies that assess evapotranspiration (McMahon et al. 2013), while the errors in the snow-covered/glacier were derived from the evapotranspiration methodology (see Model Adaptation section above).

Based on these assumptions, we ran one-at-a-time sensitivity analyses by varying these inputs within the error bounds defined above. Intermediate values between the baseline and the upper/lower bounds were added to better assess the shape of the relationship (for example, if the upper bound was 50 percent higher than the baseline, an additional run was done with the value 25 percent higher than the baseline).

Figure 5 confirms the monotonic relationship between model outputs and input parameters that is expected given the equations governing the model. This result simplifies the uncertainty estimates, with the extreme (minimum and maximum) scenarios being developed from extreme parameter values.

Validation

Based on the above analyses, we computed the total water yield for the baseline scenario and the upper and lower bound analyses (Figure 6). As indicated in the Model Adaptation

Figure 5: Sensitivity analyses conducted for the water yield model for Ghanvi and Baspa

a) Ghanvi

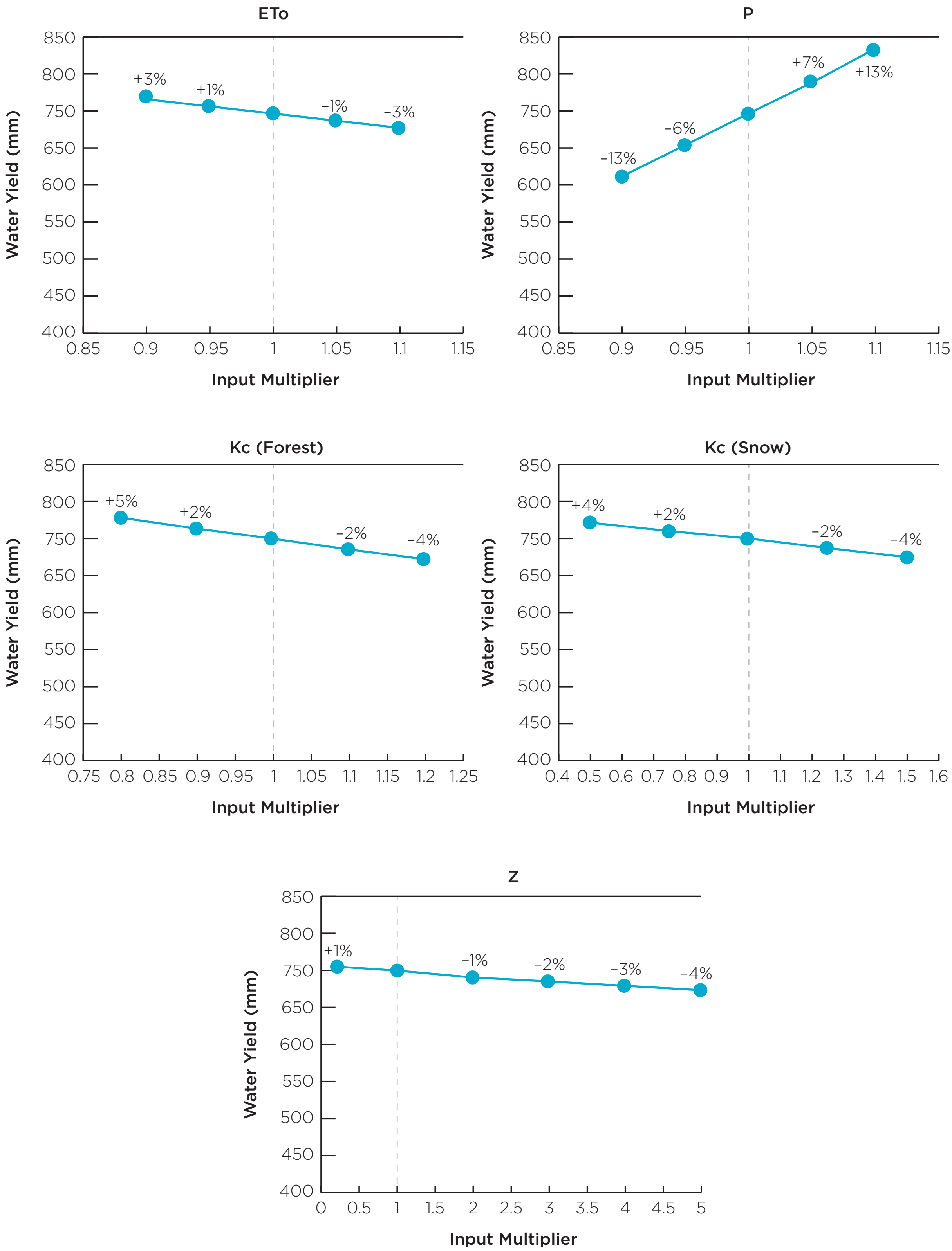


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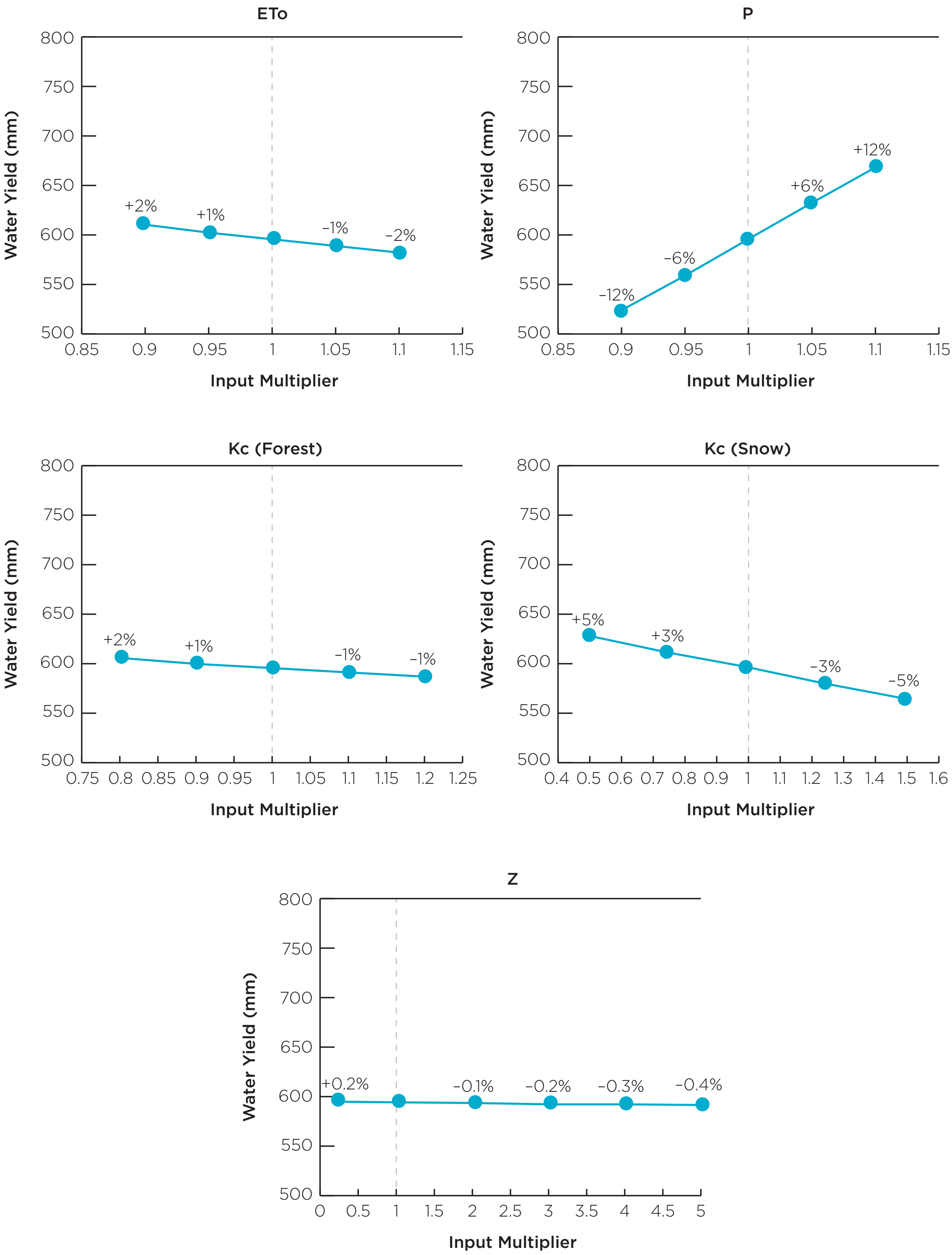
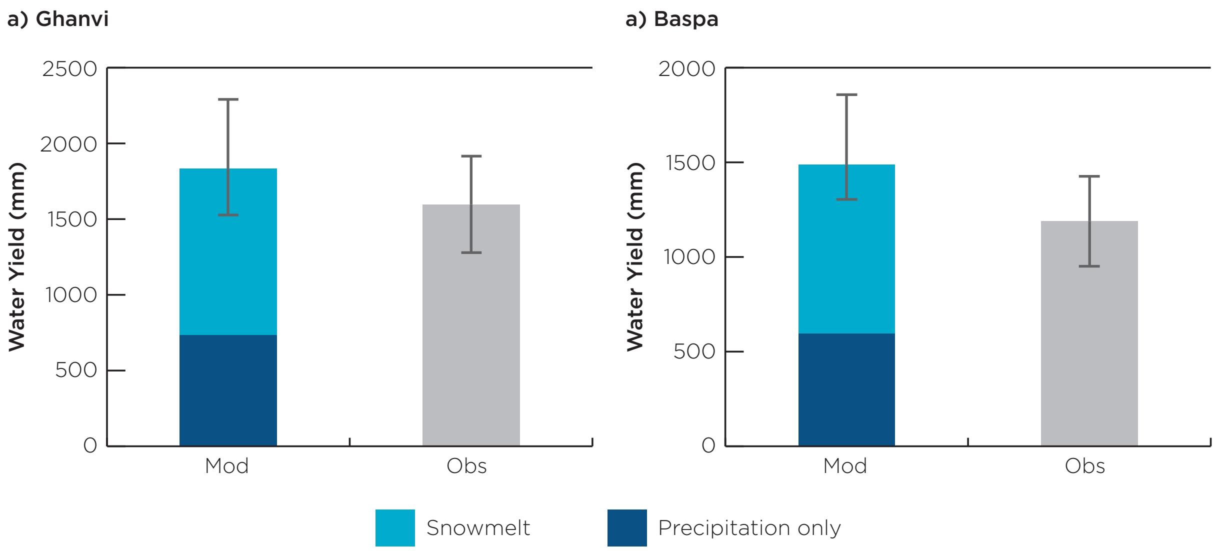
Figure 5: Sensitivity analyses conducted for the water yield model for Ghanvi and Baspa *(continued)*

b) Baspa



Note: On the X axis, 1 represents the baseline parameter value, and the percentages noted above represent changes compared to the baseline.

Figure 6: Comparison of observed water yield and modeled water yield for Ghanvi and Baspa



Note: Error bars are 20 percent for the measurement errors (observed data), and 20 percent of the snowmelt contribution for the modeled values. Uncertainties around the InVEST modeled value (precipitation contribution only) are not represented here.

section, these values were then divided by 0.4 to represent the additional contribution of glacier and snowmelt, which comprise 60 percent of total yield. Uncertainties around the contribution of glacier and snowmelt were estimated around 20 percent based on the cited literature.

Comparison of the simulated and observed water yield for the two catchments shows that the model performs reasonably well, predicting a range of 1,322 to 2,284 mm/yr for Ghanvi and a range of 1,306 to 1,670 mm/yr for Baspa, compared to an observed average of 1,598 and 1,190 mm/yr for Ghanvi and Baspa, respectively. This implies that the model, modified in this way to include estimates of glacial melt and snowfall, is capable of predicting the contribution of land management to direct runoff on an average annual basis. The model performs better in the Ghanvi catchment than in the Baspa catchment, which is likely because there is less area in the snow/glacier LULC in Ghanvi. This makes sense given that the basic InVEST model formulations lack algorithms to estimate glacial melt; our estimate of 60 percent contribution to annual yield is based on a study where 43 percent of the area is covered in snow/glacier, as well as the lack of observations of glacial melt in two study catchments on which to calibrate that portion of our estimate. It follows that this approach will likely perform better in areas with lower glacial coverage (for example, ≤ 44 percent).

Sediment Model

Table 4 gives a summary of the available data used in our uncertainty assessment.

Model adaptation

Sediment production and transport in the Himalayas remains poorly understood, with researchers noting large uncertainties in both modeled and observed loads (Chakrapani and Saini 2009; Singh et al. 2008). One major challenge is that traditional erosion models were not developed to represent glacier areas and monsoonal climate. For example, models based on the Universal Soil Loss Equation (USLE), such as InVEST (Revised USLE) or SWAT (modified USLE),

Table 4: Summary of sediment model inputs (ranges for the raster data are the spatial minima and maxima)

Input	Type	Source[a]	Values	Uncertainty Bound
Erosivity	Raster	WorldClim annual precipitation and equation from (Singh et al. 1981)	G: [310; 783] mt ha.cm^{-1} B: [296; 447] mt ha.cm^{-1}	+/−30%, homogeneous
Erodibility	Raster	Soil and Land Use Survey of India	G: [0.02; 0.29] t ha^{-1} per unit R B: [0; 19]	+/−30%, homogeneous
C Factor (USLE)	Coeff (LULC)	Average of several USLE studies in India, SWAT default values	Forest: 0.012 Glacier/snow: 0.001 Scrub: 0.22 Barren: 0.5	+1000% for Forest +/−50% for Scrub or barren
P Factor (USLE)	Coeff (LULC)	Tirkey et al. 2013; Wischmeier and Smith, 1978	Forest: 1 Glacier/snow: 1 Scrub and barren: 1	[b]
Threshold Flow	Constant	Calibrated with streamflow map	2000	[b]
Slope Threshold	Constant		75	[b]
Observed TSS	Time series	Directorate of Energy, HP	Mean (modeled): G: 222,935 ton/yr B: 800,694 ton/yr	[b] +/−1 SD

Note: errors on LULC and DEM are not considered in this summary table.
Estimated errors are examined for their impact on model outputs relative to observed data (see details of error sources in section on sensitivity analyses). "G" and "B" stand for Ghanvi and Baspa watersheds, respectively.
[a] See main report for details on sources and data processing.
[b] Errors are not studied in the sensitivity analyses.

can only represent the sediments contributed by sheet flow erosion. However, the contribution of debris flows or landslides, either natural or induced by road construction activities, to observed suspended solids is significant, likely much larger than that from other sediment sources (Chakrapani and Saini 2009).

In general, much finer temporal analyses would be necessary to estimate the contribution from landslides resulting from individual rain events. This also holds for the annual contribution from areas covered with snow in winter, which remains uncertain. As noted in the water yield model section above, only a static LULC map was available in this project, such that analyses of temporal variations are limited.

In light of these caveats, we run the sediment model in its standard version and focus on sheet flow erosion only. By doing this, we acknowledge the large uncertainties that remain in sediment modeling and focus on the processes most significantly affected by land use change in existing vegetated areas. The larger proportion of mass erosion (for example, from landslides) is a distinct issue that is outside the scope of this study. Our approach comprises a thorough analysis of parameter uncertainties, estimating the contribution of sheet flow erosion to the total sediment load.

Sensitivity analyses and errors in input parameters

As suggested by Sanchez-Canales et al. (in review), we focus the sensitivity analyses on the following inputs: erodibility (E), erosivity (R), and the C, P factors of the USLE for the dominant LULC in each study catchment (see the Water Yield – Sensitivity Analyses section for a detail of these LULCs). Estimates of uncertainty bounds for each input are given below and in Table 4:

- For E and R, very few data are available in the literature. Most researchers working in that area use values developed in the 1980s by Singh et al. (for example, Kumar and Kushwaha 2013) and do not explicitly provide uncertainty bounds. Based on the large uncertainties reported on the USLE, we assume an error of 30 percent: this assumption has a minimum impact on the results since the model responds linearly to a change in these factors (see below).
- For the C factor in the forest LULC, we analyzed the typical values from the literature (for example, Kumar and Kushwaha 2013) to estimate an upper bound: in fact, our initial estimate assumes a dense forest (C=0.012), whereas it is possible that some patches are less dense (C=0.08) or even open (C=0.4); for scrubland and barren LULCs, we chose arbitrarily 50 percent to reflect typical uncertainties related to the RUSLE theory. The negligible value of C for snow/glacier was not varied since it forms part of the modeling hypotheses (that is, this LULC does not contribute to sheetwash erosion but it will contribute to mass erosion, addressed separately).
- P factors were not investigated since management practices are not the focus of this study, where nonmanaged land use dominates (P value are set to 1 for these LULCs).

Our sensitivity analyses confirmed the results from the study by Sanchez-Canales et al. (in review), being that sediment exports respond linearly to changes in E and R, with a coefficient 1. In other words, a 50 percent error in one of these parameters resulted in a 50 percent error in the modeled load. In addition, the response to changes in C factors is monotonous with a ratio <1 (that is, a 100 percent difference in C results in a <100 percent difference in sediment export). Based on these results, we computed the uncertainty bound of model outputs with the minimum and maximum R, E, and C values determined from our uncertainty analyses on inputs.

Validation

Processing of observed total suspended solids data

For the Ghanvi catchment, daily flow and total suspended solids (TSS) data were available for the years 2004–13. Because TSS data comprised large gaps (Table 5), we estimated the missing

Table 5. Summary of the annual TSS data for the Ghanvi watershed. (The years 2004 and 2005 were not computed because of missing flow data.)

	2006	2007	2008	2009	2010	2011	2012	2013	Average	Median	St. dev.
Days with observations	157	15	31	77	264	222	103	260	**n.a.**	**n.a.**	**n.a.**
Loads (t/yr)	370,600	n.a.	60,600	133,200	176,600	99,600	70,800	44,600	**136,600**	**99,600**	**112,800**

TSS days with a power law regression using daily flow data. Details of the regression are provided in Appendix B. We note that the years 2004 and 2005 had missing flow data, and the year 2007 only had 15 TSS observations. These years were, thus, discarded from the analyses. Daily loads (in g/day) were then computed by multiplying the daily flow (in m^3/day) by TSS (in mg/L).

Despite the errors introduced by the regression, our method is acceptable since most missing TSS data are during the nonmonsoonal season (September to May), which represent a minor contribution to the total sediment load. For example, the years 2010 and 2013 have minimal missing data during the monsoonal season (June, July, and August) and it was estimated that sediment loads from the monsoonal season represented 96 and 82 percent, respectively, of the annual load. These ratios were confirmed by several studies in the literature (for example, Singh et al. 2008).

For the Baspa watershed, TSS data were available for the years 2008 to 2012. However, the data for the months of March to July 2012 were suspicious, with the exact same series repeated for each month. The year 2012 was, therefore, discarded from the analyses. For the remaining years, both flow and TSS data were available at a daily time step, which allowed for the computation of daily loads as detailed above (Table 6).

Annual summaries of TSS data for the two catchments are provided in Tables 5 and 6. Large differences are observed between years, as illustrated by the high standard deviations and by the year to year ratios: in the Ghanvi watershed, for example, the year 2006 contributed six times as much as the year 2008. Such variability is expected given the likely sources of much of these sediments (debris flows from glaciers, landslides). It may also be due to the sampling procedure, resulting in higher annual loads in years with more observations (since these observations were taken during high TSS days).

Comparison between observed and modeled sediment loads

Although complete validation of the model is not possible because of important processes not being represented in the model (bank erosion, glacial debris, and so on), the uncertainty analyses allow one to estimate the contribution from sheet flow erosion (mainly from forests) to the total sediment load.

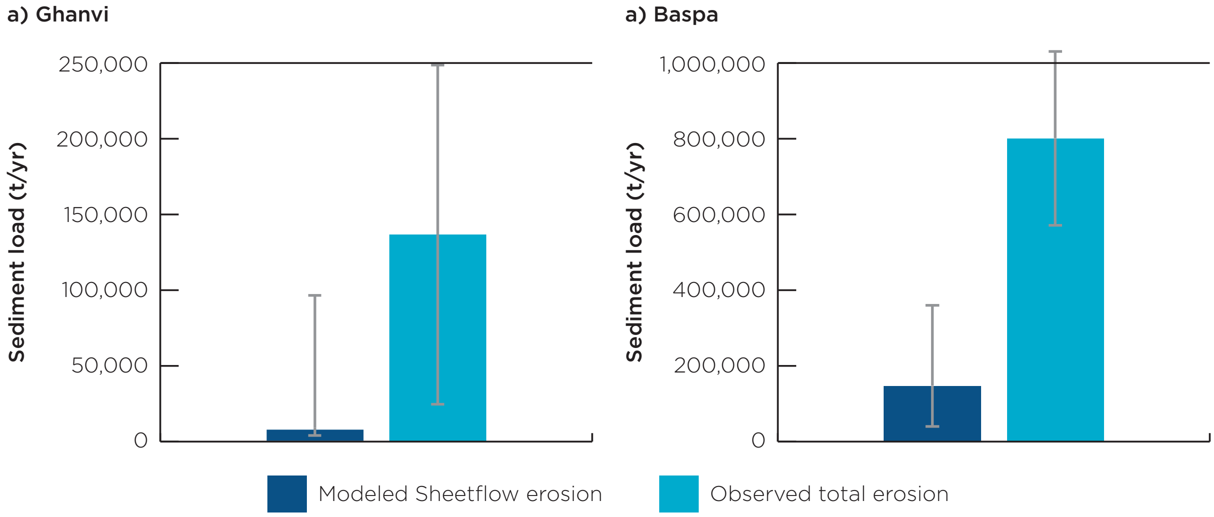
First, we note that the average values of observed sediment loads are in the range of values found in the literature (Kumar et al. 2003; Singh et al. 2008), which provides confidence in this estimate. Large observed variations are also seen in the literature, with the total load standardized by catchment area ranging from ~200 ton/year/km^2 (Singh et al. 2008) to 30,000 ton/year/km^2 (Kumar et al. 2003). Our estimates based on the available observational data are within this order of magnitude (1,200 and 800 ton/year/km^2, respectively, for Ghanvi and Baspa) and confirm a high interannual variability, with a standard deviation equal to 112,800 and 230,000 ton/year.

Next, we computed the model predicted sediment load with the initial input parameter values, yielding an annual load of 9,900 and 146,500 ton/year, respectively, for the Ghanvi and Baspa

Table 6. Summary of annual TSS data for the Baspa watershed. (Only one day of data was missing during the four-year period.)

Year	2008	2009	2010	2011	Average	Median	St. dev.
Load (ton/yr)	1,057,600	765,800	872,600	506,900	**800,700**	**819,200**	**230,000**

Figure 7: Comparison of modeled (sheetflow) erosion and observed total erosion for the Ghanvi and Baspa watersheds



Note: Error bars correspond to one standard deviation for the observed erosion, and to the upper and lower bounds described in the text for modeled sheetflow erosion.

watersheds (Figure 6). Using the upper and lower bounds based on our estimates of uncertainties in input parameters, the predicted ranges were large, 5,000 to 96,000 ton/year in Ghanvi, and 39,600 to 359,000 ton/year in Baspa (Figure 7). Therefore, given the parameter values in Table 4, the model predicts the contribution from sheetflow erosion of about 7 percent and 18 percent on average, respectively, for Ghanvi and Baspa (between 4 and 71 percent in Ghanvi and between 5 and 45 percent in Baspa).

Summary and Conclusions

The analysis presents slight adaptations of the InVEST models to establish the sensitivity of estimates of the water yield and sediment loads in the Ghanvi and Baspa watersheds. The uncertainty bounds for both model outputs are large, reflecting the state of the science in hydrologic modeling in the peculiar environment of the Ghanvi watershed, which is characterized by monsoonal rains and presence of glacier/snow-covered areas. However, the analyses provide insight into the potential for land management activities to influence water yield and sediment by offering estimates of the contribution of rainfall-driven runoff and sheet erosion to total water and sediment yields. This enables a better interpretation of the modeled outputs used in the project.

Because of the difficulty of directly calibrating model parameters given the large uncertainty bounds around the outputs, the literature-based coefficients for land use-derived parameters (such as Kc, C or P) were used for the RIOS and InVEST analyses performed in the following section of this report. Values in such studies are reported from direct experimental observation or from calibrated models. They are seen as more reliable than modified values based on the above analyses, because so much uncertainty remains around the contribution from processes that are not well represented in the InVEST models (such as glacier melt, landslide, and gully erosion). For the same reason, results from the water and sediment yield models given below that show potential benefits of soil and water conservation activities are presented in relative terms only.

The literature-based parameters used in the following analyses result in an improvement in model fit for the sediment outputs. The modified parameters produce estimates of 630,124 t/year for Baspa and 28,335 t/year for Ghanvi, putting them at the low end but within the range of plausible observed values (given the standard deviation around the annual mean sediment load, observed values range from 570,670 to 1,030,720 t/year for Baspa and between 23,820 to 249,343 t/year for Ghanvi). Therefore, for the parameter values given in Appendix A, the model predicts the contribution from sheetflow erosion of about 77 percent on average for Baspa and 28 percent for Ghanvi.

The goal of applying hydrologic models is to determine the potential for soil and water conservation activities, when directed toward areas with highest ecosystem service benefit, to result in positive improvements in sediment loads and baseflow regulation in catchments in HP. The analysis described above helps to set clear boundaries around the potential for impact from such activities. In the case of water yield, because the runoff from vegetated areas represents on average 40 percent of total yield, the impacts from land management are limited to influencing this 40 percent fraction. Clearly climate change, glacial retreat, and other regional climatic processes will be a major driving factor for future water yields in these areas, although the potential remains for land management interventions to have some impact. Intra-annual variations in this impact resulting from land management (such as forests role in regulating baseflows) is not possible with the InVEST model, which relies on annual averages.

