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Assessing the Economic Benefits of Sustainable Land Management Practices in Bhutan

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ABSTRACT

This study was conducted with the objective of determining the returns to sustainable land management (SLM) at the national level in Bhutan. The study first uses satellite data on land change (Landsat) to examine land use change in 1990–2010 and its impact on sediment loading in hydroelectric power plants. The study then uses the Soil and Water Assessment Tool (SWAT) model to analyze the impact of land use change and land management on sediment loading. The results from the land use change and SWAT analyses are used to assess the economic benefits of SLM. We estimate the benefits and costs of SLM practices and compare them with the land-degrading practices that are most prevalent in Bhutan—that is, business as usual. An analysis of the drivers of adoption of SLM practices is also done to draw conclusions about strategies that Bhutan could use to enhance adoption of SLM practices.

The land cover change results show that the vast majority of forested areas remained as such between 1994 and 2010. SWAT results show that with long-term SLM practices such as contouring, increased forested cover and density, terracing, and other SLM practices, soil erosion from forested area could be reduced by 50 percent.

Analysis of returns to SLM practices showed that citrus orchards are the most profitable enterprises in 13 of the 20 districts (dzongkhag), but they require farmers to wait for at least six years before the first harvest. Improved pasture management is the second most profitable enterprise—underscoring the potential role it can play to meet the growing demand for livestock products as household incomes increase. Returns to community forest management are low but profitable at a 10 percent discount rate.

Considering the drivers of SLM adoption, our research shows an inverse relationship between returns to land management and their corresponding adoption rates. The factors that increase adoption of SLM were land security, access to extension services, and roads.

In summary, Bhutan's policies and its cultural and historical background have set the country on the path to becoming a global green growth success story. Results of this study vindicate the country's efforts to invest in sustainable land and forest management and highlight the additional policies and strategies that will enhance achievement of Bhutan's SLM objectives.

Keywords: sustainable land management, Bhutan, Soil and Water Assessment Tool, hydroelectric power, sediment

ABBREVIATIONS AND ACRONYMS

AEZ	agroecological zone
BAU	business as usual
CF	community forest
CFM	community forest management
DGPC	Druk Green Power Company
FAO	Food and Agriculture Organization of the United Nations
GDP	gross domestic product
HEP	hydroelectric power
HRU	hydrologic response unit
IRR	internal rate of return
ISFM	integrated soil fertility management
MoA	Ministry of Agriculture
MRR	marginal rate of returns
NPV	net present value
NSE	Nash-Sutcliffe model efficiency
NSSC	National Soil Services Center
NTFP	non-timber forest products
PA	protected area
PBIAS	percent bias
RGoB	Royal Government of Bhutan
RNR	renewable natural resource
SFM	sustainable forest management
SLM	sustainable land management
SWAT	Soil and Water Assessment Tool/ Soil and Water Analysis Tool
SWM	soil and water management
WOCAT	World Overview of Conservation Approaches and Technologies

1. INTRODUCTION AND CONTEXT

Bhutan's economy is dominated by hydroelectric power (HEP) generation—a sector that contributes about 22 percent of the country's gross domestic product (GDP), which makes HEP the largest sector (NSB 2009). Sediment loading leads to significant cost for most HEP plants in the world (IPCC 2012), relating to power generation loss, reduction of turbine efficiency and lifetime, and increased repair costs (Lysne et al. 2003). This underscores the role played by sustainable land management (SLM) in Bhutan, whose economy heavily depends on the HEP sector. In addition, about 69.1 percent of the population of 733,033 live in rural areas and depends on agriculture—a sector that contributed only 17 percent of the GDP in 2013 (NSB and ADB 2013). Crops—excluding horticultural crops—account for only 7.7 percent of the land area, whereas pasture and horticulture, respectively, account for 3.9 percent and 0.1 percent (Ministry of Agriculture, 1995; currently Ministry of Agriculture and Forests [MoAF]).

Forests—which cover 70 percent of the land area—contributed only about 6.9 percent of Bhutan's GDP in 2010, but this contribution was from only timber and paper products (Food and Agriculture Organization of the United Nations [FAO] 2011). The value of non-timber forest products (NTFP)—including regulating and supporting ecosystem services—is much greater. Unlike in other countries, Forest and Nature Conservation Acts and Rules (NCD 2003) allow communities currently living in protected areas (PAs) to continue living in PAs on the condition that they observe key rules and regulations (Choden et al 2010; Phuntsho et al 2011).[1]Our study estimates that at least 25 percent of Bhutan's population lives in PAs. The PAs comprise 19,751 square kilometers (km), which is more than 51 percent of the land area of 38,394 km^2, a level that only a few countries have achieved (MoA 2009). This suggests that the PAs provide abundant ecosystem services to the population living both inside and outside PAs. The PAs also serve as the catchment and source of rivers supplying water to HEP plants. Out of the four major HEP plants of Bhutan, the sources of water for Chhukha, Kurichhu, and Tala HEP come from the PAs.

This study was undertaken with the objective of assessing the economic benefits of SLM in clear monetary terms and conducting a national-level cost-benefit assessment of investments into SLM. Results of the study will be used to design Bhutan's SLM strategies to achieve its 2020 Vision of Peace, Prosperity and Happiness of the Bhutanese people by enhancing their traditional values and improving their standard of living and environmental sustainability (RGoB 2002). Based on the economic analysis, the study would also identify priority investments with the highest economic benefits for the country. Furthermore, the analysis will allow the Royal Government of Bhutan (RGoB) to mainstream SLM in its five-year plan's programs and provide budgetary support on a priority basis.

This analysis will also support the inclusion of Bhutan in a global study assessing the economics of land degradation led by the International Food Policy Research Institute in collaboration with the University of Bonn, which includes 11 case countries (Argentina, Bhutan, Ethiopia, Kenya, India, Niger, Nigeria, Senegal, Tanzania, Uzbekistan, and Zambia). The global assessment is an ongoing research project that will enable inclusion of RGoB in an exchange of experiences and lessons learned derived from the Bank-implemented, Global Environment Facility–financed SLM Project and facilitate South-South learning exchange with the other countries participating as case studies.

The next section summarizes Bhutan's opportunities and challenges related to SLM. A brief discussion about the study background and approach is provided to set the stage for subsequent sections. This is followed by a discussion of Bhutan's land cover change trends and major biophysical characteristics. Analysis of soil erosion using the SWAT model follows the Land Use Change section. Using data collected by the renewable natural resource (RNR) household survey conducted in 2009, the study then analyzes land management practices and the drivers of adoption of SLM practices. This is followed by the economic analysis of the SLM practices at a national level. The final section concludes the study and gives policy implications.

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[1] For example, each household living in a protected area is entitled to harvest timber for construction of a new house once in 30 years and once after every 5 years for renovation of an existing house (Choden, Tashi, and Dhendup 2010).

2. BHUTAN'S OPPORTUNITIES AND CHALLENGES RELATED TO SUSTAINABLE LAND MANAGEMENT

Opportunities

- Bhutan's mountains provide immense opportunities for HEP. The HEP sector currently accounts for up to 40 percent of government revenue (DGPC 2009) and has the potential to grow. Owing to the large quantity of suitable terrain, the currently installed capacity of 1,488 megawatts (mw) is only about 5 percent of the estimated total HEP potential. Bhutan's vision is to achieve 10,000 mw installed capacity by 2020 (DGPC 2009).
- The large area under cover provides local benefits—including serving as a source of water used for HEP generation—and global benefits of carbon sequestration, biodiversity, genetic information, and other forest ecosystems. Such services provide opportunities for Bhutan to derive payment for ecosystem services from the global community.
- Bhutan's deep-rooted traditions and its cultural values of Mahayana Buddhism serve as a robust cultural foundation for realizing the benefits of sustainable development. It is these cultural values, which stress the co-existence of people with nature and the sanctity of life, compassion for others, and happiness in general, that led Bhutan to adopt the Gross National Happiness measure instead of the traditional GDP. However, given that Bhutan's economy is heavily dependent on natural resources, these cultural values also have been contributing to the long-term economic welfare of the Bhutanese people by encouraging sustainable development as Bhutan works toward its 2020 Vision of Peace, Prosperity and Happiness.

Challenges

- Only 30 percent of the population uses inorganic fertilizer and 60 percent uses manure. As a result of this and other challenges, yields of maize and rice are only about 67 percent and 50 percent of the potential yield (Chetri, Ghimiray, and Floyd 2003).
- Bhutan's forest development policy from 1961 to the 1980s followed centrally managed and industrial forest harvesting, which eroded community responsibility for forest management and subsequently led to forest degradation (Gyamtsho, Singh, and Rasul 2006). In response to this, a royal decree in 1979 and the Forest and Nature Conservation Act in 1995, among other statutes, gave communities a mandate to practice CFM) (Gyamtsho, Singh, and Rasul 2006; Phuntsho et al. 2011). In 2010, fewer than 300 CFM systems existed, and it is expected that the total number of community forests (CFs) will reach only 400 by 2013, covering a negligible 4 percent of the total forest area. The total forest area appropriate for CFM is 2,380 km^2, or 20 percent of forest area managed by the central government (Phuntsho et al. 2011). The slow pace of CFM adoption poses a challenge to ensuring sustainable forest management (SFM).
- Significant soil erosion leads to high repair costs of HEP plants. DGPC spends US$16 million each year to repair turbines and other underwater structures due to sediment loading. About 60 percent of such cost is associated with sediment loading.
- Bhutan's topography makes land management and transportation infrastructure development a challenge. Road and other market infrastructure development is costlier and could trigger more severe soil erosion than is the case in flatter landscapes. About 30 percent of Bhutan's population lives in areas from which it takes more than three hours to walk to the nearest motor-road (RNR 2008).

3. STUDY BACKGROUND AND APPROACH

There are many definitions of SLM, and each emphasizes some elements of two key issues: long-term maintenance of ecosystem services and provision of ecosystem services desired by people (Winslow et al. 2011). The World Overview of Conservation Approaches and Technologies (WOCAT) defines SLM as the use of land resources for the production of goods and services to meet changing human needs while simultaneously ensuring the long-term productive potential of land resources and the maintenance of their environmental functions (WOCAT 2007). However, the United Nations Convention to Combat Desertification (UNCCD) defines SLM as "land managed in such a way as to maintain or improve ecosystem services for human wellbeing, as negotiated by all stakeholders" (Winslow et al. 2011). The element of *desired functions* is context specific since human needs differ significantly. One type of land management practice may be viewed as land degrading in one part of the world but as SLM in another. So our working definition will be in the context of Bhutan's needs according to 2020 Vision: "Peace, Prosperity and Happiness of the Bhutanese people by enhancing their traditional values, improving their standard of living and environmental sustainability" (RGoB 2002). For RGoB to be able to achieve such a goal, our analysis will look at both on-farm and off-site benefits of SLM practices and the costs and benefits of land-degrading management practices. In this study, the primary off-site benefit of SLM considered is the reduction of sediment, which has large benefits to HEP plants. The SWAT model results will be used to determine the impact of SLM on sediment loading.

SLM—as used in this study—does not necessarily mean complete prevention of land degradation or complete rehabilitation of degraded lands. A land management practice will be regarded as SLM if it completely or partially prevents or reduces land degradation. This could apply to land management that may still be causing a reduced form of land degradation but is better than the prevailing land-degrading practices. For example, the amount of chemical fertilizer applied may be less than the amount required to fully replenish soil nutrients taken up by crops but is regarded as SLM if it is better than the prevailing land-degrading practice. However, to ensure that we reflect Bhutan's desired function and needs, a land management practice is regarded as sustainable if it is undertaken according to the country's recommended practices. For cropland, the recommended soil fertility management practices and crop varieties will be regarded as SLM. Improved pasture management is regarded as SLM for livestock management. Likewise, the country's effort to promote CFM is regarded as SLM for the relevant and available forested area.

Responding to Bhutan's desired functions, our SLM analysis will focus on HEP, forest, livestock, and agricultural land management. Given the large data needs required for determining the on-farm and off-farm benefits of SLM, our study will rely heavily on existing data and studies. The study will also use the SWAT simulation model to assess the short- and long-term impacts of management practices on the watersheds. This approach will allow us to determine the off-site impact of upstream SLM practices on sediment loading in HEP.

The study was motivated by an SLM project that was funded by the Global Environment Facility (GEF) under the World Bank's administration. The main objective of the SLM project—which ended in June 2013—was to protect vulnerable land and to rehabilitate degraded lands. Table 3.1 summarizes SLM project's major activities and their expected outcomes.

Table 3.1 Prevention of land degradation and rehabilitation of degraded lands by sustainable land management project

Sustainable land management project	Area (hectares) covered	Expected major outcome
Protection of vulnerable lands	2,410	
• Bamboo plantation	296	Bamboo planted in rills gullies to reduce gully formation
• Community and private forest	1,422	Sustainable timber production, protection and use of natural forests and water resources, and rehabilitation of barren area through plantation
• Check dams	937[a]	Water conservation and availability through water source protection
• Planting leguminous crops	141	Improved soil fertility through nitrogen fixation
• Other	17	
• Stonewalling/bunding		Prevention/reduction of soil erosion
• Rehabilitation of degraded lands	2,573	Conversion of slash-and-burn agriculture practice (ex-*tseri* land) to more sustainable land use
• Dryland terracing	45	This involves conversion of steep-sloped land to terraced land that is used for irrigated crops (*chhuzhing*) if irrigation water is available.
• Wetland terracing	49	Terracing irrigated areas (wetlands) to reduce soil erosion
• Contour	157	Reduced soil erosion
• Hedgerow	326	Reduced soil erosion
• Agroforestry	39	Reduced soil erosion, nitrogen fixation
• Orchard plantation	833	Planting of fruit trees on steep dry land previously used as *tseri* or allowed to lie fallow, generate income for fruit sales
• Annual crops	1,126	Income generation
• Manure shed construction		Reduction of forest degradation and soil erosion by reducing number of stray grazing animals, increase crop yield through use of farm yard manure, increase milk production

Source: GEF (2012)
Notes: *tseri* = shifting cultivation/slash-and-burn cultivation; *chhuzhing* = wetlands. [a] Number of check dams constructed.

Just as in the SLM project, our study will focus on land management practices that prevent land degradation and those that rehabilitate degraded lands. However, our study was conducted at a national level and will move beyond SLM project's focus on agricultural land. The focus will be on the three land use types—forests, cropland, and grazing lands. We will focus on selected land management practices that are the most commonly used. The discussion for each of the major land use types gives its corresponding economic importance and land area coverage.

Forest

Forest contributed about 24 percent of the agricultural GDP in 2000–2009 and grew at a modest average of 1.7 percent during the same time (Christensen, Fileccia, and Gulliver 2012). About 70.5 percent of the land area in Bhutan is covered with forests (RGoB, MoAF 2010), and the constitution states that forest cover should be at least 60 percent of the total land area (RGoB 2008). The small contribution of forest to GDP is due to the nonvaluation of other ecosystem services provided by forests. As discussed earlier, rivers supplying HEP originate from forests, but the water catchment, prevention of soil erosion, and other roles of the forests are not taken into account when computing GDP.

The RGoB has realized the importance of decentralizing forest management and has encouraged communities to manage the forest resources to meet their forest needs. As of 2012, 21,723 rural households—or 24 percent of all rural households—managed CF, which covered 62,237 hectares (ha) or 1.8 percent of forested area (Dukra 2013). There are two ways that more households could participate in CF programs: (1) converting centrally managed government forest reserve to CF and (2) converting unused lands to CF. As shown in Table 3.2, only about 4,000 km^2 is available for CF. The government had estimated that the CF area would account for 4 percent of the total forested area by 2013 (RGoB, MoAF 2010), but only 1.8 percent of the forested area was CF by 2012 (Dukra 2013).

Table 3.2 Available area for community forest in Bhutan

Sustainable land management project	Area (km^2)	Estimated impact on forest ecosystem services (% Change)
Convert centrally managed non–protected area forests to community forests	3974.3[a]	25
Convert unused lands to community forest (km^2)	2.4[b]	

Source: Ministry of Agriculture and Forests data (2010).
Note: km^2 = square kilometers. [a] Total forest area (27,053.0 km^2) – protected area (19,751.0 km^2) – community forests (622.4 km^2) – government forest reserve (2705.3 km^2) = 3974.3 km^2. [b] Unused land (Figure 5.11): agriculture to fallow, bushland, or bare land (2.17) + unused land (0.17) + deforested area (0.02) = 2.36 km^2.

SFM can be achieved in part by reforesting cleared lands and by increasing forest density of degraded forests. As shown below, only a small area experienced deforestation. But there is large potential for improvement of forest density through better management, which could be achieved through decentralization of public forest to CF management.

Crops and Citrus

The contribution of the major cereal crops (rice, maize, barley, and wheat) to the agricultural GDP has declined significantly since 2007 (Christensen, Fileccia, and Gulliver 2012). One of the reasons for such decline is land degradation. We focus our analysis on maize and rice, which, respectively, account for 42 percent and 52 percent of the cultivated crop area. We also analyze fruit crops, which occupy a small land area, yet form the largest cash income of the rural households and dominate the commercial agriculture for both domestic and export markets. Thirteen out of 20 districts (dzongkhag) are major growers of citrus (mainly mandarin orange)[2] (MoAF 2011).

Maize: Maize contributed 17 percent of the crop GDP in 2009 (Christensen, Fileccia, and Gulliver 2012), but 69 percent of farmers in Bhutan grow maize, and the crop accounts for 49 percent of the food basket and 42 percent of the cultivated area (Tobgay and McCullough 2008). Cultivated mainly in the eastern region of the country, maize is the second most important food crop in Bhutan after rice (Tobgay and McCullough 2008).

Rice: Paddy rice contributed 23.3 percent of the crop GDP in 2009 (Christensen, Fileccia, and Gulliver 2012)—the largest contribution, shared with citrus. Rice production occupied 59,609 ha or 52 percent of the cultivated area of 112,550 ha in 2010 (NSB2012). The crop is mainly irrigated and grown in the warmer areas in the mid-altitude and low-altitude areas. Rice is an important staple crop, and its demand is growing, putting pressure on domestic production.

Fruit and horticultural crops: Citrus production contributed 73.6 percent of the crop GDP growth in 2000–2009 (Christensen, Fileccia, and Gulliver 2012) and 66 percent of the household cash income.

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[2] The thirteen major citrus producers dzongkhag (descending order) are: Pemagatshel, Dagana, Sarpang, Tsirang, Chhukha, Zhemgang, Samtse, S/Jongkhar, Mongar, Punakha, Trashigang, and Trashiyangtse (MoAF 2011).

Fruit production has increased faster than production of cereals due to fruit's high returns and increasing demand. Fruit and horticultural crops are grown mainly during the summer period and are grown in the following agroecological zones (AEZs): warm temperate, dry subtropical, humid subtropical, and wet subtropical.

The SLM practice to be analyzed for maize and rice production is integrated soil fertility management (ISFM), which entails the use of organic inputs, judicious amounts of chemical fertilizer, and improved seeds (Vanlauwe and Giller 2006). The ISM matches the manure shed construction done by the SLM project to increase the production and use of farm yard manure. Studies in Bhutan have shown that ISFM significantly increases yields of rice and maize (Chhetri, Ghimiray, and Floyd 2003). ISFM is used since it performs better than the use of mineral fertilizer or organic input alone (Vanlauwe and Giller 2006; Nandwa and Bekunda 1998).

Livestock

Livestock accounted for about 28 percent of the agricultural GDP from 2000 to 2009 and grew at an average of 2.7 percent during the same period (Christensen, Fileccia, and Gulliver 2012). Two-thirds of rural households own cattle; most have two or more head of cattle (NSB and ADB 2013). Livestock ownership is inversely related to consumption quintile. About 78 percent of households in the poorest quintile and 18 percent of the richest quintile own cattle (NSB and ADB 2013). However, in the rural areas, 82 percent of the poorest quintile and 44 percent of the richest quintile own cattle (NSB and ADB 2013).

The grazing area covers 11 percent of the land area (Wangdi 2006), which is greater than the cropland area. The SLM practice that will be used is improved pasture, which could lead to both prevention of soil erosion and greater livestock productivity. Improved pasture includes planting leguminous seeds, improved grasses such as cocksfoot, and Italian rye and lotus (Samdup et al. 2013; Dorji 1993). Improved pasture also includes rotational grazing on rangelands, which allows pasture to recover (Chophyel 2009). Rearing of few improved breeds in lieu of large numbers of local breeds to reduce pressure on resources is encouraged.

4. METHODOLOGICAL ANALYSIS AND DATA

To achieve a national-level SLM analysis, we will rely heavily on existing data and on simulation modeling to analyze SLM and its economic impact. The first aspect to analyze is land use change, which will help determine the potential impact on sediment loading. The effect of land use change on sediment loading will be analyzed using SWAT model simulation. The SWAT modeling will also include SLM practices beyond land use changes, including those that could affect sediment loading, for example, using SWM practices on cropland to reduce soil erosion. The economic analysis will include all results to determine the returns to all SLM practices.

Land Use Change

To measure the accuracy of and consistency between records of land cover, we use two datasets to analyze land use change:

Landsat Land Cover Dataset, Covering the 1990–2010 Period

The 30 meter (m)×30–m resolution data were derived from Landsat ETM+ Satellite imagery and evaluated using Advanced Land Observation Satellite imagery and Google Earth. The data were harmonized and standardized by the International Center for Integrated Mountain Development in collaboration with the Bhutanese Ministry of Agriculture and Forests.

