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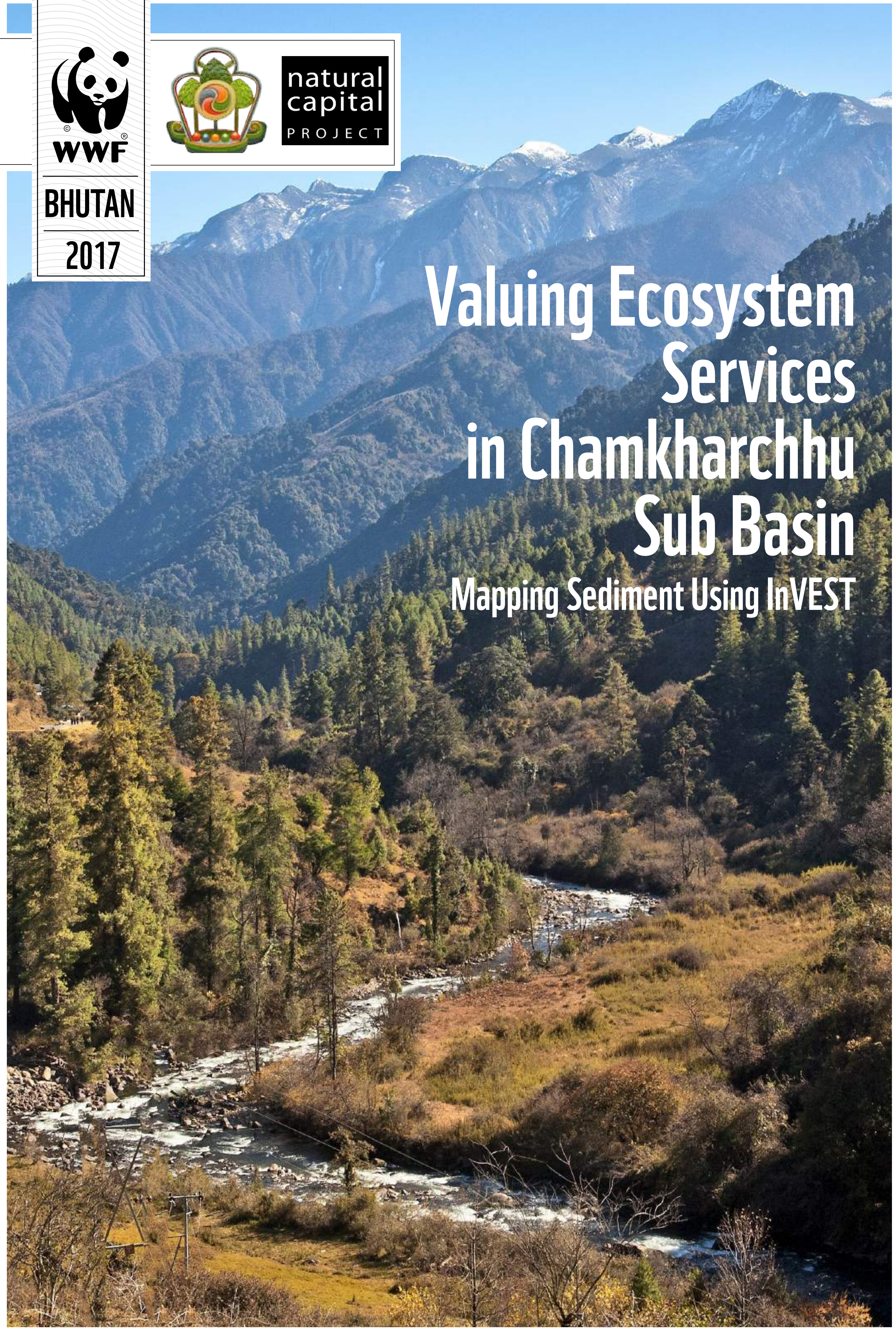

Valuing Ecosystem Services in Chamkharchhu Sub Basin

Mapping Sediment Using InVEST

WWF is one of the world's largest and most experienced independent conservation organizations, with over 5 million supporters and a global Network active in more than 100 countries.

WWF's mission is to stop the degradation of the planet's natural environment and to build a future in which humans live in harmony with nature, by: conserving the world's biological diversity, ensuring that the use of renewable natural resources is sustainable, and promoting the reduction of pollution and wasteful consumption.