For sediment, the potential to reduce loads into rivers from upland land management activities alone appears from this analysis to be more limited in some catchments than in others (to about 28 percent and 77 percent of the total potential sediment sources, in Ghanvi and Baspa). To note, this analysis is limited to two study catchments, and the InVEST model is missing several key processes (such as rill and gully erosion) and the representation of subannual variability that could provide better estimates of total soil loads, if other models are applied. In the other study catchments and for the purposes of producing relative reductions in sediment load resulting from activity scenarios, we assume that the modeled sediment loads represent 50 percent of all potential sources of sediment to the rivers.

1.4| Results

Priority Investment Portfolios

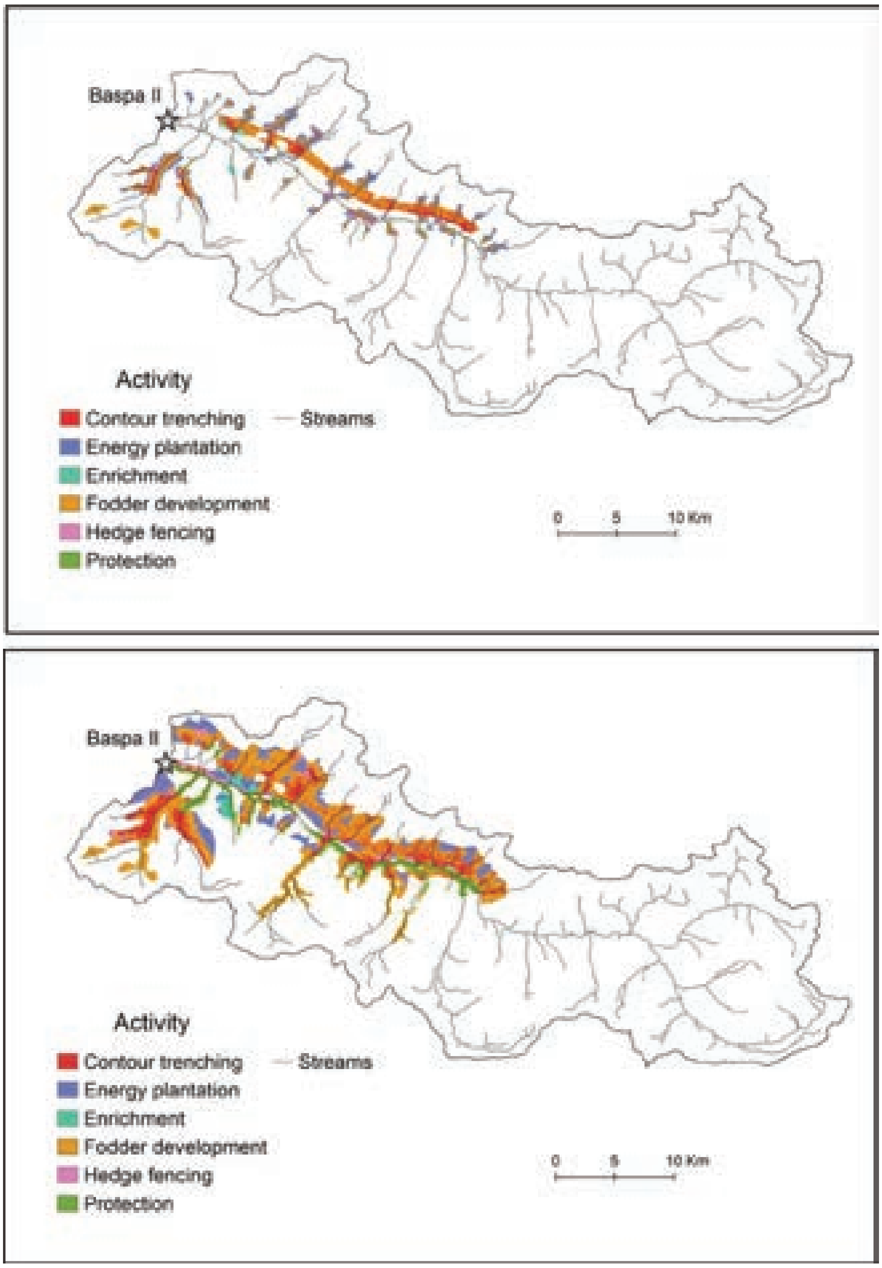
A budget is used by RIOS to find the best places to invest within a given spending cap. The CAT plans for the Satluj basin include budget prescriptions for activities, but these totals contain information on activities not considered in the RIOS analysis. In addition, the CAT plan budget totals do not correspond to the catchment boundaries used in our modeling. Lacking numbers on budgets specific to our study areas and activities, we highlight the best places to invest and estimate relative change in ecosystem services across a range of potential budget levels. The levels chosen correspond to a final coverage of 5 percent, 15 percent, 25 percent, 35 percent, and 45 percent of the land available for each type of activity. According to information provided by the HP Department of Forests (Vaidya 2014, personal comm.) the Department has a goal of developing soil and water conservation activities on 15 percent of the land. Therefore our budget range includes the HP target, as well as demonstrating if and where additional benefits may be achieved above and below the target.

The results of our RIOS model are below. Figures 8 through 12 show the recommended activity portfolios at 15 percent and 45 percent for each study area. Activity maps at the lowest budget levels can be interpreted as the locations where the specified activities may have the most

Figure 8: RIOS results for the Baspa II catchment at budgets corresponding to 15 percent (a) and 45 percent (b) of the available land area for each activity

a)

b)



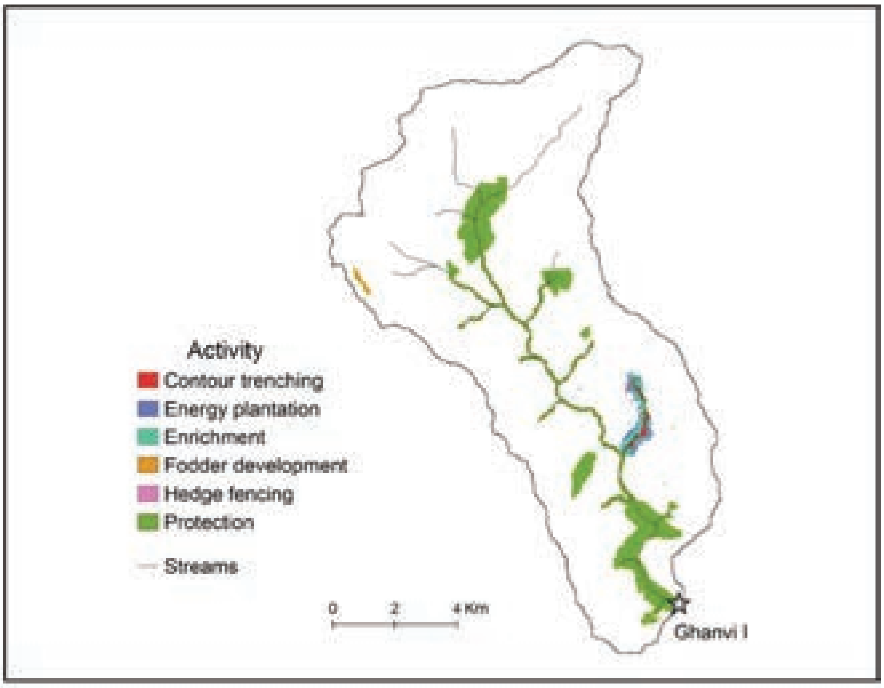
impact, because the RIOS model selects activities starting with the maximum score and going down until the available budget is spent. We also attempted to compare directly the results from the RIOS model with activity prescriptions from the CAT Plan for the Satluj basin. See the discussion section below for the conclusions from the comparison.

Ecosystem Service Benefits

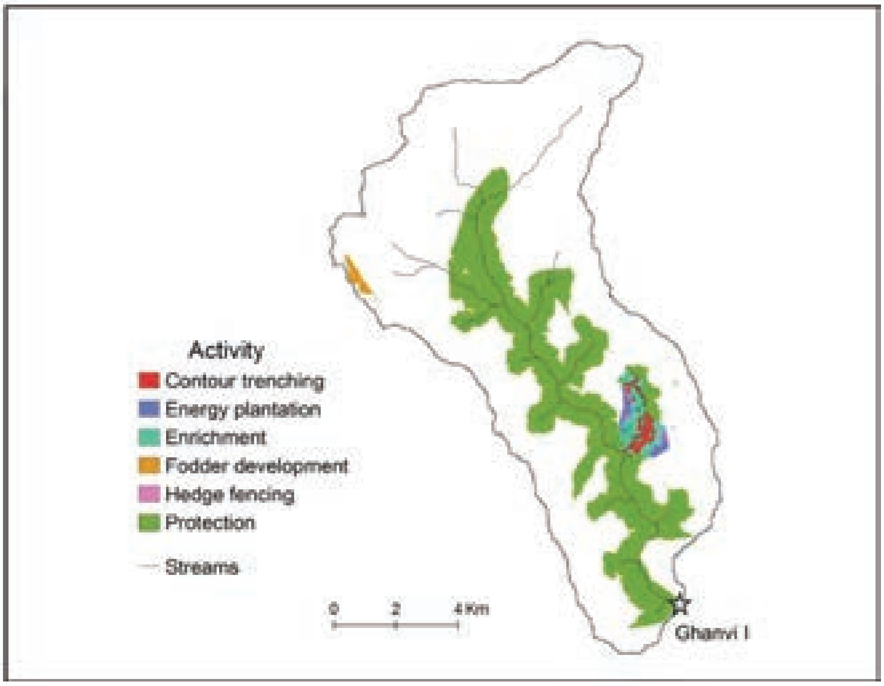
Given the activity portfolios resulting from the RIOS analysis (Figures 8 through 12), we used the InVEST water yield and sediment models to calculate the relative change in services that could be expected from implementation of the activities. To simulate the impacts of activities using a

Figure 9: RIOS results for the Ghanvi I catchment at budgets corresponding to 15 percent (a) and 45 percent (b) of the available land area for each activit

a)



b)

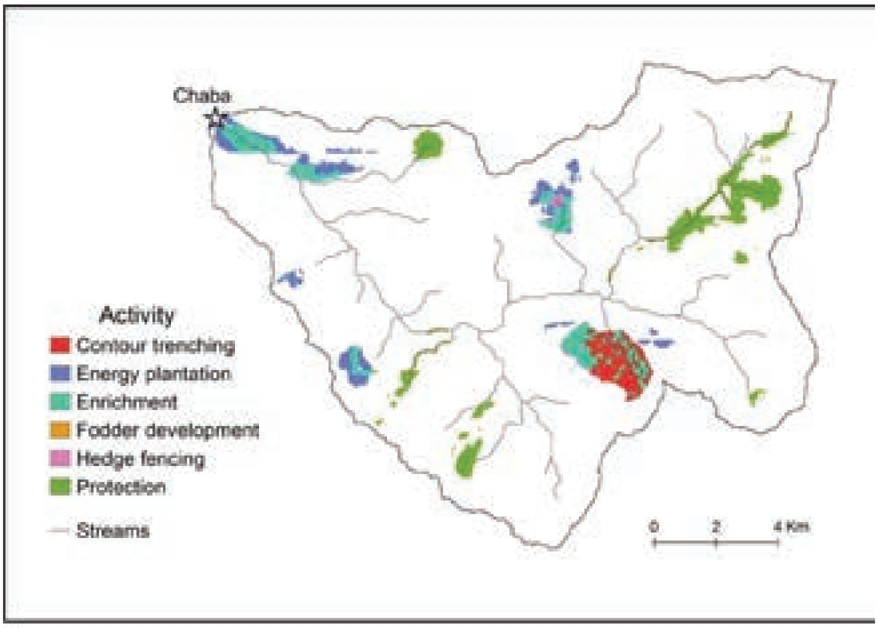


hydrologic model, it is necessary to translate the activities into changes to the specific parameters that drive the model. In this case, we changed the model parameters based on a series of assumptions about activity effectiveness as detailed in Table 7 below.

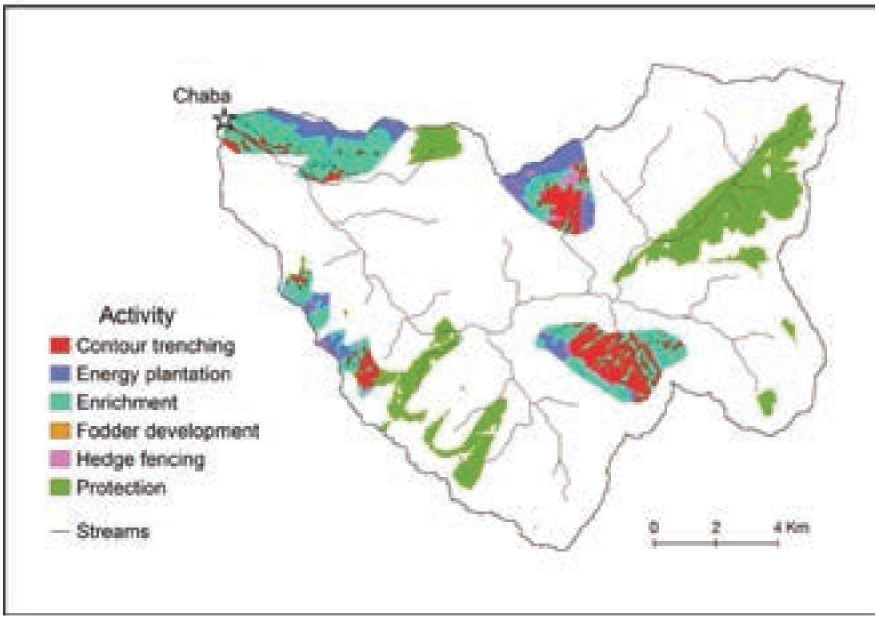
Areas where activities have been designated by RIOS were converted to a new land cover class that represents the combination of original land cover and activity (for example, "grass land/

Figure 10: RIOS results for the Chaba catchment at budgets corresponding to 15 percent (a) and 45 percent (b) of the available land area for each activity

a)



b)

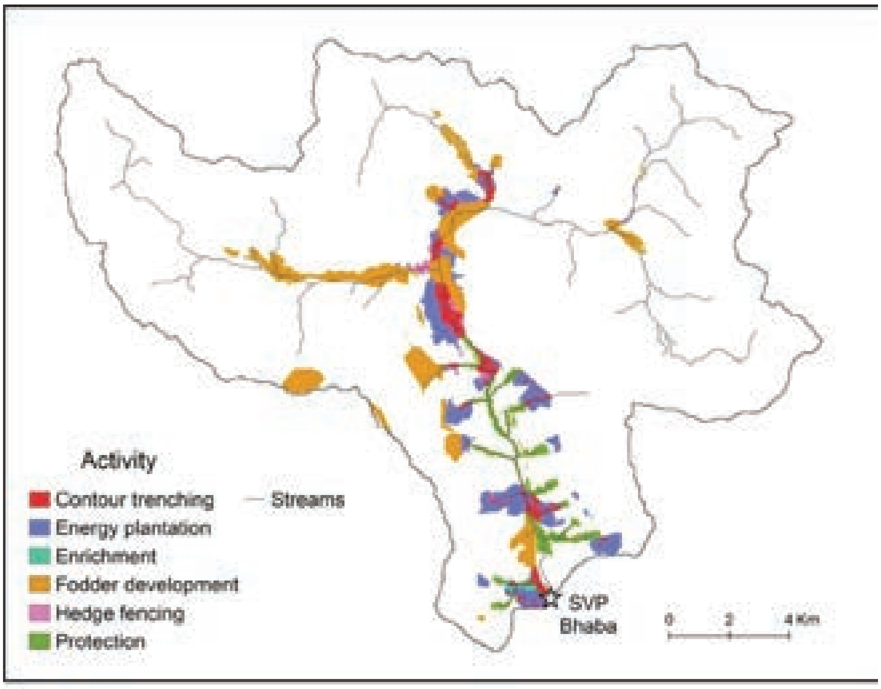


grazing land plus fodder development"). Model parameters were assigned to the new land cover classes according to the assumptions listed above in Table 7. The InVEST water yield and sediment models were then run on the baseline and each of the scenarios and the relative change in outputs was calculated.

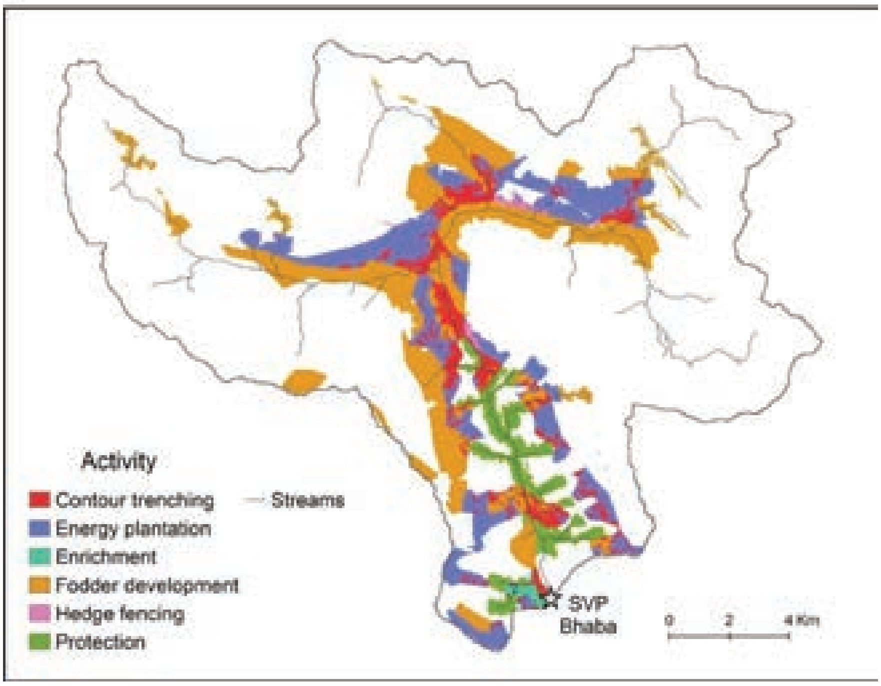
Information from the model validation and uncertainty assessment (see previous section) shows that the water yield simulated by the InVEST model represents about 40 percent of the total water yield for each catchment, and simulated sediment load represents between 28 and 77 percent of the total sediment load (based on analyses from Ghanvi and Baspa, respectively). Therefore the baseline simulated water yield for each catchment was divided by 40 percent to

Figure 11: RIOS results for the SVP Bhaba catchment at budgets corresponding to 15 percent (a) and 45 percent (b) of the available land area for each activity

a)



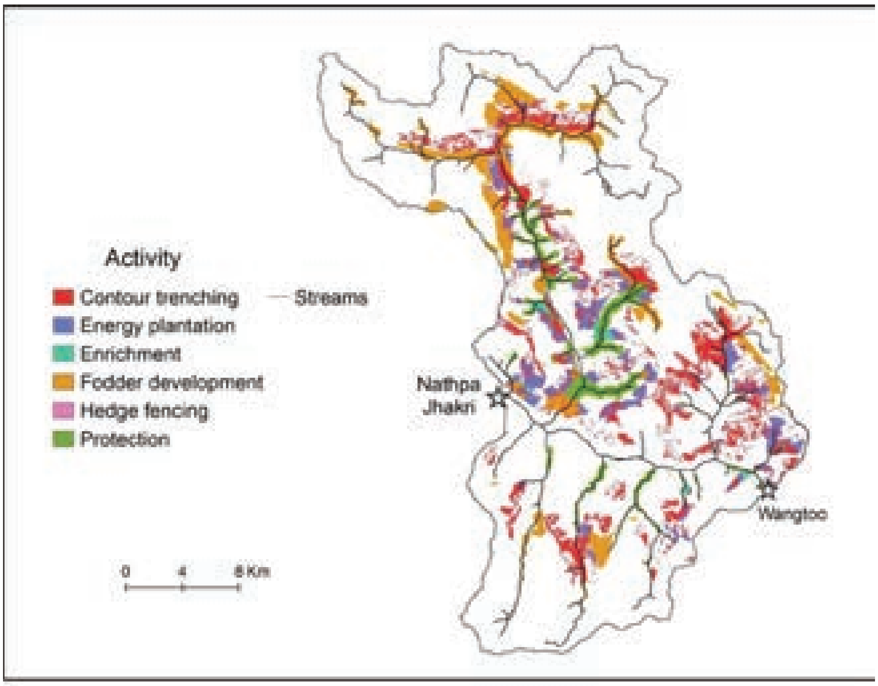
b)



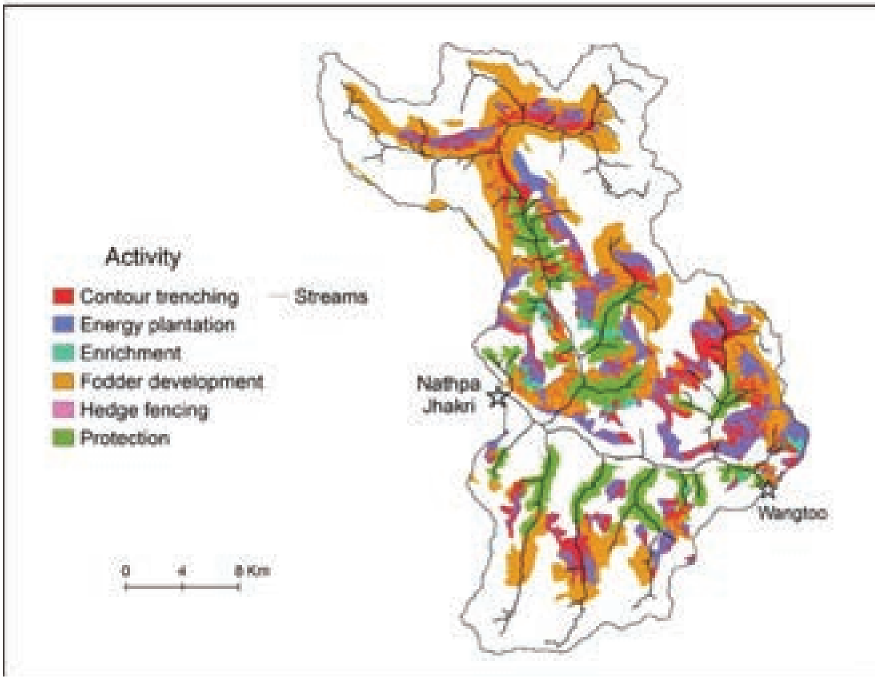
arrive at an estimate of total (adjusted) water yield that includes both precipitation-derived runoff and snow/glacier melt (see model validation and uncertainty assessment above for details). Similarly, changes in sediment load resulting from activities might reduce modeled sediment loads by 45 percent, but it is important to note that the model is only simulating a portion of the total sediment sources within the watershed. Some important processes, such as gully/rill erosion, landslides, and channel scour, are not included in the model. Therefore,

Figure 12: RIOS results for the Nathpa Jhakri catchment (downstream of Wangtoo) at budgets corresponding to 15 percent (a) and 45 percent (b) of the available land area for each activity

a)



b)



reporting a 45 percent reduction in sediment load from activities would be overstating their effectiveness, because that 45 percent reduction only affects a portion of the total load. Therefore, the baseline simulated sediment load was divided by 28 percent for Ghanvi and 77 percent for Baspa, to estimate a total (adjusted) baseline sediment load that includes all potential sources. For the other catchments where model validations were not possible, an average value of 50 percent was used for the contribution of sheetflow erosion to total load (so in those

Table 7. Assumptions used to assign parameters for modeling activities with InVEST

Original Land Cover Type	Activity	Assumption
Evergreen/ Semigreen Forest	Without protection (degraded)	Areas that are not protected in the portfolio are assumed to be degraded. Parameter values are assigned equal to degraded forest.
Degraded Forest/Scrub Land	Energy plantation	Energy plantation on degraded forest improves the quality of the forest, but does not return it to the same state as a natural evergreen/ semigreen Forest. Parameter values are assigned equal to an average of degraded forest and evergreen/ semigreen forest.
Degraded Forest/Scrub Land	Live hedge fencing	Live hedge fencing will allow for the regeneration of native forests. In addition, fencing has additional benefits for reducing sediment export and sediment retention. Parameter values are assigned as follows: USLE C—reduce by 40 percent (a range of 23 to 98 percent reduction is reported in the literature); retention efficiency (sedret_eff)—increase by 25 percent; other parameters equal to evergreen/ semigreen forest.
Degraded Forest/Scrub Land	Contour trenching	Contour trenching will allow for the regeneration of native forests. In addition, trenching has additional benefits for reducing sediment export and sediment retention. Parameter values are assigned as follows: USLE C—reduce by 40 percent (a range of 93 to 98 percent reduction is reported in the literature); retention efficiency (sedret_eff)—increase by 50 percent; other parameters equal to evergreen/ semigreen forest.
Degraded Forest/Scrub Land	Enrichment	With enrichment, degraded forest is regenerated to a healthier state, and parameter values are assigned equal to evergreen/ semigreen forest.
Grass Land/Grazing Land	Fodder development	Default parameters for grasslands assume that there is already some degradation. Therefore fodder development activities act to restore grazing lands to an average grassland state, based on parameters reported in the literature.
Land with or without Scrub	Fodder development	Default parameters for grasslands assume that there is already some degradation. Therefore fodder development activities act to restore grazing lands to an average grassland state, based on parameters reported in the literature.
Land with or without Scrub	Energy plantation	Energy plantation on land with or without scrub improves the quality of the land, but because of a poorer starting condition it does not return immediately to the same state as a natural evergreen/ semigreen forest or even a degraded forest. Therefore parameter values are assigned equal to an average of Land with or without Scrub and Degraded Forest.