Bhutan Land Cover Assessment, Covering the 1994–2010 Period

The data sources, classification, and methods differed between the data collected in 1994 and that collected in 2010, which makes computation of land use change less reliable. The 1994 data were obtained from Panchromatic (black-and-white photographic film) images and were processed manually to delineate land use types. The 2010 data were obtained from Advanced Land Observation Satellite (AVNIR-2) images with a 10-m resolution. Unlike the 1994 dataset, the 2010 dataset was rigorously conducted with extensive ground truthing, an aspect missing from the Landsat dataset.

An analysis of the 2010 Landsat and 2010 national land cover datasets demonstrated that they compare favorably in their classification of agriculture, urban area, forested area, shrubland, and grassland. The comparison lends considerable credibility to the Landsat dataset, which was not ground-thruthed in the same rigorous manner as was the national land cover dataset. The moderate differences in the grassland/shrubland classes and more pronounced differences in snow cover and barren land may be explained in part by seasonality. The season in which the satellite images were taken will strongly influence the advance/retreat of the snowpack, grassland, and shrubland in the northern regions of Bhutan.

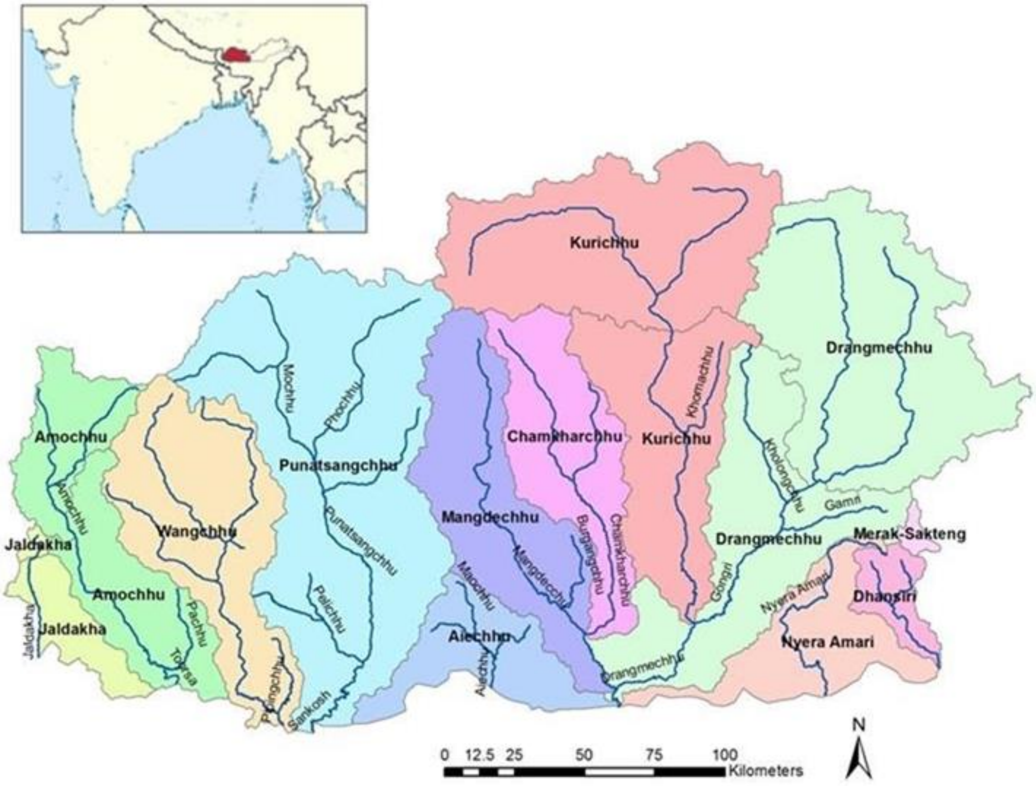
The decision about which land cover dataset—if not both—to use in the land cover change detection was based on the intended purpose of each dataset. The documentation for the national land cover dataset states explicitly that the dataset is not intended to be used in a change analysis given the methodological advances between the two datasets. But the Landsat-derived dataset produced all three years of coverage simultaneously with the express purpose of maintaining consistency in the methodology. While the Landsat dataset does have validation shortcomings (discussed previously), the consistency between years makes it ideal for land cover change analysis. In the case of pastureland, however, the Landsat dataset does not distinguish between grassland/shrubland and pastureland. For calculation of pastureland expansion and contraction the national dataset was used. These results should be interpreted keeping in mind the change in classification methods between 1994 and 2010.

Soil Erosion Analysis

Study Area

The total drainage area of the 11 river basins in Bhutan is approximately 47,541 km^2. The northern region of Bhutan consists of glaciated mountain peaks, with the highest elevations more than 7,000 m above sea level. In the south, the southern foothills are covered with dense, deciduous forests; alluvial lowland river valleys; and mountains up to 1,500 m above sea level (Figure 4.1).

Figure 4.1 Main rivers and major river basins



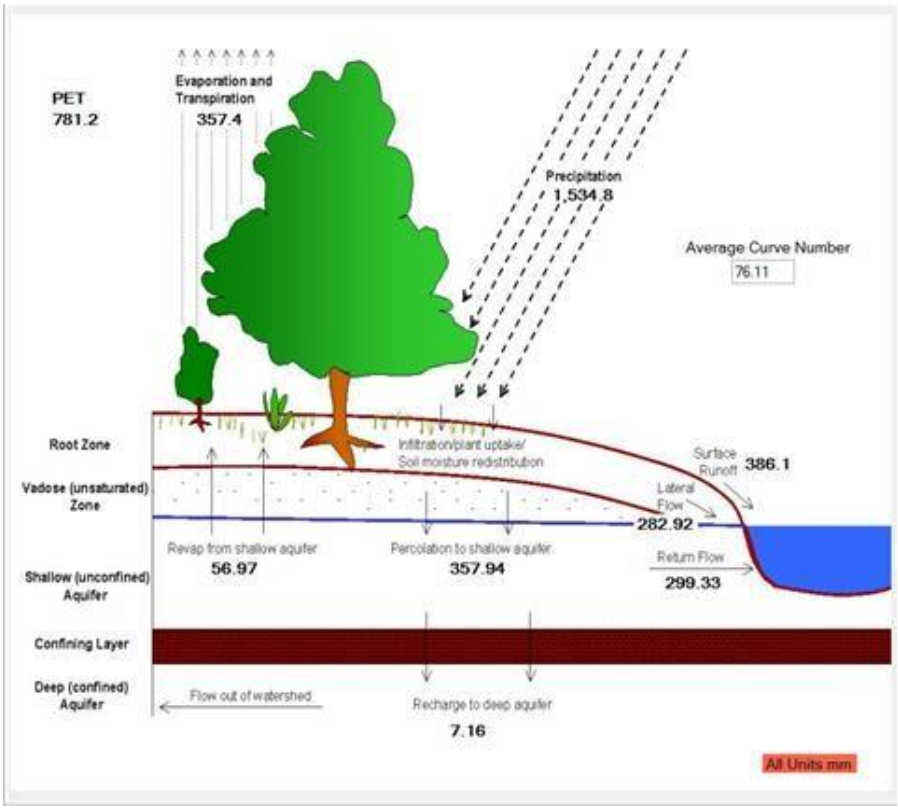
Source: Ministry of Agriculture and Forests data (2013).

According to the United Nations Environment Programme (2009), Bhutan can be divided into three climatic zones: subtropical zone in the southern foothills with high humidity and heavy rainfall between 2,500 and 5,550 millimeters (mm) per year; temperate zone in the highlands with cool winters and hot summers, rising to 3,000 m; and alpine climate zone under perpetual snow, with elevations up to 7,550 m and average annual precipitation of 400 mm. Bhutan's water resources are confined to four major river basins: Amo Chhu, Wang Chhu, Puna-Tsang Chhu, and Manas Chhu. They all originate from the high-altitude alpine area and from the perpetual snow cover in the north and flow into the Brahmaputra River in the Indian plains.

SWAT

SWAT (Arnold et al. 1998) is a physically based, continuous simulation model developed to assess the short- and long-term impacts of management practices on large watersheds. The model requires extensive input data, which can be supplemented using internal model databases and algorithms for generating synthetic weather data (Di Luzioet al. 2002). The model divides watersheds into a number of sub-basins and adopts the concept of the hydrologic response unit (HRU), which is delineated according to a number of key parameters, such as land use, soil, and slope. SWAT is able to simulate rainfall-runoff based on separate HRUs, which are aggregated to generate output from each sub-basin. SWAT is a combination of modules for water flow and balance, sediment transport, vegetation growth, nutrient cycling, and weather generation. SWAT can establish various scenarios detailed by different climate, soil, and land cover as well as the schedule of agricultural activities including crop planting, tillage, and best management practices (Flay 2001). A schematic presentation of SWAT hydrological modeling is presented in Figure 4.2.

Figure 4.2Hydrologic budget of the basin from SWAT-check



Source: Authors.

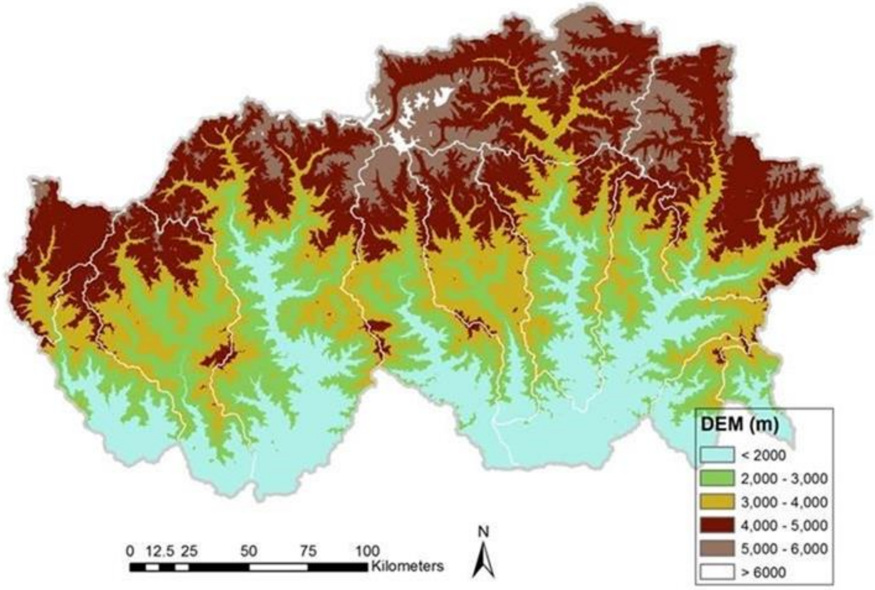
Note: SWAT = Soil and Water Assessment Tool. PET = Potential Evapotranspiration; mm = millimeters.

In summary, the benefits of using SWAT for this project are that, first, SWAT offers finer spatial and temporal scales, which allow the user to observe an output at a particular sub-basin on a particular day. Second, it considers comprehensive hydrological processes, estimating not only surface runoff with associated sediment and nutrients but also groundwater flow and channel processes within each sub-basin and at the watershed scale. However, nutrients were not modeled as part of this study. Third, on completion of this study, the calibrated model can be developed to further analyze scenarios such as best management practices, land use changes, climate change, and more.

Data Required for SWAT Analysis

Elevation (digital elevation model DEM): The National Soil Services Center (NSSC) provided DEM data with 10-meter resolution. The DEM was used to automatically delineate watershed boundaries and channel networks. Elevation ranges from 22 to 7,456 m (Figure 4.3). Steep area (slope of more than 63 percent) accounts for 42.9 percent of the area, whereas less than 6 percent of the area is flat with slopes of 0 percent to 2 percent.

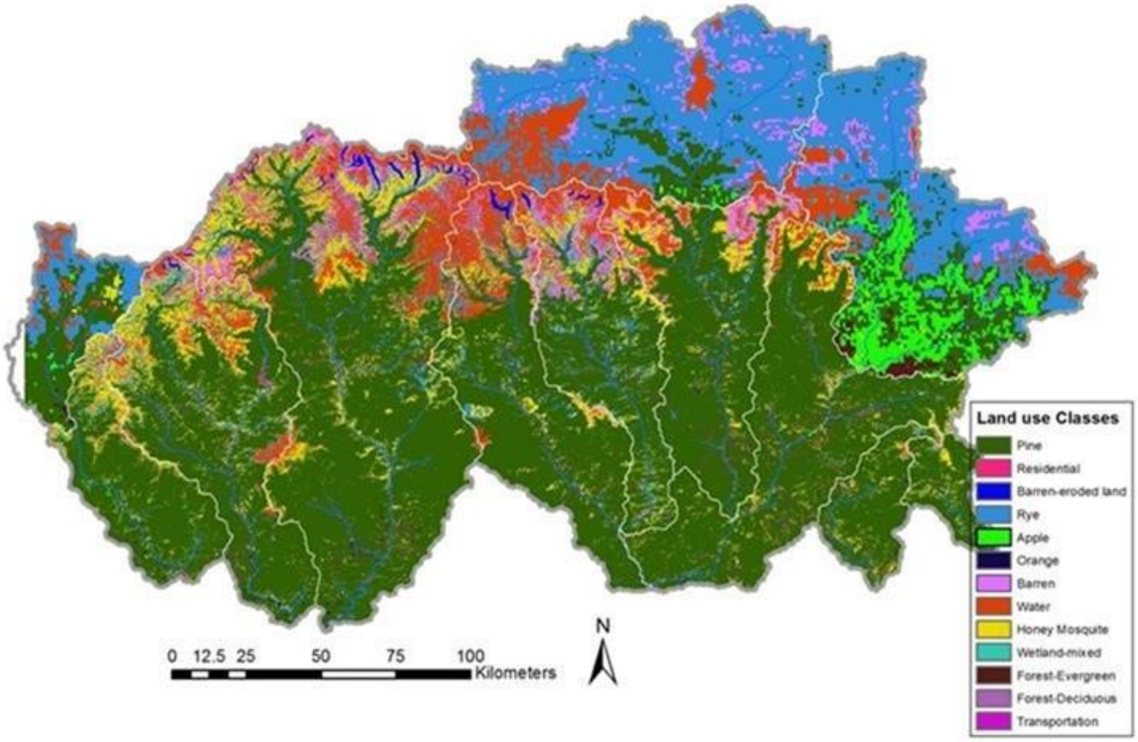
Figure 4.3DEM of for the country of Bhutan at 10-meter resolution



Source: National Soil Services Center data (2013).
Note: DEM = digital elevation model; m = meters.

Land use: NSSC provided the land cover dataset created in 2010 (Figure 4.4). Percentages of each land cover are summarized in Table 4.1. However, as seen above, Landsat land cover datasets were also used to analyze land use change. For 2010, land use types consist primarily of pine (55.35 percent) and cool-season grass (17.91 percent). Concerning land use change, there are more than 600 glaciers in Bhutan with an area of approximately 1,300 km^2 (Beldring and Voksø 2011). There is an increasing tendency to go for cash crops such as apples in the temperate north and oranges in the subtropical south (Wangdi 2006).

Figure 4.4 Bhutan national land cover dataset (30-meter resolution) created in 2010



Source: National Soil Services Center data (2010).

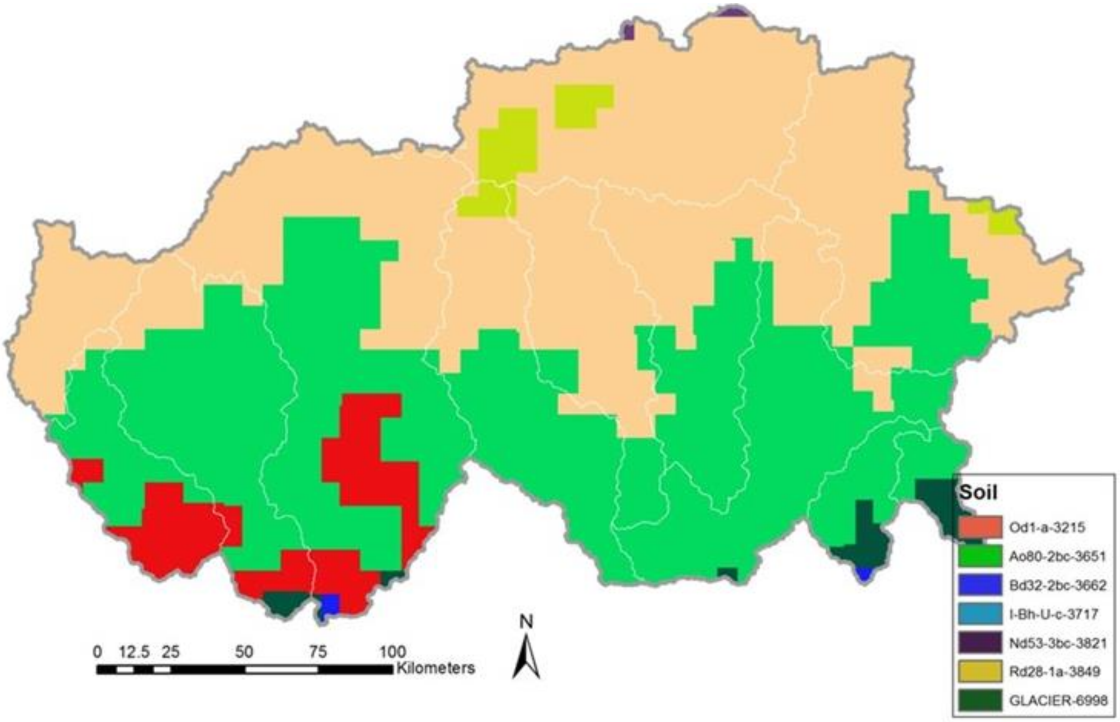
Table 4.1 Land use categories determined by the national land cover dataset (2010)

Land use type	Percentage of watershed area
Pine	55.35
Residential	0.08
Barren-eroded land	0.38
Natural grassland	17.91
Apple	2.56
Orange	0.08
Barren	4.31
Water	10.03
Honey mesquite	8.42
Wetlands-mixed	0.01
Forest-evergreen	0.39
Transportation	0.48
Total	100.00

Source: National Soil Services Center data (2010).

Soil: FAO/UNESCO provided soil data in shape file format and converted it to GRID format at a 1:5,000,000 scale (Figure 4.5). The FAO/UNESCO soil map (FAO/UNESCO 1977) classified about 27 percent of Bhutan as having either cambisols or fluvisols (cambisols are most common in the medium-altitude zone, and fluvisols mostly occur in the southern belt). Less fertile acrisols, ferrasols, and podzols were estimated to cover 45 percent of the country. The same study also reports that 21 percent of the soil-covered area suffers from shallow depth with mostly lithosol occurring on steep slopes (Roder et al. 2001).

Figure 4.5FAO/UNESCO soil map of Bhutan



Source: FAO/UNESCO (1977).

Note: Legend references FAO soil type codes. Od1-a-3215: Dystric Histosols, Ao80-2bc-3651: Orthic Acrisols, Bd32-2bc-3662: Dystric Cambisols, I-Bh-U-c-3717: Lithosols - Humic Cambisols – Rankers, Nd53-3bc-3821: Dystric Nitosols, Rd28-1a-3849: Dystric Regosols, GLACIER-6998: Glacier.

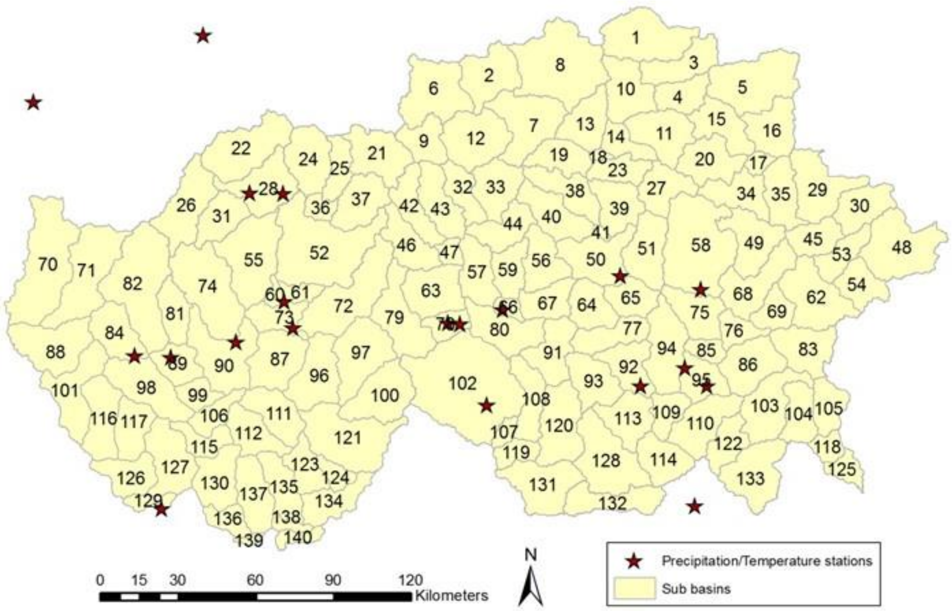
Weather stations: The Hydromet department provided daily precipitation and temperature (minimum and maximum) data within and near the watershed from 1996 to 2012 (Table 4.2 and Figure 4.6). A total of 20 local weather stations were used in this study (Figure 4.7). The National Centers for Environmental Prediction’s Climate Forecast System Reanalysis provided daily wind speed, relative humidity, and solar data in SWAT file format with ~31 km horizontal and ~35 km vertical resolution from 1979 through 2010.