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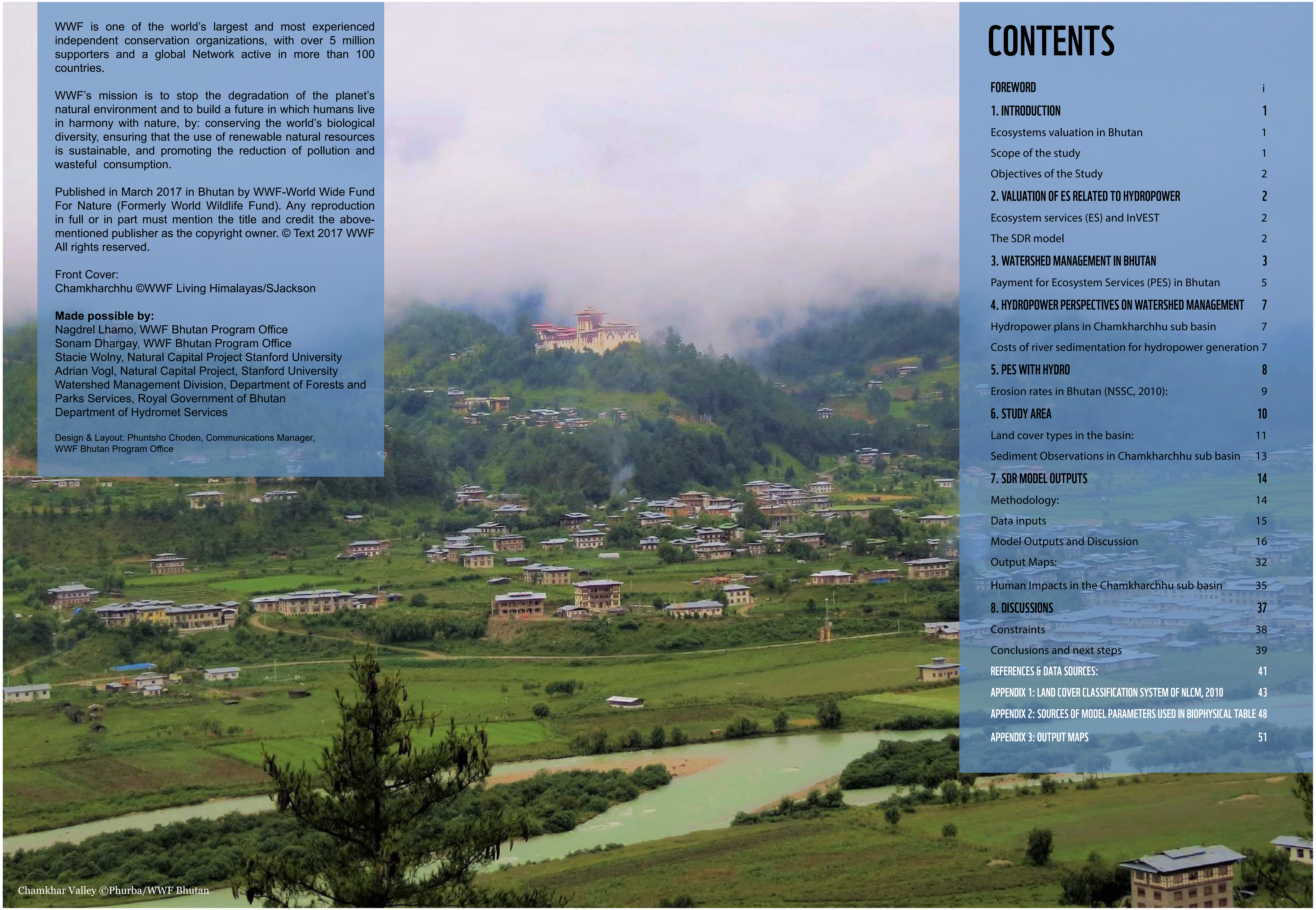


Chamkhar Valley ©Phurba/WWF Bhutan

MINISTER

སོ་ནམ་དང་ནགས་ཚལ་ལྷན་ཁག།

ROYAL GOVERNMENT OF BHUTAN

Ministry of Agriculture & Forests

Tashichhodzong, Thimphu : Bhutan

FOREWORD

Minister, Ministry of Agriculture and Forests

Benefit-sharing from ecosystem services is being promoted in a number of developing countries around the world to enhance the management of natural ecosystems through arrangements that generate direct social and economic benefit for the local communities who are the immediate custodians of these ecosystems and, consequently, responsible for their conditions. It is based on the notion that if the benefits of ecosystem services are shared tangibly and fairly with the local communities, they will be a positive and potent force in the sustainable management of the natural ecosystems that provide these services.