(*continued on next page*)

Table 7. Assumptions used to assign parameters for modeling activities with InVEST (*continued*)

Original Land Cover Type	Activity	Assumption
Land with or without Scrub	Live hedge fencing	Live hedge fencing will allow for some regeneration of native vegetation. In addition, fencing has additional benefits for reducing sediment export and sediment retention. Parameter values are assigned as follows: USLE C—reduce by 40 percent (a range of 23 to 98 percent reduction is reported in the literature); retention efficiency (sedret_eff)—increase by 25 percent; root depth—no change; other parameters equal to evergreen/semigreen forest.
Land with or without Scrub	Contour trenching	Contour trenching will allow for some regeneration of native vegetation. In addition, trenching has additional benefits for reducing sediment export and sediment retention. Parameter values are assigned as follows: USLE C—reduce by 40 percent (a range of 93 to 98 percent reduction is reported in the literature); retention efficiency (sedret_eff)—increase by 50 percent; root depth—no change; other parameters equal to evergreen/ semigreen. Forest.

catchments, simulated sediment load is divided by 50 percent). This method allows for a more realistic representation of the relative impact of activities on the total sediment loads to rivers in the study areas. For each of the scenarios considered, we divided the scenario water yield and sediment load by the base total (adjusted) water yield and sediment load, respectively, to arrive at a value of percent change for each output.

For each study area and budget level, two different scenarios were considered to arrive at a calculation of total benefit from activities. First, a series of scenarios were modeled where all of the activities are implemented. These scenarios reflect implementation of all the activities that make some physical change in land cover or management, while areas that were designated for "protection" are left under the natural forest cover. The results are shown in Figures 13 through 17.

The above results reflect the desired outcome of the watershed investment program, where soil and water conservation activities are implemented and natural forests are protected in their current state. However the percent change from baseline shown here reflects the impacts of the activities only and does not consider the marginal benefit that is achieved with protection. To better understand the marginal benefit of protection, it is important to consider what might happen to the watershed in the absence of such protection. In order to represent the total benefit of all the activities plus protection, we modeled another set of scenarios in which the activities are implemented, but the areas designated as "protected" are instead degraded (converted to degraded forest). The total benefit is then calculated as the benefit of land management activities plus the marginal benefit of protection:

$$(S_p - B) + (S_p - (S_A)$$ Eq. 1

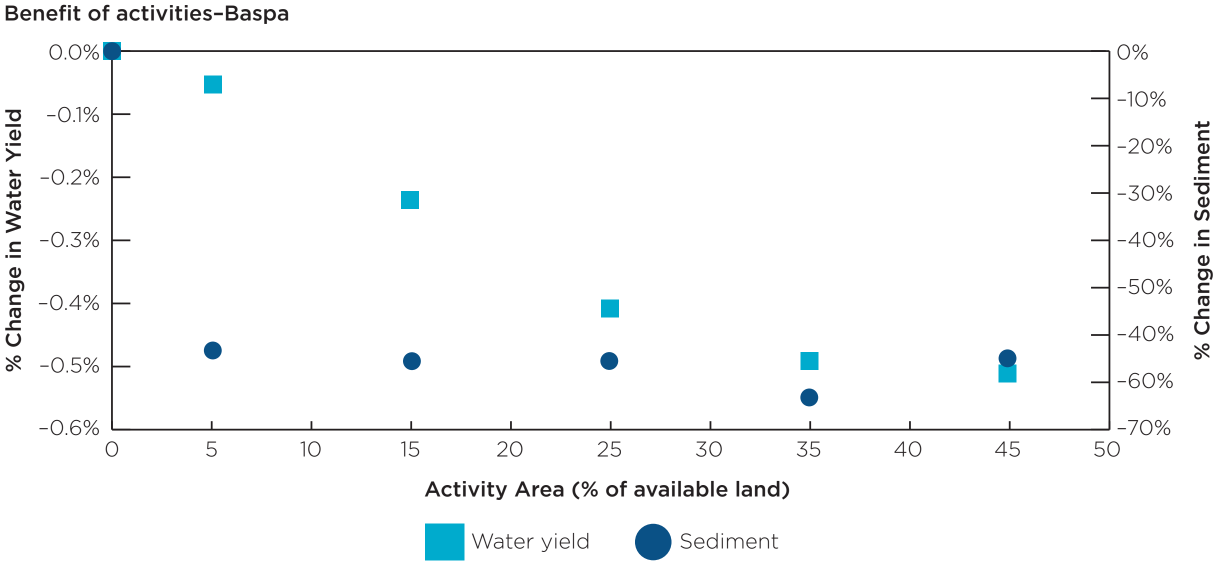
Where

S_p = Scenario of activities with protected areas unchanged

B = Baseline (adjusted) value

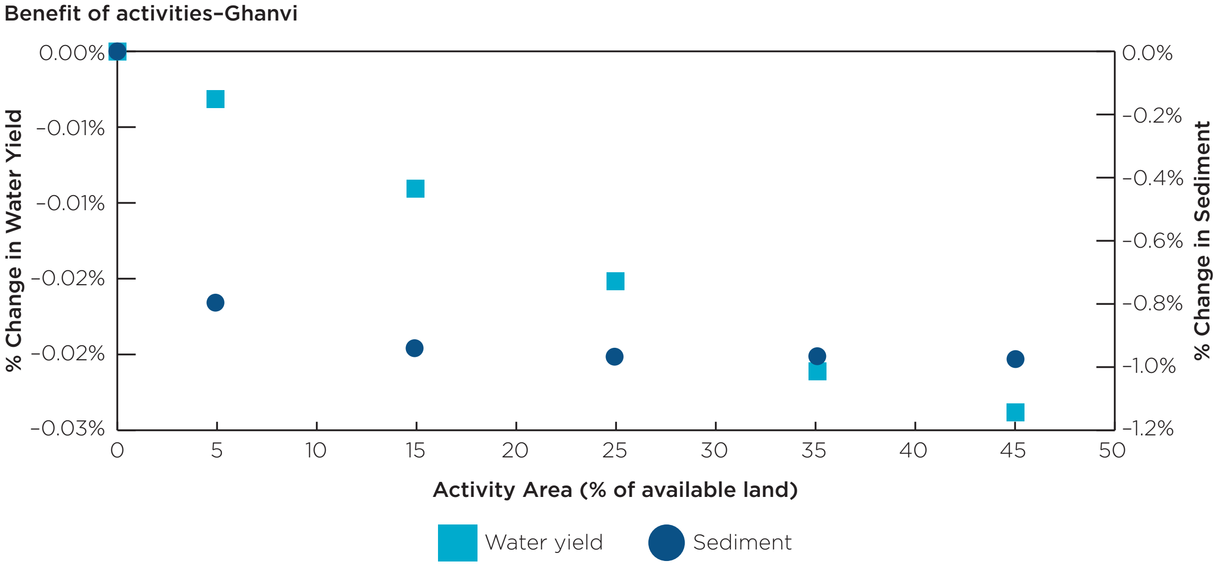
S_A = Scenario of activities with protected areas converted to degraded forest

Figure 13: Results of the InVEST water yield and sediment models for the Baspa catchment at each budget level considered, showing the percent change in adjusted annual water yield (left axis) and sediment load (right axis) from the baseline scenario



Note: These results are for implementation of land management activities only and do not consider potential degradation that could result, if forests in these scenarios are not protected.

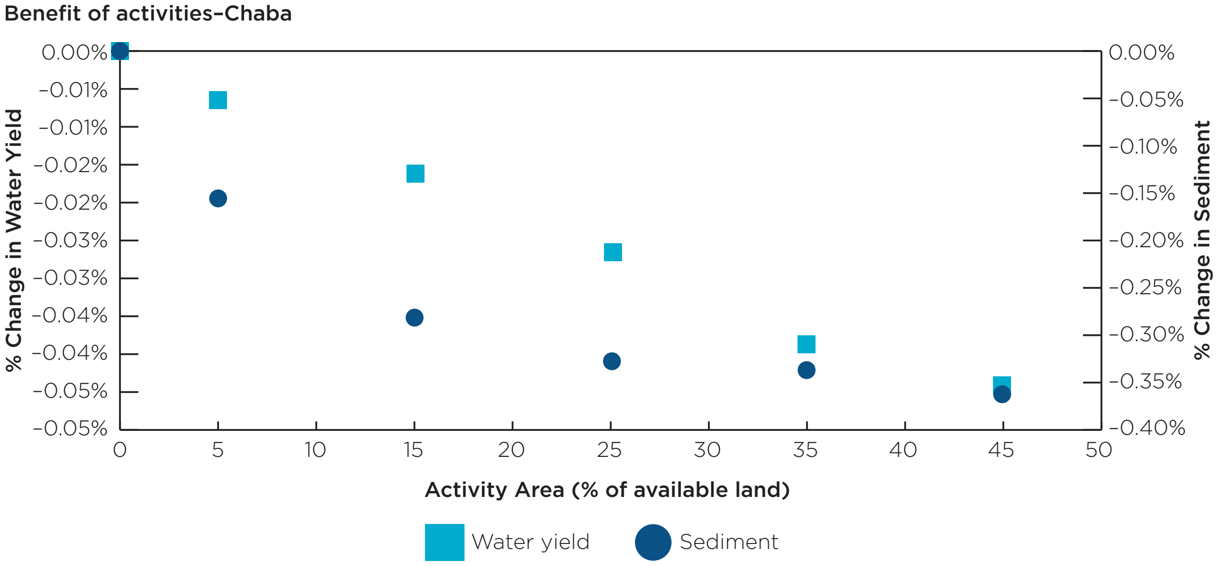
Figure 14: Results of the InVEST water yield and sediment models for the Ghanvi catchment at each budget level considered, showing the percent change in adjusted annual water yield (left axis) and sediment load (right axis) from the baseline scenario



Note: These results are for implementation of land management activities only and do not consider potential degradation that could result, if forests in these scenarios are not protected.

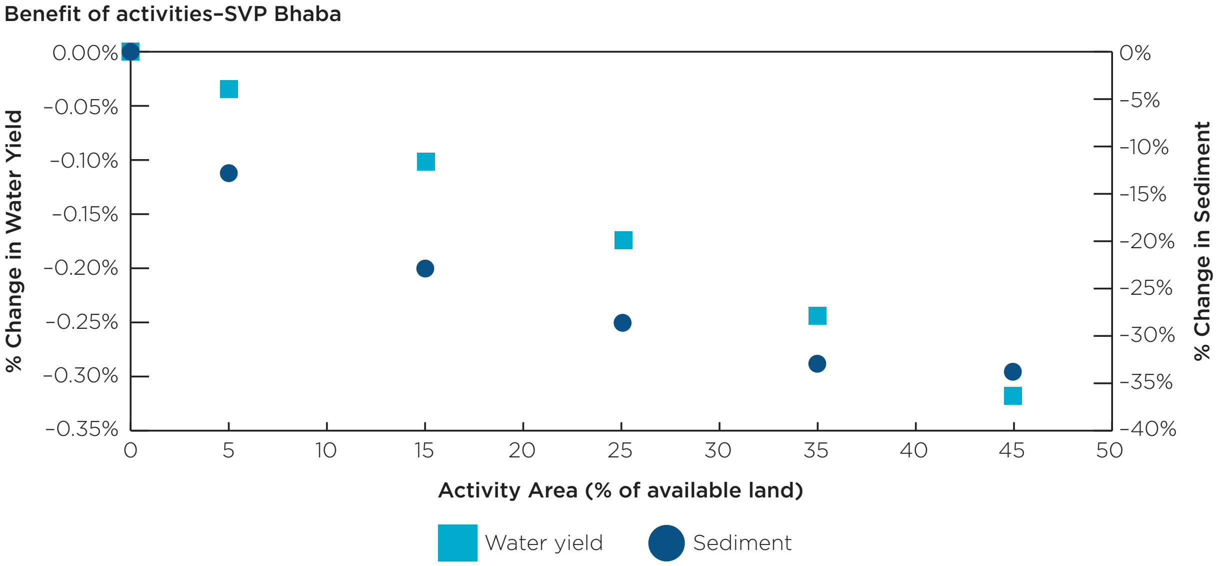
Because forest degradation often results in large increases in sediment load and water yield into streams (because of reducing vegetation cover and infiltration, while increasing potential erosion), the ecosystem service benefits are higher when one considers the extent of degradation that could happen without protection. The results from the second scenario analysis, representing the total benefit from the scenarios following Equation 1, are shown in Figures 18 through 22.

Figure 15: Results of the InVEST water yield and sediment models for the Chaba catchment at each budget level considered, showing the percent change in adjusted annual water yield (left axis) and sediment load (right axis) from the baseline scenario



Note: These results are for implementation of land management activities only and do not consider potential degradation that could result, if forests in these scenarios are not protected.

Figure 16: Results of the InVEST water yield and sediment models for the SVP Bhaba catchment at each budget level considered, showing the percent change in adjusted annual water yield (left axis) and sediment load (right axis) from the baseline scenario

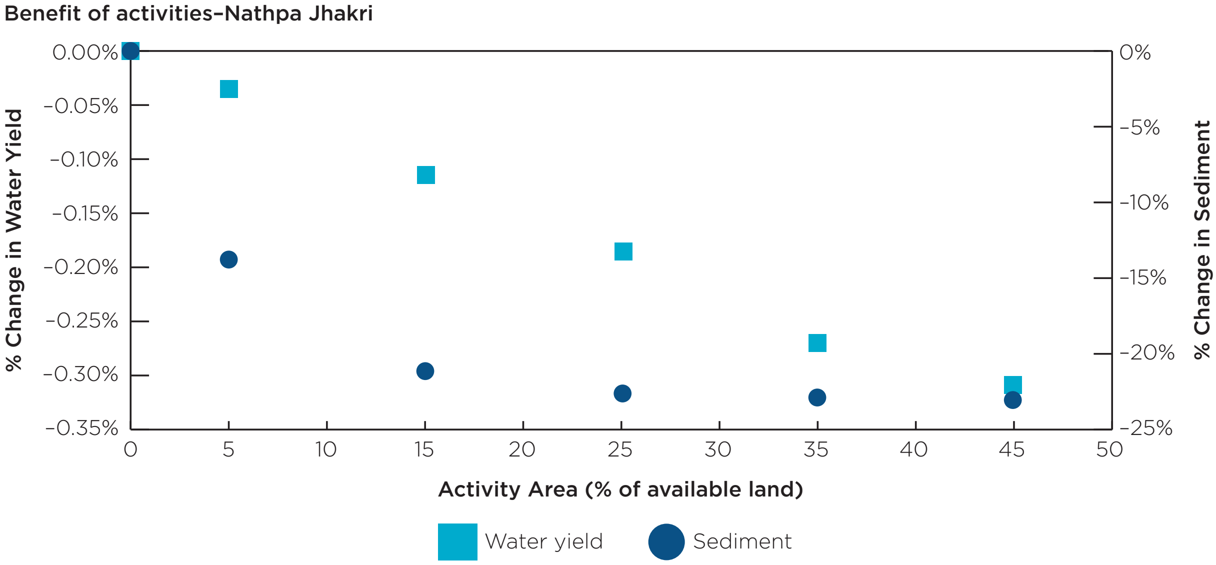


Note: These results are for implementation of land management activities only and do not consider potential degradation that could result, if forests in these scenarios are not protected.

1.5| Discussion

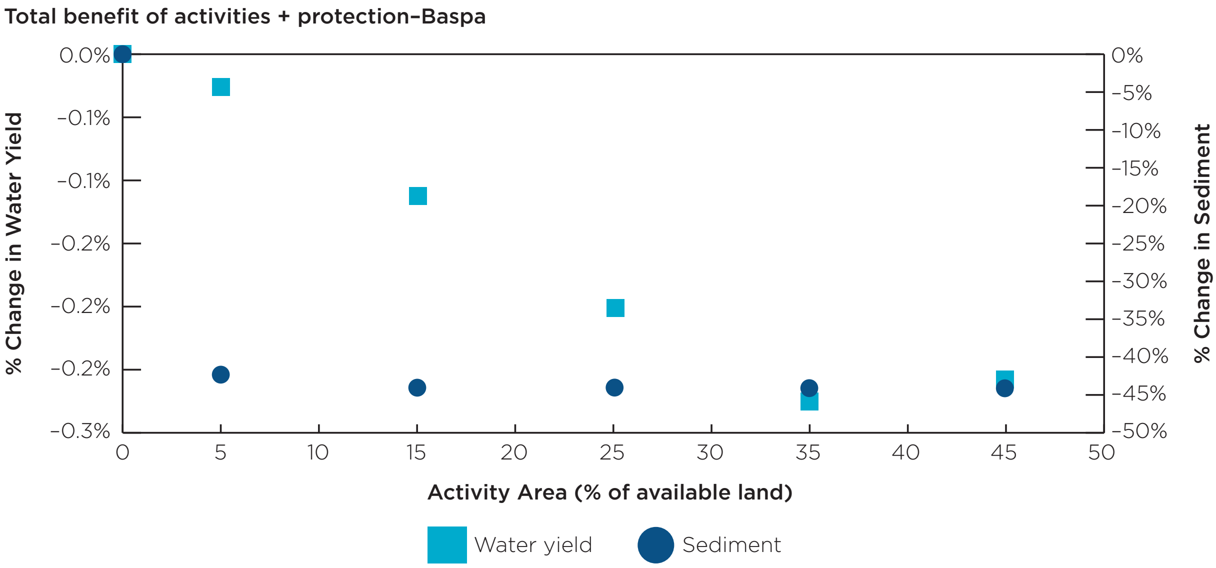
Results of the analysis show that given biophysical data and information on feasible activities in the study watersheds, it is possible to apply a landscape-level screening method (RIOS) to

Figure 17: Results of the InVEST water yield and sediment models for the Nathpa Jhakri catchment (downstream of Wangtoo) at each budget level considered, showing the percent change in adjusted annual water yield (left axis) and sediment load (right axis) from the baseline scenario



Note: These results are for implementation of land management activities only and do not consider potential degradation that could result, if forests in these scenarios are not protected.

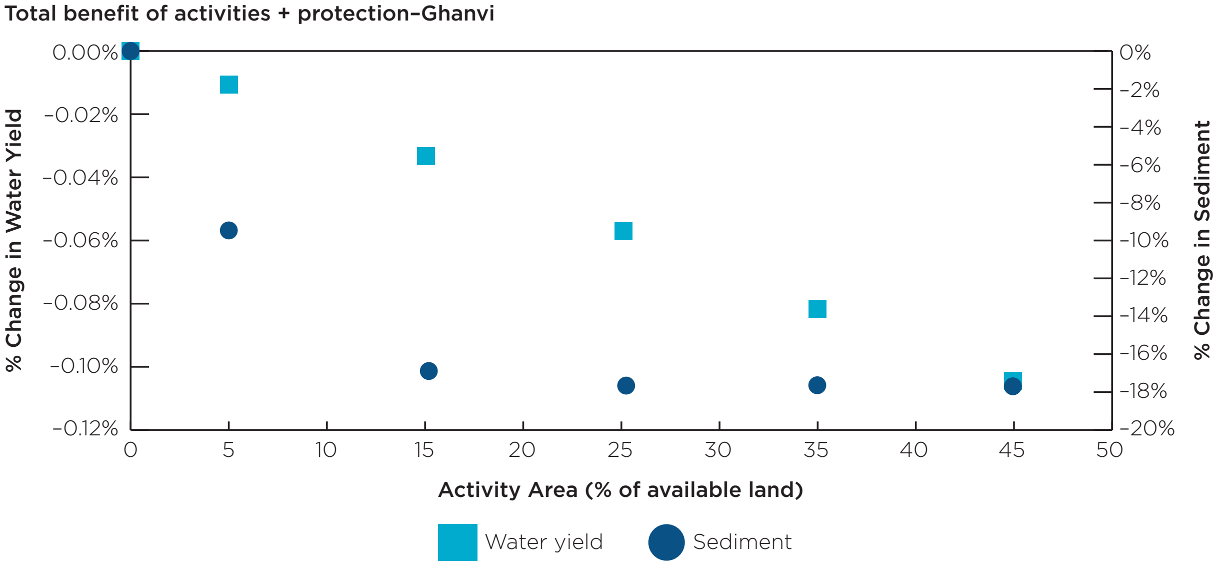
Figure 18: Results of the InVEST water yield and sediment models for the Baspa catchment at each budget level considered, showing the total benefit of the activity portfolios in terms of percent change in adjusted annual water yield (left axis) and sediment load (right axis) from the baseline scenario



Note: These results show the change resulting from implementation of land management activities plus the marginal benefit of protection, considering that forest areas would likely be degraded without protection in place.

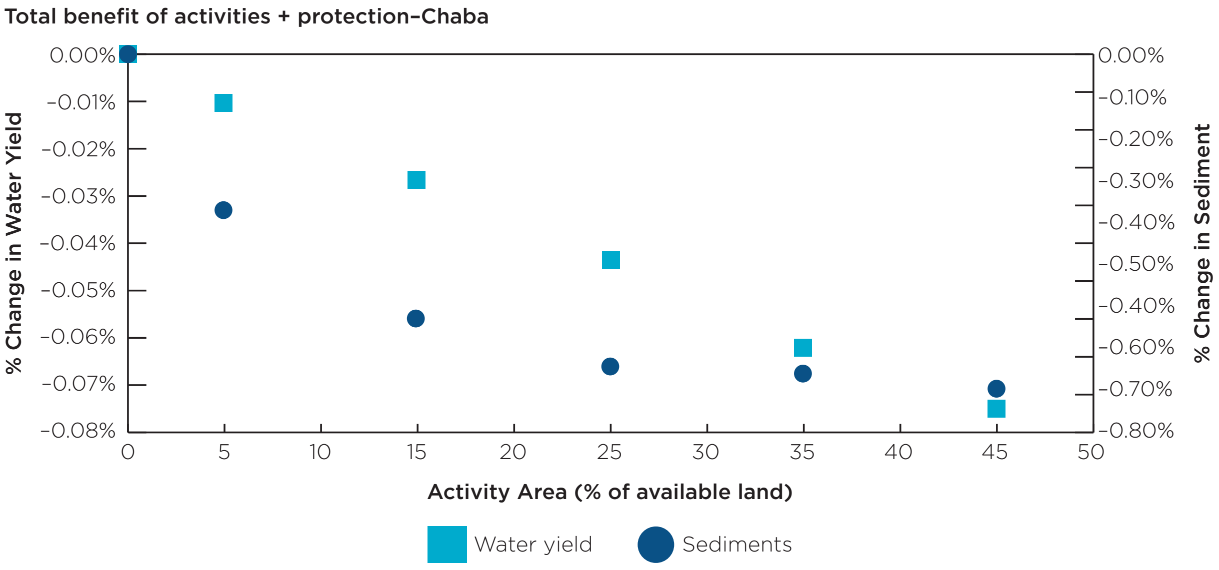
identify places where the ecosystem services' return on investment are highest. In this case, we examined portfolios at different budget levels that will maximize returns for sediment retention and baseflow enhancement above hydropower dams. The underlying input data on land cover

Figure 19: Results of the InVEST water yield and sediment models for the Ghanvi catchment at each budget level considered, showing the total benefit of the activity portfolios in terms of percent change in adjusted annual water yield (left axis) and sediment load (right axis) from the baseline scenario



Note: These results show the change resulting from implementation of land management activities plus the marginal benefit of protection, considering that forest areas would likely be degraded without protection in place.

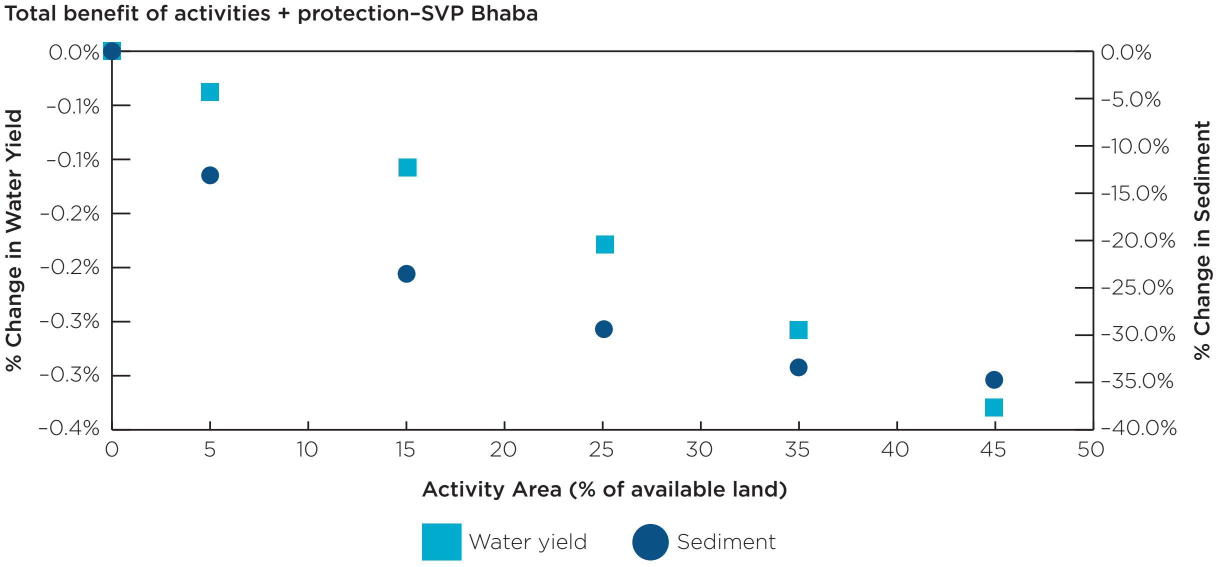
Figure 20: Results of the InVEST water yield and sediment models for the Chaba catchment at each budget level considered, showing the total benefit of the activity portfolios in terms of percent change in adjusted annual water yield (left axis) and sediment load (right axis) from the baseline scenario



Note: These results show the change resulting from implementation of land management activities plus the marginal benefit of protection, considering that forest areas would likely be degraded without protection in place.