Table 4.2Local precipitation and temperature stations throughout and near the basin

Name	Latitude	Longitude	Elevation
Simtokha	27.44	89.68	2,310
Paro	27.38	89.42	2,406
Haa	27.39	89.28	2,711
Punakha	27.58	89.86	1,239
Gasakhatey	27.96	89.73	2,760
Wangdue	27.49	89.90	1,214
Trongsa	27.50	90.51	2,195
Zhemgang	27.22	90.66	1,862
Mongar	27.28	91.26	1,597
Lhuentse	27.66	91.18	1,430
Phuntsholing	26.86	89.39	280
Sipsu	28.51	89.54	423
Bhur	28.27	88.87	377
Damphu	27.50	90.55	1,564
Dagana	27.96	89.86	1,865
Deothang	26.86	91.46	861
PemaGatshel	27.34	91.43	1,723
TrashiYangtse	27.61	91.50	1,839
Kanglung	27.28	91.52	2,005
Bumthang	27.55	90.72	3,032

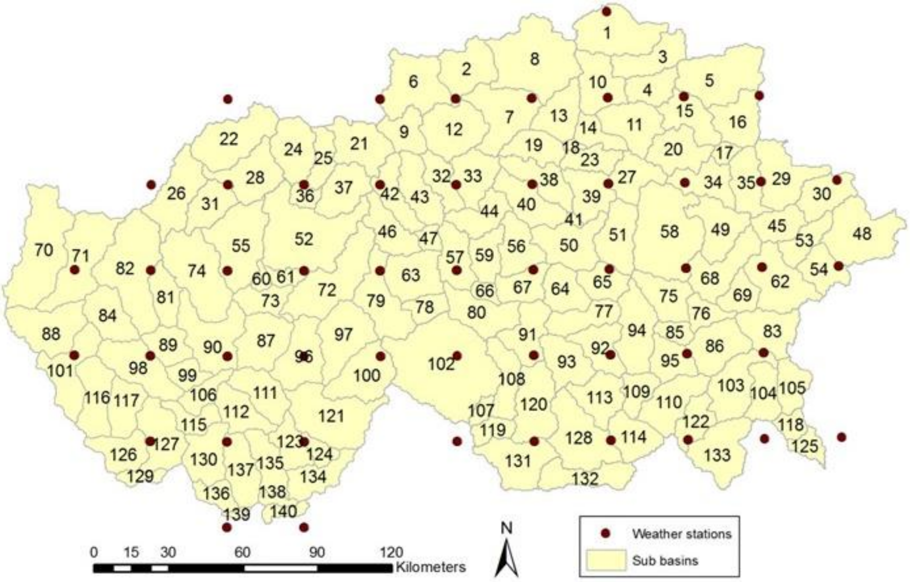
Source: Hydromet data (2013).

Figure4.6Local precipitation and temperature stations throughout and near the basin



Source: Hydromet data (2013).

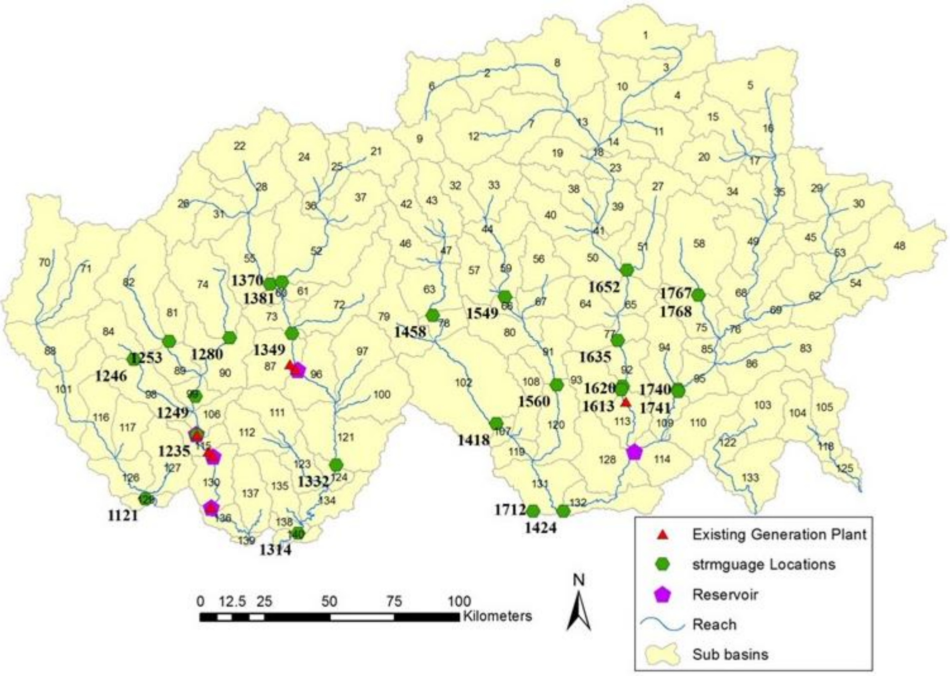
Figure 4.7Weather stations used in this project



Source: Hydromet data (2013).

Streamflow gauging stations: Hydromet provided flow data at stream gauging stations, 24 of which were available in the basin (Figure 4.8). Of those stations, 20 were used for modeling. All other stations were eliminated either because they had too much missing data or the gauging stations were located in a minor tributary and could not be analyzed. Table 4.3 summarizes the available gauging stations.

Figure 4.8 Stream gauging stations available in the basin



Source: Hydromet data (2013)
Note: strmguage = stream gauge.

Table 4.3List of available gauging stations

Station ID	Name	Sub-basin	Elevation	Drainage area	Latitude	Longitude
			(meters above sea level)	(km^2)		
1121	Doyagang on Amochhu	129	355	3,650	26.89	89.34
1235	Chimakoti Dam on Wangchhu	106	1820	3,550	27.11	89.53
1246	Hachhu	84	2700	320	27.37	89.29
1249	Damchhu on Wanchhu	99	1990	2,520	27.24	89.53
1253	Parochhu	82	2255	1,049	27.43	89.43
1280	Lungtenphug on Wangchhu	74	2260	663	27.45	89.66
1314	Kerabari on Sankosh	138	150	10,355	26.77	89.93
1332	Turitar on Sankosh	121	320	8,593	27.01	90.08
1349	Wangdirapids on Phochhu + Mochhu	73	1190	6,271	27.46	89.90
1370	Yebesa on Mochhu	55	1230	2,320	27.63	89.82
1381	Samdingkha on Pho chhu	52	1220	1,284	27.64	89.86
1418	Tingtibi on Mangdechhu Down Stream	102	530	3,322	27.15	90.70
1424	Tingtibi on Dakpichhu	132	580	122	26.84	90.96
1458	Bjizam on Mangdechhu	63	1848	1,390	27.52	90.45
1549	Kurjey on Chamkharchhu	59	2600	1,350	27.59	90.74
1560	Bemethang on Chamkharchhu (Singkhar)	91	320	—	27.28	90.94
1613	Lingmethang on Maurichhu	93	565	284	27.26	91.19
1620	Kurizampa on Kurichhu	92	519	8,600	27.27	91.19
1635	Autsho on Kurichhu	77	814	8,453	27.43	91.18
1652	Sumpa on Kurichhu	50	1170	—	27.68	91.22
1712	Panbang on Dangmechhu		136	20,925	26.84	90.84
1740	Uzorong on Gongri	95	554	8,560	27.26	91.41
1741	Sherichhu on Sherichhu	94	542	437	27.25	91.41
1767	Muktirap on Kholong Chhu	58	1640	905	27.59	91.49

Source: Hydromet data (2013)

Note: Sub-basin numbers indicate the contributing sub-basins for each gauging station. Dashes indicate no data

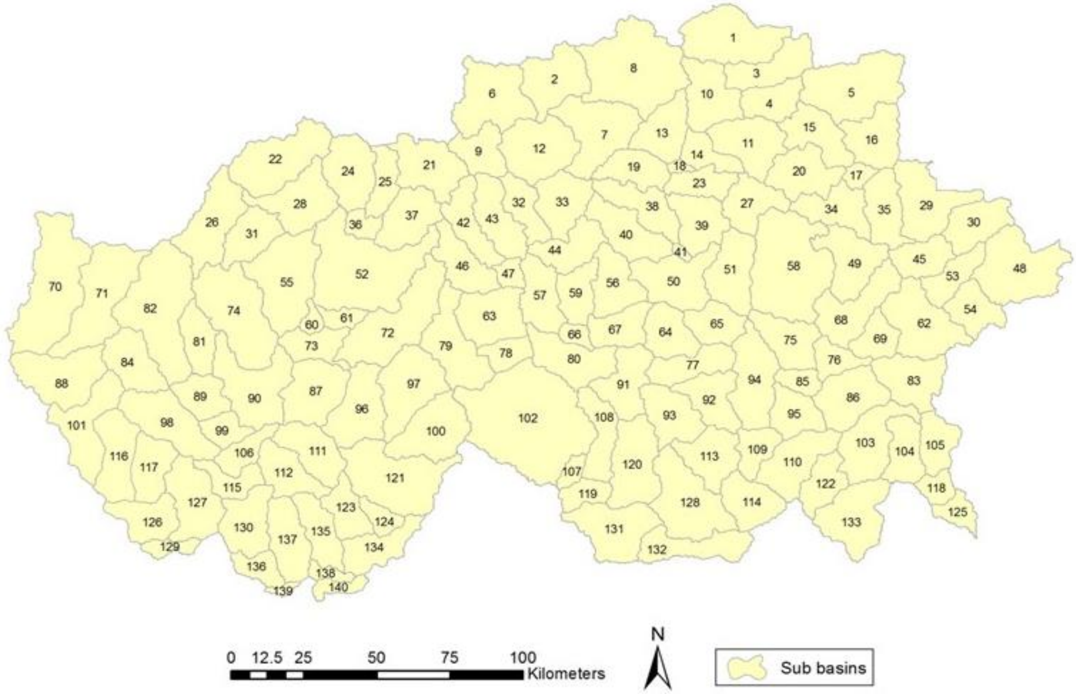
Project Setup

Watershed delineation: The basin was delineated using a DEM in SWAT. The maximum drainage area threshold was 22,500 ha. When a gauging station was available for calibration, an outlet was inserted manually, splitting the sub-basin in two, with a gauged upper half and non-gauged lower half.

Automatic sub-basin delineation, based on given threshold areas and manual input of sub-basin outlets, generated 140 sub-basins (Figure 4.9). SWAT then divided each sub-basin into more detailed HRUs. HRUs represent unique combinations of land use, soil type, and slope. SWAT delineates HRUs with user-defined thresholds represented as percentages of each land use, soil type, and slope. In this project, land use and soil type thresholds were set at 2 percent, meaning that any land use covering more than 2 percent of a sub-basin was considered an HRU, and from that portion of land use, any soil type covering more than 2 percent was considered an HRU. These thresholds were chosen to avoid creating too many HRUs, which would make analyses too complicated and time consuming for the model process.

Based on the thresholds selected, there were a total of 4,508 HRUs in the basin. These HRUs can be used for analyses on a particular land use or soil type.

Figure 4.9 Map of the basin showing sub-basin delineation



Source: Hydromet data (2013).

HEP plant and reservoirs: All of the hydroelectric plants in this study generate power through run-of-the-river hydroelectricity. Five reservoirs were modeled at sub-basins 87, 106, 113, 115, and 130 (Figure 4.8). The Tala Hydropower plant located at Wangchu contains a 92-meter-high concrete dam and underground powerhouse. The Kurichhu Hydropower plant—located on Kurichhu river in the Mongar District—consists of a dam and has a 1-million-cubic-meter capacity cement reservoir and four turbines. The plant became operational on a staggered basis between April 2001 and May 2002. The list of the dams and HEP plants are summarized in Table 4.4.

Table 4.4 SWAT input information used in the watershed

Plant name	Location	River	Design capacity (mw)	Year commissioned	Component	Comments
KuriChu[a]	Gyelposhing	Mongar	60	2001	Dam+PH	Capacity of main reservoir: 15.7 Height: 55 m Crest length: 285 m
Basochhu[a]	Wangdue-phodrang	Basochhu	40	2002	PH	Height: 4.5 m
Tala[a]	Wangkha	Chukha	1,020	2007	Dam+PH	Reservoir surface area: 0.75 km^2 Capacity of main reservoir: 9.8 million m^3 Height: 92 m
Chhukha[b]	Tsimakhoti	Chukha	336	1988	Dam	Catchment area: 3,108 km^2 Height: 43 m

Source: [a] Powerhouse. [b]GlobalEnergyObservatory.org (2013).
Note: SWAT = Soil and Water Assessment Tool; mw = megawatts; m = meters; km^2 = square kilometers; m^3 = cubic meters.

Point sources: This study did not include any point sources, but they were set up in most modeled sub-basins for future use. All outputs from point sources were set to zero in this project. There is no wastewater treatment in Bhutan.

Model Calibration and Validation

Monthly streamflows were simulated against gauging station data; however, time periods with available data varied by gauging station (Table 4.5).

Table 4.5 Comparison statistics of simulated and actual monthly streamflow at 20 monitoring sites

Station ID	Sub-basin number	R^2	NSE	PBIAS	Station ID	Sub-basin number	R^2	NSE	PBIAS
1121	129	.87	0.74	+1.80	1418	102	.94	0.81	+13.03
1246	84	.89	0.56	–33.89	1424	132	.93	0.84	+4.04
1249	99	.90	0.79	+9.10	1458	63	.86	0.75	+1.28
1253	82	.90	0.77	–2.39	1549	59	.94	0.87	+1.81
1280	74	.92	0.83	+13.00	1560	91	.93	0.81	+14.00
1314	138	.91	0.44	+44.17	1620	92	.80	0.15	+28.84
1332	121	.89	0.37	+49.67	1635	77	.77	–0.80	–56.80
1349	73	.89	–40.86	+37.20	1652	50	.70	–1.61	–61.66
1370	55	.85	0.46	–1.61	1740	95	.88	0.82	+6.16
1381	52	.79	–0.05	+1.40	1767	58	.83	0.19	+45.75

Source: Hydromet data and Soil and Water Assessment Tool results (2013).
Note: NSE = Nash-Sutcliffe model efficiency; PBIAS = percent bias.

For statistical analyses of the calibration and validation, coefficient of determination (R^2), Nash-Sutcliffe model efficiency (NSE; Nash and Sutcliffe 1970), and percent bias (PBIAS) were examined. R^2 can range from 0.0 to 1.0, with higher values' indicating better model performance in predicting the variations of observed data. NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. NSE ranges from $-\infty$ to 1.0; 1.0 indicates a perfect fit, and negative values indicate that average values of observed data are more reliable than the model predictions. Positive values show a better match of observed data and predicted values. NSE is calculated with equation 1:

$$\boldsymbol{NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}} \tag{1}$$

where O is the observed statistic for month i, P is the SWAT-simulated statistic for the same month i, and $\bar{O}$= the average of all the monthly observation data.

PBIAS measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (Gupta, Sorooshian, and Yapo 1999). The optimal value of PBIAS is 0.0, with low values' indicating accurate model simulation in term of magnitude. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias (Gupta, Sorooshian, and Yapo 1999). It is calculated as

$$\boldsymbol{PBIAS = \left[\frac{\sum_{i=1}^{n}(O_i - P_i) * 100}{\sum_{i=1}^{n} O_i}\right]} \tag{2}$$

P = SWAT prediction. All other variables are as defined in equation 1.

According to Moriasi et al. (2007), model predictions can be classified as satisfactory if 0.5 < NSE ≤ 0.65 while ±15 percent ≤ PBIAS < ±25 percent, good if 0.65 < NSE ≤ 0.75 while ±10 percent ≤ PBIAS < ±15 percent, and very good if 0.75 < NSE ≤ 1.00 while PBIAS ≤ ±10 percent. Model performance is unsatisfactory if NSE ≤ 0.5 and PBIAS ≥ ±25 percent.

Table 4.5 and Table 4.6include statistical comparisons of long- term means, standard deviations, R^2, NSE, and PBIAS. Model performance statistics used to assess calibration efforts indicate that SWAT model estimates are satisfactory with a range of .70 to .94 for R^2 and an NSE value greater than 0.50 for 11 gauged subwatersheds and unsatisfactory with an NSE value less than 0.50 for 9 subwatersheds. Differences between observed and modeled monthly streamflow, averaged over the entire simulation period at each gauging station, range from 1.45 percent to 61.67 percent with an average difference of +3.92 percent (Table 4.6). Table 4.7presents predicted average monthly outflow from sub-basins for the relevant simulation period. Average monthly and annual basin values are presented in Table 4.8 and Table 4.9, respectively. According to the model outputs, 70 percent of fallen snow is melted or evaporated, and only 5 percent of total precipitation remains on the ground and is added to the snowpack each year.

Table 4.6Multiyear average and standard deviation of monthly streamflow

		Monthly Average Flow (cm)		Standard Deviation		Simulation Period
Station ID	Sub-basin Number	Observed	Simulated	Observed	Simulated	
1121	129	182.39	179.74	169.45	125.00	2006–2012
1246	84	5.75	7.70	4.44	4.81	2000–2012
1249	99	65.84	59.85	60.34	57.27	2002–2012
1253	82	25.51	25.96	25.17	26.52	1997–2012
1280	74	22.77	19.81	22.02	21.47	1997–2012
1314	138	454.01	256.35	409.39	217.69	2007–2012
1332	121	359.47	180.90	315.62	147.77	2006–2012
1349	73	296.69	186.32	256.57	158.73	2003–2012
1370	55	113.49	111.44	105.50	90.34	2005–2012
1381	52	43.06	42.45	31.61	41.40	2008–2012
1418	102	147.76	128.50	121.49	89.04	2005–2012
1424	132	723.80	694.53	695.11	552.31	2011–2012
1458	63	59.78	58.25	52.02	51.86	2003–2012
1549	59	53.64	52.31	46.87	47.23	1997–2012
1560	91	97.06	83.46	82.72	63.54	2009–2012
1620	92	272.16	332.13	222.86	320.57	2006–2012
1635	77	223.39	329.42	178.59	318.37	2006–2012
1652	50	176.39	285.16	149.86	291.83	2007–2012
1740	95	304.89	286.11	236.06	205.83	1997–2012
1767	58	64.96	35.14	53.57	20.76	2001–2012

Source: Soil and Water Assessment Tool results (2013).

Table 4.7Average monthly streamflow from sub-basins

Reach number	Area (km^2)	Flow (cm)	Sub-basin number	Area (km^2)	Flow (cm)	Sub-basin number	Area (km^2)	Flow (cm)
1	546.30	4.22	48	594.90	21.90	95	8304.00	289.30
2	1166.00	41.11	49	2686.00	92.39	96	6492.00	157.60
3	865.60	8.86	50	7280.00	167.90	97	480.20	6.62
4	234.20	2.09	51	659.00	14.11	98	778.60	14.50
5	619.80	20.14	52	2342.00	42.54	99	2605.00	59.96
6	766.90	11.51	53	1213.00	46.46	100	441.20	15.35
7	983.80	30.17	54	843.90	33.39	101	2352.00	102.10
8	2017.00	52.45	55	2301.00	87.43	102	3319.00	149.10
9	243.30	1.34	56	310.10	13.15	103	418.10	10.18
10	1474.00	17.42	57	306.20	9.11	104	260.00	5.79
11	387.00	5.13	58	882.50	37.59	105	225.60	5.14
12	469.60	23.05	59	1378.00	52.94	106	3558.00	76.67
13	3311.00	91.41	60	2361.00	87.81	107	3393.00	150.80
14	2043.00	26.51	61	2438.00	43.39	108	281.70	9.72
15	321.00	5.67	62	2556.00	99.87	109	8942.00	310.20
16	957.30	29.86	63	1388.00	76.59	110	386.30	7.10
17	737.50	16.24	64	274.70	8.26	111	321.50	3.44
18	5384.00	118.70	65	8175.00	185.60	112	283.40	1.64
19	258.80	5.82	66	1451.00	53.54	113	9664.00	205.80
20	343.50	7.17	67	557.00	15.77	114	9624.00	348.40
21	397.50	3.47	68	3094.00	108.10	115	3739.00	98.68
22	537.70	21.78	69	2747.00	103.90	116	2724.00	105.90
23	5850.00	129.30	70	816.80	42.12	117	276.50	3.22
24	374.20	4.10	71	612.50	31.52	118	600.60	13.08
25	594.00	8.06	72	638.30	15.29	119	3817.00	163.80
26	461.00	23.16	73	5662.00	148.20	120	3177.00	88.56
27	287.60	5.58	74	663.40	19.94	121	8064.00	186.00
28	953.00	39.25	75	1196.00	45.51	122	650.00	14.24
29	452.20	18.55	76	6003.00	215.30	123	831.10	6.43
30	303.70	7.97	77	8722.00	196.70	124	8175.00	186.50
31	738.20	35.00	78	1541.00	80.34	125	727.80	26.47
32	226.50	9.40	79	454.50	18.75	126	3280.00	141.60
33	330.10	14.80	80	2390.00	73.26	127	412.10	48.67
34	304.90	14.28	81	232.50	5.12	128	19850.00	559.10
35	2000.00	60.71	82	808.40	26.11	129	3785.00	200.90
36	1070.00	17.22	83	359.50	11.39	130	4078.00	141.30
37	338.90	5.02	84	323.50	7.69	131	7445.00	262.50
38	312.00	8.08	85	7313.00	265.20	132	20170.00	593.10
39	6160.00	136.00	86	743.10	19.74	133	1103.00	62.98
40	353.20	9.56	87	6072.00	153.00	134	9289.00	223.20
41	6497.00	144.50	88	1914.00	91.20	135	270.10	29.25
42	281.00	15.50	89	1266.00	32.36	136	4227.00	160.90
43	328.20	19.13	90	1191.00	26.85	137	332.40	38.98
44	838.70	38.41	91	2721.00	76.84	138	9627.00	260.10
45	993.20	38.39	92	9017.00	199.20	139	4590.00	203.30
46	301.30	22.53	93	323.40	4.07	140	9718.00	270.50
47	694.90	39.00	94	448.40	19.55			

Source: Soil and Water Assessment Tool results (2013).
Note: km^2 = square kilometers; cm = centimeters.