The Watershed Management Division (WMD), Department of Forests and Park Services (DoFPS), Ministry of Agriculture and Forests is responsible for designing and implementation of benefit-sharing schemes or Payment for Environmental Services (PES) in Bhutan. The WMD conducted feasibility studies on a number of PES schemes around the country related to protection of drinking water source areas, hydropower water supply and scenic beauty services. Due to many implementation factors, only the PES for protection of drinking water areas was found to be suitable for implementation on the ground and currently under implementation are at Yakpugang in Mongar, Pasakha in Chhukha and Namay Nichu in Paro.

There is a need to resolve the issues which hamper the adoption of other PES schemes, particularly related to the hydropower sector. On the technical level, there is a need for assessments that can guide the channeling of such funds from the hydropower sector to the upstream priority areas including the communities that take care of the water source areas and watersheds.

I am happy to see that the WMD in collaboration with the Natural Capital Project, WWF Bhutan and other partners has taken a concrete step in this direction with the completion of this pilot study into the sediment retention services being provided by the upstream areas of the Chamkharchhu sub basin. The preliminary results are encouraging and there is a need for addressing the data gaps and constraints identified in the report.

I look forward to seeing the further development of this work, and the MoAF through DoFPS and WMD will prioritize it accordingly.

Trashi Delek

Lyonpo Yeshey Dorji
MINISTER

དཔལ་ལྡན་འབྲུག་གཞུང་།
རྒྱལ་ཡོངས་དགའ་སྐྱིད་དཔལ་འཛོམས་ལྷན་ཚོགས།

Royal Government of Bhutan
Gross National Happiness Commission

MESSAGE FROM THE SECRETARY

Bhutan has adopted a Green Economy (GE) approach which is in harmony with the national development philosophy of pursuing Gross National Happiness (GNH). Environment is one of the 4 pillars and 9 domains in the GNH framework and the Royal Government of Bhutan is planning to develop a system of GNH accounting which can support policy analysis and actions that can guide and monitor progress towards achieving GNH.

An initial study commissioned by the Royal Government has estimated the value of the Ecosystem Services provided by Bhutan to be around USD 15.5 billion. A key part of the Green Economy approach is the pursuit of a low carbon growth path and increasing resource usage efficiency and social inclusivity, which is equivalent to the principles of sustainable development as enshrined in the Sustainable Development Goals (SDG) adopted by the global community in 2015.

The hydropower sector is the largest contributor to the national economy and depends on the proper management of watersheds for sustained flows of water especially in the lean season. The proper management of these upstream watersheds is dependent on the land use practices and livelihood choices adopted by these upstream communities. Ensuring the continued downstream benefits will require taking care of the needs of these communities living upstream through appropriate Payments for Ecosystem Services (PES) mechanisms.

With support from WWF, the GNHC has developed a framework for Ecosystem Based Spatial Planning approaches. Studies such as this one, carried out by the WMD, WWF and the Natural Capital Project, in the Chamkharchhu sub basin will provide the required detailed information and form the basis for implementation of Ecosytem Based Spatial planning and help in moving forward the initiative of Green Growth and Economy in the country.

Trashi Delek!

SECRETARY
Gross National Commission Secretariat

World Wildlife Fund

MESSAGE FROM THE COUNTRY REPRESENTATIVE

Capital has often been thought of narrowly as physical capital – the machines, tools, and equipment used in the production of other goods, but our wealth and wellbeing also relies on natural capital. If we forget this, we risk degrading the services that natural ecosystems provide, which support our economies and sustain our lives. These services include purifying and regulating flow of our rivers, regulating our climate, reducing flood risk, and pollinating our crops.

The Natural Capital Project—a partnership among WWF, The Nature Conservancy, University of Minnesota and Stanford University—works to provide decision makers with reliable ways to assess the true value of the services that ecosystems provide. An essential element of the Natural Capital Project is developing tools that help decision makers protect biodiversity and ecosystem services.