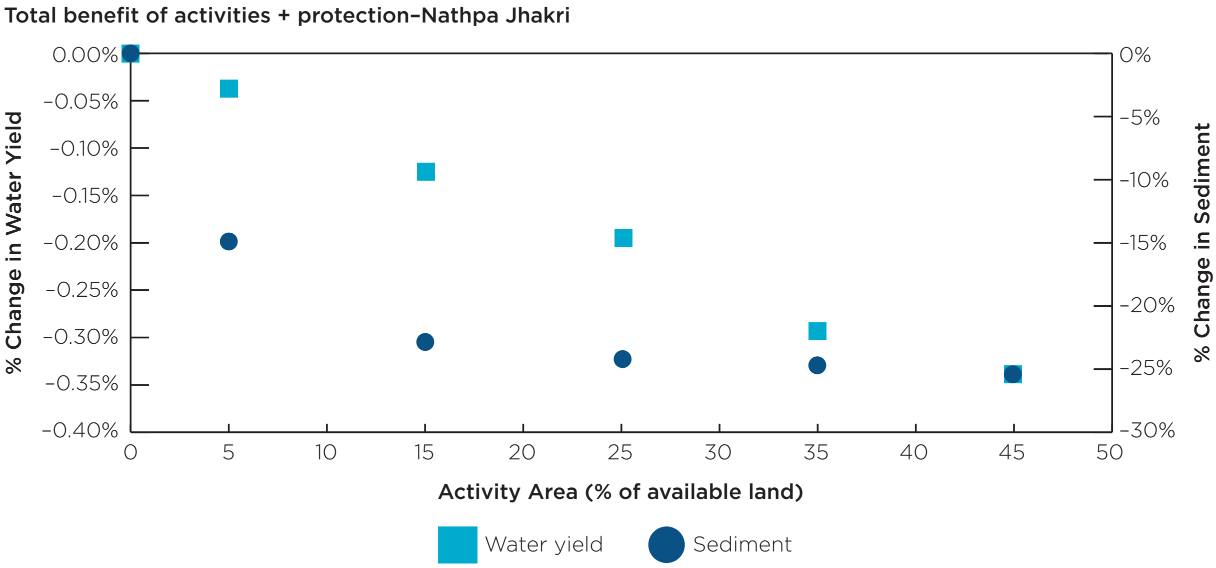
highly influence the RIOS model results and where different activities are allowed, which highlights the need to improve these results with the best possible high-quality local data on

Figure 21: Results of the InVEST water yield and sediment models for the SVP Bhaba catchment at each budget level considered, showing the total benefit of the activity portfolios in terms of percent change in adjusted annual water yield (left axis) and sediment load (right axis) from the baseline scenario



Note: These results show the change resulting from implementation of land management activities plus the marginal benefit of protection, considering that forest areas would likely be degraded without protection in place.

Figure 22: Results of the InVEST water yield and sediment models for the Nathpa Jhakri catchment (downstream of Wangtoo) at each budget level considered, showing the total benefit of the activity portfolios in terms of percent change in adjusted annual water yield (left axis) and sediment load (right axis) from the baseline scenario



Note: These results show the change resulting from implementation of land management activities plus the marginal benefit of protection, considering that forest areas would likely be degraded without protection in place.

land use and management. The RIOS results demonstrate how a landscape-level approach could be added to the watershed management and prioritization process, potentially reducing the amount of time spent up-front in costly field assessments by narrowing the range of potential sites considerably.

The InVEST model results show that the model can predict with reasonable confidence trends in water yield and sediment loads. Because of the large uncertainties around the input parameters and model outputs, and the lack of representation of certain key processes (as discussed in Part II. Model Validation and Uncertainty Assessment), we recommend interpretation of the results in relative terms only. The results show that even without considering rill/gully erosion and landslides, the potential for targeted soil and water conservation activities to positively impact sediment loads is high, although the results vary by study catchment. The results also demonstrate that while activities are targeted to improve infiltration and help augment baseflow, a potential trade-off between afforestation and total annual water yield exists. In all cases, implementation of activities resulted in modest decreases in total annual water yield (although typically less than 1 percent). These decreases in yield are accompanied, however, by significant decreases in total sediment loads (up to 44 percent).

To note, these model results show annual averages only. While small decreases in water yield on an annual basis are possible, it is important to understand seasonality of water flow to comprehend impacts on hydropower peak production and value. The total amount of water yield during a year could decrease because of reforestation; however, the presence of better forest cover could help to capture water that would otherwise be lost during very wet periods, storing that water and releasing it during the dry season and thereby improving hydropower production during that time. The InVEST annual model is not able to demonstrate these important seasonal impacts that come from improved water storage and regulation capacity in the catchment area. Additional modeling and monitoring is needed, for example, using a model capable of simulating on a subannual basis to determine the precise impacts of reforestation activities on low-season water flows in this area.

2| Summary and Recommendations for Ecosystem Service Management in HP

2.1| Improving and Integrating Models in CAT Planning Process

If the HP government's plans to develop a system of natural capital accounts and a supporting PES scheme is to succeed, then a rigorous methodology for assessing the value of natural capital and ecosystem services is crucial. Such a method must be able to connect land conversion and land management with consequences for service delivery to different beneficiaries and sectors. Beyond this longer-term goal, the outcomes of current efforts to implement soil and water conservation activities in HP could improve, if activities were targeted at a landscape scale. Landscape-level targeting could augment the current approach of identifying and mitigating problems at the local or point scale, providing a larger perspective and potentially reducing the overall cost and time needed to define optimal investment plans.

The work presented in this report demonstrates how biophysical and economic modeling may be combined to bring scientific information into the process of watershed management, and how impacts on the flows of ecosystem services could be quantified for the hydropower sector. The results from these analyses can also provide targets to measure against using data from flow and silt monitoring. When designing monitoring schemes, it is important to ensure that the locations being monitored, and the locations where model outputs are simulated, are as closely matched as possible, to make direct comparisons appropriate.

In the course of this study, we also attempted to compare RIOS portfolios directly with the CAT Plan activity prescriptions. This proved to be challenging for several reasons: a mismatch between the way that activities are prescribed and accounted for in the CAT plan and the way that they are implemented in RIOS because of differences in model structure; differences in the input data sources, resolutions, and the scale at which activities are selected; and the difficulty obtaining reliable coordinates for the location of activity prescriptions. Table 8 highlights the key differences between the RIOS screening approach and the CAT Planning approach to collecting and analyzing data and assigning activity locations.

Given these differences, it is clear that a landscape screening approach provided by RIOS is not a substitute for the CAT Planning process in which HP has already invested heavily. Instead, a model, such as RIOS, can augment the existing process by providing a broad screening to narrow possibilities and maximize potential for watershed-scale beneficial outcomes, before departments invest in intensive sampling and field validation, such as used in developing the final CAT plans (Figure 23). A final critical step would be to use hydrologic models (such as InVEST or SWAT) to predict the expected impacts from CAT plan activities and to establish monitoring protocols to measure impacts on the ground.

For this approach to be most effective, it will be important to better align the data inputs used in the two processes. Data used in this study for RIOS do not reflect well the ground-truthing that was done through the CAT planning process. Critical steps to align the two approaches include ground-truthing the land use data that are input into RIOS and improving the assumptions on feasible activities, locations, and other restrictions. Implementing the model and data input improvements suggested by participants in the training workshops (see Final Training section above) will be key to better modeling results and alignment with the CAT plans.

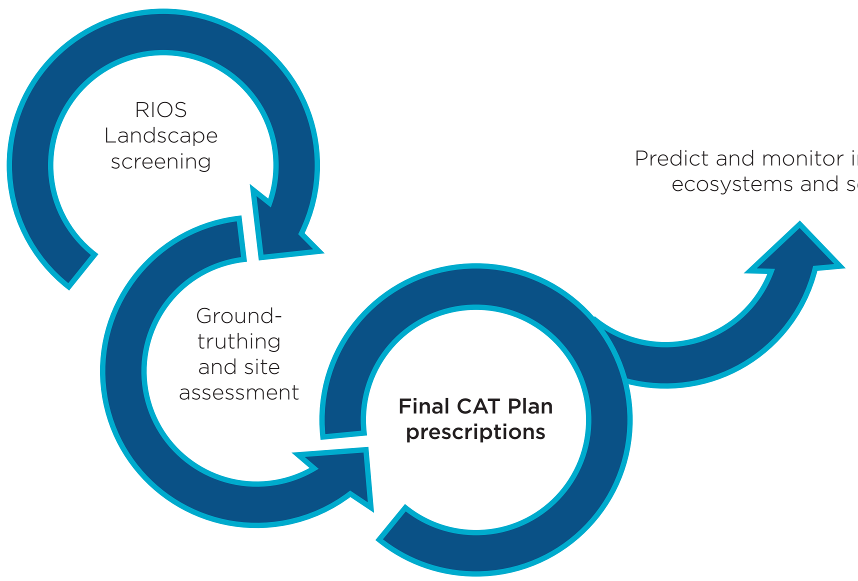
For achieving the final step in this framework—estimating and monitoring impacts (Figure 23)—the choice of hydrologic model will be critical and must be driven by the level of detail deemed necessary for the economic valuation and the available technical capacity. Monitoring efforts should be closely aligned with the model set up in terms of the locations of interest, the parameters measured, and the time step of model outputs to be compared. The

Table 8: Key Differences in Methodology between RIOS and CAT Plan.

	RIOS	CAT Plan
Input Data	Raster (grid-based)	Micro-watershed and site-based
Data Sources	Large-scale, state level	Local, site based assessments
Analysis Unit	Individual cells, in landscape context	Point or site
Prescription	Individual cells ($900m^2$)	Point-based, aggregated by microwatershed
Types of Activities	Land management	Land management and infrastructure

Source: NERIL 2011.

Figure 23: Suggested process for integrating the RIOS model into existing Catchment Area Treatment (CAT) Planning Process



Note: A final critical step is to use hydrologic models (such as InVEST or SWAT) to predict the expected impacts from CAT plan activities and to establish monitoring protocols to measure impacts on the ground.

following section summarizes the strengths and weaknesses of the InVEST and SWAT models in the context of valuing hydropower in HP.

2.2| Summary of Hydrologic Modeling Options for Himachal Pradesh

SWAT and InVEST estimate water and sediment flows via significantly different approaches and at different resolutions. Both models can lead to valuation of hydropower ecosystem services, but those values may be different and require different techniques. We suggest that each model may be appropriate under different circumstances, and that applying the appropriate model is a key decision. Here, we sum up the strengths and weaknesses of each model for the assessment of hydropower ecosystem services.

SWAT's strengths are primarily its explicit representation of many processes, daily model estimates of variables relevant to hydropower production, and its wide acceptance for assessing the effects of land use and management. SWAT includes many of the most relevant processes involved in the discharge of water through rivers. These processes are all based on either basic physics or on models and parameterizations that have been widely used, at least within the United States. As a result, SWAT may provide accurate estimates of flow characteristics with large changes in either climate or land use, cover, and management. The daily scale estimates of water flows allow for typical assessment approaches to hydropower generation, and for linking potential power production into economic models that consider variations in demand, which may affect the value of the investment. Finally, SWAT is widely accepted for assessing changes in water and sediment flows; it is not difficult to convince officials, investors, or others to use its results for driving future investments.

SWAT also has weaknesses, including the need for specific data that may not be widely available, significant scientific and computational capacity necessary for appropriate calibration, and the potential for over-calibration (resulting in a good fit of model outputs to observed data but using parameter values that are physically meaningless or inappropriate). SWAT was developed in agricultural areas in the United States, and application of the model outside the United States is often challenging because of the lack of similar high-quality soil and point-focused climate data that were used in the model formulation. Also, SWAT includes many parameterizations based on work done in the United States, especially in the Midwest, which may not apply to other geographic locations. In addition, many international agencies may lack appropriate scientific capacity to appropriately calibrate SWAT or deal with the model's complexity. The scientific literature includes numerous SWAT models that do not appropriately adjust for local conditions or have a reasonable calibration. Over calibration may fit current observations well, but may internalize some system behaviors into the wrong parameters; as a result, estimates of water and sediment flows may not be accurate under changed conditions.

The InVEST water yield model's strengths are its simplicity in operation, computational efficiency, and explicit consideration of spatial patterns of land use and management. InVEST was designed to operate worldwide and thus uses globally available datasets, although better local datasets are recommended to improve the quality of the model. In addition, InVEST's computational simplicity reduces the time necessary to build a model for a site and allows for easy use with other ecosystem service models to assess trade-offs (for example, where significant ecosystem service value could be destroyed if only water yield for improving hydropower ecosystem services is considered). InVEST enables the easy prioritization of investment in landscape management to increase water yield or reduce sediment loading. In addition, InVEST is parsimonious, a desirable feature, and explicitly designed to describe the behavior of entire watersheds, which is a very relevant goal for models looking at ecosystem services.

One advantage of such simple models as InVEST is the low computational cost. The total computing time is generally a few hours rather than weeks, which allows for easier sensitivity analyses or other uncertainty assessment techniques that require multiple runs. This ability was used in this project in the form of sensitivity analyses to test and validate the use of the model for some questions.

The InVEST annual model also has significant weaknesses focused around its particular structure and difference from typical process-based hydrologic models. The InVEST annual model is not widely accepted for the management of land use and cover. InVEST lacks a number of processes that may be important for hydropower ecosystem services, such as deep groundwater interactions and, especially for Himachal Pradesh, snow. These processes may be especially vital under potential climate change scenarios. Moreover, the InVEST annual water yield and sediment models only provide estimates of water and sediment flows at the annual scale, and hydropower ecosystem services are more difficult to assess at these scales.

Overall, SWAT is a more powerful model and useful for assessing hydropower at fine temporal scales. However, SWAT is much more difficult to run and may be impractical in some cases. In contrast, InVEST does not provide the same power to assess hydropower at fine temporal scales but can be run relatively easily worldwide. InVEST's ability to provide quantitative guidance can be very valuable when more sophisticated models are not practical.

These results are useful for developing PES policies to target priority areas and setting targets for improvement in outcomes at the watershed scale. However, to accurately assign economic value to watershed services relative to run-of-river hydropower facilities common in HP, it is important to consider seasonal changes in water yield and even daily changes in sediment loads. The InVEST model is not designed to produce this level of output; therefore, another watershed model should be considered to provide detailed estimates of economic value (Table 9).

Table 9. Comparison of SWAT and InVEST hydrologic models in terms of input complexity and appropriate application in HP ecosystem services assessment and valuation

	SWAT	InVEST
Input and calibration data required	High	Med
Number of parameters required	High	Low
Ability to calibrate/validate	High	Low
Model complexity/ physical processes represented	High	Low
Time step	Daily	Annual
Technical capacity required for model set-up, validation, and analysis	High	Med
Appropriate application in HP	Ecosystem service valuation	Relative change assessment

2.3| Recommendations for Future Work

A major purpose of this project was to demonstrate the use of modeling in ecosystem services assessment and to assess the potential for using hydrologic modeling to provide estimates of the value of forests for hydropower production. Two potential future applications are suggested by this study: 1) the use of RIOS and InVEST within the HP Forest Department to provide a landscape-level perspective on targeting investments in soil and water conservation to ensure ecosystem service delivery from forests; and 2) the use of SWAT (and RIOS, as appropriate) to provide estimates of impacts on daily stream flows and sediment that can be used to account for the value of forests to the hydropower sector in HP.

For the first application, some additional capacity needs have been identified and are discussed in Part IV. Capacity Building. Detailed recommendations for next steps include the following:

1. Build capacity in the HP Forest Department by creating a node of GIS and ecosystem services modeling specialists.
2. Begin a “train the trainers” program that will identify key personnel in the Department for intensive training on RIOS and InVEST models and GIS. We recommend that a small group of key personnel attend the Natural Capital Project’s Annual Meeting and Training, held annually in Stanford, CA, United States, in March. The cost of attendance (per person) is estimated at $3,600 ($600 registration, $2,000 transportation, and $1,000 meals and lodging).
3. Advanced GIS training is recommended for the core trainers. Such training can likely be obtained from an Indian technical institute or consulting firm. ESRI, the industry leader and developer of ArcGIS, holds a user conference annually in December through their ESRI India office and provides hands-on training courses for a fee.
4. After training, the core trainers could provide capacity building within the node and build connections within the Forest Department, AGiSAC, and other academic and government institutions (such as IIT-Delhi, IIFM) with expertise in InVEST modeling or those that gather and house relevant data for ecosystem services assessment. Additional technical support

could be provided by Natural Capital Project staff through their training program, with timing and rates negotiated on a case-by-case basis (typical fees are $500 per day for staff time, plus all other expenses for travel and logistics).

5. Finally, the Forest Department must develop a methodology and workflow for using RIOS/InVEST within their current operations and distribute this to staff with appropriate incentives and accountability to implement the method. A step-by-step manual for using the models should be created and tailored to users in the Forest Department.
6. It will be important to improve capacity with the simpler RIOS and InVEST models first, building understanding of how this type of approach can help the Forest Department to demonstrate their contribution to ecosystem services management for hydropower (and potentially other sectors). Later, the Forest Department can build on this foundation by bringing in more advanced modeling approaches such as SWAT, which will promote an understanding of how outputs from advanced hydrologic models can assist in the Department's management decisions. It is unlikely that the Forest Department will have the capacity internally to run the SWAT model, rather the focus should be on developing a core of staff with knowledge of how a modeling approach can inform decision-making and be used to assess ecosystem services within the defined workflow. The core group can then lead projects, scope modeling needs, and hire out contractors as appropriate to perform modeling analyses with SWAT.

For the second application, additional work is needed to expand the current analyses to incorporate more complex hydrologic modeling and achieve monetary valuation. Future work in this area should incorporate subannual hydrologic models, such as SWAT, along with economic data on facilities costs and the price of hydropower, to evaluate returns on investment at a temporal scale appropriate for the run-of-river hydropower facilities common in HP. Such an analysis could provide a quantitative estimate of ecosystem services value for hydropower that can directly inform the development of natural capital accounts. The Natural Capital Project and IIT-Delhi can provide the technical support to complete this analysis in partnership with the Departments of Forest and Economics and Statistics.

Recommended next steps for the valuation of hydropower ecosystem services are the following:

1. Estimate economic impacts of changes in land cover and management:
   a. Calibrate and validate SWAT model for selected study areas within HP.
   b. Parameterize econometric model and validate with observed hydrologic data.
   c. Develop scenarios of land management to provide basis for natural capital accounting study.
   d. Apply econometric model to assess change in hydropower value from scenarios.
2. Synthesize results and develop method to apply these findings to PES scheme for ecosystem services to support hydropower.
3. Final synthesis and develop recommendations for scaling the methodology to a state-wide forest accounting scheme. This step will require good collaboration between the project partners to develop a method in which SWAT modeling results can be used to determine current values for forest accounts and be periodically updated to address impacts from proposed management or policy changes.
4. Build capacity throughout the above process:
   a. Technical capacity for understanding how modeling can support assessments of policy options and impacts on hydropower.

b. Technical and policy capacity to translate economics approach to policy recommendations.

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4| Appendixes

4.1| Appendix A. Data Used for Modeling in Himachal Pradesh

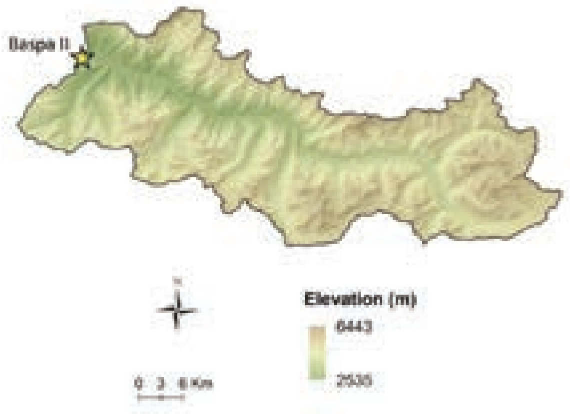
Spatial Data Inputs

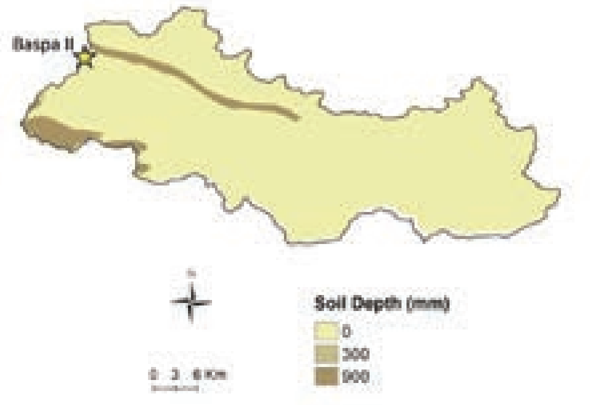
The following data are required for a RIOS/InVEST analysis:

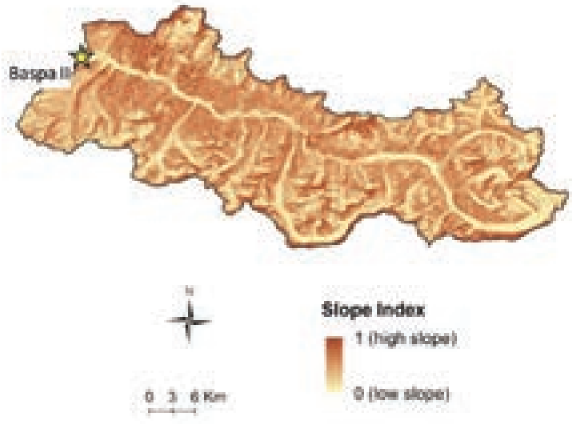
- Digital Elevation Model (DEM)
- Slope index: Generated from the DEM
- Soil depth: Derived from the original soil map
- Soil texture index: Derived from the original soil map
- Soil erodibility: Derived from the original soil map
- Land use/land cover (LULC)
- Vegetation cover index: Reflects the likelihood of each LULC type to generate runoff
- Vegetation roughness index: Reflects the ability of each LULC type to retard water flow
- Sediment export index: Reflects the ability of each LULC type to serve as an erosion source
- Sediment retention index: Reflects the ability of each LULC type to retain sediment
- Annual mean precipitation: Derived from monthly precipitation
- Rainfall erosivity: Derived from annual mean precipitation
- Potential evapotranspiration: Derived from monthly precipitation
- Actual evapotranspiration: Calculated by the InVEST Water Yield model using annual mean precipitation
- Beneficiaries: The final beneficiaries layer is generated by calculating how many people (based on village population) are located downstream of each pixel on the landscape. This reflects how many people are likely to benefit from the ecosystem service provided by that pixel. Shown below are village location and population and the stream network.

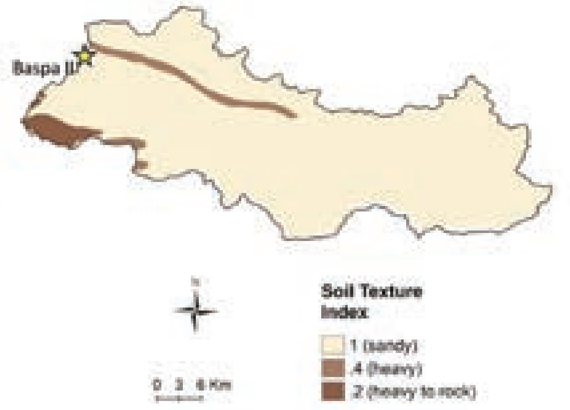
For each selected hydropower station catchment, maps for these data layers are given below. Note that to run the models, these data are required in GIS (spatial) formats.