Table 4.8Average monthly basin values (millimeters)

Month	Rain	Snow fall	Surface runoff	Lateral flow	Water yield	Evapotranspiration
1	18.61	11.95	0.37	0.69	25.60	15.25
2	34.97	19.53	1.10	1.71	22.23	23.17
3	63.76	27.75	4.09	4.65	25.72	34.46
4	119.23	34.62	15.15	14.92	43.59	40.32
5	155.05	28.12	35.78	25.86	75.14	45.94
6	252.00	25.29	80.70	47.86	144.27	36.97
7	308.85	31.15	97.25	67.94	188.66	29.74
8	269.82	32.49	79.12	60.51	171.30	29.26
9	188.69	26.95	49.55	43.57	129.29	30.24
10	95.04	23.11	21.55	17.80	77.46	32.20
11	17.45	9.77	0.91	1.97	36.04	23.47
12	12.20	7.45	0.30	0.69	30.31	16.83

Source: Soil and water assessment tool results (2013).

Table 4.9Average annual basin values (millimeters)

Precipitation	1534.80	Groundwater	56.74
Snow fall	277.70	Deep aquifer discharge	7.06
Snow melt	173.54	Total aquifer discharge	353.20
Sublimation	22.26	Total water yield	969.03
Surface runoff	385.85	Percolation out of soil	353.19
Lateral soil flow	288.14	Evapotranspiration	357.20
Shallow aquifer percolation	295.05	Potential evapotranspiration	781.20

Source: Soil and water assessment tool results (2013).

Overall, the model compared well at a monthly temporal scale across 11 monitoring sites, given the input data developed in this study, while predicted flow from gauging stations on the Kurichhu (1620, 1635, 1652) and Puntasangchhu (1381, 1349, 1370) was not satisfactory. The main reason for poor results in these stations could be associated with the large gaps in precipitation data at these regions. Considerable uncertainty has been reported for the variations of precipitation with elevation in the mountainous terrain of Bhutan as well. For further improvements in monthly streamflow, more detailed information (for example, reservoirs, dams, and irrigation) needs to be collected.

To save space, six gauges—two in the west (1249 and 1121), one in the northwestern mountains (1370), two in the lower middle (1418 and 1549), and one in the east of the basin (1740)—were used to graphically illustrate simulated and observed streamflow. The simulated and observed streamflow at these gauges is shown in Figure 4.10. Flow time series curves show the model captured well seasonal variation in streamflow, snowmelt, and evapotranspiration, although peaks are not always perfectly simulated. The hydrological regime of the rivers in this region is characterized by low flow in the cold dry winter, resulting in accumulation of snow at high altitudes, and high flow during summer caused by monsoon precipitation and melting of glacier ice and snow.

Snow season in the mountain area elevation of 3,000 m often starts from late autumn to the next early summer. In the pre-monsoon and early monsoon season (May to July), snowmelt from all subwatersheds contributes significantly to river discharges. Every June to September is wet season, with frequent showers and night rainfalls. There is permanent snow cover in the area of elevation of 6,000 meters. Sub-basins delineated by elevation is depicted in Figure 4.11. The monthly flow duration curve of major rivers, sorted from west to east, is presented in Figure 4.12.

Figure 4.10Observed and simulated monthly streamflow (m^3/sec) at selected gauges

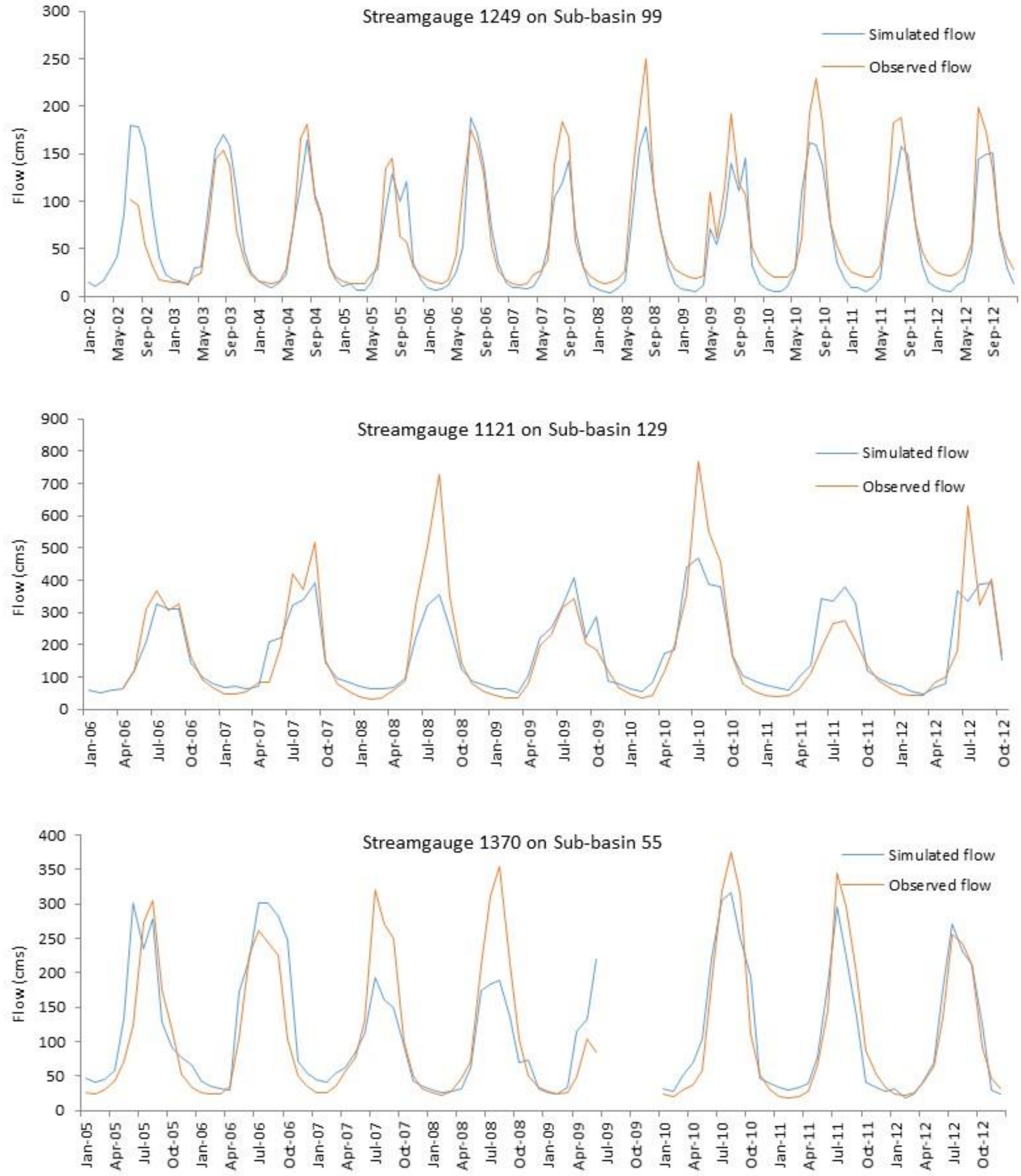
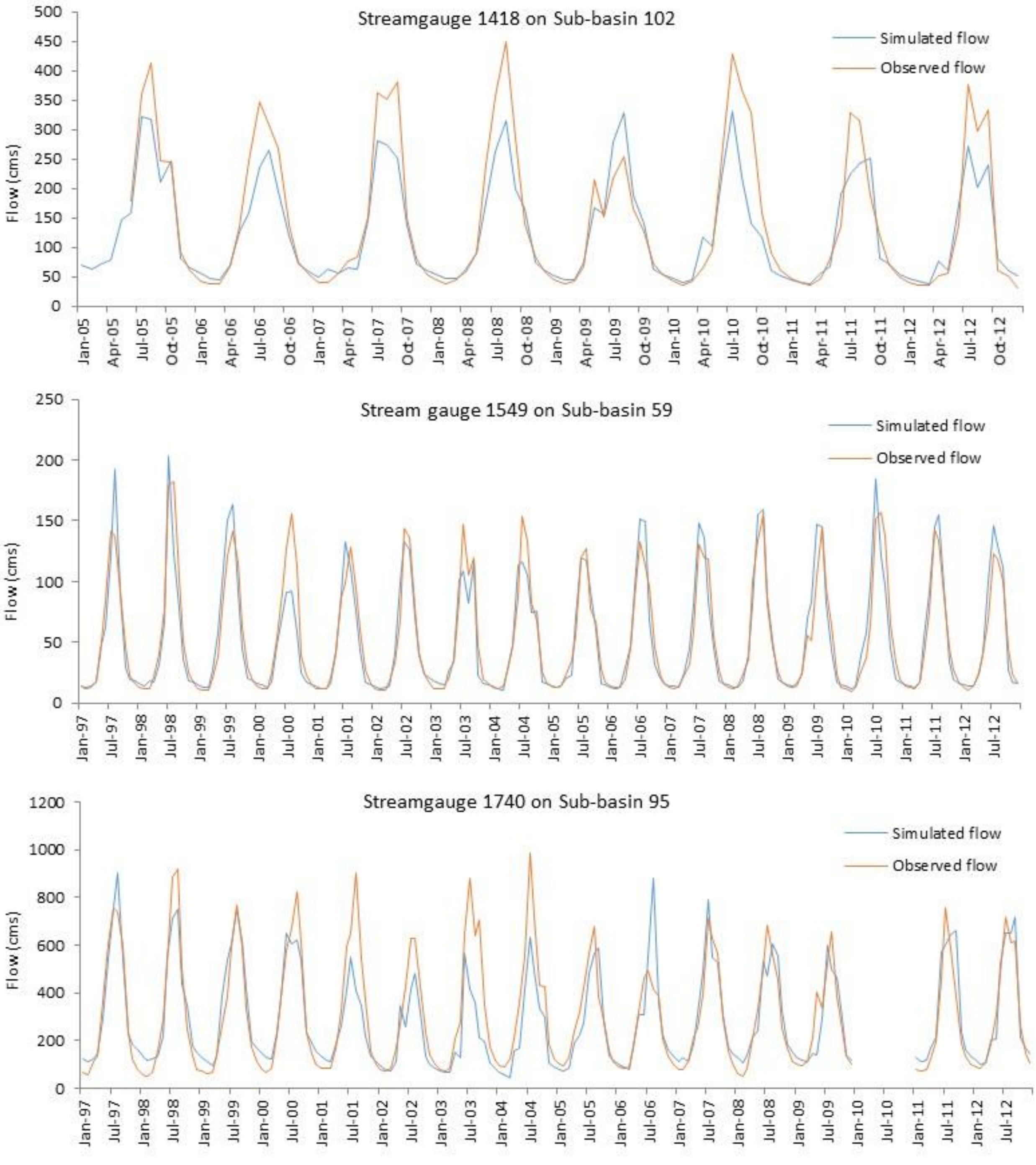


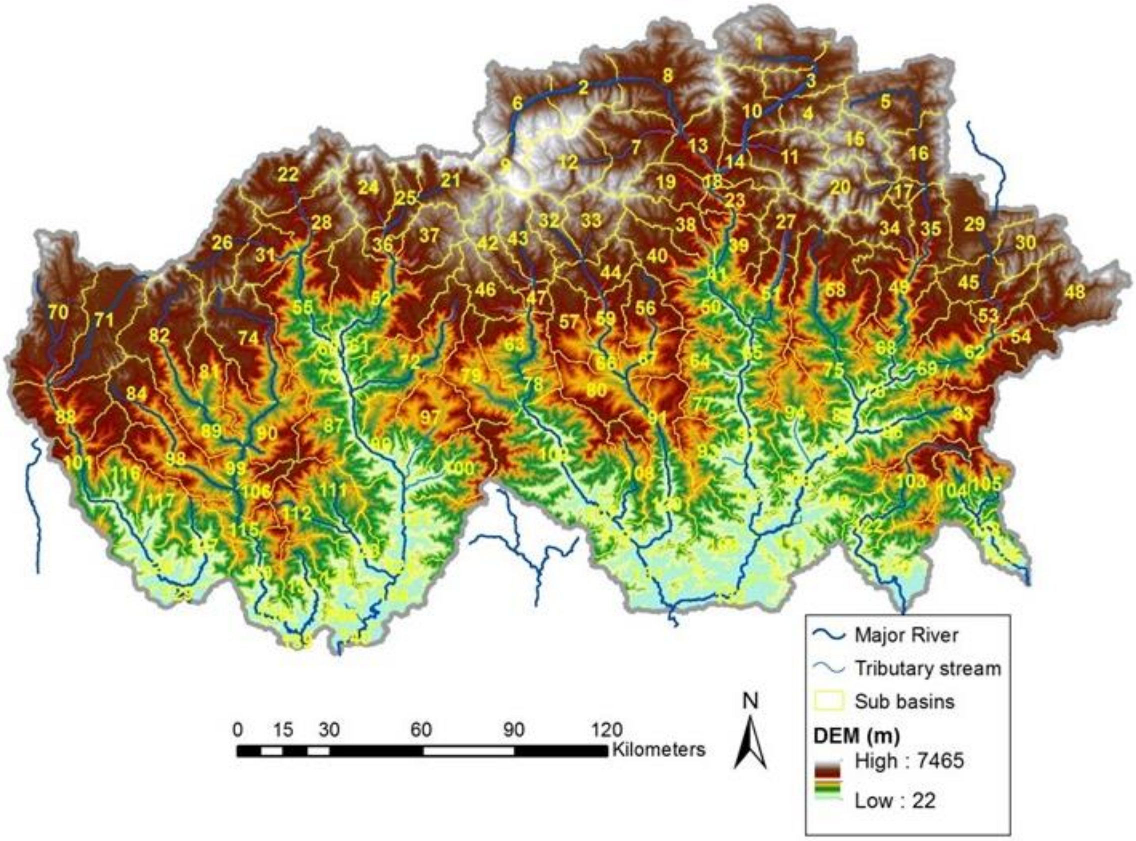
Figure 4.10 Continued



Source: Soil and water assessment tool results (year?).

Note: cms = centimeters; Jan = January; Sep = September; Apr = April; Jul = July; Oct = October.Gauges 1249 and 1121 in the west; 1370 in the northwestern mountains; 1418 and 1549 in the lower middle, and 1740 in the east of the basin.

Figure 4.11Topographic situation of subwatersheds and gauging stations



Source: National Soil Services Center data (2013).
Note: DEM = digital elevation model; m = meters.

Figure 4.12Duration curve of monthly flow of major rivers, sorted from west to east

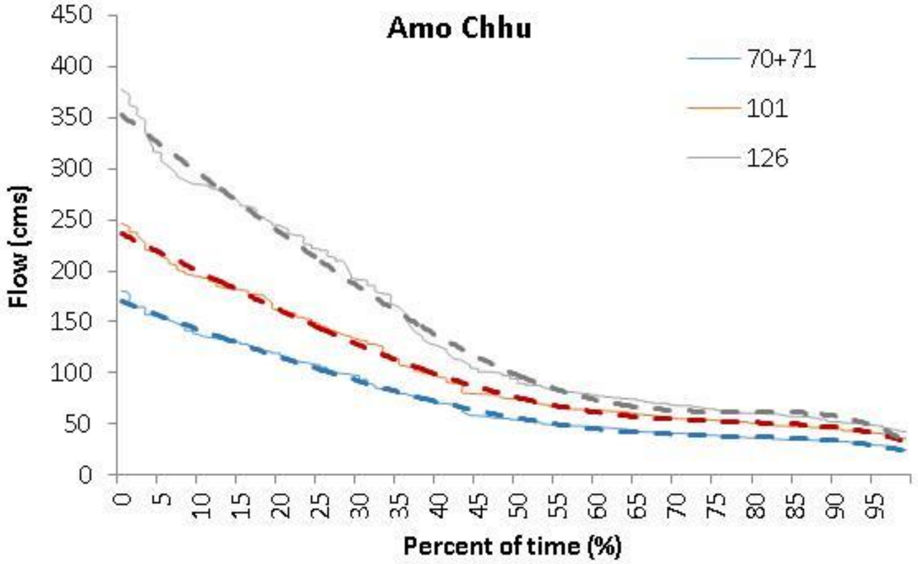
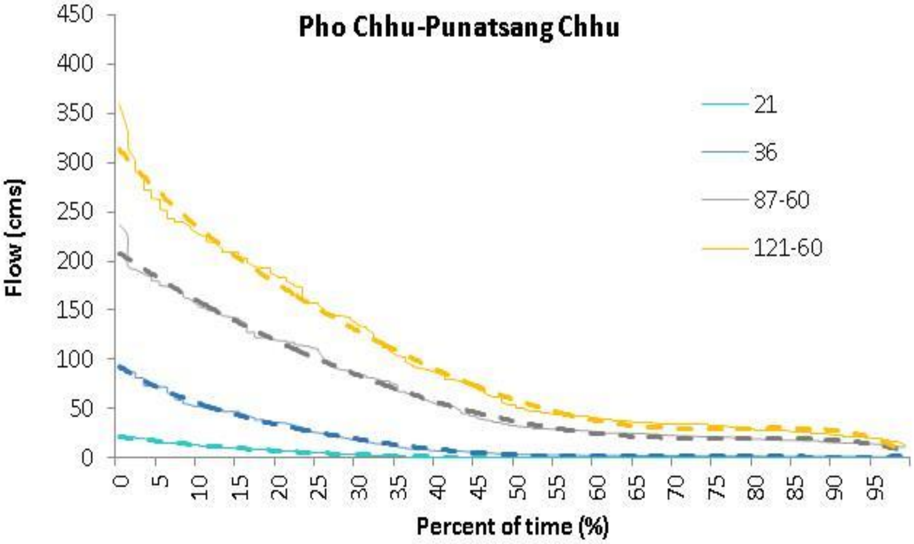


Figure 4.12 Continued



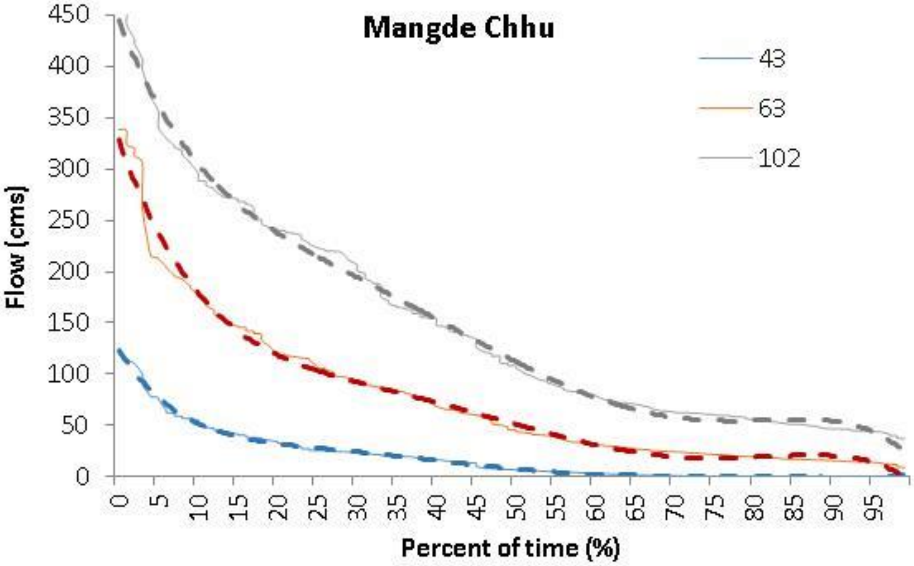
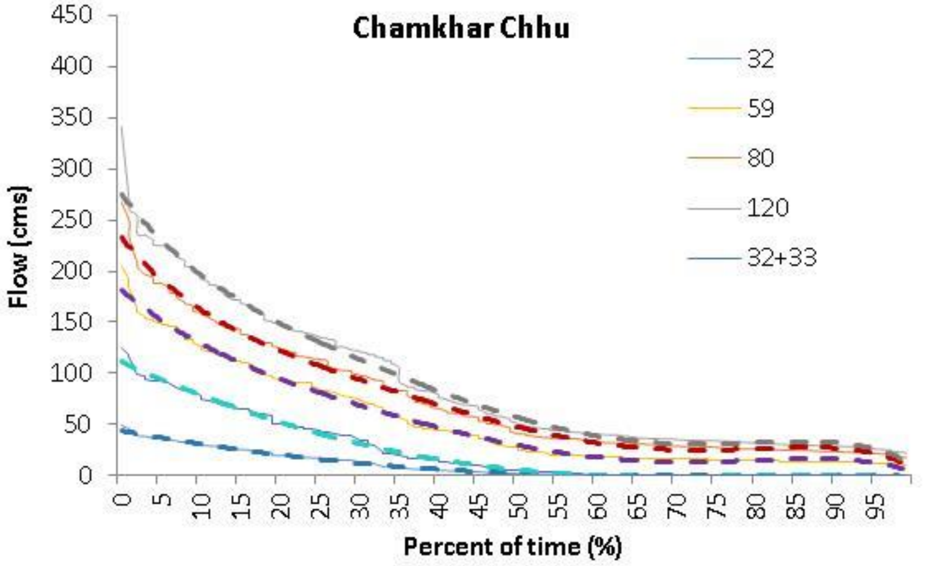
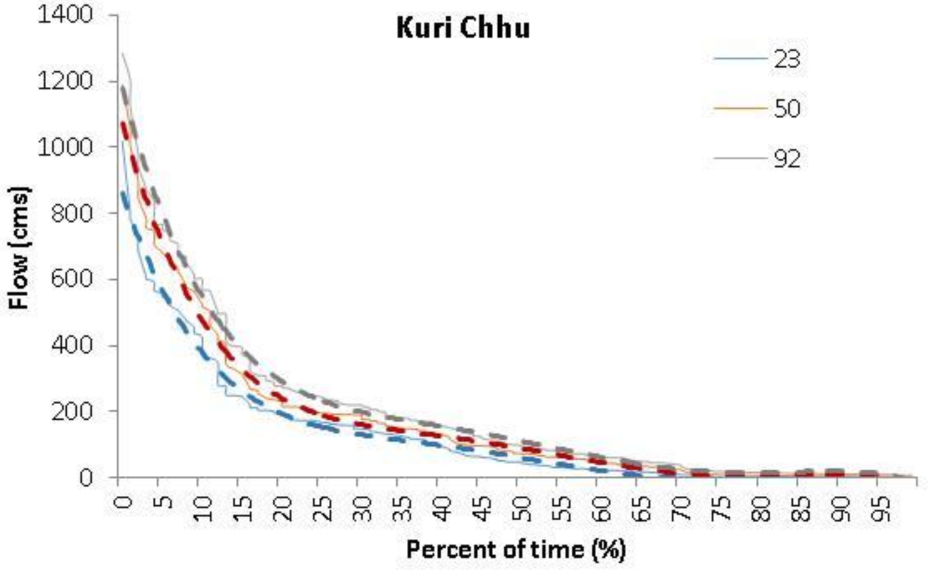