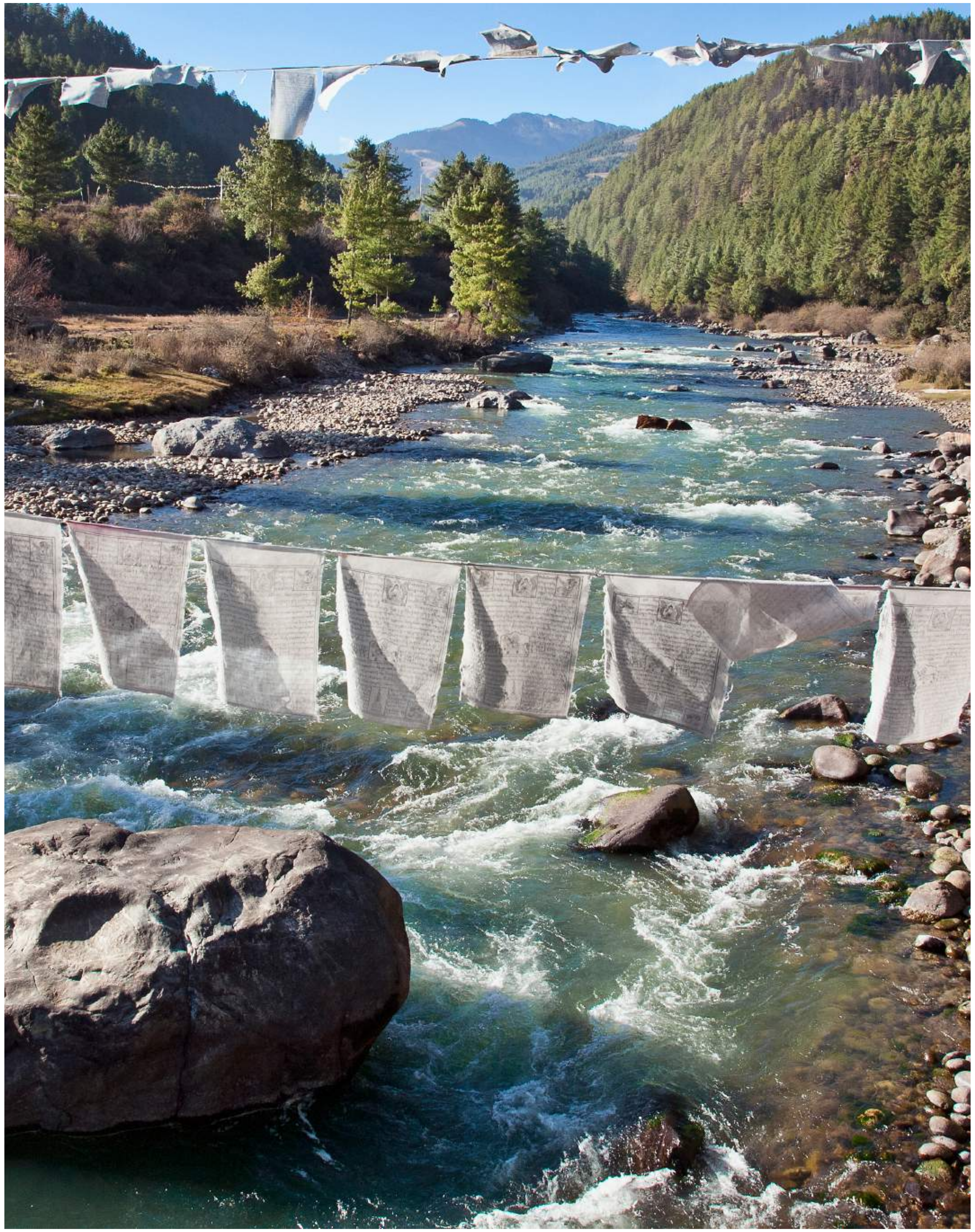
WWF scientists have helped develop a range of software tools for integrating the value of ecosystem services and biodiversity in different decision contexts. InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) is a unique software tool that models and maps the delivery, distribution, and economic value of ecosystem services and biodiversity. InVEST helps decision makers visualize the impacts of decisions and identify tradeoffs and compatibilities between environmental, economic, and social benefits.