Terrain/Soil Layers—Baspa II

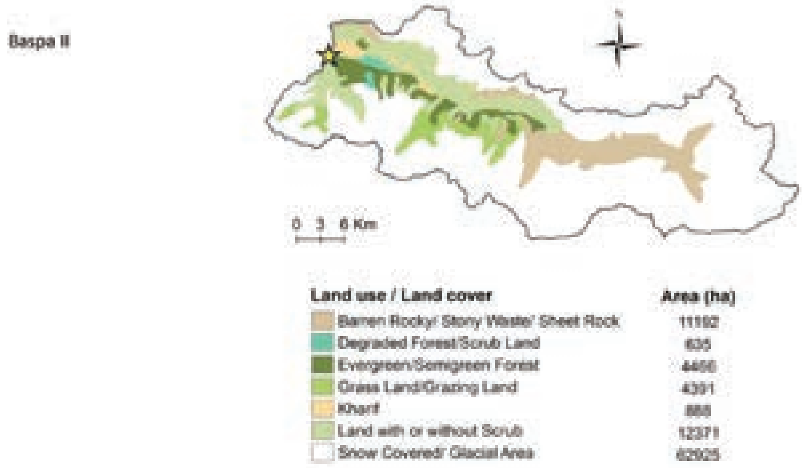


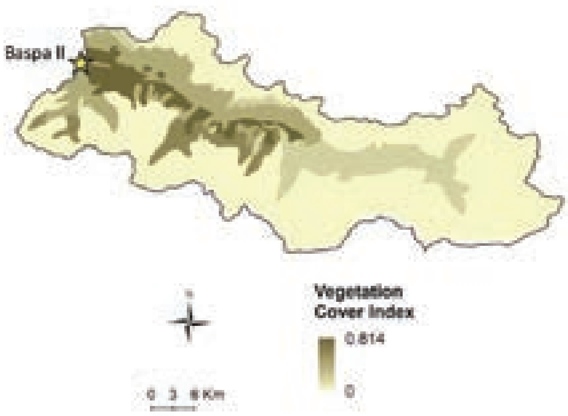


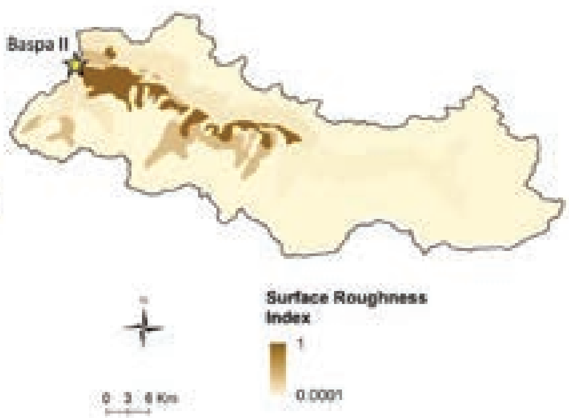


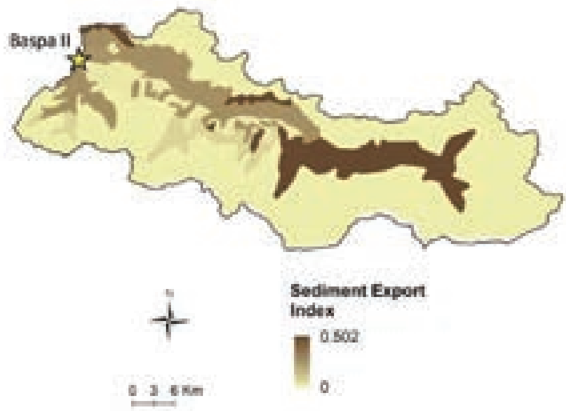


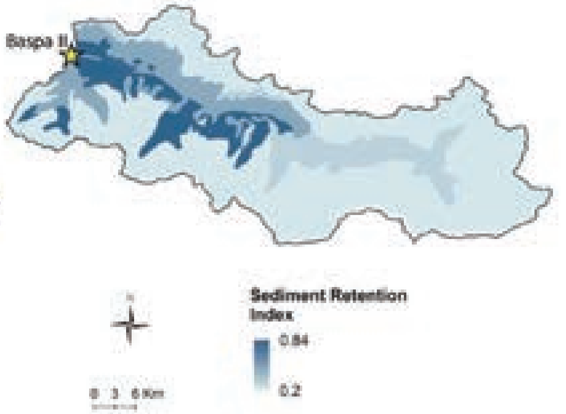
Land Use/Land Cover-derived Layers—Baspa II



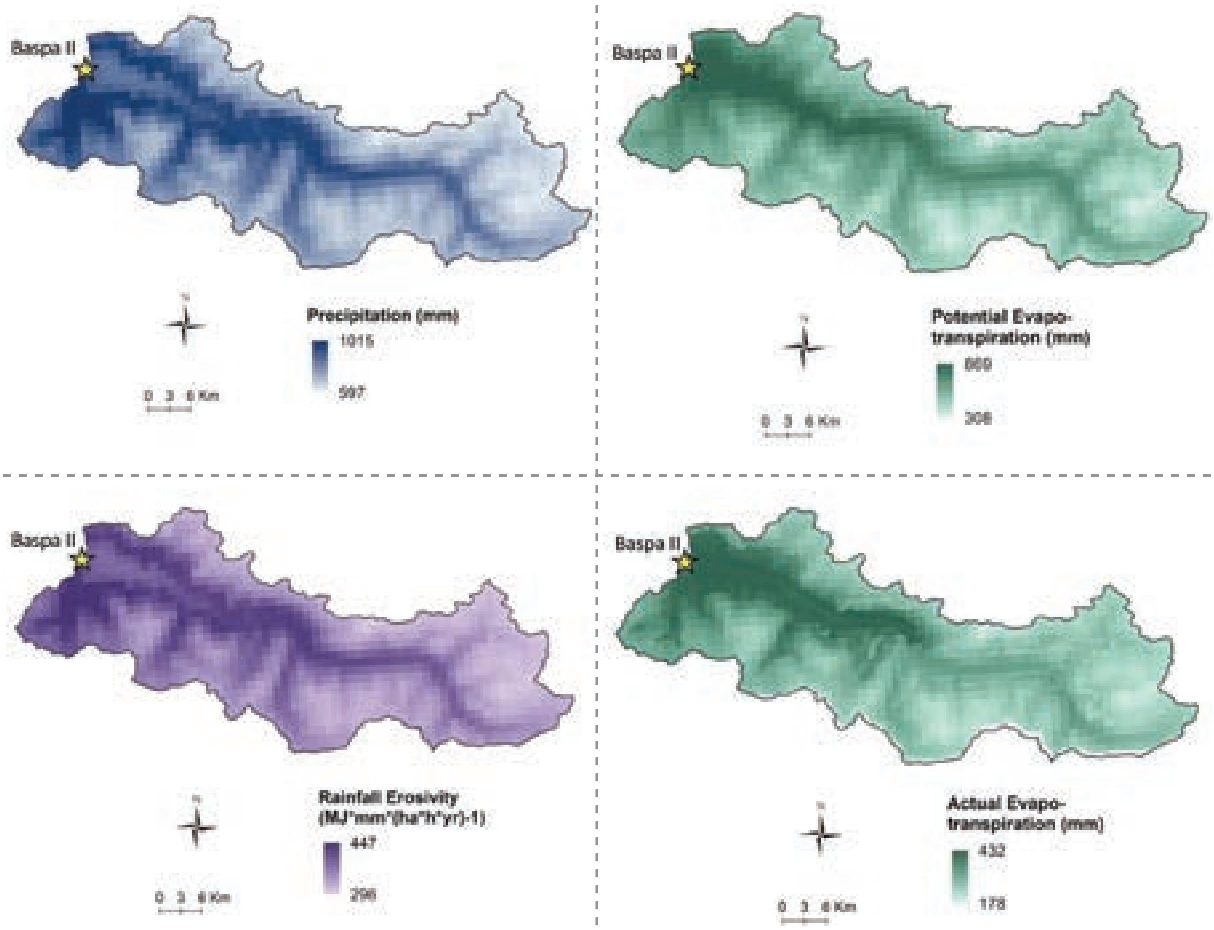




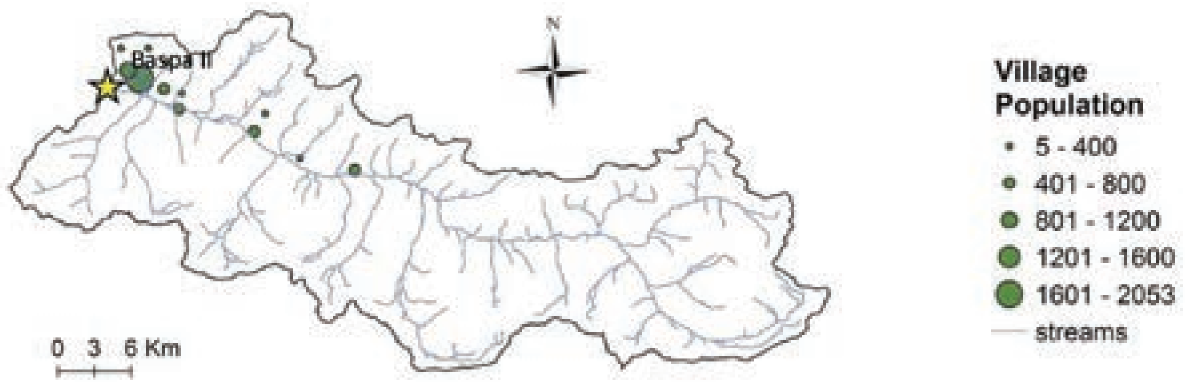




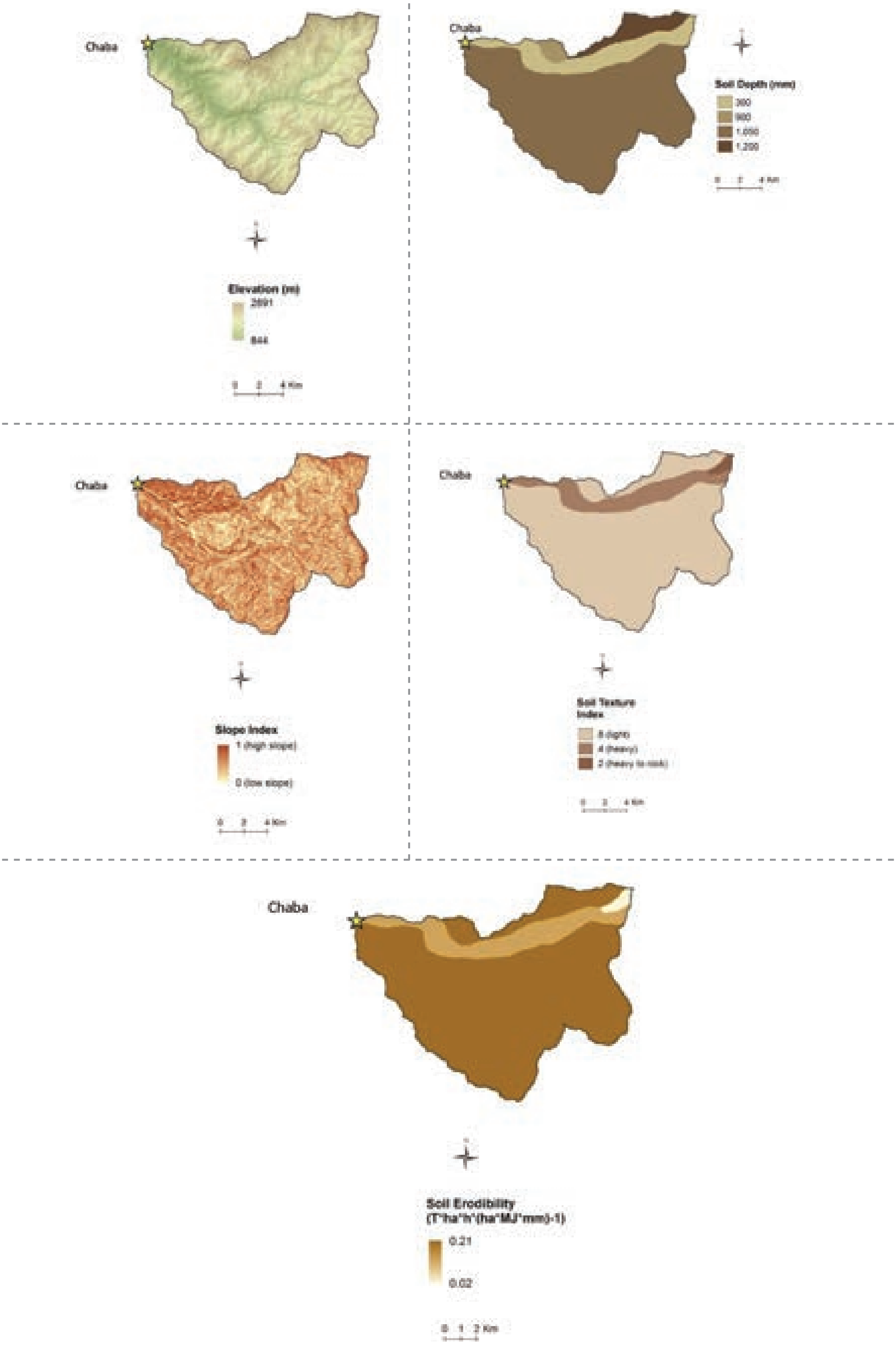
Climate Layers—Baspa II



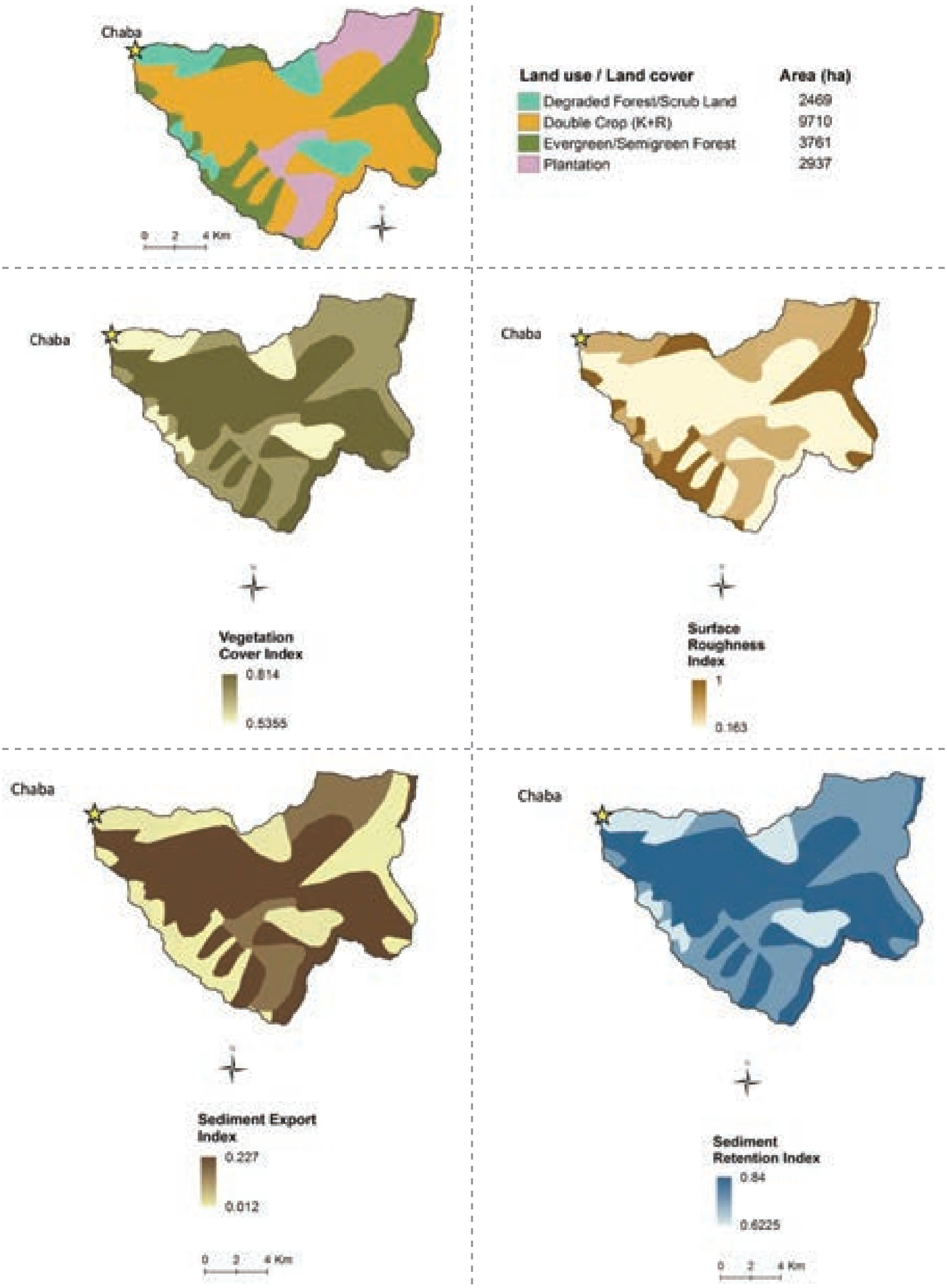
Beneficiaries—Baspa II



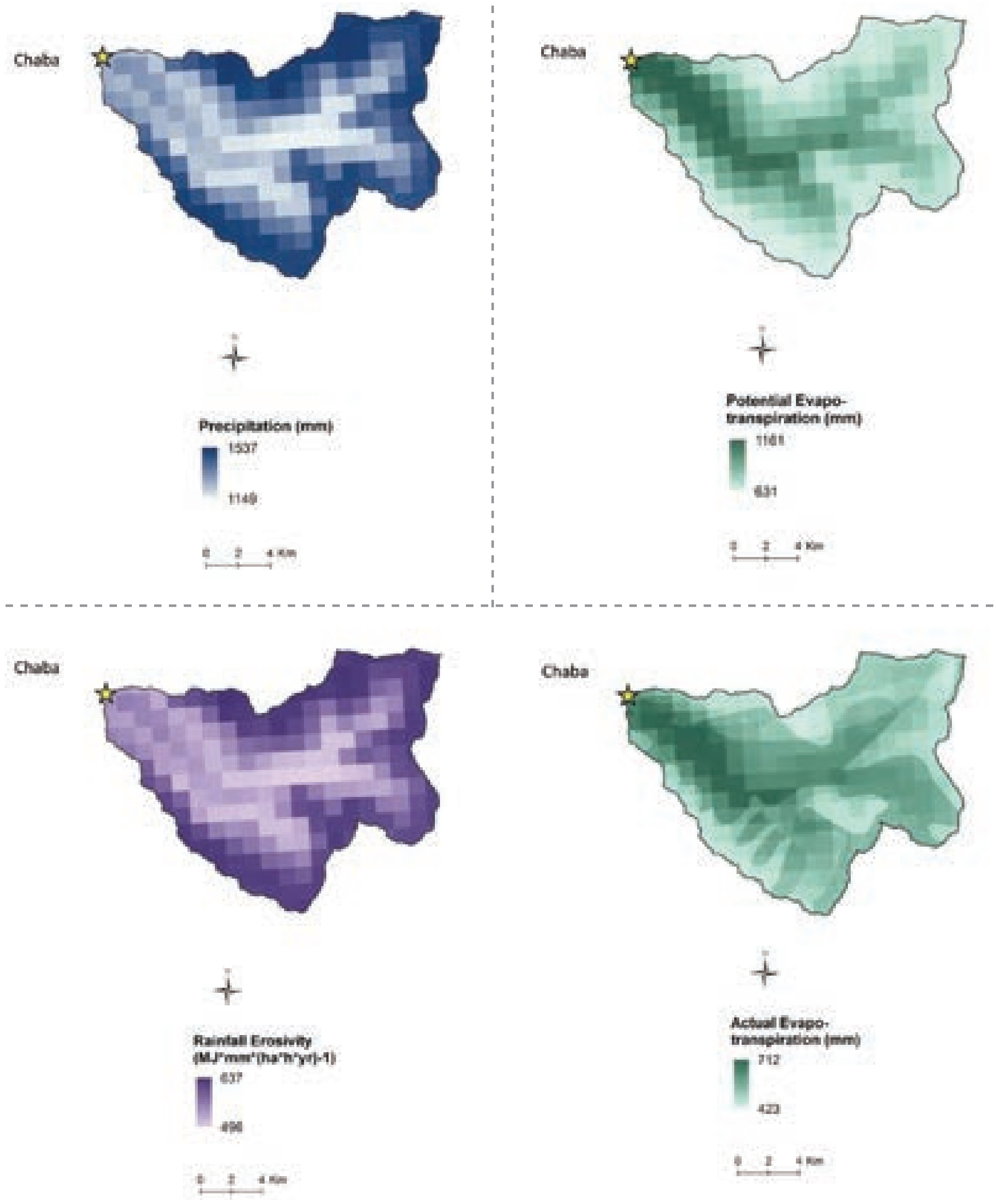
Terrain/Soil Layers—Chaba



Land Use/Land Cover-derived Layers—Chaba



Climate Layers—Chaba



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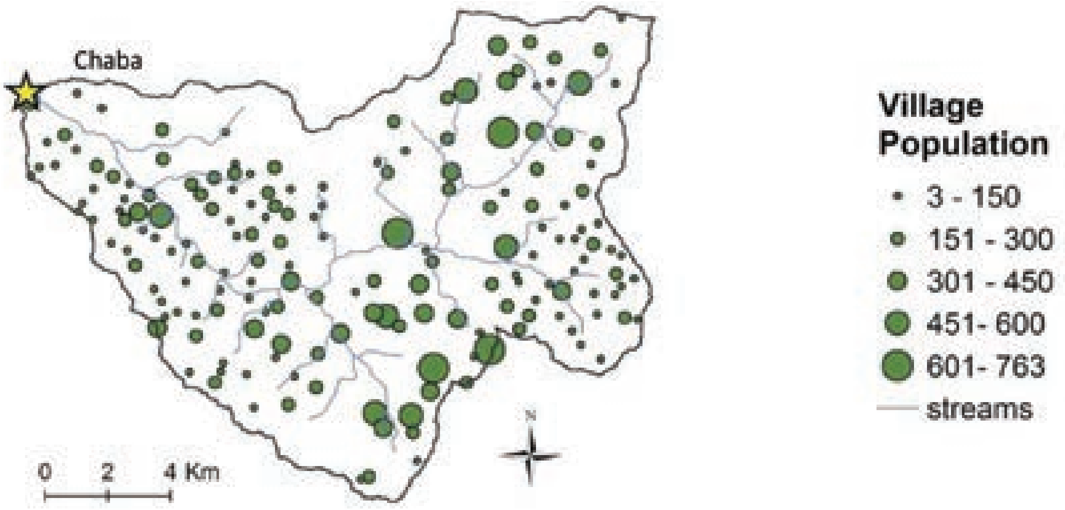
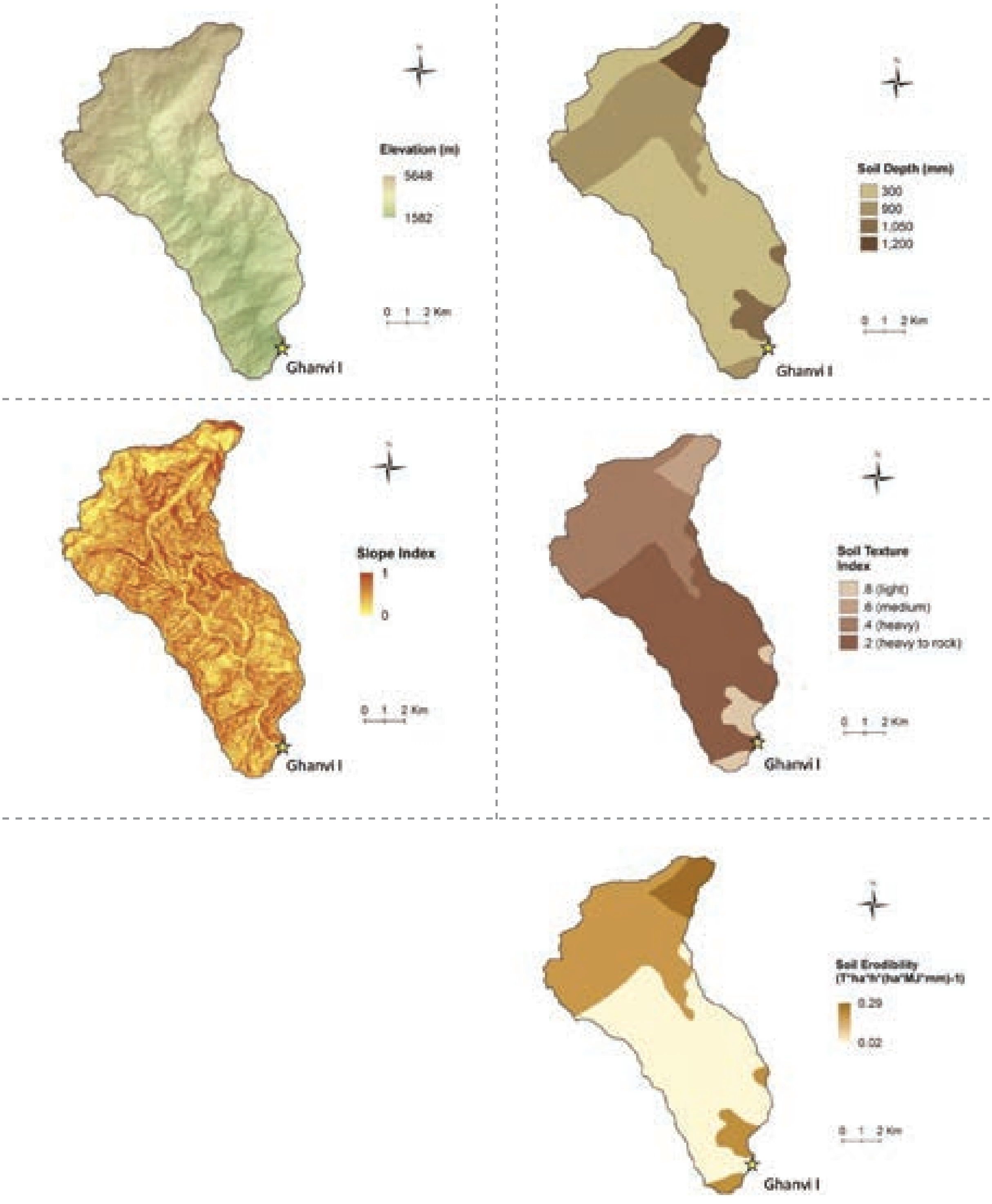
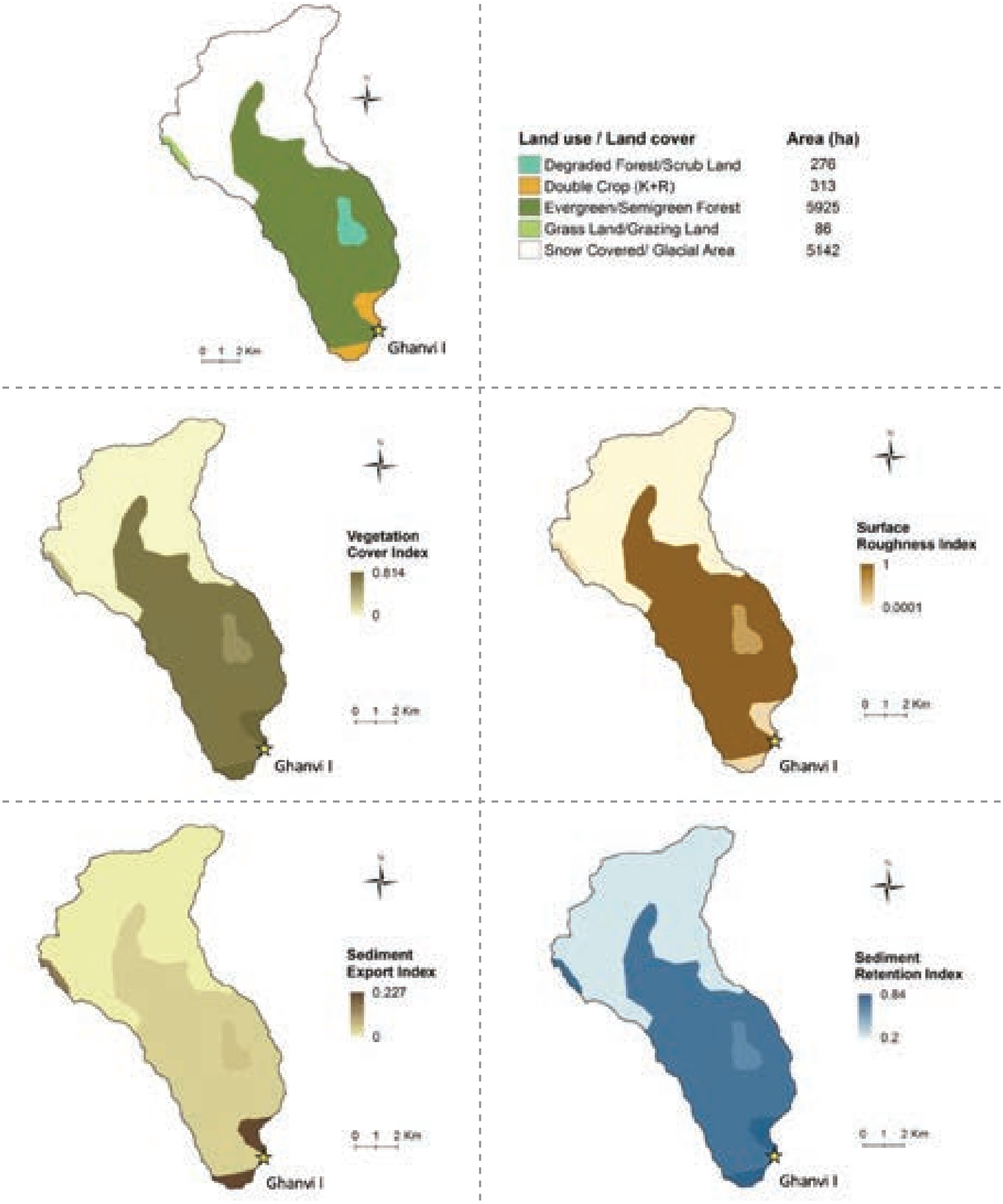