Figure 4.12 Continued





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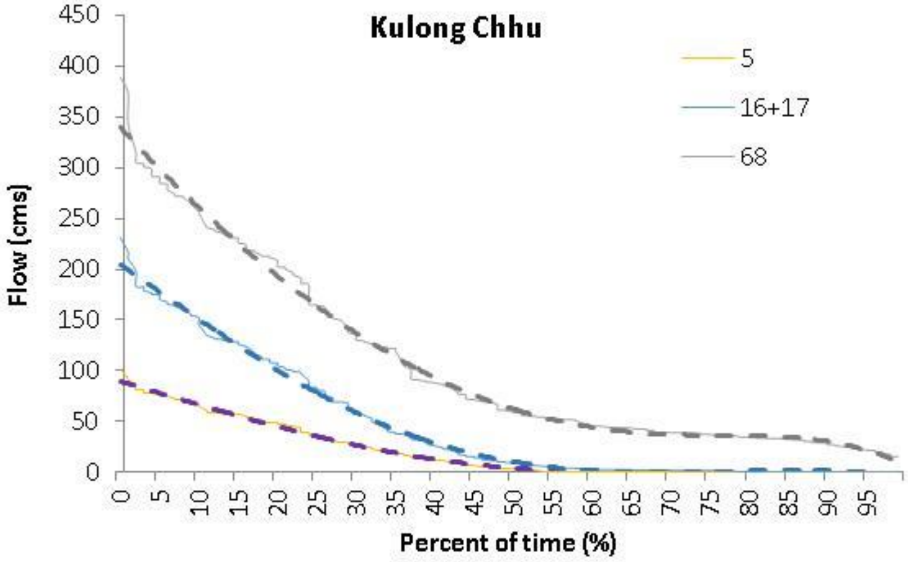
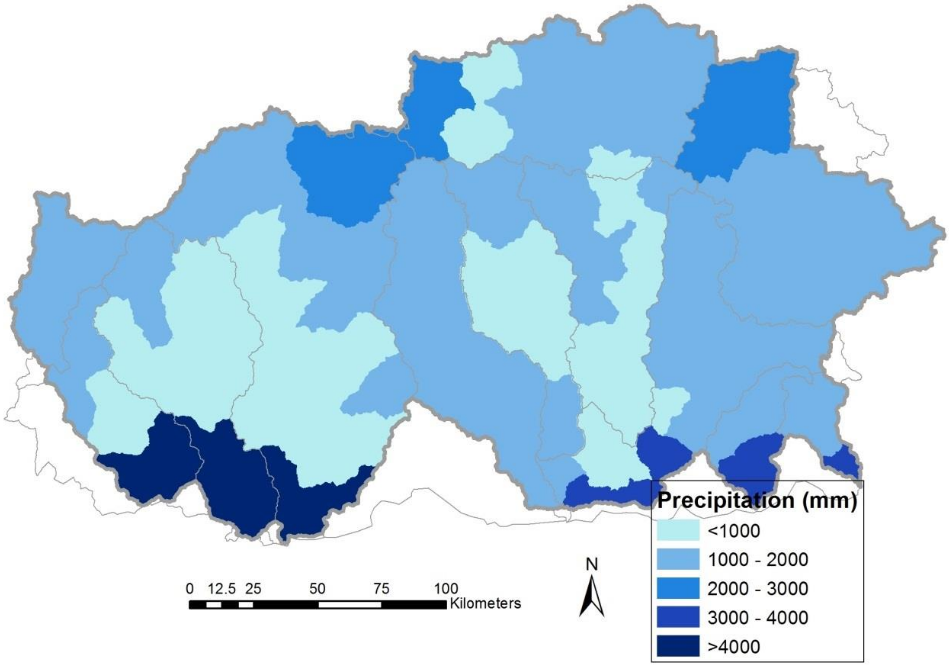


Source: Soil and water assessment tool results (2013).
Note: cms = centimeters.

Spatial Distribution of Hydrologic Components by Subwatersheds

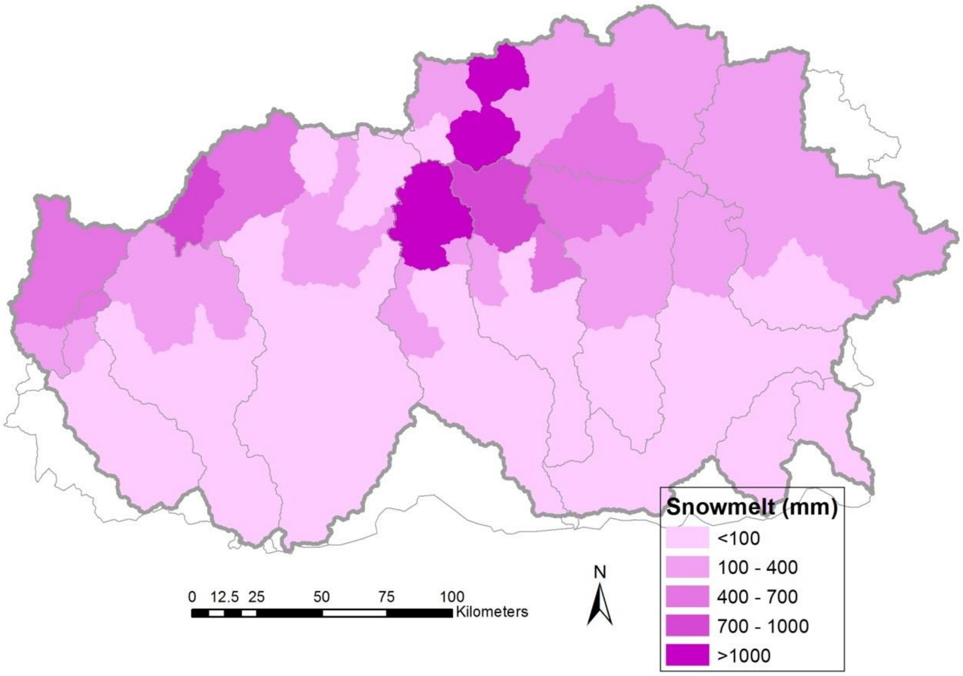
In southern subwatersheds with the elevation of 1,500 m, there are frequent heavy rains during summer and stream contribution dominated by rainfall (Figure 4.13). Snowmelt from higher-elevation ranges contributes more water to discharge despite lower rainfall in these subwatersheds. Figure 4.14 shows the spatial distribution of annual snowmelt. Note the high percentages derived from snowmelt in the upper central subwatersheds as well as in the high elevations (subwatersheds 42, 43, 48, 2, and 12). The frontal areas are dominated by rainfall and thus have a low snowmelt contribution. Figure 4.15 shows the evapotranspiration by sub-basin. Figure 4.16 shows the spatial distribution of surface runoff, which is highly dominated by rainfall contribution at the south and snowmelt contribution at mountainous subwatersheds.

Figure 4.13Spatial distribution of average annual precipitation



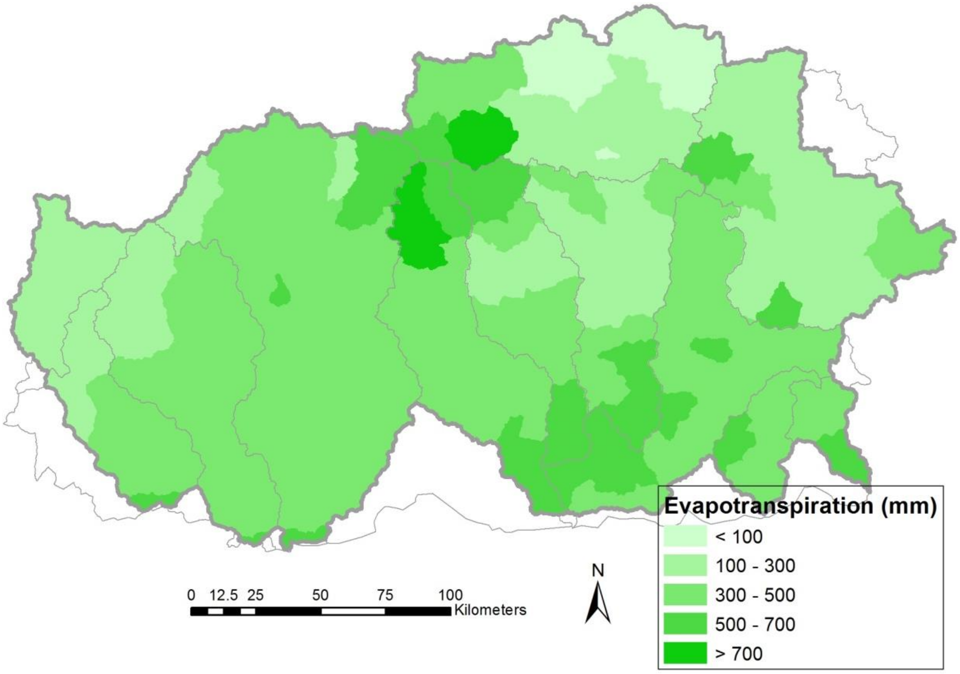
Source: Hydromet data (2013).
Note: mm = millimeters.

Figure 4.14Spatial distribution of average annual snowmelt



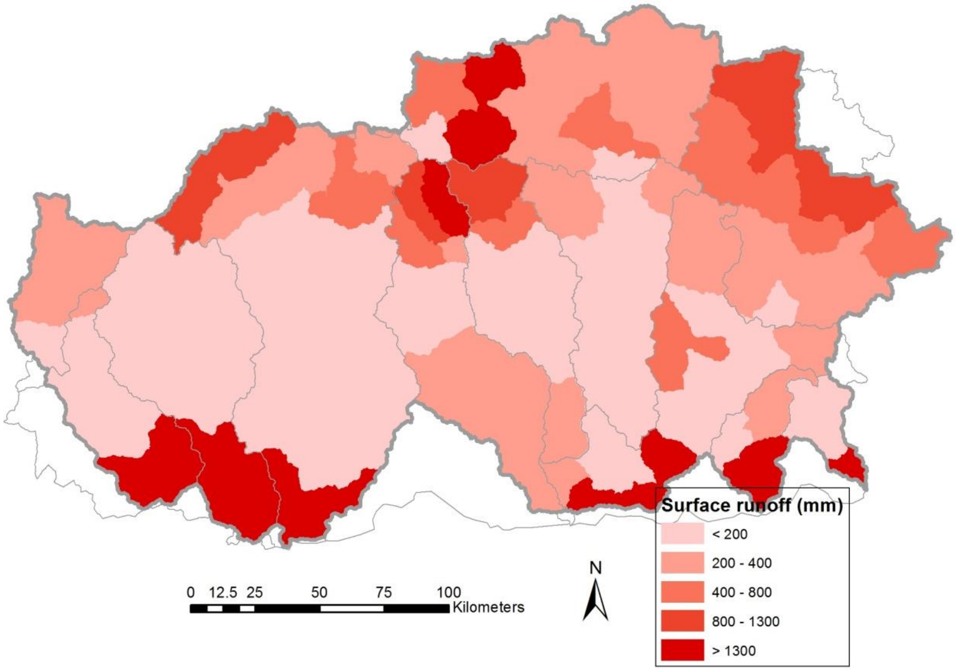
Source: Hydromet data (2013).
Note: mm = millimeters.

Figure 4.15Spatial distribution of average annual evapotranspiration



Source: Hydromet data (2013).
Note: mm = millimeters.

Figure 4.16Spatial distribution of average annual surface runoff



Source: Hydromet data (2013).
Note: mm = millimeters.

Economic Analysis of SLM

To assess the economic benefits of SLM, we estimate the benefits and costs of SLM practices and compare them with practices that are most prevalent in Bhutan—that is, business as usual (BAU). Since land degradation, SLM investments, and their returns are long-term processes, time series data are required to determine the impact of SLM on land productivity. For example, greater yield due to terraces built in one year to prevent soil erosion may prevail over many years. Similarly, plants established to fix nitrogen may take years to show significant impact on crop yield, but once well established, nitrogen fixation and consequent higher crop yield could continue until when the leguminous tree is cut. As mentioned earlier, our analysis will include both on-farm and off-farm costs of land degradation and benefits of SLM. Assessment of the off-farm costs and benefits is complicated and difficult to measure (Berry et al. 2003; Hein 2006). Hence there has been a limited number of studies that have assessed the on-farm and off-site costs and benefits of land degradation and SLM investment. As mentioned earlier, the off-site benefits of SLM considered in this study are reductions in sediment loading. Accordingly, the off-site costs of land degradation are higher sediment loadings due to use of land-degrading practices. This study will use fairly simple methods and approaches that can be easily replicated in other studies. The approach compares profit of land productivity with and without SLM practices and includes both on-farm and off-site benefits and costs of management practices.

The returns to SLM investment (profit) analysis will be on a per-hectare basis for each of the major AEZs. However, for livestock production, the unit of analysis will be at the household level—the livestock production per household using SLM practices (that is, improved pasture management). To obtain national-level results, the results under each AEZ will be extrapolated to the relevant AEZ (Table 4.10).

Factors Influencing Adoption of SLM Practices

We analyze the drivers of adoption of SLM practices using the RNR 2009 data. Such analysis will help to determine the policies and strategies that could be used to achieve Bhutan’s objectives of SLM stated in its 2020 Vision and other policies. Understanding of the factors influencing adoption of SLM practices will help the government to design strategies that will enhance adoption of SLM practices. The focus of the discussion will be on factors that have policy relevancy. These include farmer access to rural services (extension services and rural roads), land tenure security, and household physical capital endowment (land area and livestock) and human capital (sex and age of household head) (Barrett, Place, and Aboud 2002).[3]

We use a nonlinear bivariate Probit model as specified below:

$$P(\mathbf{y}=1|\mathbf{x_i}) = f(\beta_0 + \beta\, \mathbf{x_i} + \mathrm{e_i}),$$

where f(z) is normally distributed with a probability density function of the following:

$$\frac{1}{\sigma\sqrt{2\pi}} exp\left(\frac{(x_i-\mu)^2}{2\sigma^2}\right)$$

where P = probability that the household uses SLM practices. P = 1 if the household uses SLM; P = 0 otherwise.

$$\mathbf{x_i} = \mathbf{x_1} + \mathbf{x_2} + \mathbf{x_3},$$

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[3] As noted below, choice of the factors affecting SLM was also determined by data availability. For example, education is among the human capital endowment factors that affect SLM adoption but was not included in the model since it was not available.

where $\mathbf{x_1}$ = the vector of the household capital endowment—which includes human capital (age and sex household head); $\mathbf{x_2}$ = vector of land rights, method of acquisition (own land, renting, leasehold, and unused land—fallow), or both; $\mathbf{x_3}$ = ownership of physical capital (livestock used as an indicator of physical capital); and $\mathbf{z}$ = vector of access to rural services (time to nearest road and access to extension services).

β_i = coefficients associated with the corresponding covariate *i*.

The choice of covariates to include in the model was dictated by data availability. Some important variables—such as the level of education of the household head or other family members and total farm area—were not collected.

We do not include prices of commodities in this model since this is a generalized model that explains the adoption of any type of SLM practice—regardless of the type of land use (cropland, livestock, or forests). The next section on benefits-costs analysis of SLM will address price aspects.

Multicollinearity was not a serious problem since the average variance inflation factor was 2.28 and the largest variance inflation factor only 6.41, less than 10—a level deemed the threshold for serious bias due to multicollinearity (Mukherjee et al. 1998). We corrected for heteroskedasticity by estimating robust standard errors.

Returns to SLM Practices

Profit with SLM Practices

The general model for returns to SLM practices for all land use types (forest, cropland, and livestock) is given in equation 1, and the corresponding model for land-degrading practices is given in equation 2.

$$\boldsymbol{\pi_t^c = p_t y_t^c - z_t^c - \lambda_t} \tag{3}$$

where π_t^c= profit per hectare or household with SLM practices in year *t*. For brevity, we will simply refer to returns per hectare, but this also means returns per household for livestock production land management practices.[4]

y_t^c production per hectare with SLM practices in year *t*.

Pt = a constant price of output in year t.

This will be the social price, that is, price that excludes market failures or policy-induced distortions—including subsidies and taxes.

z_t^c= social cost of production using SLM practices per hectare in year *t*.

λ_t= external (off-site) costs or benefit of SLM practice per hectare—for example, clearing forest area for crop production could lead to greater sediment loading in HEP dams. If $\lambda_t > 0$, then off-site impact is a benefit to society, and if $\lambda t < 0$, then off-site effect is a cost.

Profit with Land-degrading Practices (BAU)

$$\boldsymbol{\pi_t^d = p_t y_t^d - z_t^d - \tau_t} \tag{4}$$

where

y_t^d = production per hectare with BAU in year *t*.

π_t^d = profit with BAU per hectare in year *t*.

---

[4] The *c* superscript refers to conservation and is used to represent SLM practices in all cases. The *d* superscript refers to degradation and represents land-degrading practices.

P_t = social price of one unit of output in year t. A specific price will be applied for each enterprise analyzed (maize, rice, forest livestock products, and so forth). A private price is important to analyze since it determines farmers' choices to use SLM practices. However, we did not use it in this study since we used market prices that are not affected by government failure, subsidies, or taxes.

z_t^d = social cost of production of per hectare using land-degrading practices.

τ_t = external (off-site) costs or benefit of land-degrading management practice per hectare, for example, sedimentation.

The decision by a landowner to use SLM will depend on the marginal rate of returns (MRR), which is defined as the returns per unit of investment. Holding all else constant, the higher the MRR, the greater is the uptake of SLM. For example, Heisey and Mwangi (1998) observed adoption of fertilizer among smallholder farmers in Africa south of the Sahara requires an MRR of at least 100 percent; that is, for every unit of currency (for example, Bhutanese ngultrum) invested, one or more additional units are obtained.

MRR analysis will help to determine the attractiveness of SLM practices over time. MRR is given by

$$\boldsymbol{MRR_t = \frac{\pi_t^c - \pi_t^d}{z_t^c + \lambda_t^c - z_t^d - \lambda_t^d}} \qquad (5)$$

However, MRR_t is given at one point in time, that is, MRR_t in year t. This could differ for each planning horizon. An analysis that looks at the streams of benefits of SLM and associated costs is the net present value (NPV). NPV is summed over the planning horizon and therefore reflects the benefits and costs of investment during the entire planning horizon (Gardner and Barrows 1985). The social NPV (NPV^s) of adopting SLM practices is therefore given by

$$\boldsymbol{NPV = \rho^t \left\{\sum_{t=1}^{T} (\pi_t^c - \pi_t^d)\right\}} \qquad (6)$$

where T = farmer's planning horizon.

$\rho^t = \left(\frac{1}{1+r}\right)^t$ = farmers' discount factor, where r is the farmer's discount rate.

Discounting the future value is an integral part of farmers' decisionmaking processes (Duquette, Higgins, and Horowitz 2011) as it reveals farmers' time preferences and risk attitudes. The discount rate varies widely even among poor farmers. Recent social experiments have elicited valuable information about farmer discount rates (Duflo, Mullainathan, and Bertrand 2004; Duquette, Higgins, and Horowitz 2011; D'Exelle, van Campenhout, and Lecoutere 2012). Using experimental evidence from American farmers, one study showed an annual discount rate of 28 percent (Duquette, Higgins, and Horowitz 2011). Lower discount rates have also been used (for example, Pagiola 1996 used a 10 percent discount rate for SLM practices in Kenya). Based on this, we use a discount rate of 25 percent. But we also conduct sensitivity analysis of NPV and internal rate of return (IRR) by using discount rates of 10 percent, 25 percent, and 30 percent to determine robustness of the results. The sensitivity analysis of MRR is not conducted since this is not affected by the discount factor given that MRR is a ratio of net benefits and costs, both of which are discounted, hence canceling out the effect of the discount factor.

Farmers find it profitable to adopt an SLM practice if NPV > 0. However, a given farmer's decision to adopt SLM practices typically does not take into account the off-site costs and benefits that result from adoption or nonadoption of SLM practices. The literature on these issues establishes that a positive NPV may be far from sufficient to induce investment (for example, Pender 1996; Dixit and Pindyck 1994; Fafchamps and Pender 1997). Hence, the MRR trend over the planning horizon will also be used to evaluate the change in attractiveness of SLM practices over time. For example, this analysis is likely to show a negative or small MRR at the beginning, after the initial large fixed costs of SLM are incurred. The MRR will improve over time as the large initial overhead investments decrease and their returns become more significant. Robustness of the MRR to the discount factor also will be computed using the three levels used for NPV, that is, r = 10 percent, 25 percent, and 30 percent.