This study represents the first practical application of the InVEST tool in Bhutan for assessing the sediment services provided by the watershed of the Chamkharchhu sub basin. The InVEST analysis results show that under the scenario of allowing degradation of just a small area upstream which provides high sediment retention services, there is a significant increase in the amount of soil erosion produced in the watershed. Conversely, restoration of just a small area upstream which are highly prone to soil erosion has a significant impact on reducing the soil erosion produced by the watershed.

These biophysical outputs from the InVEST tool can then inform and guide the valuation approaches to be adopted in order to attach a monetary or economic value to the ecosystem services being provided by the landscape to various stakeholders such as the hydropower sector. With mutual agreement on the monetary value assessed between various stakeholders an appropriate payment mechanism could be designed that will then ensure the sustainable and long-term conservation of this natural capital for the benefit of present and future generations.

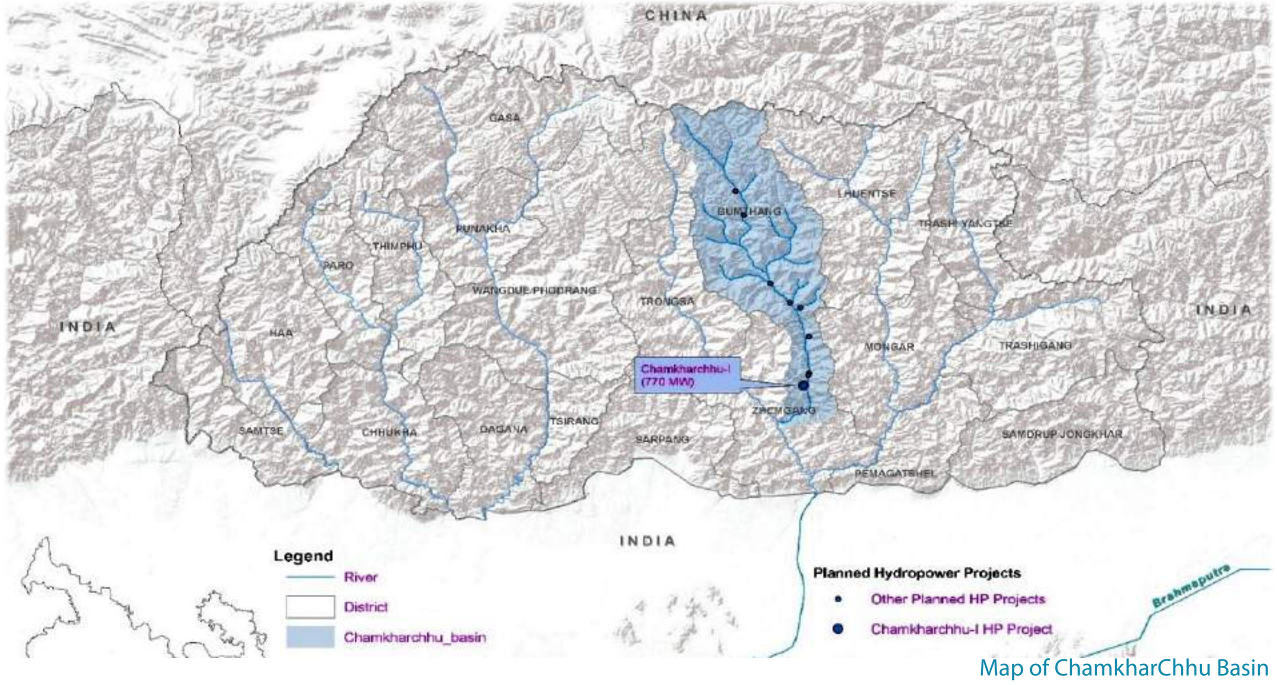
A lot of work still remains to be done and WWF looks forward to working with all stakeholders to make this vision a reality in Bhutan.

Dechen Dorji
COUNTRY REPRESENTATIVE
WWF Bhutan



Chamkharchhu River ©WWF Living Himalayas/SJackson

1. INTRODUCTION



Map of ChamkharChhu Basin

ECOSYSTEMS VALUATION IN BHUTAN

Bhutan has a unique development philosophy of maximizing GNH (Gross National Happiness) rather than GDP (Gross Domestic Product) of the country. GNH aims to integrate sustainable and equitable economic development across nine domains: psychological wellbeing, health, education, culture, time use, good governance, community vitality, ecological diversity and resilience, and living standards. Environment is one out of the nine domains in GNH, making it critical to determine how natural capital and ecosystems services contribute both directly and in interaction with the other eight domains, to sustainable human well-being in Bhutan.