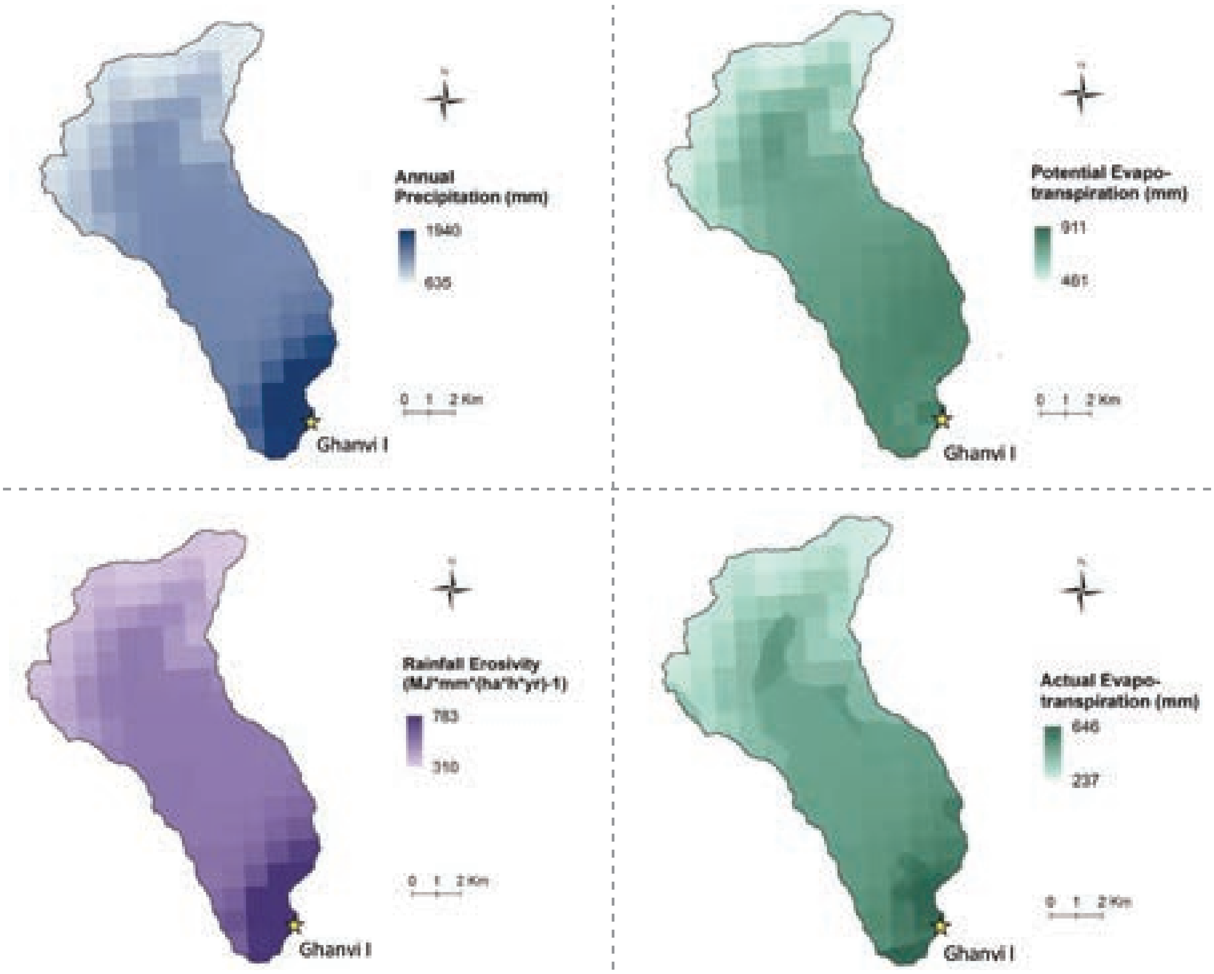
Terrain/Soil Layers—Ghanvi I



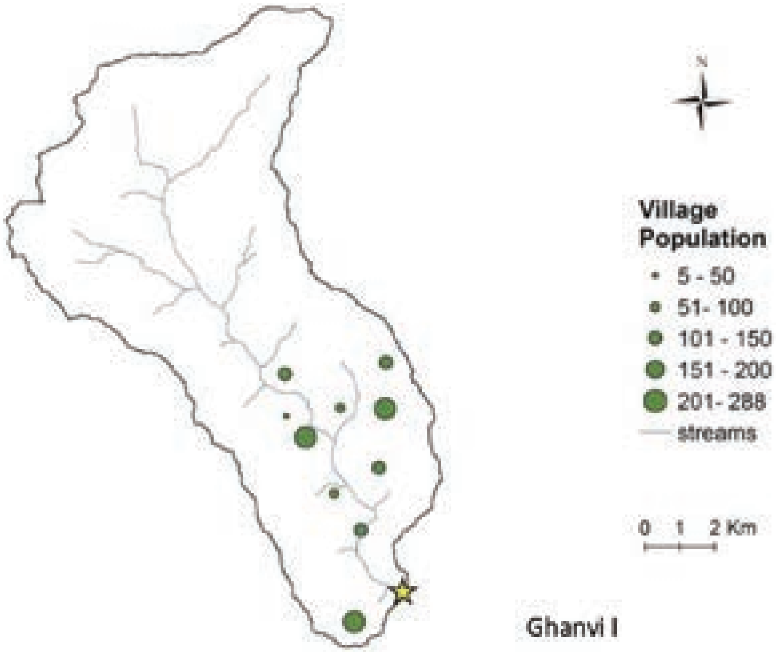
Land Use/Land Cover-derived Layers—Ghanvi I



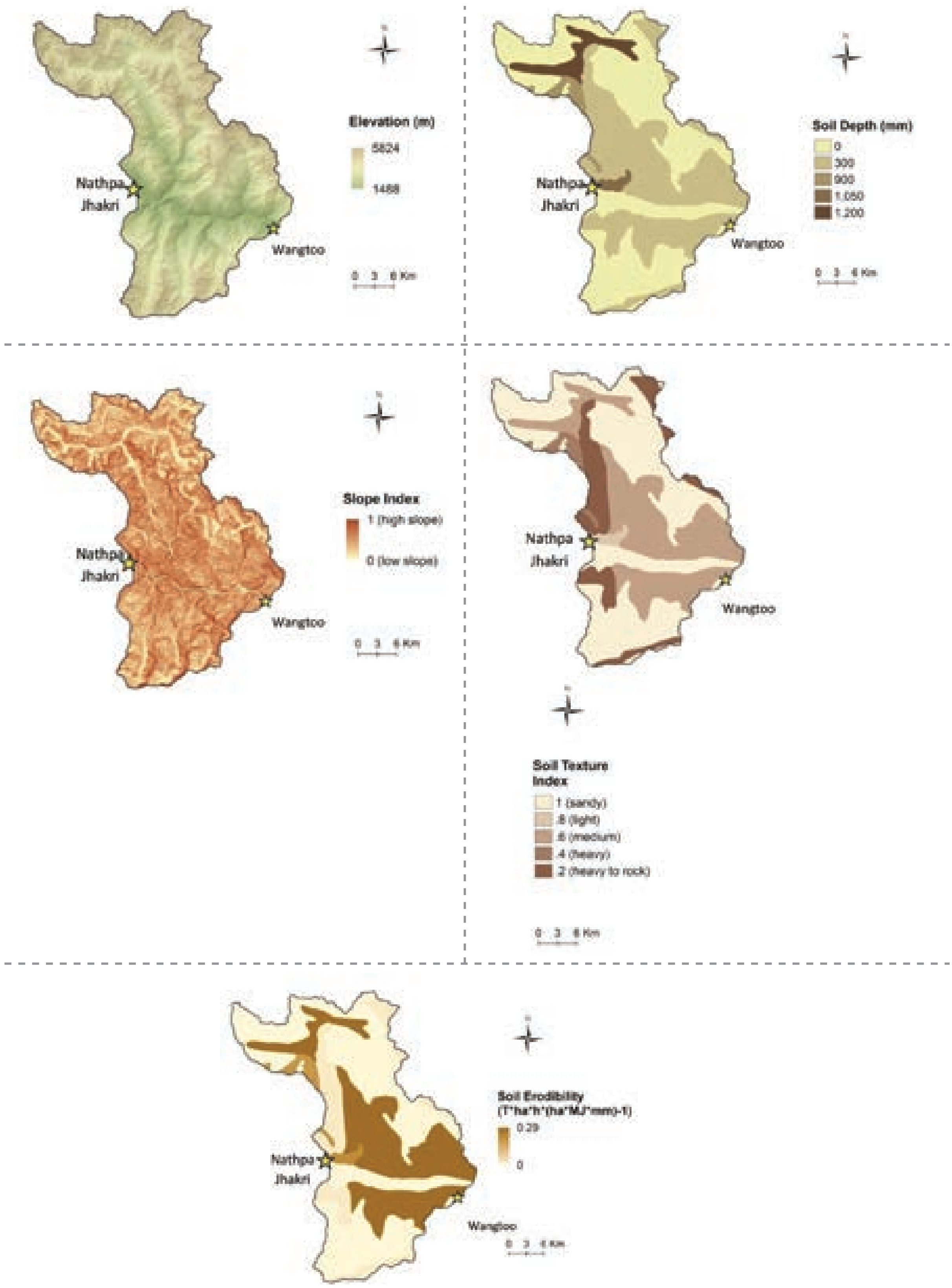
Climate Layers—Ghanvi I



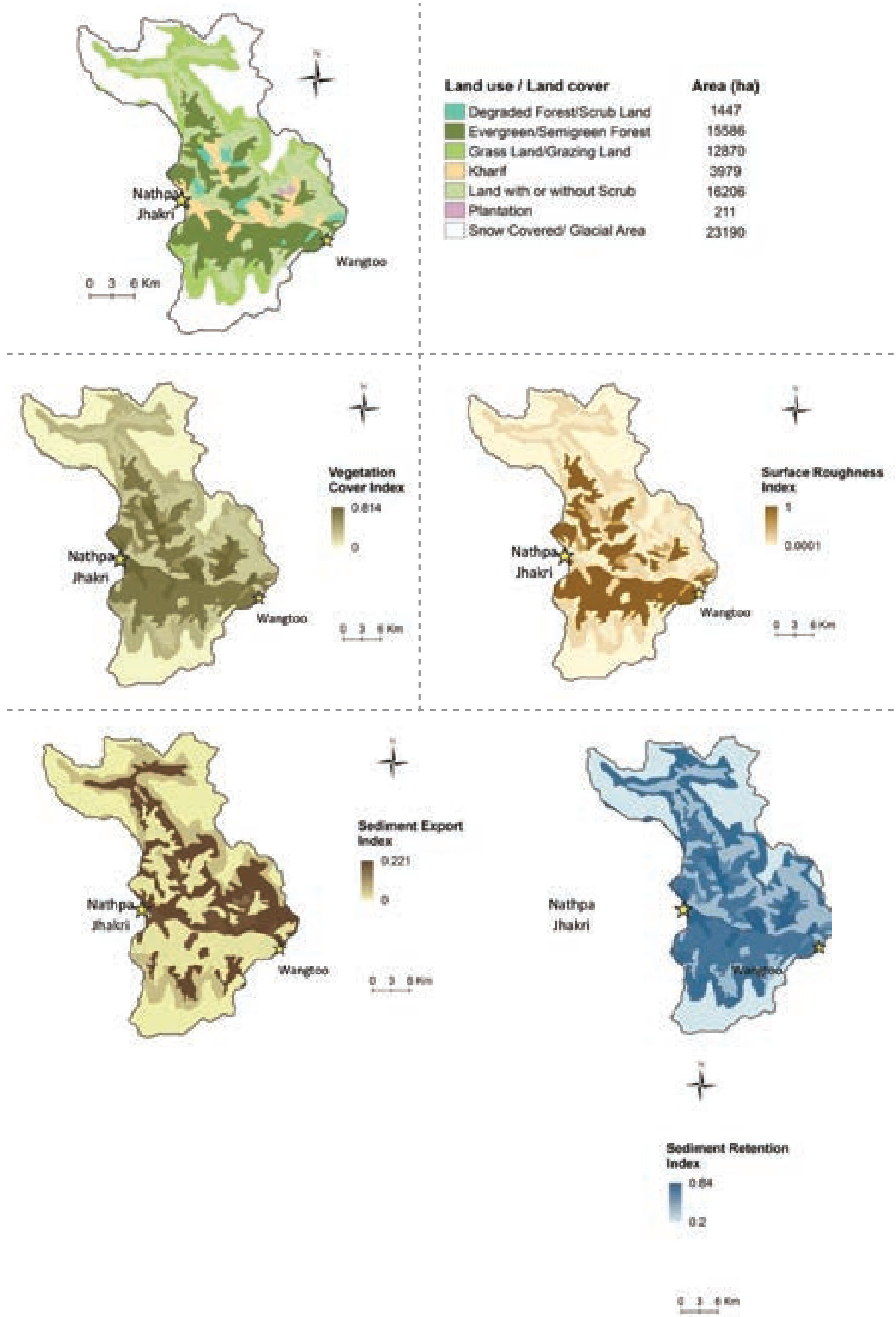
Beneficiaries—Ghanvi I



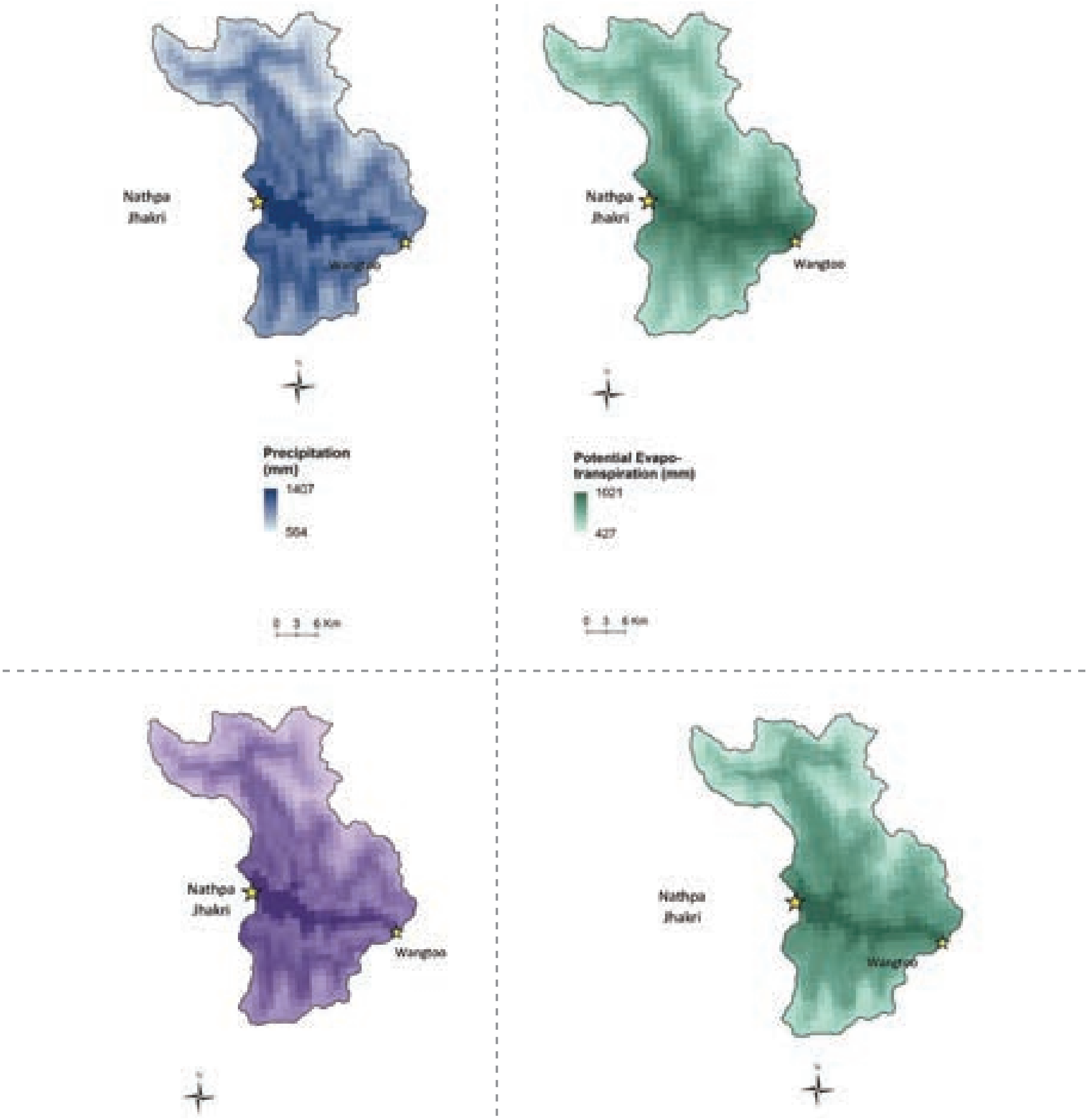
Terrain/Soil Layers—Nathpa Jhakri Subbasin



Land Use/Land Cover-derived Layers—Nathpa Jhakri Subbasin



Climate Layers—Nathpa Jhakri Subbasin



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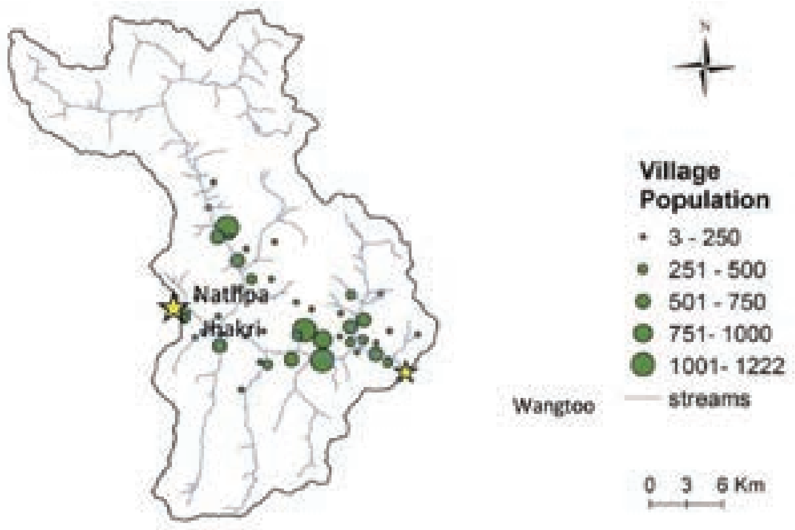
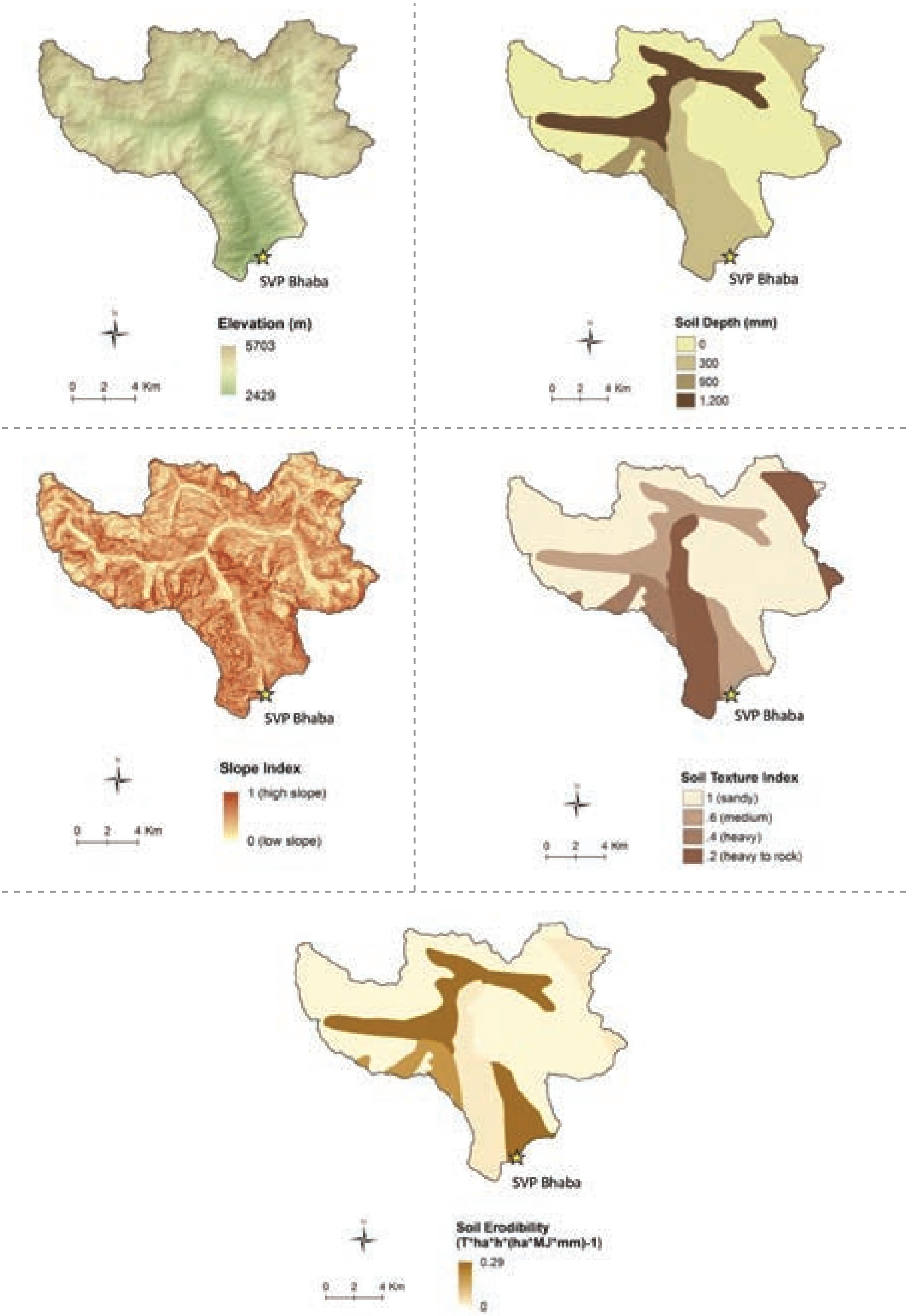
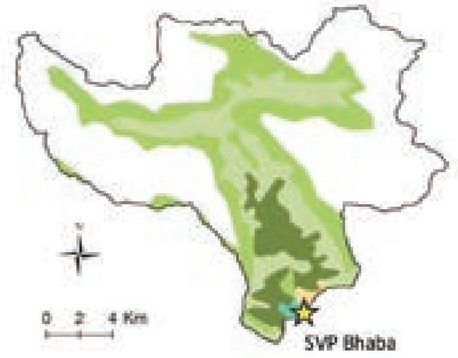