Economic Data Used

Returns to SLM Practices

For all three land use types (forests, croplands, and grazing lands), we assume that the land management practices recommended by the Ministry of Agriculture and Forests lead to SLM. So we use experimental results to determine the land production per hectare when farmers use or do not use SLM. We discuss each of the data sources under each land use type and corresponding to the six AEZs (Table 4.10). Other studies (for example, United Nations Environment Programme 2009) divide Bhutan into only three major agroclimatic zones, which are largely determined by altitude: (1) alpine zone (>4,000 m)—the alpine zone, where glaciers and glacial lakes are located, account for 10 percent of the total land area of Bhutan (Choden, Tashi, and Dhendup 2010); (2) temperate zone (1,000–4,000 m)—this zone lies in the middle belt; and (3) subtropical zone (200–1,000 m)—this zone lies in the southern part (Choden, Tashi, and Dhendup 2010). We will use the six AEZs (Table 4.10) since this reflects well the forest ecosystem that occupies the largest land area.

Table 4.10 Agroecological zones and the corresponding agricultural enterprises

Agroecological zone	Altitude (meters above sea level)	Annual rainfall (mm)	Major enterprises
Alpine	3,600–4,600	<650	Yak herding by nomadic communities, dairy products, barley, buckwheat, mustard, and vegetables
Cool temperate	2,600–3,600	650–850	Yak, cattle, sheep, horses, dairy products, barley, wheat and potatoes on dryland, buckwheat and mustard under shifting cultivation
Warm temperate	1,800–2,600	650–850	Rice on irrigated land, double cropped with wheat and mustard; barley and potatoes on dryland; temperate fruit trees; vegetables; cattle
Dry subtropical	1,200–1,800	850–1,200	Maize, rice, millet, pulses, fruit trees and vegetables, wild lemon grass, cattle, pigs and poultry
Humid subtropical	600–1,200	1,200–2,500	Irrigated rice rotated with mustard, wheat, pulses, and vegetables; tropical fruit trees
Wet subtropical	150–600	2,500–5,500	Irrigated rice rotated with mustard, wheat, pulses, and vegetables; tropical fruit trees

Source: Tobgay (2005).
Note: mm = millimeters.

Cropland

As discussed earlier, we focus only on maize, rice, and citrus. Data required for conducting returns to SLM practices are SLM practices and their impact on crop yield—that is, yield with and without SLM practices. We use experimental results from the Bhutan Overview of Conservation Approaches and Technologies (WOCAT) conducted by NSSC[5]in collaboration with WOCAT to identify the SLM practices and their impact on maize and rice yields—that is, yield with SLM practices. The literature of past soil fertility studies also is used to determine crop yield with SLM practices. Yield obtained by farmers (BAU) was obtained from the 2011 RNR household survey data. Table 4.11 reports the SLM and yield under BAU.

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[5] For details see http://www.nssc.gov.bt/bhucat-bhutan-catalogue-of-soil-and-water-conservation-approaches-and-technologies.

Table 4.11 Enterprises and their potential and actual yield

Enterprise	Location	Price or value per unit (US$)	Yield potential	Farmer yield/ farmer practice	Input recommended	Inputs farmer practice	Source
Maize	Eastern regions	231.21/ton	4.15	2.79	kg of N,P, and K per ha = 100, 80, and 60 plus 7 tons/ha FYM	6.7 kg N/ha, 1.9 kg P_2O_5/ha, 1.3 K_2O/ha	RNR 2011 NSSC (211), FAOSTAT 2013
Paddy rice	Humid subtropics and humid tropics	662/ton	7 tons/ha	3.5 tons/ha	7 tons/ha FYM + 17 kg P/ha		Chetri, Ghimiray, and Floyd (2003)
Oranges		754/ton	10.17 tons/ha	Fallow land	Plantation		FAOSTAT
Livestock	Cool and warm temperate, humid, and dry subtropical zones						
	Milk[a]	55.96/ton	0.96 tons/cow/year[b]	2.5 liters/cow/day, 240 lactation days = 0.6 tons/year/cow	Improved pasture	No pasture improvement	
	Meat	120/ton	1.54 tons/year/household	0.8775 tons/year	As above	As above	NSSC (2011)
Private forest (value per ha)[c]							
	Alpine—cool conifers		Plant or protect trees, adopt sustainable annual harvest limit = 26% of forest value	Unsustainable tree harvesting and forest grazing	Observe sustainable AHL	Land and labor input	NSSC (2011)
	WFP[d]	41,918/ha	Tree density in the Himalayan region = 1,900 trees/ha (Kharkwal and Rawat 2010)				
	NWFP[d]	419/ha		As above	As above		
	Broadleaf trees—humid deciduous temperate				As above		
	WFP	26,108/ha	As above				
	NWFP	261/ha					
	CFM[*]	1,231/ha					

Source: [a] Gyaltsen and Bhattarai (2002).[b] Delgado, Narrod, and Tiongco (2002).[c] Chiabai et al. (2011), Phuntsho et al. (2011). Note this is total value including unused value. AHL will involve harvesting 26 percent of the forest value.[d] Source food prices: numbeo.com (2014). [e] Brooks (2010).

Note: kg = kilograms; FYM = farm yard manure; RNR= Renewable natural resources; NSSC = National Soil Services Center; FAOSTAT = Food and Agriculture Organization Corporate Statistical Database; AHL = annual harvest limit; WFP = wood forest product; NWFP = non-wood forest product; CFM = community forest management. [*] Zhasela community CFM—with 15 households participating—is used as an example. The community CFM has 33.9 ha. AHL = 36 mature trees (>50 cm dbh = diameter at breast height or drashing size trees). NWFP from CFM includes mushrooms, wild asparagus, and bedding material. Sexual maturity of the *Pinus roxburghii*—the most common tree in the Zhasela CFM—is 12 to 14 years (Sharma, Khanduri, and Ghildiyal 2012). The tree can live up to 120 years—rotation period (Sharma, Khanduri, and Ghildiyal 2012). The value of US$1,231 includes timber harvest of 26 percent of AHL (Phuntsho et al. 2011).

Maize

For the major maize-growing zone—the dry subtropical zone, which runs from central to eastern Bhutan—the recommended SLM practices are ISFM with nitrogen, phosphorus, and potassium per hectare of 100, 80, and 60, respectively, plus 7 tons /ha farm yard manure (Chetri, Ghimiray, and Floyd 2003). With these inputs, the maize yield potential for improved varieties is 4.15 tons/ha (Chetri, Ghimiray, and Floyd 2003), while the farmer yield is only 2.79 tons/ha (RNR 2011) or 67 percent of the yield potential. For a given crop, yield potential is the maximum yield of a crop under given agroecological characteristics (solar radiation, temperatures, soil characteristics, and so forth) and varietal characteristics (fraction of photosynthetic efficiency of converting biomass into economically important yield) (FAO 1996). Yield potential is used in studies determining yield gap and associated production constraints such as land degradation (for example, Licker et al. 2010).

Rice

Irrigated rice is grown in the humid (wet) and subhumid subtropics. ISFM is also recommended for irrigated rice with 7 tons/ha of farm yard manure and 17 kg of phosphorus /ha (Chetri, Ghimiray, and Floyd 2003). With ISFM and improved seeds, irrigated rice yield potential is 7 tons/ha (Chetri, Ghimiray, and Floyd 2003), but farmer yield is only 3.5 tons/ha (RNR 2009).

Citrus

The SLM practice used for oranges is to plant on fallow land, ex-tseri land (slash and burn), and on cropland where there is high risk of land degradation through soil and water erosion. About 23 percent of rural households reported that they had left their land fallow in the 2009 RNR survey (Christensen, Fileccia, and Gulliver 2012).[6] Such land could be used for citrus production, and this could greatly contribute to reducing poverty since—as will be seen later—citrus is among the most profitable crops and, as discussed earlier, orchard production contributed 73.6 percent of crop GDP growth in 2000–2009 (Christensen, Fileccia, and Gulliver 2012) and 66 percent of household cash income. Planting pure stand citrus trees could be a challenge due to their long gestation period (six years), which investment smallholder farmers may not be able to afford. Using the farmer practice, oranges yield 10.7 tons/ha (FAOSTAT 2013).

Forest

Forest plantations span all zones in Bhutan, and their productivity and value vary accordingly. As shown in Table 5.11, converting centrally managed non-PA forests to CFs and converting unused lands to CFs are the major SLM practices proposed to reduce soil erosion in HEP plants. A review by Bowler et al. (2010) showed that tree density under community-managed forests (CF) improved as compared to density under government management. For example, Agarwal (2009)’s study showed the forest density of CFs improved from the condition of CFs before in Nepal and India by 50 percent and 36 percent, respectively. The SWAT model results reflect the benefit of reduction of soil erosion due to planting trees on unused lands and increase in forest density (Table 4.12). The value of other forest ecosystem services—timber, NTFP, and so forth—will also increase accordingly. To ensure that the forest value is relevant to the local economy, we will consider only ecosystem services that are felt at the national level. This includes water catchment, regulating services, timber and NTFP, and medicinal plants. It is well documented that the value of a forest differs depending on its use (for example, see Secretariat of the Convention on Biological Diversity 2001). Holding all else constant, forests closer to high population density have greater value than forests in remote areas (Pearce 2001). Forests used for tourism or those with rich biodiversity and other ecosystem values have higher values than those with lower ecosystem values

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[6] The major reasons for leaving land fallow—with percentage of farmers reporting their reasons in parentheses—were wildlife (34), long distance from home (29), lack of irrigation (16), land is unusable (15.3), and land is unproductive (13.7) (Christensen, Fileccia, and Gulliver2012).

(Secretariat of the Convention on Biological Diversity 2001). The private forests considered in this study are closer to human population and will have relatively higher values.

NTFP that are harvested from the forest include mushrooms, bamboo shoots, herbs, medicinal plants, canes, fodder, and loppings. For timber products, SLM is achieved when harvesting does not exceed the regeneration rate. The Ministry of Agriculture and Forests gives the annual harvest limit for each type of forest. For forest products, the sustainable annual harvest limit is determined using guidelines given by the Ministry of Agriculture and Forests.

Grazing Land (Livestock Production)

SLM for grazing land is improved pasture management—which includes planting leguminous seeds and improved grasses such as cocksfoot, Italian rye, and lotus (Samdup et al. 2013; Dorji 1993). It also includes rotational grazing on rangelands, which allows pasture to recover (Chophyel 2009). Improved pasture management could increase total digestible nutrient fivefold from 0.654 tons/ha for traditional pasture management (Dorji 1993) to 4.0 tons/ha (Roder et al. 2001). Improved pasture management can increase the live weight of livestock by up to 100 percent. For example, a study in Australia showed that sowing pasture using improved pasture management increased cattle live weight 2.3 fold (Alcock and Hegarty 2006). NSSC (2011) showed that improved pasture management can increase livestock productivity between 50 and 100 percent. We assume a minimum increase of 50 percent of livestock productivity if a farmer uses improved pasture management. As shown in Table 4.13, only 12 percent of farmers reported to have improved pastures.

Meat production is about 51,000 metric tons (mt) and 0.6 mt per cow per year of milk (Wangdi 2012). This suggests each of the 58,120 households that own cattle (NSB and ADB 2013) produce 0.8775 tons/year. Hence, with a 50 percent increase in livestock productivity, this will translate to 0.96 tons per cow/year of milk and 1.54 tons/year of beef per household.

Due to lack of livestock management data, a farmer was deemed to be using SLM if he or she reported use of improved pasture management. We use data from past studies to determine the different values of forest ecosystem services, reported in Table 4.11.

Table 4.11 summarizes the data used for the benefits-costs analysis of SLM, showing the three major enterprises for each of Bhutan's major AEZs.

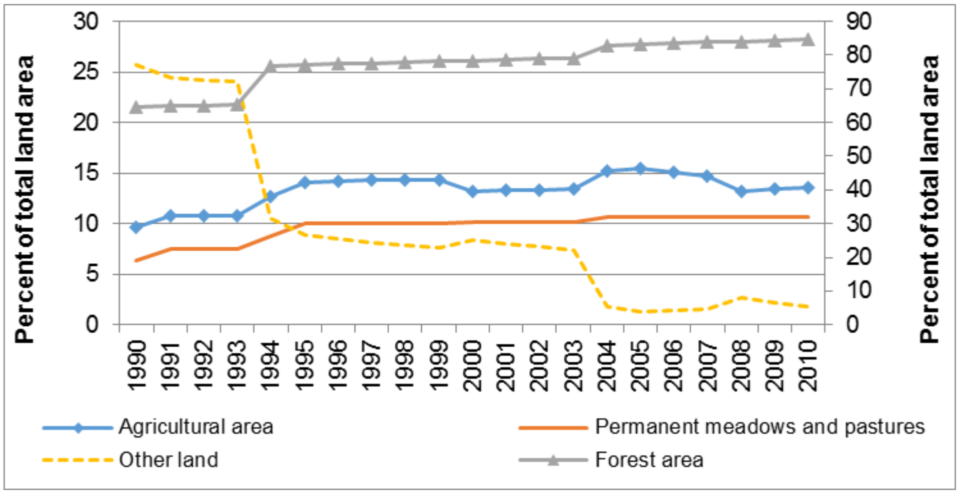
The next section discusses the results, starting with the land use change descriptive analysis, which reveals a 20-year pattern ranging from 1990 to 2010. This is followed by results on soil erosion analysis using SWAT modeling. The third section uses the results from the land use change analysis and the SWAT results to analyze the economic returns to SLM investments to address land degradation.

5. RESULTS

Land Use Change

Figure5.1—which is drawn from Food and Agriculture Organization Corporate Statistical Database data—shows that forest area as a share of total land area in 1990–2010 has increased while the corresponding share for agriculture has fallen from its peak in 2005. As will be seen in the Landsat data below, however, forest and agricultural area remained unchanged.

Figure 5.1Trend of land use type as percentage of total land area, 1990–2010



Source: FAOSTAT (2013)

Land Cover Change Classes

We focus on four major land use types: forest, agricultural, pasture, and barren land. Table 5.1 describes the classification system used in this analysis and the interpretation of each class: deforestation and agricultural expansion. Two datasets were used to assess land cover change: The national land cover dataset was used to assess changes in pastureland, and an independently produced classified Landsat dataset was used to analyze other land cover changes. While methodological changes in the classification system between 1994 and 2010 precluded use of the national land cover dataset in much of the land cover change analysis, it was considered more reliable for static analyses and for diagnosing changes in pastureland, which is not separated from other grasslands in the Landsat data.

Table 5.1 Land cover change classes

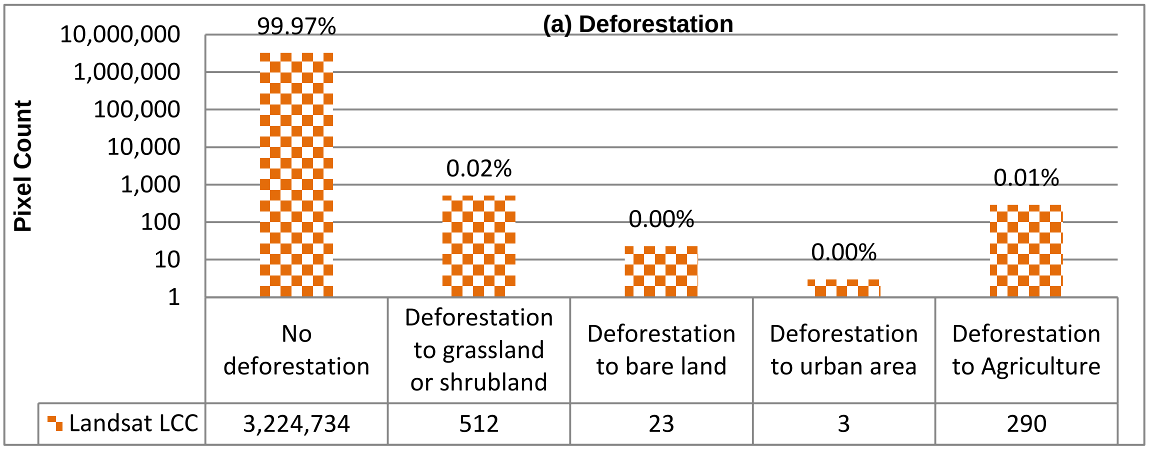
Deforestation	**Agriculture Expansion**	**Agriculture Contraction**
• Forest to grassland or shrub	• Barren land to agriculture	• Agriculture to unused land
• Forest to bare land	• Grassland or shrubland to agriculture	• Agriculture to forest
• Forest to urban area	• Forest to agriculture	• Agriculture to urban area
• Forest to agriculture		
Land Clearing	**Pasture Expansion**	**Pasture Contraction**
Agriculture, shrubland, or grassland to barren land	• Forest to pasture	• Pasture to forest
	• Grassland, shrubland, or barren area to pasture	• Pasture to grass, shrubland, or barren land
	• Agriculture to pasture	• Pasture to agriculture

Source: Authors.

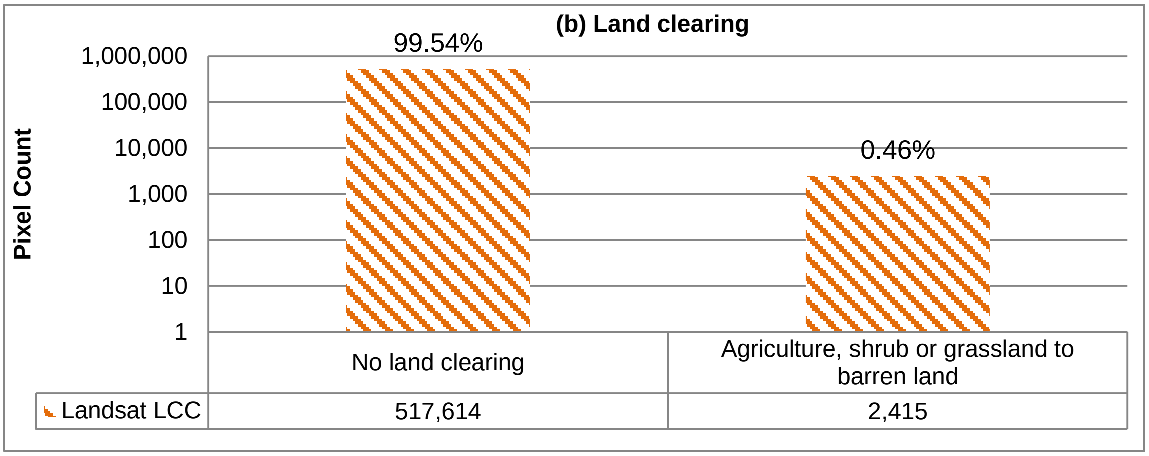
Figures 5.2 (a–f) provides a visual representation of each land cover change class, including those pixels that did not change. Figure 5.2(a) illustrates that the vast majority of forested area remained as such between 1990 and 2010. The minor deforestation that was present primarily consisted of a conversion from forest to grassland/shrubland or agriculture. Despite agriculture's being a primary player in the minor deforestation, as a whole, agricultural expansion occurred mostly in barren land, grassland, or shrubland (Figure 6.2[c]). In fact, nearly as much agriculture was converted back to forested land as forest was to agriculture (Figure 5.2[d]). For the time period analyzed, there was a net expansion in agriculture, although with only two images it is difficult to know if the agriculture that was converted to unused land in Figure 6.2(d) is fallow land or if it is the beginning of a longer trend as was suggested by many local officials and researchers.

According to the land use change analysis conducted on the national dataset to assess pastureland expansion and contraction, pastureland as a whole is in slight decline. Although the dataset indicates a substantial conversion from agricultural land to pasture, it also demonstrates that twice as much pasture was converted to forested land. These conversions may be real observed trends, but they may also be spurious artifacts of the difference in methods between the 1994 dataset and the 2010 dataset. To assess the validity of the observed decline, independent land cover assessments were analyzed. FAO data (Figure 5.1) indicate a stagnation in permanent meadows and pastureland while classified Landsat data from 1990 and 2010—produced independently from the national land cover dataset—indicate a significant decline in grasslands. While not all grasslands can be assumed to be pasture, the decline in grasslands in combination with the FAO data lends credence to the observed trend in the national land cover data.