There is thus a strong interest in Ecosystem services valuation as an integral input to the efforts to start a system of GNH accounting which can support policy analysis and actions that can guide progress towards achieving GNH. An initial study has estimated the value of Bhutan's Ecosystem Services to be worth US$ 15.5 billion per year, with more than half of the benefits (53%) flowing out of the country (Hayward et al, 2012 & Kubiszewski et al, 2013). This estimate was made using a simple benefits transfer methodology and using coarse available data, and is recognized to be an underestimate of the true value. There is now a need to undertake more accurate valuations and to track changes in the quality and quantity of the country's ecosystem services, which can be monitored in annual national GNH accounts.

SCOPE OF THE STUDY

As Bhutan has a rich natural capital with very less information on the ecosystem services it provides, a study on the ecosystem services derived from the natural capital was felt necessary. Although Bhutan enjoys a rich forest cover and a strong policy to support conservation, it still faces a lot of challenges. Forest fires, excessive use of forest resources, overgrazing, unsustainable agricultural practices, infrastructure development, mining, industrial development without proper enviornmental measures are some of the key threats to the natural capital.

Chamkharchhu sub basin was selected as the study area since work on developing a management plan in one of the watersheds is ongoing and also taking into consideration the planned hydropower project in the Chamkharchhu sub basin. Chamkharchhu sub basin at present also has most of its watersheds in a pristine and undisturbed conditions. With NatCap and WWF collaboration having done considerable work on Natural Capital Projects in countries such as Indonesia, Myanmar and Mozambique, WWF Bhutan in partnership with the Department of Forests and Parks Services embarked on studying some ecosystem services in the Chamkharchhu sub basin using InVEST modelling tools.

A workshop was held in Paro in May 2015 where participants were introduced to the concept and a hands on training was provided on the use of NatCap's InVEST tool for carrying out valuation of ecosystem services. Facilitators were from the NatCap Project at Stanford University. This workshop was well attended with participation from a number of relevant technical staff from relevant government agencies like the GNHC, Ministry of Economic Affairs and Ministry of Agriculture and Forests as well as WWF Bhutan; and it enhanced the capacity of local experts in using InVEST. It was realized during the Paro workshop that there were a lot of issues with obtaining local data of the required accuracy, detail, quality and spatial resolution. However, the fact that InVEST has been designed for use in such data-poor scenarios, enables it to be used with open data sources of coarse resolution in order to get an approximate idea of the ecosystem services being provided. This could then be refined later upon the availability or generation of better quality local datasets.

Following upon this workshop and in view of time and resource limitations, it was decided to focus on evaluation of an ecosystem service (sediment retention/erosion prevention) which is most relevant for supporting a Hydropower PES scheme, using the Sediment Delivery Ratio (SDR) model of InVEST. After running the SDR model, analysis would be done to identify priority areas for conservation and restoration activities which would be of particular interest to Hydropower facilities.This initial study would then serve as a proof of concept study, for other more detailed assessments to follow in the future.

OBJECTIVES OF THE STUDY:

1. Study the extent of sediment retention services that the different land cover types in the Chamkharchhu sub basin can offer.
2. Plan interventions such as soil and water conservation programs around the areas which shows high sedimentation
3. Contribute towards design and plan of a PES model.
4. Demonstrate the kind of study and results that can be expected from an InVEST model for use in conservation related activities in priority areas.
5. Develop capacity in of the government as well as in WWF on ecosystem service valuation.

2. VALUATION OF ECOSYSTEM SERVICES RELATED TO HYDROPOWER

ECOSYSTEM SERVICES (ES) AND INVEST

The Millennium Ecosystem Assessment (2005), which represents the first global attempt at quantification of the ES provided by nature, defines the term ecosystem services as: "the benefits people obtain from ecosystems." Ecosystems incorporate both biotic and abiotic components and yield a flow of services that are vital to humans, including the production of goods (e.g., food), life support processes (e.g., water purification), and life fulfilling conditions (e.g., beauty, recreation opportunities), as well as the conservation of options (e.g., genetic diversity for future use).