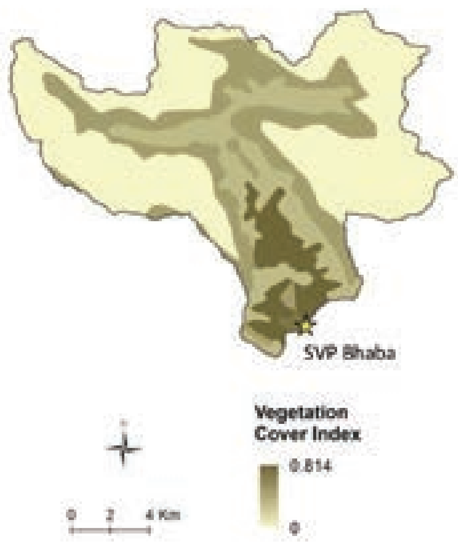
Terrain/Soil Layers—SVP Bhaba

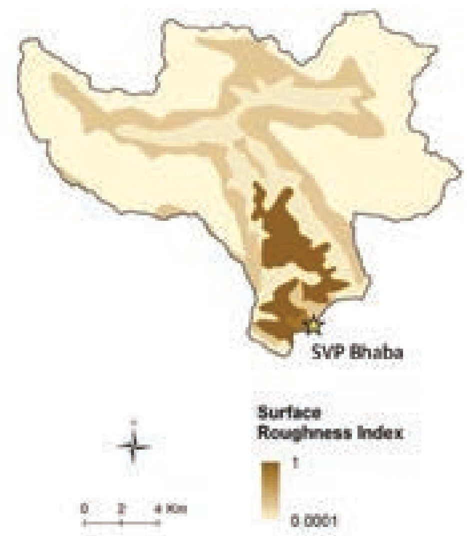


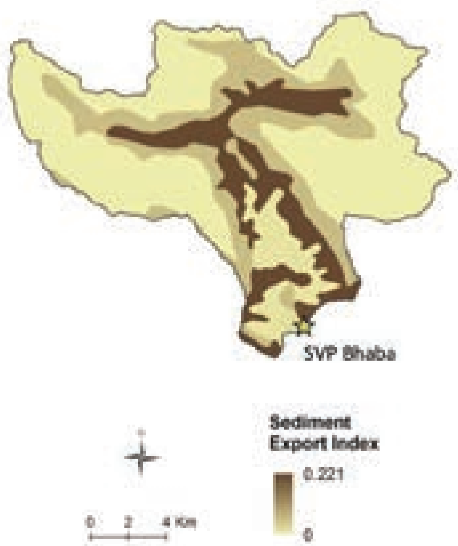
Land Use/Land Cover-derived Layers—SVP Bhaba

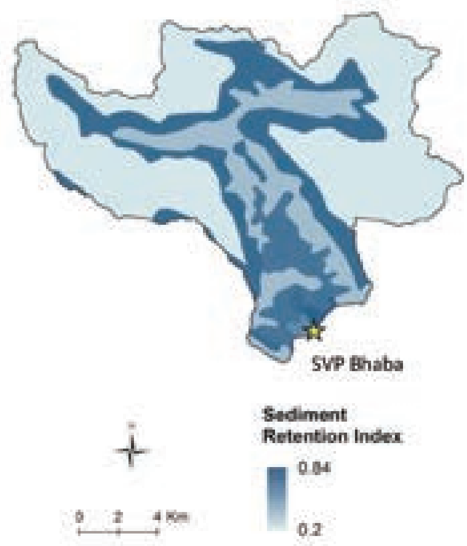


Land use / Land cover	Area (ha)
Degraded Forest/Scrub Land	122
Evergreen/Semigreen Forest	1941
Grass Land/Grazing Land	6221
Kharif	145
Land with or without Scrub	4442
Snow Covered/ Glacial Area	14311

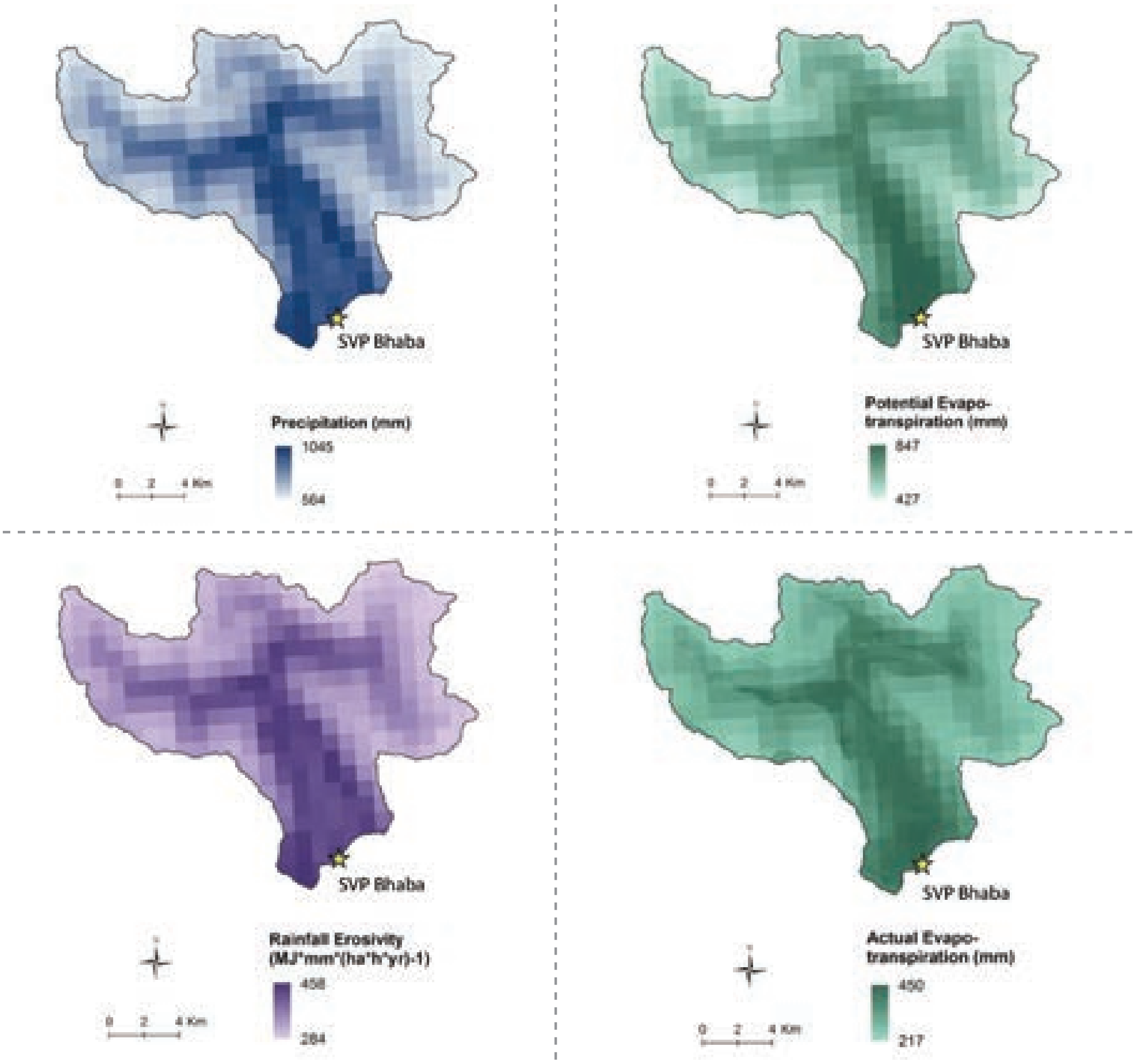


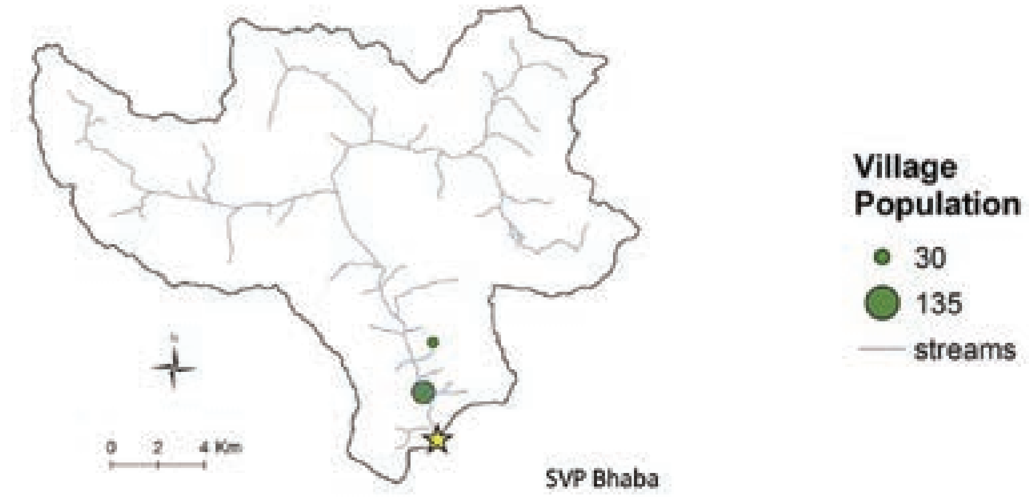






Climate Layers—SVP Bhaba





Nonspatial Data Inputs

Table A1: Parameters used by the RIOS and InVEST models that are assigned to each land cover class

Land Cover Class	Activity	USLE C	USLE P	Sediment Retention Efficiency	Root Depth	Evapotran-spirtaion Coefficient	Roughness	Cover
Evergreen/ Semigreen Forest		0.012	1	0.74	1120	0.93	1	0.714
Degraded Forest/ Scrub Land		0.018	1	0.6225	990	0.91	0.5345	0.5355
Land with or without Scrub		0.221	1	0.3825	1650	0.89	0.041	0.2355
Plantation		0.16	0.9	0.74	1130	1	0.5	0.714
Kharif		0.205	0.9	0.84	900	0.88	0.163	0.814
Double Crop (K+R)		0.227	0.9	0.84	1100	1.1	0.163	0.814
Grass Land/ Grazing Land		0.138	1	0.5863	950	0.93	0.102	0.2963
Gullied or Ravinous Land		0.644	1	0.26	0	0.61	0.013	0.114

(continued on next page)

Table A1: Parameters used by the RIOS and InVEST models that are assigned to each land cover class *(continued)*

Land Cover Class	Activity	USLE C	USLE P	Sediment Retention Efficiency	Root Depth	Evapotran-spirtaion Coefficient	Roughness	Cover
Barren Rocky/ Stony Waste/ Sheet Rock Area		0.502	1	0.26	0	0.72	0.013	0.114
Snow Covered/ Glacial Area		0	1	0.2	0	0.82	0.0001	0
Evergreen/ Semigreen Forest	Without protection (degrad-ed)	0.018	1	0.6225	990	0.91	0.5345	0.5355
Degraded Forest/ Scrub Land	Energy plantation	0.015	1	0.68125	1055	0.92	0.76725	0.62475
Degraded Forest/ Scrub Land	Live hedge fencing	0.0108	1	0.7781	1120	0.93	[b]	[b]
Degraded Forest/ Scrub Land	Contour trenching	0.0108	1	0.93	1120	0.93	[b]	[b]
Degraded Forest/ Scrub Land	Enrich-ment	0.012	1	0.74	1120	0.93	1	0.714
Land with or without Scrub	Fodder develop-ment	0.054	1	0.79	950	0.96	0.163	0.357
Land with or without Scrub	Energy plantation	0.1195	1	0.5025	1320	0.9	0.28775	0.3855
Land with or without Scrub	Live hedge fencing	0.1326	1	0.4781	1650	0.91	[b]	[b]
Land with or without Scrub	Contour trenching	0.1326	1	0.574	1650	0.91	[b]	[b]
Grass Land/ Grazing Land	Fodder develop-ment	0.054	1	0.79	950	0.96	0.163	0.357

Note: These values are used wherever a land cover class is designated on a landscape, so the values are nonspatial (do not change based on location).
[a] Parameters are not applicable in this study.

4.2| Appendix B. Estimating Sediment (TSS) in Ghanvi Catchment

The following looks at regression (power law) between the daily flow and TSS data for the Ghanvi catchment for the period between April 2010 and August 2011.

The time window was selected to obtain a representative sample (>500 days), which avoids the bias toward high TSS values. Selection of all data would, indeed, result in an overrepresentation of high TSS values, because the sampling protocol focused on these conditions. The resulting regression equation (shown in the figure below) was then applied to estimate missing values for daily TSS based on the available flow data.

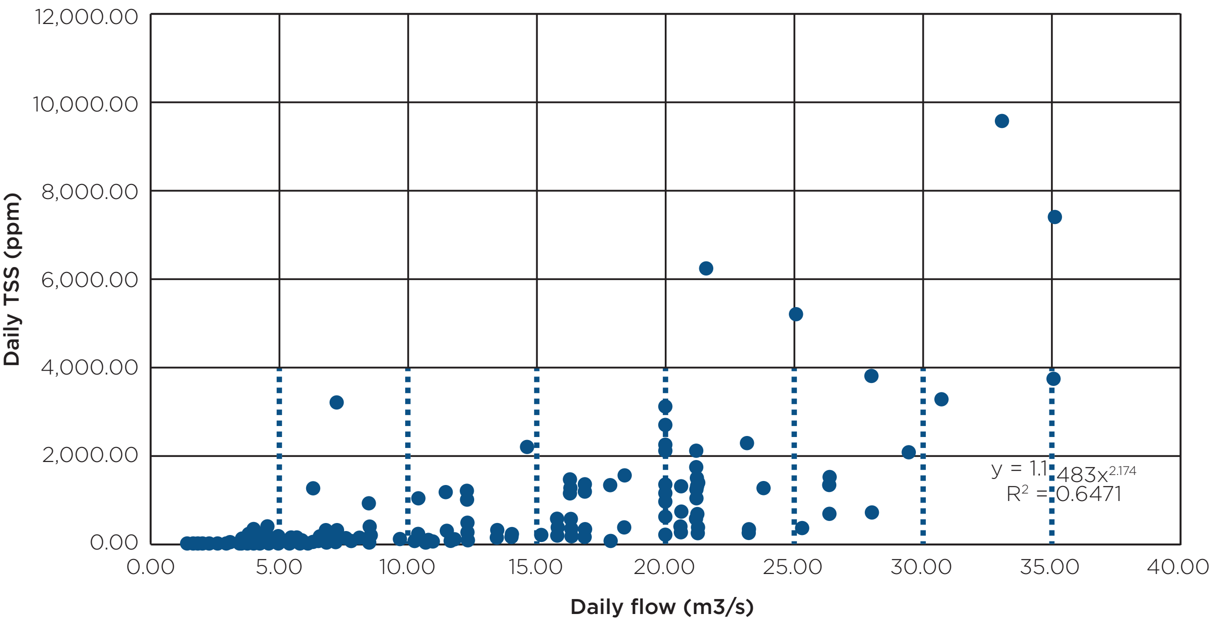
4.3| Appendix C. Hydrologic Model Comparison

Introduction

In this project, we assess the strengths and weaknesses of two modeling approaches: SWAT, a process-based model commonly used for management of hydrologic systems in the United States and Europe; and the InVEST annual water yield and sediment models, an integrated catchment model developed to estimate hydropower ecosystem services and erosion control for reservoir maintenance and water quality. We address the philosophical understanding of each of these models, the structure and equations that each solves, the data requirements, necessary scientific capacity, and the questions that each model can reliably address. We focus our assessment for potential power production on the use of the flow-duration approach. In addition, we consider the power production lost because of excess sediment concentration and the ability to formally optimize hydropower ecosystem services through landscape management. We also discuss the ability to consider how power demand and flow characteristics vary, and the resulting value of ecosystem services.

In a flow-duration approach, potential power production is calculated from the multiplication of head drop and flow rate, with adjustment for appropriate units. This approach requires a

Figure B1: Results of regression analysis used to estimate daily sediment loads based on observed flow in the Ghanvi catchment



combination of flow characteristics and information on existing or proposed dam infrastructure. The amount of sediment that can be handled, as well as the most productive flow-duration curve, depends upon the engineering details of the dam infrastructure. The required dam infrastructure information is listed here:

- Dam leakage (volume/time)
- Minimum head for turbine operation
- Minimum discharge for turbine operation (corresponds to maximum head)
- Rated and design head for turbine
- Full-gate discharge
- Turbine efficiency

For flow characteristics, the flow-duration approach requires an estimate of discharge distribution over the year and information on the tailwater elevation-discharge relationship. From this information, power-duration curves can be constructed that show the amount of power that can be created at different percentages of the time. The actual times of these discharges (and resulting power) can be made explicit using a time series approach. Alternately, the peak demand months can be separated and the power generation during those months can be calculated to assure that power is available when necessary.

Model Philosophy

Two distinct approaches (and a variety of combinations and in-between approaches) are used for building hydrologic models. These two approaches go under a number of different names: bottom-up versus top-down, Newtonian versus Darwinian, and so on. For the rest of this document, we will refer to the first as process-based models (bottom-up, Newtonian) and the second as integrated catchment models (top-down, Darwinian). Process-based models are often used for management in the United States and Europe, come from an engineering background, and extend the results of small-scale understanding of physical processes to much larger scales. Integrated catchment models were developed to understand the behavior of catchments as systems, and often fit into a physics-based thinking about complexity and emergent behavior.

Process-based models, such as the Soil Water Assessment Tool (SWAT), combine scientists' understanding of small-scale hydrologic behavior into large-scale hydrologic simulators. Mathematical models of small-scale hydrologic flows are developed to accurately represent the behavior of these flows in ideal situations and to parameterize how they vary with flow circumstances (for example, the development of Darcy's law to describe saturated flow through porous media, and the variation with the permeability of the porous media). Then these flows are linked together by combining processes temporally in a given location and spatially across locations. At each location, the flows respond based upon that location's parameters, and feed into neighboring flows (both spatially and temporally). The sum of these flows is compared with observations, and often the parameters are adjusted to better match the flow sum to the observations (calibration). Calibration is necessary because common parameters vary significantly on scales much smaller than the measurement scale, so the parameters need to serve as "effective" values rather than true measurements. Most often calibration is performed using observed stream discharge, although other options (for example, evapotranspiration measurements from satellites) are possible and have begun to be used more broadly.

In contrast, integrated catchment models such as the InVEST annual water yield model (hereafter InVEST annual), predict the integrated catchment response based on large-scale (in both space and time) measurement of catchment characteristics and forcings. This top-down approach views the catchment (or some flow path in the catchment) as a system with emergent properties, and models those emergent properties, instead of the individual steps from which they emerge. Integrated catchment models do not consider known physical and chemical processes at small scales; instead, an understanding of the small-scale processes is derived from the structure of a successful large-scale model.

Both of these modeling approaches have advantages and disadvantages. Integrated catchment models are more parsimonious and are generally computationally inexpensive so that many different scenarios can be run quickly. However, integrated catchment models have not been shown to perform well away from the sites or scales for which they are developed, because alternative processes may have a greater influence on the overall response. Moreover, integrated watershed responses vary significantly across sites and scales. Process models, in comparison, have the advantage of beginning with known physical and chemical processes. As long as all the relevant processes are included, they may be applicable in all locations and across a variety of scales. But bottom-up models are more computationally expensive, and calibration can be highly uncertain and nonunique and requires significant expertise to perform correctly (refer to Part II. Model Validation and Uncertainty Assessment).

Model Structure

SWAT and InVEST annual models have significantly different structures as discussed here briefly. More details are available in the documentation for each model. Note, the theoretical documentation for SWAT runs to 600 pages, so the description here is very simplified and focuses on the water flow and sediment components of the model, not on water chemistry, plant growth, crop management, weather generation, and other components.

InVEST

The InVEST annual water yield model uses a Budyko Curve framework (Figure C1) after Zhang et al. [2004]. The Budyko curve states the following: on a long-term average the evaporation index (evaporation/precipitation) plotted against the dryness index (potential evapotranspiration/ precipitation) must fall within an envelope constrained by the 1:1 line (above this and there would be more evapotranspiration than energy available to evapotranspire) and the evaporative index of 1 (above this and more water would be evapotranspiring than fell as precipitation). The Budyko curve assumes that the watershed has no groundwater mining and that no water transfers are occurring. More recent work by Zhang et al. (2004) suggested that different land-use/land-covers fall along consistent curves depending upon the local dryness index. Zhang et al. (2004) parameterizes this relationship between evapotranspiration (AET_x) and precipitation (P_x) as

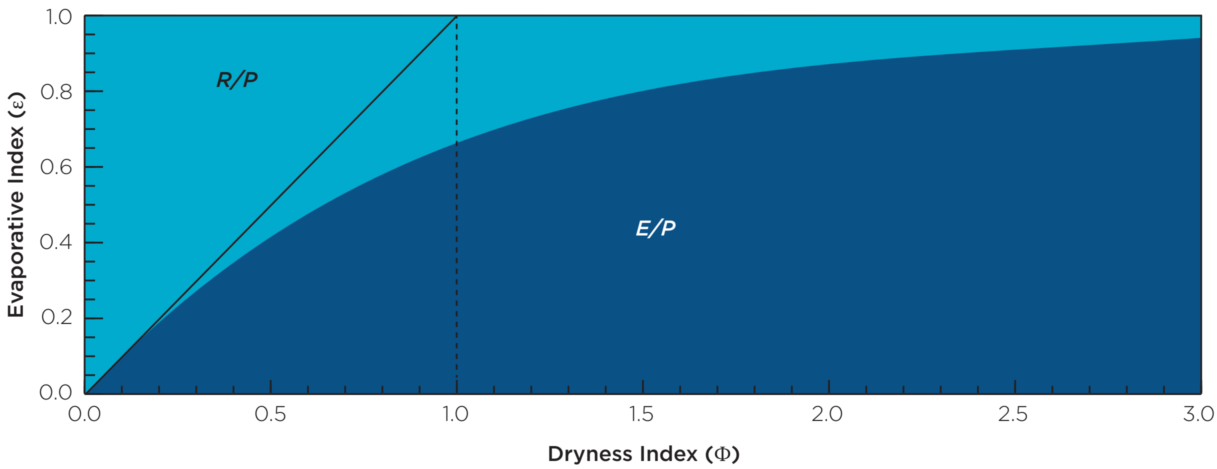
$$\frac{AET_x}{P_x} = \frac{1+\omega_x R_x}{1+\omega_x R_x + 1/R_x}$$

with larger ω corresponding to curves that come closer to matching the envelope.

The InVEST annual model applies this calculation for each pixel (x), looking at the annual balance of precipitation and energy for evapotranspiration adjusted by a storage term. The water yield is defined as the water left after evapotranspiration, or

$1-\frac{AET_x}{P_x}$. This calculation involves two terms. The first, R_x, is an energy term that specifies the

Figure C1: The Budyko curve



Note: The Budyko curve states that on a long-term average the evaporation index (evaporation/ precipitation –y axis) plotted against the dryness index (potential evapotranspiration/precipitation—x axis) must fall within an envelope constrained by the 1:1 line (above this and there would be more evapotranspiration than energy available to evapotranspire) and the evaporative index of 1 (above this and more water would be evapotranspiring than fell as precipitation).

demand for water over the year relative to the supply, using a crop coefficient to adjust the potential evapotranspiration (that is, the evapotranspiration of an ideal, well-watered crop). The second term, ω_x, is a storage term that adjusts the demand for water by: (1) the ability of the soil to store water; and (2) the relative seasonality of energy demand for water and the water supplied through precipitation:

$\omega_x = Z \frac{AWC_x}{P_x}$. In this equation *Z* is a term that adjusts for seasonality and *AWC* is the vertical storage capacity of the soil available to plant roots. If *AWC* is large then the seasonality does not matter much because a great deal of water can be stored locally and used over the course of the year; if *Z* is large this suggests that the energy demand for water and supply of water occur in sync, leading the system to be close to the envelope.

After the calculation of water yield, a hydropower valuation model can be applied in InVEST. First water consumed upstream of the dam is subtracted from the water yield. Then the power produced is calculated based on an average annual flow rate and an average head drop across the turbine (supplied by the user), which is then adjusted by efficiencies of the turbine. Note that this is the same basic approach as the flow-duration approach but relies on average annual values.

The InVEST annual sediment retention model uses the Universal Soil Loss Equation (USLE) and an iterative soil trapping scheme to estimate the amount of soil eroded from each pixel and the amount of sediment trapped by vegetation on each pixel. The USLE is a widely-used, empirically-based model for erosion losses based on erosion experiments run in the United States. In the USLE erosion is broken down into several components which are multiplied:

$$USLE = R * K * LS * C * P$$

R is the rainfall erosivity (a measure of the strength of rainfall), *K* is the soil erodibility factor, *LS* is the topographic factor, *C* is the land cover and management factor, and *P* is the land practice factor. *R, K,* and *LS* are considered to be features of the local climate, geology, and topography, but *C* and *P* can be adjusted by changing local land use, cover, and management practices in order to manage erosion. In InVEST, the USLE is applied on a per-pixel basis, although the equation was originally developed to assess subbasin-scale erosion. The USLE provides an estimate of the erosion that occurs on a parcel of land.

In addition, the InVEST annual sediment retention model implements an iterative soil trapping scheme to estimate the amount of soil trapped by vegetation downstream of soil erosion. To start, a route to the channel is assessed for the runoff from each pixel. Each land use type is assigned a sediment-trapping efficiency. The sediment is then iteratively routed from the upstream-most pixels, with sediment coming from upstream pixels being trapped at a given efficiency rate (usually derived from published studies of erosion), and the sediment going down-route being the combination of that sediment that is not trapped at an individual pixel and the sediment eroded from that pixel. The model also includes several valuation steps, one for water quality excluding sediment under and annual-accepted load, and avoided dredging for reservoirs excluding amounts that fill the engineered dead volume.