Figure 5.2Land cover change statistics, with percentage change on top of each histogram

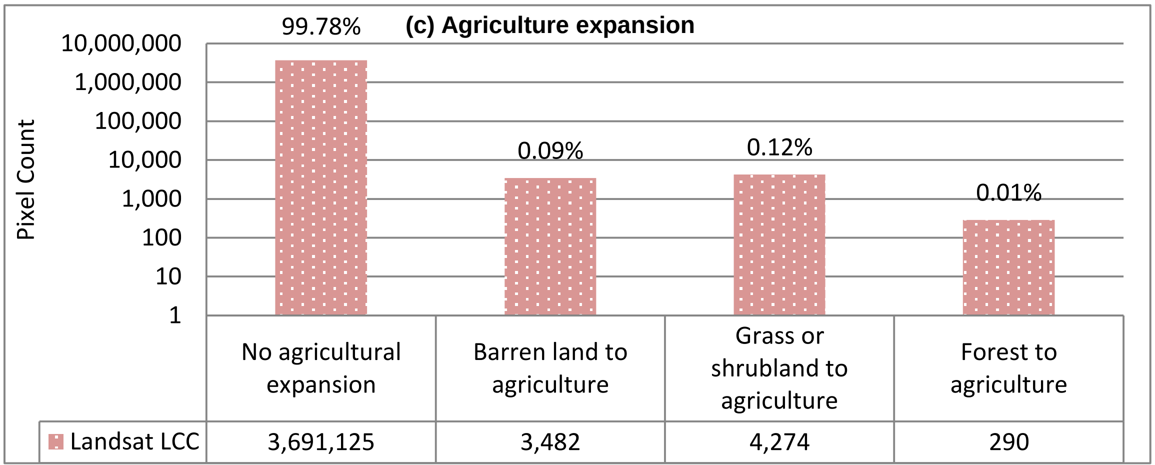


	No deforestation	Deforestation to grassland or shrubland	Deforestation to bare land	Deforestation to urban area	Deforestation to Agriculture
▚ Landsat LCC	3,224,734	512	23	3	290

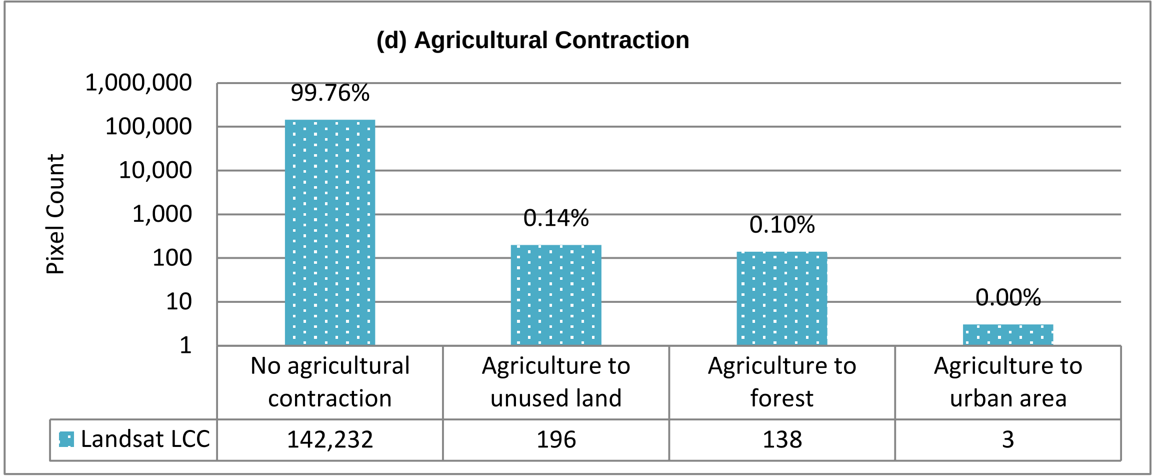


	No land clearing	Agriculture, shrub or grassland to barren land
▧ Landsat LCC	517,614	2,415

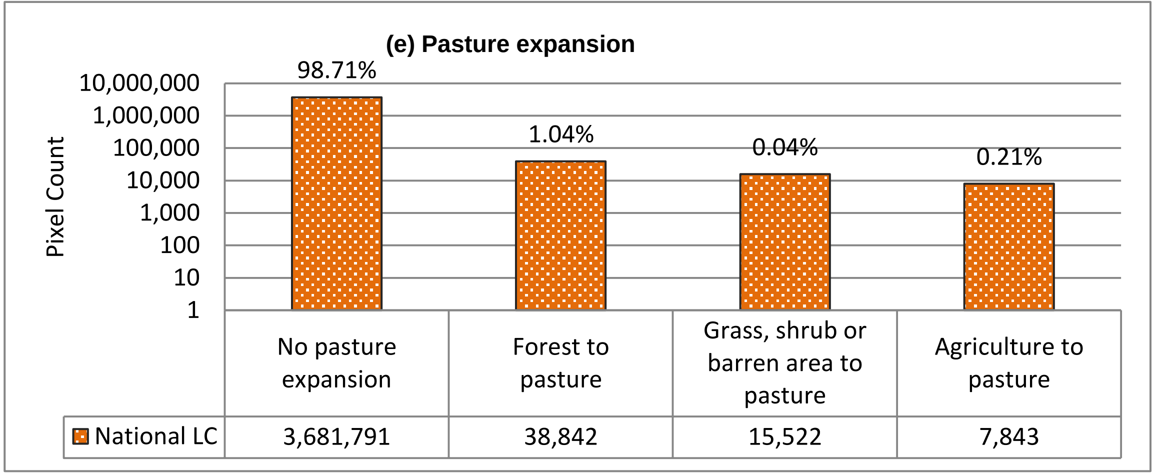
Figure 5.2 Continued



	No agricultural expansion	Barren land to agriculture	Grass or shrubland to agriculture	Forest to agriculture
Landsat LCC	3,691,125	3,482	4,274	290

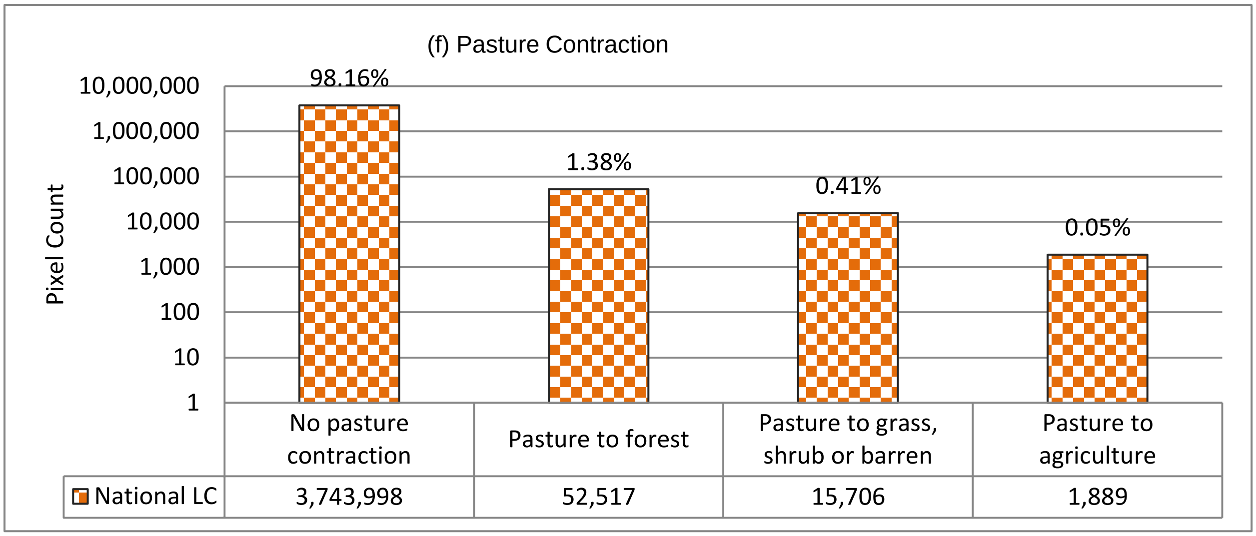


	No agricultural contraction	Agriculture to unused land	Agriculture to forest	Agriculture to urban area
Landsat LCC	142,232	196	138	3



	No pasture expansion	Forest to pasture	Grass, shrub or barren area to pasture	Agriculture to pasture
National LC	3,681,791	38,842	15,522	7,843

Figure 5.2 Continued



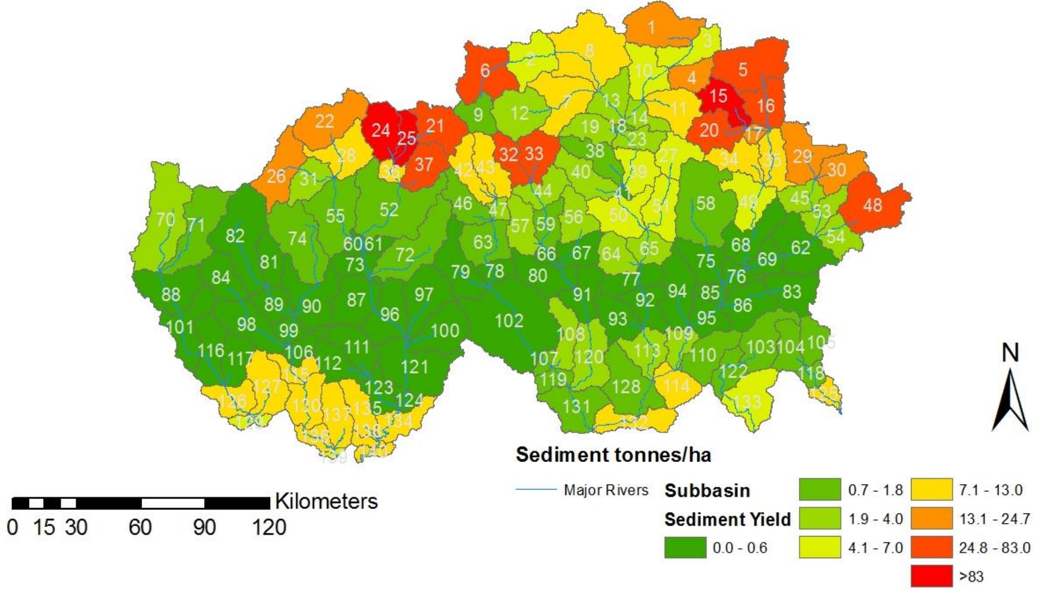
Source: Authors calculations using Landsat data (1990, 2010) and NLCD (1994, 2010).

Impact of Land Use Change and Land Management on Soil Erosion

Sediment Results

Using the SWAT model sediment algorithms, the landscape total sediment yield for BAU was calculated for each sub-basin, and the average annual result is presented in Figure 5.3. There are similar patterns in Figure 5.3 and Figure 4.13, which correspond to rainfall and runoff. As these two factors, rainfall and runoff, drive the sediment process, it is obvious that higher sediment was observed at these high rainfall/runoff regions. However, land cover, slope, and soil erodibility factors play major roles in the sediment yield potential. In this case, Table 5.2 provides the distribution of hydrology and sediment yield by land use and corresponding slope and slope length combined factors. Most of the sediment was coming from higher elevations in the north of the country including the Chinese part of the watershed but also from the southernmost part of the watershed draining into India. In the northern part of the basins, sediment delivery is mainly due to high snowfall and snowmelt processes with steeper slopes. However, due to lack of quality soils data and poor soil scale (1: 1,000,000 scale) maps, the simulated outputs may contain large uncertainity. The sedimentation process has been going on for thousands of years, and most of the soils may have been eroded already. But the sedimentary rocks in the higher altitudes with steep slopes can contribute to the sediment yields slowly over many years to come. The high volume of snow and runoff process due to glacier lake breaks, heavy boulders, rocks, and large aggregates may contribute to the sediment process. It is unlikely that small suspended particles are seen from these area, which is also evident from the observed sediment data collected by the Hydromet department.

Figure 5.3 Average annual (1997–2012) sediment load (tons per hectare) from each sub-basin



Source: Hydromet data (1997-2010) and Author's calculation using Soil and water assessment tool results.

Table 5.2 Average basin hydrology and sediment results from SWAT (1997–2012) by land use

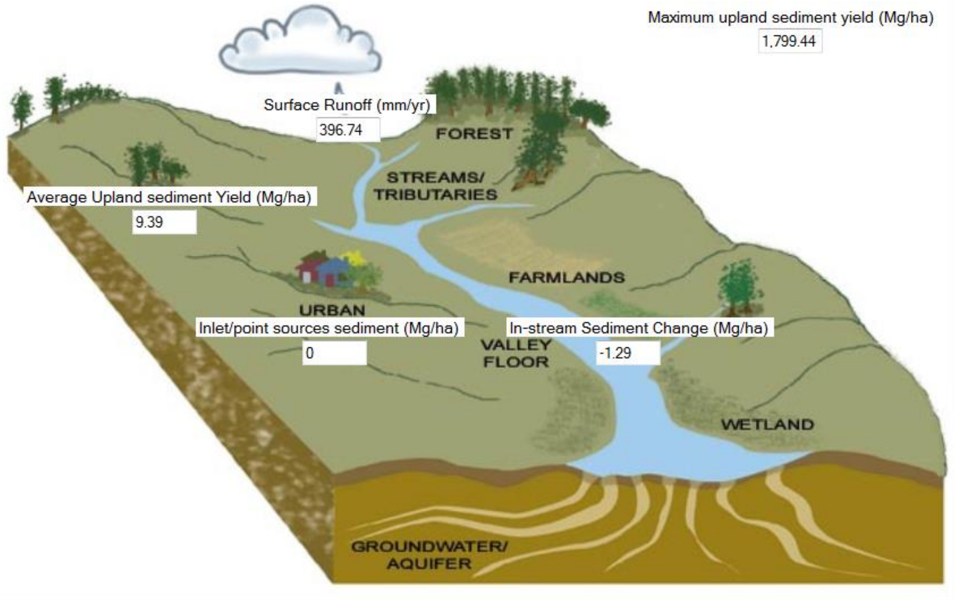
Land use	Area* (2010)	Area* (2000)	Slope and slope length factor	Precipitation⁺	Runoff⁺	GW⁺	Actual evapo-transpiration⁺	Sediment (t/ha) (2010)	Sediment (t/ha) (2000)
Pine	26.312	26.312	11.50	1,548	365.48	752.04	329.42	3.50	3.50
Grassland	8.515	8.821	10.02	1,516	614.24	284.51	126.46	5.41	5.52
Barren	2.051	1.743	10.96	1,535	716.49	229.48	130.74	116.75	114.46
Water/Snow	4.770	4.770	0.18	1,582	0.00	0.00	1,153.54	0.00	0.00
Evergreen forest/ shrubland	4.190	4.190	11.32	1,395	390.46	643.43	239.35	4.74	4.74
Cropland	1.217	1.217	0.37	1,565	355.66	892.01	231.27	5.93	5.93
Erodible land	0.179	0.179	9.32	2,097	925.06	130.07	185.63	223.8	223.8
Urban	0.040	0.040	0.83	1,469	711.61	391.7	394.61	0.84	0.84
Wetland	0.003	0.003	0.18	972	232.33	99.53	537.32	0.63	0.63
Roads	0.226	0.226	11.10	1,456	1,017.19	94.24	348.67	6.03	6.03
Oranges/Orchards	0.039	0.039	11.38	3,015	1,409.88	813.06	667.39	5.96	5.96

Source: Soil and water assessment tool results (2013)

Note: GW = groundwater; km^2 = square kilometers; mm = millimeters; t/ha = tons per hectare. *In thousand km^2. $^+$ In mm. For details of second and third columns, see Figure 4.11.

During the field visit it was clear that there were several boulders and rocks removed from the river bottoms and stored on the side of the stream as protection from additional stream bank erosion in the large river sections and flat areas.The southern part of the watershed experiences very high rainfall during the monsoon season from June through October. The main sources of sediment are highly managed agriculture and urban development including road construction between various small to medium towns and across international trade. These exist along with a high slope area with barren and erodible land, and they contribute significant sediment loading to the rivers. The middle part of the watershed, where the rainfall is low and of less intensity, contributes little or no sediment and is also well covered by forest and grass on the ground to protect from any sediment contribution. Figure 5.4 shows the average annual sediment load from the entire basin simulation as 9.39 tons /ha/year during the simulation period f 2007–2012. It also shows that as the sediment reaches the flat areas, some of the sediment—up to 14 percent—may get deposited into the channels and river network, resulting in only about 8 tons /ha/year of sediment leaving the watershed. However, the sediment delivery varies by each major river basin.

Figure 5.4 Average sub-basin sediment load from the entire basin and sediment deposition in the stream for the entire period of the simulation (1997–2012)

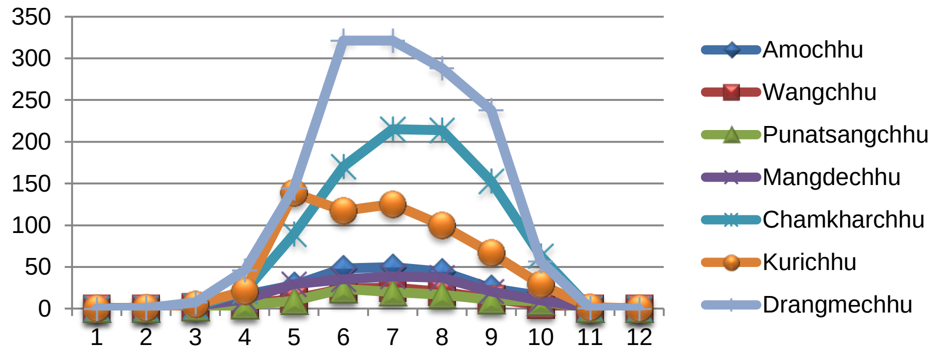


Source: Authors.
Note: Mg/ha = megagram (ton) per hectare; mm/yr = millimeters per year.

In addition, the land use change data between 2000 and 2010 were used in the model. The major changes observed were from grassland to brushland and barren land. Also in 2000 the percentage of barren land was less compared to 2010 by almost 10 percent, with more grassland. This information is reported in Figure 5.2. With these changes the model predicted 8.61 tons/year, that is, about 8.3 percent less sediment in 2000 than the current land use based on 2010 data. This is mainly because there was less barren and highly erodible land in 2000 than now and these lands were covered by grassland that protected the soil surface. The overall 2000 land use area and corresponding sediment yield per ha is shown in Table 5.2. There were some land use changes between 2000 and 2010 in the water/glacier/snow area. Most of this area was either grassland or barren land. Even though there was more water/glacier/snow area in 2000 than in 2010, this could be due to the various remote sensing scenes used for classification that may be from the winter or spring seasons’ snapshots. So this change was not included in the simulation.

Figure 5.5 shows the average monthly distribution of sediment in tons per square kilometers drainage area by major river basins. As can be seen, most of the sediment comes between June and October. However, in Kurichhu Basin, sediment contribution starts in April–May (snow melt process) as this river is dominated by a high-altitude drainage area with a large glacier presence. But the lower elevation and higher rainfall area is small in this basin in the southern portion of the basin/country. The maximum sediment may come from Drangmechhu River as it contains one of the largest glaciers and also reaches high rainfall in the plains part of the drainage basin. In general the rainfall in the east is higher than in the west and thus contributes to higher sediment rates by far than in any other basin. Next to this Chamkharchhu Basin contributes most of the sediment from June through October. Punatsangchhu and Wangchhu Rivers contribute the least sediment in the country.

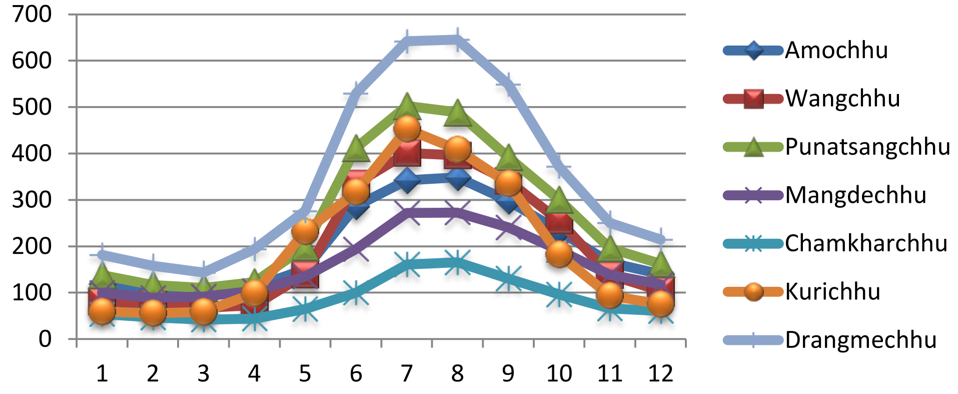
Figure 5.5Average monthly (1997–2012) sediment load (tons/km2) at the various river outlets by month of the year



Source: Raw data from Hydromet (1997-2010).

Figure 5.6 shows the average monthly stream flow distribution from 1997 to 2012 in cubic meters per second per day. When studying Figures 5.5 and 5.6 in combination, it is clear that the large amount of sediment is coming from the highest flow of the river. However, if you look at some of the other basins that produce high flow, such as Punatsangchhu, the amount of sediment is ranked close to the bottom since most of the stream flow is generated in the southern part of the watershed where the land is flat or has less slope.

Figure 5.6Average monthly (1997–2012) streamflow at the river basin outlets in m3/sec/day by month of the year



Source: Raw data from Hydromet (1997–2010).
Note: m3/sec/day = cubic meters per second per day.