InVEST is a tool designed to inform decisions about natural resource management. Essentially, it provides information about how changes in ecosystems are likely to lead to changes in the flows of benefits to people. InVEST uses a simple framework delineating "supply, service, and value" to link production functions to the benefits finally derived by people. It has a suite of over 18 models to model different types of supporting and final Ecosystem services. InVEST has been used world-wide since its development over a decade ago, to help to shape decisions using an ecosystems services approach in a variety of contexts such as spatial planning, PES design, development permitting and climate adaptation. (InVEST 3.1.3 documentation)

THE SDR MODEL

Erosion and overland sediment retention are natural processes that govern the sediment concentration in streams. Sediment dynamics at the catchment scale are mainly determined by climate (in particular the rain intensity), soil properties, topography, and vegetation; and anthropogenic factors such as agricultural activities or dam construction and operation. On a landscape, the main sediment sources include overland erosion (soil particles detached and transported by rain and overland flow), gullies (channels that concentrate flow), bank

erosion, and mass erosion or landslides). However, SDR only models overland erosion, which represents only a portion of the total erosion occurring in a watershed.

Sinks include on-slope, floodplain or instream deposition, and reservoir retention. Conversion of land use and changes in land management practices may dramatically modify the amount of sediment running off a catchment. The magnitude of this effect is primarily governed by: i) the main sediment sources (land use change will have a smaller effect in catchments where sediments are not primarily coming from overland flow); and ii) the spatial distribution of sediment sources and sinks (for example, land use change will have a smaller effect if the sediment sources are buffered by vegetation).

The sediment retention service provided by natural landscapes is of great interest to water managers. Understanding where the sediments are produced and delivered allow them to design improved strategies for reducing sediment loads. Changes in sediment load can have impacts on downstream irrigation, water treatment, recreation and reservoir performance.
SDR is based on the Universal Soil Loss Equation (USLE), which is a standard method for estimating the amount of erosion generated by the landscape; and the Sediment Delivery Ratio (SDR), which estimates how much of that generated erosion is likely to enter the stream, instead of being retained by the landscape.

The outputs from the sediment model include the sediment load delivered to the stream at an annual time scale (sediment export), as well as an index of sediment retention, where erosion under current land use is compared with a bare watershed to identify areas that contribute more to retention services. Using these biophysical outputs, appropriate valuation approaches can be adopted, which will be highly dependent on the particular application and context, and may need to be implemented independent of InVEST. (InVEST 3.1.3 documentation).

3. WATERSHED MANAGEMENT IN BHUTAN

Although the watersheds of Bhutan are regarded as being in generally good condition (WMD, 2011), there is concern over the growing degradation of watersheds due to a multiplicity of causes such as rapidly expanding farm roads network, power transmission lines, rapid urbanization, and over-extraction of forest resources (Figure 2). In view of the multi-sectoral nature of the challenges watersheds are facing the government has set up the Watershed Management Division (WMD) in 2009, within the Ministry of Agriculture & Forest in order to coordinate activities for integrated watershed management.

The rapid assessments of watersheds along Chamkharchhu sub basin were carried out with the use of Watershed Classification Guideline in 2015, which indicated that watersheds were either pristine or normal in the current situation. However, the regular monitoring of watersheds along with sub basin is critical as the rising degrading influences can have adverse impacts with time. Considering the several rationale and purposes, the lower Choekhor watershed under Chamkharchhu sub basin is being selected for detail assessment and the management plan development is being developed for implementation. With additional information from this study, concerned development agencies and policy decision makers would also be able to understand the ecosystem goods and services provided by the watersheds which will help in future planning. The plan is still being developed and the outputs from this InVEST study is expected to contribute towards the development of the plan especially in terms of identifying management interventions and areas.

Mass wasting due to natural processes

Land slips caused by roads across steep hillslopes

Figure 2. Growing evidence of land degradation in Bhutan (WMD, 2011).

Figure 3. Sustainable land management practices (NSSC, 2015).

PAYMENT FOR ECOSYSTEM SERVICES (PES) IN BHUTAN

The WMD has adopted a holistic approach through participatory, integrated watershed management including community involvement and contribution, treating symptoms as well as underlying causes of degradation. The approach emphasizes the upstream-downstream biophysical interactions and socio-economic linkages; ensuring not only economic benefits for all parties, but also preserving the watershed potentials for continued provision of environmental services in the longer-term.

With support from FAO, the WMD has assessed the feasibility of establishing Payment for Ecosystem Services (PES) schemes in Bhutan (FAO & WMD, 2009).