SWAT

SWAT is a semidistributed process-based hydrologic model that operates primarily on a daily time-step (it can also be run at subdaily scales, but this is less common). SWAT is semidistributed in that, rather than having an explicit calculation for each pixel, it groups areas with similar land use types, soils, and slopes within each subwatershed (defined by an accumulation area specified by the user). These similar areas are called hydrologic response units (HRUs). SWAT calculates water flow for each of HRU and then assumes that each HRU is connected directly to the main stream channel (Neitsch et al. 2011).

HRUs can be spatially discontiguous and so do not represent real patches of land. As such, SWAT estimates flow characteristics at the subbasin level rather than on a pixel-by-pixel basis. Nonlinear flow feedbacks (for example, forest uphill of pasture vs. pasture uphill of forest) may be missed because of this lack of spatial information.

For the purpose of this publication, we separate the SWAT water processes into four categories: 1) atmosphere-land surface interactions, primarily precipitation and evapotranspiration; 2) surface processes including flow and instream routing, as well as snow deposition and melting; 3) subsurface processes including infiltration and interflow, shallow groundwater flow, and water loss to deep aquifers; and 4) sediment processes.

Atmosphere-land surface interactions

Atmosphere-land surface interactions in SWAT consist primarily of precipitation and evapotranspiration. Daily precipitation can either be defined by the user or by a weather generator that calculates precipitation and other climate factors based on a distribution and the monthly means for the location. This precipitation is added to the surface minus canopy interception, which can vary across plant types. Evapotranspiration is calculated based on both the potential evapotranspiration (as defined above) and water available within each soil depth. Potential evapotranspiration is calculated using one of three systems: 1) Penman-Monteith; 2) Priestly-Taylor; and 3) Hargreaves. The actual evapotranspiration fills this energy demand: 1) first through any water trapped in the canopy; 2) second through transpiration through plants (maximum plant transpiration is set as $ET_{max} = \frac{LAI}{3.0} PET$); and 3) then through evaporation from the soil.

Evapotranspiration from both plants and soil proceeds soil layer by soil layer until the potential evapotranspiration is satisfied, with two parameters (EPCO and ESCO) controlling the depth distribution of transpiration (Plant) and evaporation (Soil) through the soil column.

Surface processes

Surface (overland) flow is determined in most cases using the SCS (Soil Conservation Service) Curve Number approach, which sets the partitioning between surface flow and infiltration based on a curve number. The percentage of runoff rises nonlinearly with the curve number, so that at curve number of 100 all precipitation goes as runoff and at a low curve number all water infiltrates. In addition, the curve number method includes an initial abstraction, which removes some water from runoff because of plant interception, immediate soil infiltration, and so on. Curve numbers have been calculated for a wide variety of land types in different hydrologic groups (defined by the tendency of water to infiltrate when thoroughly wetted). These curve numbers are based on a broad set of studies in small watersheds across the United States by the Soil Conservation Service. In SWAT, the curve number is adjusted for the hydrologic condition of the soil based on previous rainfall and infiltration. This adjustment assures that at full soil saturation, all the water will partition to runoff and at wilting point most water will infiltrate into the soil. For more details see the SWAT theory document.

Surface runoff is added into the subbasin stream channel, from where it proceeds downstream through the entire watershed. SWAT assumes a trapezoidal-shaped channel. The channel depth and width can be set automatically through DEM analysis with the ArcSWAT package, which enables a SWAT model to be set up through ArcGIS. In-stream flow follows the standard Manning's equation with the Manning's coefficient by default set to 0.0014 to account for channel roughness effects. The storage and flow rate through the channel are calculated using one of two techniques: the Muskingum method or the variable storage method. The Muskingum method allows for storage in two components: the "rectangular"

cross-section of a flat channel and a prism whose shape is specified by a weighting factor that determines the relative importance of inflow and outflow in storage. The variable storage method divides the storage in the channel by the flow rate out to calculate the travel time, sets that travel time as a constant, and then calculates the flow rate out. Additional calculations in SWAT account for the loss of water from the channel to evaporation and to transmission through the streambed to the aquifer, as well as the storage of water in the stream banks.

SWAT also specifies snowfall and snow melt differently from rainfall and runoff. Snowfall and rainfall are separated by a user-set threshold, which is compared to the mean daily temperature (T_{mean}): if T_{mean} is larger than the threshold precipitation results in rainfall; if smaller, precipitation results in snowfall.

Snowfall is added to a snow storage term that is kept for each HRU. The snow temperature is tracked based upon a user-specified lag factor, and snow melt is calculated based upon a linear difference of the snow temperature and the maximum daily temperature. Snow melt is also weighted by a melt fraction that varies seasonally, being maximum on the summer solstice and minimum on the winter solstice.

Subsurface processes

Subsurface processes in SWAT occur after accounting for daily infiltration from the surface flow component. The soil is divided into a number of layers based on user input; each layer can have a distinct bulk density (and, hence, porosity), percent clay, available water content (the amount of water that can be stored after gravity drainage), and hydraulic conductivity, among other factors.

Downward flow through the soil layers occurs by percolation, which is parameterized by an exponential term with a rate set by both the amount of excess water and the hydraulic conductivity of the layer. Percolation out of the bottom soil layer is sent to the shallow aquifer. Lateral flow occurs in the saturated thickness of the soil and discharges directly into the stream channel. Lateral flow is controlled by the hydraulic conductivity of the layers, the slope and length of the topography, and by an exponential term, which includes a lag parameter. In addition, flow through vertisols (soils that develop large cracks when dried because of shrinkage and that swell when moistened and thus can strongly affect vertical flow in soils) can be modeled using an additional routine.

Water that percolates out of the bottom soil layer enters the aquifer system implemented in SWAT. The water can be delayed by a user-specified time with a decaying exponential function, which represents an unsaturated zone separating the soil and the aquifer system. Water that enters the aquifer system is partitioned between the deep aquifer and shallow aquifer by a user-specified parameter. Water that enters the deep aquifer is essentially lost to the system, representing deep aquifer recharge that can be accessed only by pumping. Water that enters the shallow aquifer can have two fates: (1) it can be discharged into the stream channel as baseflow, which is calculated for the simple case of an unconfined aquifer with uniform recharge undergoing horizontal flow; or (2) it can be evaporated and reenter the unsaturated zone above the aquifer system.

Sediment processes

SWAT models sediment erosion and overland flow using the Modified USLE (MUSLE) approach. This approach is similar to the USLE approach described for InVEST above, but rather than an annual sediment load it predicts a daily sediment load based on the USLE soil erodibility factor, cover and management factor, support practice factor, and topographic factor, as well as a coarse fragment factor $(sed = 11.8(Q_{surf} \cdot q_{peak} \cdot area_{hru})^{0.56} K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG)$. Instead of a rainfall erosion index the MUSLE uses a term that is the surface runoff volume (as a depth) times the peak runoff rate times the area $[(Q_{surf} \cdot q_{peak} \cdot area_{hru})^{0.56}]$, which allows it to be applied to individual storm events. This term integrates the energy of both detachment and flow, so that delivery ratios are not needed as in the USLE. The K_{USLE} term is calculated by a number of terms involving the percent clay, percent silt, percent very fine sand, and organic material of the soil. The C_{USLE} term is calculated both by land cover type and the weight of organic residue per area, which slows raindrops and reduces their erosive energy. The P_{USLE} is defined based upon the land use defined for the HRU and the slope (see the lookup tables included in the SWAT theoretical documentation). The LS_{USLE} term is calculated based upon the average slope and length of the HRU, and *CFRG* is based upon the percentage of rock in the uppermost soil layer. Sediment in surface runoff is lagged in time using the same equations and coefficients as the surface runoff, and a parameter can be set for a constant concentration of sediment that is carried by both groundwater and soil water flow. Finally, sediment production is reduced by an exponential power of the snow water content to represent the loss of erosive energy when rainfall hits a snow-covered surface.

In addition to its modeling of surface and overland flow, SWAT models the routing of sediment through stream channels, deposition of sediment in channels, and erosion of stream channels. As part of this, SWAT assumes a relationship between the sediment size distribution of the landscape soil and the amounts that enter the reach based upon typical values from the United States Midwest. In-channel deposition and erosion are modeled using either a simple Bagnold equation or a more complex physics-based approach. The Bagnold approach calculated a maximum sediment concentration (C_{max}) as a power-law of the peak channel velocity based on coefficients set by the user. When the sediment concentration entering the stream is larger than C_{max}, deposition occurs down to C_{max}; when the concentration entering the stream is less than C_{max}, then erosion of the bed and bank occurs until the concentration equals C_{max}, modified by a channel cover factor and a channel erodibility factor. The more complex physics-based approach focuses on an erodibility factor that is a function of the effective shear stress at both the stream bank and the stream bed, separating the erosion from those two sources. It calculates the maximum concentration load based on one of four approaches (including the simple approach discussed above; see the SWAT documentation for more), and tracks the amount of sediment and sediment size distribution along both the stream banks and stream bed. The deposition of sediment on flood plains is also accounted for in this approach. In addition to these effects, SWAT calculates downcutting erosion of the streambed, widening to a constant width-to-depth ratio, and changing slopes when the stream discharge is sufficiently high.

4.4| Data Requirements for InVEST and SWAT

InVEST and SWAT each require a significant amount of spatially-distributed data to be run. However, the data requirements vary significantly between the two models. In general, InVEST requires annual or average annual data in a spatial format for all data. In contrast, SWAT was developed to use the well-developed point source climate and flow data in the United States. Therefore, while the land-based datasets are generally spatially distributed, it uses point data sources for climate drivers and flow stations (generally used for calibration). While users can process the datasets to be used for either model to convert from point data to spatial and vice versa, the processing may be complex and may reduce the effective resolution of model outputs.

Table C1 lists the different data types necessary for each model. Note that SWAT requires many more inputs than InVEST. SWAT includes many more processes and thus more details of the system must be included to parameterize these processes. For many of these parameters, SWAT includes average values for common land uses in the agriculture portions of the United States, but obtaining these data and correctly parameterizing SWAT for other locations may be a challenge.

Table C2 provides a list of some of the outputs provided by both InVEST and SWAT, including both their temporal and spatial scales. For both models, the subbasin is the typical scale of assessment for the spatial resolution. While InVEST is run on a pixel basis, model guidance states that the models should not be trusted at spatial scales below the subbasin, because the models it is developed from target larger-scale assessments. For SWAT, HRUs are spatially discontiguous groups of similar land use and cover, soil, and slope. As such, subbasins, which are spatially contiguous, are a much better choice for output assessment.

Table C3 provides some examples of the datasets that can be used for the primary input fields with both InVEST and SWAT. The color indicates the quality of the data: green is very high quality, and yellow is less high quality (although potentially still very useful). In general, we assign best quality to datasets that are local and that are direct measurements of the relevant quantities. We assign less high quality to datasets that are re-analyses of measured data or combinations of numerous datasets to form global data because of the inherent variability within those datasets. In addition, we indicate datasets that require much less processing for use with the relevant model by a high color saturation, whereas datasets that require more significant processing have low color saturation.

Table C1. Input requirements for InVEST annual water yield, InVEST annual sediment yield, and SWAT

InVEST Annual Water Yield
Climate: • Average annual precipitation (raster) • Average annual potential evapotranspiration (raster) • Zhang coefficient
Soil: • Soil depth (raster) • Plant-available water content (raster)
Land Management: • Land use/land classification (raster) • Maximum root depth per LULC • Crop coefficient per LULC
InVEST Sediment Yield
Climate: • Rainfall erosivity index (raster)
Soil: • Soil erodibility (raster)
Land Management: • Land use/land classification (raster) • Cover and management factor per LULC • Management practice factor per LULC • Sediment retention factor per LULC • Slope threshold
Shape: • Watershed definition (shapefile) • Subwatershed definition (shapefile)
Elevation: • DEM (raster) • Threshold flow accumulation
SWAT
Climate (many of these can be replaced with a weather simulator, if calibration is not a goal): • Gauge precipitation (time series) • Gauge temperature (time series) • Gauge wind velocity (time series) • Gauge radiation (time series)

(*continued on next page*)

Table C1. Input requirements for InVEST annual water yield, InVEST annual sediment yield... *(continued)*

SWAT
Soil: • Soil name • Soil hydrologic group • Crack volume potential • Soil hydrologic class **Each of these at up to 10 Soil Horizons:** • Depth • Bulk density • Average plant available water • Saturated hydraulic conductivity • Percent clay • Percent silt • Percent sand • Rock fragments • Soil albedo • Soil erodibility • Soil NO3 • Soil organic N • Soil labile P • Soil organic P
Land Management: • Land use/land classification (raster) • Maximum root depth per soil • Land management operation schedule (irrigation, fertilization, harvest, and so on) per LULC
Shape: • Stream channel network (can be formed from DEM) • Channel cross-section and other characteristics • Location of observed data for calibration
Elevation: • DEM (raster) • Threshold flow accumulation
Plant: • Plant classification • Canopy storage • Maximum LAI • LAI growth curve • Minimum LAI after decline • Harvest index for best growth • Maximum canopy height • Maximum root depth • Temperature for plant growth (minimum, optimal) • N and P uptake curves • Years for a forest to achieve maturity • Maximum biomass of a forest • Many others

Note: SWAT has by far the most data requirements and includes a number of time series data. InVEST, in contrast, generally requires spatially explicit data at the average annual scale.

Table C2. Typical outputs from InVEST and SWAT. Note that in both cases the actual scale at which outputs should be used is the subbasin scale

	SWAT	InVEST
Water	• Discharge—daily, HRU • Water yield—daily, HRU • Surface flow—daily, HRU • Interflow—daily, HRU • Baseflow—daily, HRU	• Water yield—average annual, pixel
Sediment	• Sediment load—daily, HRU • Sediment deposition in streams/ponds—daily, subbasin • Erosion of sediments from streams/ponds—daily, subbasin	• Sediment load—average annual, pixel

Table C3. Potential data sources for SWAT and InVEST, with data quality and ease of processing indicated by color and saturation respectively. X means that the data source is not necessary or cannot be used for that model

Easy to process — Difficult to process
Best Quality Data

Easy to process — Difficult to process
Difficult to process

Data	Model			
	InVEST Water Yield	InVEST Sediment Yield	SWAT Water Quantity	SWAT Sediment Processes
Precipitation				
PRISM (US only)			X	X
NCDC				
NCEP				
WorldClim			X	X
TRMM				
Local Gauges	X	X		
PET/Temperature				
MODIS			X	X
NCDC				
NCEP				

(*continued on next page*)

Table C3. Potential data sources for SWAT and InVEST, with data quality and ease of processing indicated by color and saturation respectively. X means that the data source is not necessary or cannot be used for that model *(continued)*

Data	Model			
	InVEST Water Yield	InVEST Sediment Yield	SWAT Water Quantity	SWAT Sediment Processes
CGIAR			X	X
WorldClim			X	X
Local Gauges				
DEM				
SRTM (90m)	X			
ASTER (30m)	X			
Local DEMs	X			
Soil				
SSURGO (US only)				
FAO Soil Data				
Local Soil Data				
Land Use/Land Cover				
NLCD (US only)				
GLOBCOVER				
MODIS				
UMD Land Cover Classification				
Local Maps				
Stream Discharge				
USGS NWIS (US only)	X	X		
GRDC	X	X		
Root Depth				
Canadell et al. 1996				
SWAT Database				
Local Information				

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Table C3. Potential data sources for SWAT and InVEST, with data quality and ease of processing indicated by color and saturation respectively. X means that the data source is not necessary or cannot be used for that model *(continued)*

Data	Model			
	InVEST Water Yield	InVEST Sediment Yield	SWAT Water Quantity	SWAT Sediment Processes
Crop Coefficients				
FAO			X	X
SWAT Database				
LAI			X	X
Local Information				
Watershed Definition				
USGS National Hydrography Dataset (US only)				
Hydro 1k				
Rainfall Erosivity				
EPA (US only)			X	X
FAO			X	X
Land Management Factors				
USDA Handbook				
USLE				
FAO				

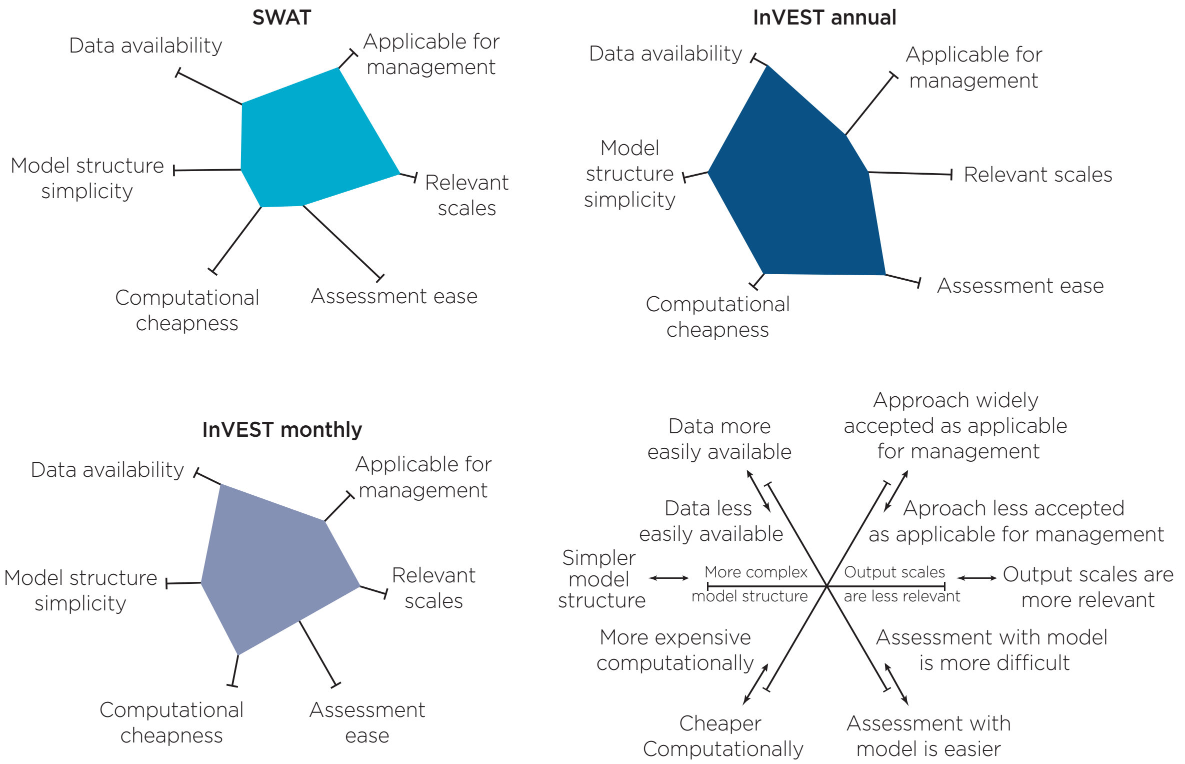
4.5| Operational Considerations for InVEST and SWAT

Users must be able to efficiently assess the quantities and values of hydrologic ecosystem services with a chosen model. These operational concerns include the necessary scientific capacity, computational capacity, and data availability for each model. SWAT and InVEST vary significantly across operational concerns, and the much lower operational hurdles to using InVEST are one of the strong arguments for its use in many cases. Here we address the operational concerns for each model. We provided an overview of the global data availability in Table C3, but will discuss these a bit more in this section. In addition, Figure C2 shows a number of axes along which the operational differences between SWAT and InVEST can be assessed.

SWAT requires computing capacity typical of modern desktop computers, although not the large-scale computing facilities common in many developed-world scientific contexts. The

Figure C2: SWAT is strongest in terms of providing outputs at relevant scales and having an approach that is widely accepted as applicable for management

Comparison of models across operational considerations



Note: The InVEST annual models are very strong along the operational considerations of having easily available data, being computationally cheap, and being easy to use. The InVEST monthly model may strike a balance between SWAT and the InVEST annual models, but it is still under development.

computational demand for a single SWAT run is actually quite modest, running usually for a few minutes for a moderate-sized watershed on a modern computer. However, SWAT calibration requires more significant computing capacity. SWAT calibration consists of varying model parameters to best match the model output to one or more observed data series. Since the parameter variation often consists of 1000 or 10,000 runs (and are often done several times), one to several weeks on a modern desktop are typically used for a SWAT calibration. This time can be reduced by parallelizing the model on a larger computing system. In addition, one can simplify the setting up of SWAT models by using an ArcGIS plugin (ArcSWAT), which requires this expensive proprietary software, but which can be run on modern desktops. There are less-used SWAT plugins for other GIS systems (some which are free).

While the scientific capacity needed to run SWAT at its most basic level is not very high, very good quality SWAT model setups may require a significant scientific capacity. SWAT model calibration is often a large component of an M.S. or M. Eng-level dissertation in the United States, so that scientists with this level of training can often perform a SWAT calibration adequately. However, calibration is an active research topic in hydrology, with scientists working on the following: creating less computationally expensive approaches for calibration (Rouholahnejad et al. 2012); finding the best objective functions for calibration (Price et al. 2012); finding solutions to the issue of equifinality, this property of a model to provide similar results with distinct parameter sets (Abbaspour et al. 2004; Vrugt and Robinson 2007); and improved parameter identifiability of such highly parameterized models as SWAT. In addition, as a highly complex model, many of the SWAT process representations are quite simple. Scientists need significant expertise to determine when obtaining a high-quality SWAT run will require changing the defaults building additional model components to perform these actions.

InVEST, in contrast, was developed to make landscape management decisions throughout the developing world and without a great deal of expertise in hydrologic modeling. As a result, the InVEST computational cost is much lower. As with SWAT, InVEST model setup can be eased with the use of ArcGIS, but the recent development of an InVEST geo-processing engine also allows use without ArcGIS. Alternate GIS programs, such as GRASS, QGIS, or MapWindow, may be useful in place of the expensive ArcGIS. Typical runs of the InVEST water yield and sediment model take a few minutes on a modern desktop. Time-series calibration is not possible as it is with SWAT, with instead a few parameters being varied to match an observed multi-annual total. As a result, the total computing time is generally a few hours, rather than weeks.

Along with its lower computational cost, InVEST was developed to be used by nonexperts. Many InVEST users are ecologists or land managers, rather than formal hydrologists. While the accuracy of a model may be questioned when used by nonexperts and without a formal calibration process, they may still be useful in certain decision contexts, especially with a basic assessment of the level of uncertainty (Pappenberger and Beven 2006).

4.6| Application to Himachal Pradesh

SWAT and the InVEST annual models differ significantly in terms of model structure and the spatial and temporal scales at which they estimate flows of water and sediment. Thus, SWAT and InVEST can answer different questions regarding how changes in land use and land management will affect hydropower capacity in Himachal Pradesh.

SWAT provides daily estimates of water and sediment flows from which estimates of hydropower ecosystem services can be derived. Potential power production can be calculated using the flow-duration approach for run-of-the-river facilities, which are common in the Himachal Pradesh. The potential power production can be examined under different scenarios of climate change and changes in land use, cover, and management. These potential power productions, combined with the value of hydropower, can address the value of both new hydropower infrastructure and existing hydropower infrastructure in a changing world (cases 1 and 2 from the introduction). In addition, although it has not been done, formal optimization could be performed to plan landscape management. However, SWAT's HRU approach presents challenges for performing such an optimization, as well as interpreting results.

SWAT results can assess the effects of daily sediment loads and the deposition of sediment in reservoirs on power production. This covers cases 4 and 5 in the introduction. SWAT's daily sediment load estimates can be analyzed to determine if sediment concentrations will damage turbines and thus require facility shutdown. In addition, SWAT can, in theory, track sediment deposition in settling ponds to assess potential power production lost because of reductions in flow rate from pond filling. While the settling ponds are relatively empty, all the water flows through the settling pond and penstock and through the turbine. If enough sediment gets added to the settling pond, some portion of that water will exit through overflows and not go through the penstock and turbine, resulting in lost power production. (This flow reduction will be a concern only if an overflow would be reached because of rising heads from an increase in sediment in settling ponds—it is unclear to the authors whether this is the case in Himachal Pradesh.)

SWAT can be used to assess hydropower ecosystem services after changes in climate; InVEST has many more questions around assessments after changes in climate. SWAT includes snow processes; therefore, a properly calibrated SWAT model should provide reasonable estimates of water flows after rising temperatures lead to more rain and less snow. In addition, SWAT sediment calculations include the increased erosive energy from rain falling on bare ground versus on dampening snow and the reduced energy of snowflakes over rain drops, which should lead to reasonable estimates of daily sediment loads. However, it is difficult to be certain that SWAT calibration is appropriate and that the estimates will be accurate. In contrast, InVEST does not include any specific accounting for snow and its effects. As a result, estimates of water and sediments flows may be inaccurate when precipitation changes from snow to rain.

InVEST annual provides average annual outputs that are easily used in existing optimization schemes to plan land cover, use, and management to maximize water yield or minimize sediment load (for example, RIOS). Thus InVEST can be used to optimize potential power production as discussed in case 3 in the introduction. However, InVEST lacks finer resolution temporal scale estimates, so it is not possible to perform a flow-duration assessment or compare potential power production with demand over short timescales. Users could assume that the annual distribution of discharge or sediment will be stationary (that is, the distribution will remain the same). However, hydrologic processes are highly nonlinear so it is quite likely that the distribution of water and sediment flows will change as the landscape is actively managed. For example, scenarios with different land use, cover, and management may have different relative amounts of overland and subsurface flow, leading to smaller flow peaks and a larger baseflow in the hydrograph.

Wealth Accounting and the Valuation of Ecosystem Services

Wealth Accounting and the Valuation of Ecosystem Services (WAVES) is a global partnership led by the World Bank that aims to promote sustainable development by ensuring that natural resources are mainstreamed in development planning and national economic accounts.

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