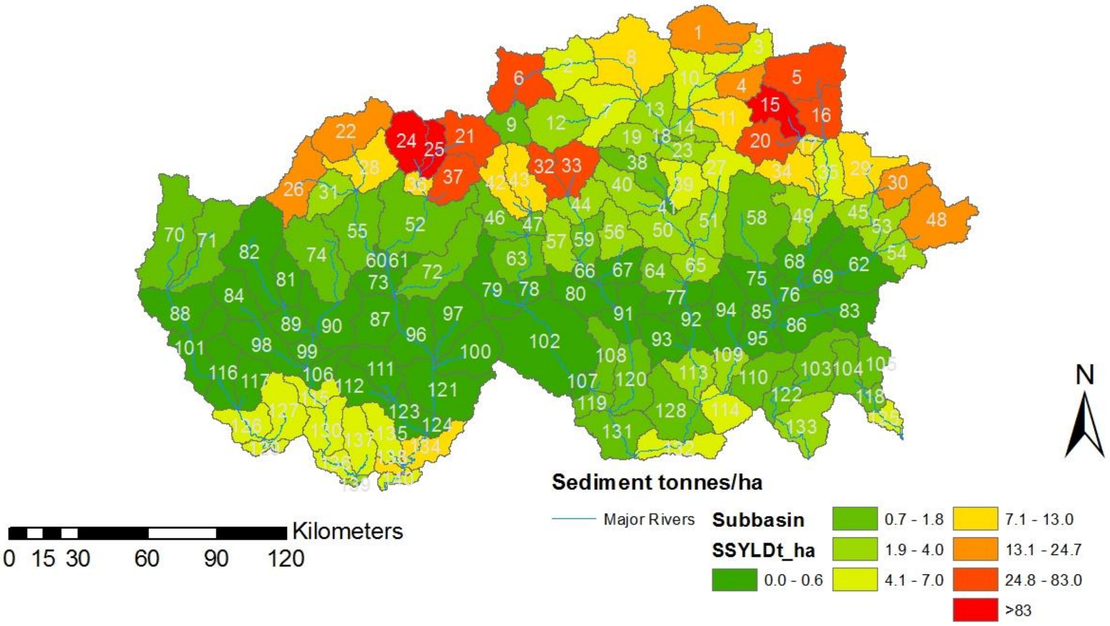
With proper land management techniques such as contouring, increased forested cover and selection of proper plants, and terracing where possible for agricultural land, the SLM techniques were applied to only needle leaf forested land, cropland, and orange landscapes in the SWAT model, and the results are summarized in Table 5.3 and Figure 5.7. Even though the expected reduction seems to be high—as much as 50 percent erosion reduction—with the combination of various SLM techniques and long-term maintenance or caretaking, one can reach the reduction goal. However, the range of reduction certainly varies based on rainfall, intensity, land use, slope, and soil condition from as low as 12 percent to 70 percent. Also it is assumed all eligible land areas have adopted SLM practices. In practice, however, the adoption rate is lower and varies across space and time. What is reported in Table 5.3 is the potential impact of SLM that Bhutan can achieve if it fully implements its 2020 Vision.

Table 5.3Basinwide annual average of sediment under sustainable land management program

Land use	Area (in km^2)	Sediment under SLM (t/ha)	Baseline sediment (t/ha)	Percentage change
High altitude forestland	26,311.71	1.75	3.50	50
Cropland	1,216.65	4.58	5.93	23
Oranges/Orchards	38.64	2.98	5.96	50

Source: Soil and water assessment tool model results (year?).
Note: SLM = Sustainable Land Management; km^2 = square kilometers; t/ha = tons per hectare.

Figure 5.7Average annual (1997–2012) sediment load (t/ha) from each sub-basin under SLM scenarios



Source: Author's calculation using the Soil and water assessment tool model results.
Note: t/ha = tons per hectare; SLM = Sustainable Land Management; SSYLDt_ha = sediment load (t/ha).

It is important to compare our results with the results of other studies done in areas with comparable topography. Ziadat and Taimeh (2013) published results from field studies in arid regions where the steep slope, soil moisture, and land management can account for as much as 90 percent of the land degradation. Such land erosion can be avoided by as much as 50 to 60 percent using proper land management techniques and preserving soil moisture with vegetation or ground cover. This is an arid region with less rain, but the intensity is high; it can be compared to humid, high-rainfall regions with soil moisture near saturation all the time, leading to similar outcomes. In addition, Ziadat et al. (2012) have published a technical report to show various agricultural land management measures in steep slopes and annual precipitation of about 700 to 1,000 mm in Syria. The soil and water conservation practices used were stone bunds, stone walls, intercultivation, and other SLM techniques. The authors showed in real field measurements that the erosion can be reduced by as much as 55 to 60 percent during a sustained long period with proper SLM techniques (Ziadat et al. 2012). Appendix 1 of the paper reports actual SLM practices and their impact on reducing soil erosion. The watershed where these were practiced is smaller, but the practices are promising. All these SLM techniques are documented qualitatively and in a simple way to understand by WOCAT and can be accessed at http://qt.wocat.net/qt_report.php.

The three SLM projects demonstrated are similar to what is experienced in Bhutan: high slopes, high rainfall, and forest degradation. As shown in Figures 5.2 and 5.7, most of the benefits from the SLM techniques will be in the lower part of the watershed where agriculture is present, and improved land management will help greatly since this is where the rainfall is also high. Appropriate pine plantation management may also be helpful; however, pine plantations above the tree line, such as at 3,800m or above, will be not be beneficial.

Economic Analysis of SLM

Use and Drivers of Adoption of SLM Practices

The discussion below analyzes returns to SLM by focusing on three land use types: forest, grazing lands, and croplands. We focus this portion of our analysis on the interaction of livestock, fertilizer, and roads. To understand current SLM practices among land users, we analyze the 2009 RNR survey data.

Descriptive statistics and an econometric analysis of the data reveal that access to roads and livestock ownership significantly increase the quantity and type of fertilizer (inorganic or manure) applied by farmers (Tables 5.4 and 5.5). An analysis of the RNR survey data shows that only 31 percent of crop farmers use inorganic fertilizer and that it is the farmers closer to roads who are more likely to apply inorganic fertilizer. This result, which is robust across both the descriptive statistics and the econometric analysis, highlights the importance of roads in the delivery and use of inorganic fertilizer. Econometric results also show that farmers closer to roads have a higher propensity to use manure than those farther away from roads. No farmer reported to have used both inorganic fertilizer and manure—suggesting that farmers substitute inorganic fertilizer with manure or vice versa. It could also mean that farmers who do not own livestock can apply only inorganic fertilizer and that farmers do not see the need to apply both manure and inorganic fertilizer.

As expected, livestock ownership increases propensity to use manure (Table 5.5). In addition, livestock and land ownership both increase the propensity to use all four SLM practices reported (manure, urea, private forest, and improved pasture). With the exception of manure use, access to extension services also increases the propensity to use all SLM practices—as expected. The results underscore the importance of rural services in enhancing SLM practices in Bhutan.

Table 5.4Share (percentage) of farmers who used inorganic and organic inputs

Category	Use inorganic fertilizer	Use manure	Have private forest	Have improved pastures
Nationally (*N* =57,705)	30.9	59.6	3.6	12.0
Distance to road				
0	19.2	69.2	0.0	0.0
Less than 1 hour	38.3	59.5	4.3	13.1
1–3 hours	29.9	68.0	3.1	9.4
3–6 hours	27.1	62.5	2.6	13
6 hours–1 day	17.5	57.5	2.1	13
>1 day	7.0	43.8	2.9	9.3
Land owned				
Land-poor tercile	35.7	57.9	3.1	9.8
Land-rich tercile	25.9	61.4	4.2	14.3

Source: RNR household survey (2009).

Constraints to access to rural services and other important drivers of adoption of SLM could lead to unexpected farmer behavior. We examined the relationship between profitability and returns to land management practices.

Table 5.5Drivers of propensity to use sustainable land management practices (marginal effects)

Driver	Manure	Urea	Private Forest	Improved Pasture
Land tenure/method of acquisition (cf. renting)				
- Own land	0.025***	0.002***	0.008***	0.012***
- Leased out land	—0.028***	–0.003**	0.021**	0.001
- Leased in land	0.009***	0.000	–0.002	–0.017**
- Fallow land	–0.014***	0.000	0.007*	0.009***
Own livestock cattle	1.363***	0.119***	0.259***	0.992***
Own donkey	0.246**	0.006	0.423***	0.220*
Own horse	0.006	0.000	–0.012	0.249***
Age of respondent	0.000	–0.000***	0.002***	0.001
Male respondent sex	–0.006	–0.010***	0.094***	0.096***
Time to Road (cf. more than one day)				
- Less than one hour	0.268***	0.128***	0.160***	0.344***
- One to three hours	0.359***	0.085***	0.038	0.140***
- Three to six hours	0.344***	0.082***	–0.087*	0.244***
- Six hours to one day	0.305***	0.034***	–0.152***	0.313***
Time to extension services (cf. more than one day)				
- Less than one hour	–0.273***	0.089***	0.151**	0.330***
- One to three hours	–0.147***	0.064***	0.135**	0.289***
- Three to six hours	–0.149***	0.064***	0.092	0.277***
- Six hours to one day	–0.228***	0.021**	0.016	0.148***
Constant	–0.845***	0.426***	–2.379***	–1.590***

Source: Computed from RNR survey data (2009).

Note: Dash in the “Driver” column indicates that the variable is part of a multi-part variable. $*p = .10$. $**p = .05$. $***p = .01$.

Returns to SLM Practices

Equation 4 summarizes the returns to SLM for the enterprises considered. To check robustness of results to farmer discount factor, NPV and IRR are reported at discount factors of 10 percent, 25 percent, and 30 percent. NPV>0 and IRR≥0.12 are considered the minimum requirements for adoption of SLM.

Results show that a citrus orchard is the most profitable enterprise, but it requires farmers to wait for at least six years before the first harvest. Such a prolonged period of time could be a challenge for smallholder farmers to be engaged in citrus production on a large scale. An amenable approach could be producing citrus on a small piece of land or planting trees in annual crops and planting them on fallow land. Profitability of citrus is robust across all three discount factors since both NPV and IRR remain higher or closer to the minimum level deemed economically desirable for farmers to grow citrus. Given this profitability, it is not surprising to see that the production of citrus and other horticultural crops and their contribution to household income has been increasing tremendously while the contribution of cereal crops to household cash income has been declining.

Improved pasture management is the second most profitable enterprise—underscoring the potential role it can play in meeting the growing demand for livestock products as household income increases. Both NPV and IRR are robust across the three discount factors and significantly greater than their corresponding minimum levels. This suggests that adoption of improved pasture is an attractive SLM practice, and its adoption is enhanced by access to rural services (roads and extension services), secure land tenure, and number of livestock owned.

Likewise, NPV and IRR for maize and rice are robust across the discount factor and greater than the minimum level, suggesting ISFM is an attractive SLM practice for two crops.

NPV and IRR for private forests under CFM are both positive, but IRR for r=25 percent and r=30 percent are both below the minimum IRR of 12 percent—suggesting that CFM may not compete favorably with other enterprises. However, CFM remains attractive for areas unfavorable to crop or livestock production. NPV for r =10 percent for publicly owned pine and broadleaf forests is greater than zero, but the corresponding IRR is about zero—hence not likely to attract private investment to increase forest density or replant deforested areas. NPV and IRR for r=25 percent and r=30 percent are negative, suggesting private investment in enhancement of pine and broadleaf forests is not economically attractive and will require payment for ecosystem services to motivate communities to engage in improvement of forest resources.

The Unholy Cross

We analyzed the relationship between the adoption of land management practices (Table 5.3) and their returns (Table 5.6). The results show an inverse relationship—that is, the greater the returns to land management, the lower is the corresponding adoption rate (Figure 5.8). Such an *unholy cross* is due to constraints to adoption of high returns as discussed in Table 5.5. For example, farmers away from roads may not be able to adopt inorganic fertilizer even when their returns are higher than nonuse of fertilizer. Likewise, the negative relationship between manure application and access to extension suggests lack of or limited advisory services on organic soil fertility management practices. This could mean that extension agents do not advise farmers to use organic soil fertility management in combination with inorganic fertilizers (ISFM), which has greater returns than use of fertilizer alone.

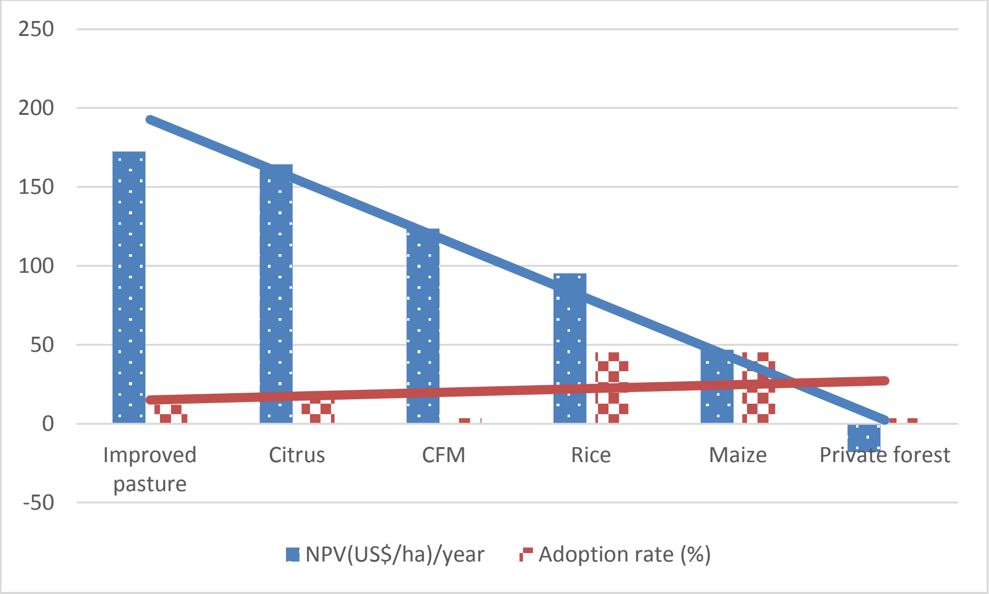
Table 5.6 Returns to sustainable land management practices

	Internal rate of return				30-year total NPV (US dollars) per hectare		
Enterprise	***r* = 10%**	***r* = 25%**	***r* = 30%**	**BCR**	***r* = 10%**	***r* = 25%**	***r* = 30%**
Maize—ISFM	2.52	2.10	1.98	2.05	3578.47	1406.86	1159.54
Rice—ISFM	0.80	0.59	0.53	4.12	7916.75	2860.29	2322.90
Citrus orchard	0.27	0.12	0.08	66.33	32520.38	4935.72	2718.17
Community forest	0.23	0.08	0.04	22.20	24404.28	3711.01	1915.71
Cool broadleaf forest	–0.01	–0.13	–0.16	2.40	299.42	–609.51	–562.69
Warm broadleaf	–0.02	–0.13	—	2.30	209.35	–626.57	–574.00
Mixed conifer forest	0.00	–0.12	–0.15	2.93	822.91	–510.33	–496.94
Chir pine (*Pinus roxburghii*)	0.00	–0.12	–0.15	3.00	887.45	–498.10	–488.84
Blue pine forest	0.01	–0.11	–0.15	3.24	1124.53	–453.19	–459.06
Improved pasture	1.36	1.08	1.00	35.46	13845.97	5173.27	4143.95

Source: Author's calculations

Note: NPV = net present value; BCR = 30-year average benefit-cost ratio; ISFM = integrated soil fertility management (combination of inorganic fertilizer and organic inputs).

Figure 5.8The unholy cross: Inverse relationship between returns to land management and adoption rate



Source: Calculated from RNR 2009.

Note: CFM = community forest management; NPV (US$/ha) = net present value (US dollars per hectare).

We now turn our analysis to the national level by extrapolating the per-hectare results obtained in Table 5.6 to each zone and consequently to the whole country. When calculating national scale returns, however, it is important to account for both on-site and off-site benefits. The results from the land use analysis and SWAT are also used to compute the off-site values of both forests and crops reported in Table 5.7. The computations are according to equation 6 and corresponding extrapolation to the national level. The calculations are done assuming *r*=10 percent since the national-level social planning discount factor is lower than the private discount factor (Rambaud and Torrecillas 2007).

The results assessing returns to SLM at a national scale show that adopting SLM could increase Bhutan's GDP by at least 2.5 percent, a level that can be achieved if certain socioeconomic conditions are taken into account. However, it is important to note that a significant portion of the benefits accrue off-site, particularly for SFM. This is unsurprising given the role that forests play in reducing sediment loading to rivers and therefore HEP plants (Table 5.7).

Table 5.7On-farm and off-farm benefits of action and cost of inaction against land degradation in Bhutan

Land Type	Annual (in NPV US dollars per hectare)	Area (in thousands of hectares)	Total benefit/loss (in million US dollars)
Forest			
On-farm benefits (millions of US dollars) of SLM			
- Cool broadleaf forest	9.98	34.80	0.35
- Warm broadleaf	6.98	1685.00	11.76
- Mixed conifer forest	27.43	612.90	16.81
- Chir pine (*Pinus roxburghii*) and fir pine	29.58	294.10	8.70
- Blue pine forest	37.48	78.30	2.94
- Total on-farm direct benefit from forests[a]			40.56
Loss due to deforestation and reduced forest density (25% of on-farm benefit)			10.14
Off-site benefit—50% reduction of sediment loading[b]			7.80
Cropland			
- Maize	119.28	28,641	3.42
- Rice	263.89	24,357	6.43
-Off-site benefit—sediment reduction due to SLM on cropland and grassland			0.15
Benefits of SLM on livestock production			17.85
Total benefit of SLM			
- On-farm			37.83
- Off-site			7.95
Change in GDP due to SLM			2.5%

Source: Author's calculations

Note: SLM = sustainable land management; GDP = gross domestic product. [a]Forest contributed 24 percent of the agricultural GDP—which was US$284.73 million in 2012. This means the value of harvesting considered in the GDP calculation (US$68.33 million) was greater than our estimates. [b] See Table 6.3. Druk Green Power Company spends US$16 million each year to repair turbines and other underwater structures due to sediment loading. About 60 percent of such cost is associated with sediment loading.

6. STUDY LIMITATIONS AND GAPS

Due to the short time and small budget of the project, we heavily relied on existing data. This was especially crucial given the national-level analysis done in this study. The heavy reliance on secondary data led to using second-best secondary data. We benefited from a large database from a number of institutions discussed in the Methodological Analysis and Data section, yet there were some key data gaps that hampered analysis. For example, the RNR household survey did not collect some important data required to determine the farmer land management practices and household-level characteristics. For the land use analysis, the data for the Bhutan Land Cover Assessment covering the 1994–2010 period had several issues. The data sources, classification, and methods differed between the data collected in 1994 and that collected in 2010, and this made computation of land use change less reliable. Unlike the 1994 dataset, the 2010 dataset was rigorously conducted with extensive ground truthing, an aspect missing from the Landsat dataset. This led to heavy reliance on Landsat data, which were consistently collected between the two time periods but were not ground-truthed.

For the SWAT modeling data, the elevation data at 10m has lots of noise including a high unrealistic slope estimation due to a high difference in adjacent pixels. Slope is an important and significant factor in estimating sediment. In addition, land use is based on broad categories such as pine and broadleaf areas, but no data exist about the density or age of these plantations, which can also affect the sediment loads from these lands. In several areas there have been mudslides, forest fires, and so forth; these were not captured in the land use map. Also, the land use map was created using 2010 satellite images, which were run from 1997 to 2012, so the map may not represent land use in the watershed for the entire time period of the simulation. There was concern about the impact of road construction on sediment loading, but no data were collected to measure such impact. This hampered inclusion of soil erosion due to road, house, and other types of construction.

Soils have significant limitations; for example, the scale of FAO soils data is 1:1,000,000, and its parameters are not measured—just estimated based on global soil properties and pedo-transfer functions—which may not capture the local metamorphism and erodibility factors properly. Finally, most of the rainfall and temperature gauge data were gathered in the lower altitudes, typically less than 3000m. However, much of the watershed covers higher than 3,000m of elevation, even though elevation correction for temperature and precipitation was used as an input to the model; the spatial variability of these parameters is not captured due to lack of any knowledge or field data. In addition, there are many months and years of data that were missing in the precipitation gauges, and those were estimated with SWAT's built-in weather generator using the historical statistics generated by Climate Forecast System Reanalysis global weather data.

Despite these limitations and gaps, this study provides empirical evidence that has important policy implications. The next section summarizes the policy implications of the study.

7. IMPLICATIONS OF THE RESULTS

Bhutan's economy is heavily dependent on generation of HEP, and the country's efforts to achieve SLM are justified by our findings, which show that the adoption of SFM could reduce the cost of sediment loading by 50 percent.

Results show that a citrus orchard is the most profitable enterprise, but its long gestation period is a hindrance to large-scale investment. Given the growing demand for citrus and horticultural crops, there is need of increasing efforts to promote citrus and horticultural crop production in a manner that is amenable among smallholder farmers. Producing citrus fruits on a small piece of land or planting citrus trees in annual crops could lead to significant production that does not burden farmers to set a large piece of land and wait for six years before the first harvest. The increasing production of fruits and horticultural crops could be accelerated by enhancing nurseries and extension services that provide both production and marketing advisory services.

Returns to CFM are low but profitable at a lower discount rate. This means CFM may not compete with annual crops or livestock but is still favorable for abandoned areas. Likewise, investment in pine and broadleaf forests is profitable at high discount factors, which suggests the importance of enhancing incentives of communities to engage in CF programs by payment for ecosystem services. As our results show, SFM can reduce sediment loading to rivers serving HEP plants by 50 percent. This justifies improvement of the current payment for ecosystem services program in which DGPC pays about 1 percent of its revenue to the government to encourage farmers to adopt SLM and SFM. Because such money is given to the government, which in turn uses the money to provide advisory services, it is hard for farmers to connect DGPC payments and the DGPC-funded advisory services provided by the government. There is great need for designing a policy that will give DGPC a mandate to interact directly with land users. DGPC has actually requested RGoB's permission to work with farmers directly, but this has not yet been approved. This could be enhanced under a CF program by allocating the forest currently under government control to communities, which in turn will increase forest density and contribute to reducing sediment loading. Instead DGPC is currently implementing corporate responsibility programs such as planting trees and supporting communities to take up environmentally friendly practices. For example, tree planting is done between Paro and Chhukha dam. In addition, around each of the HEP plants, DGPC is supporting green and clean programs.

Considering the drivers of SLM, we see that land security, access to extension services, and roads will enhance SLM and will have multiplier effects. RGoB has already started investing heavily in improving rural roads. However, road construction has contributed to increasing sediment loading. This suggests the need for adopting sustainable road construction that minimizes soil erosion.

In summary, Bhutan's policies and its cultural and historical background have set the country on the path to becoming a global green growth success story. Results of this study vindicate the country's efforts to invest in sustainable land and forest management.

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