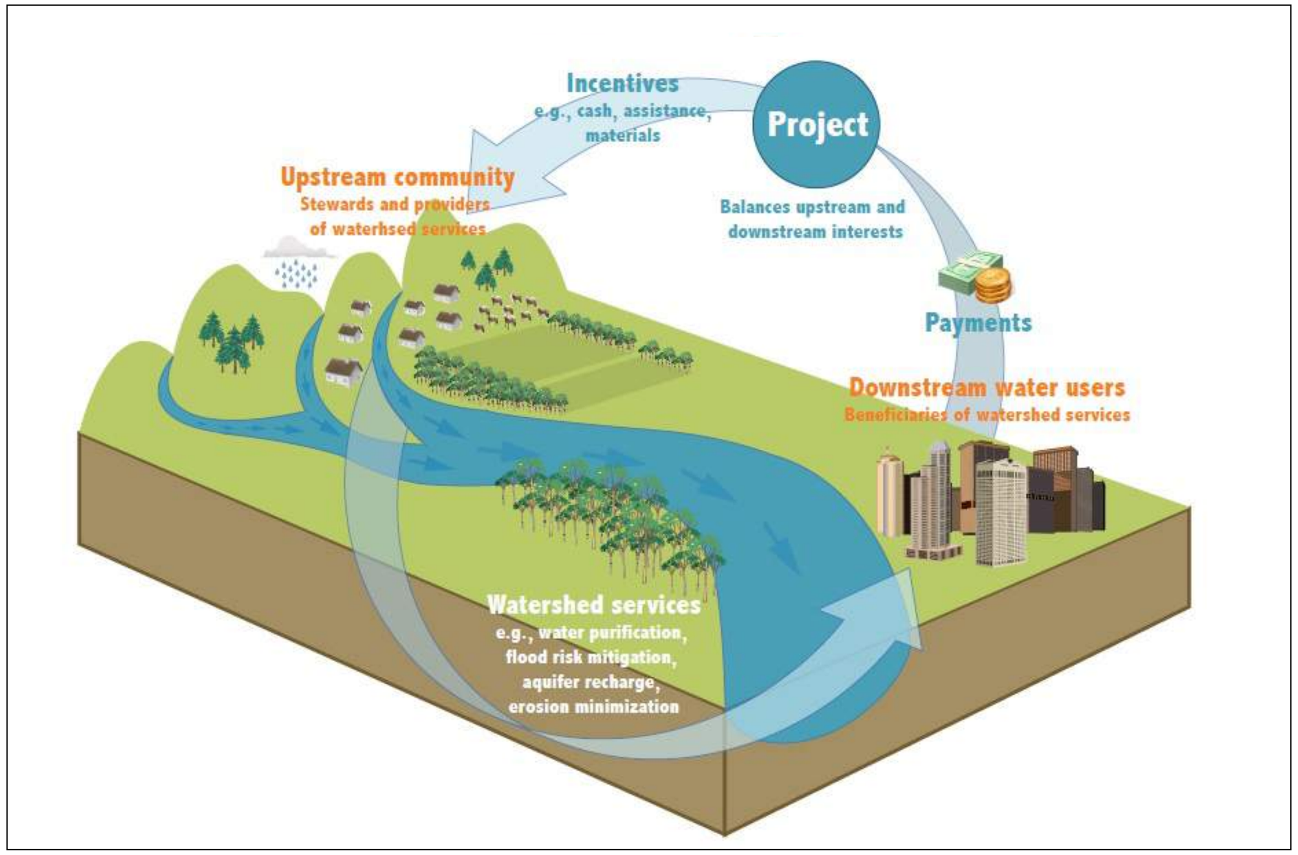


Figure 4. PES conceptual framework (WMD, 2015).

After evaluation of various sites, three pilot sites were identified for conducting feasibility studies to implement PES for providing three different ES services.

1. Hydropower water supply service PES in Woochu sub-watershed, Paro district
2. Drinking Water supply service PES in Yakpugang sub-watershed, Mongar district
3. Biodiversity/scenic beauty service PES in Phobjikha valley, Wangdue Phodrang district

From the above identified pilot sites, only the PES related to ensuring water supply service was actually implemented in 2011 in Yakpugang. This scheme was for 3 years' duration between the service providers (Community Forest Management Group of Yakpugang), and the service users (Mongar Municipality).

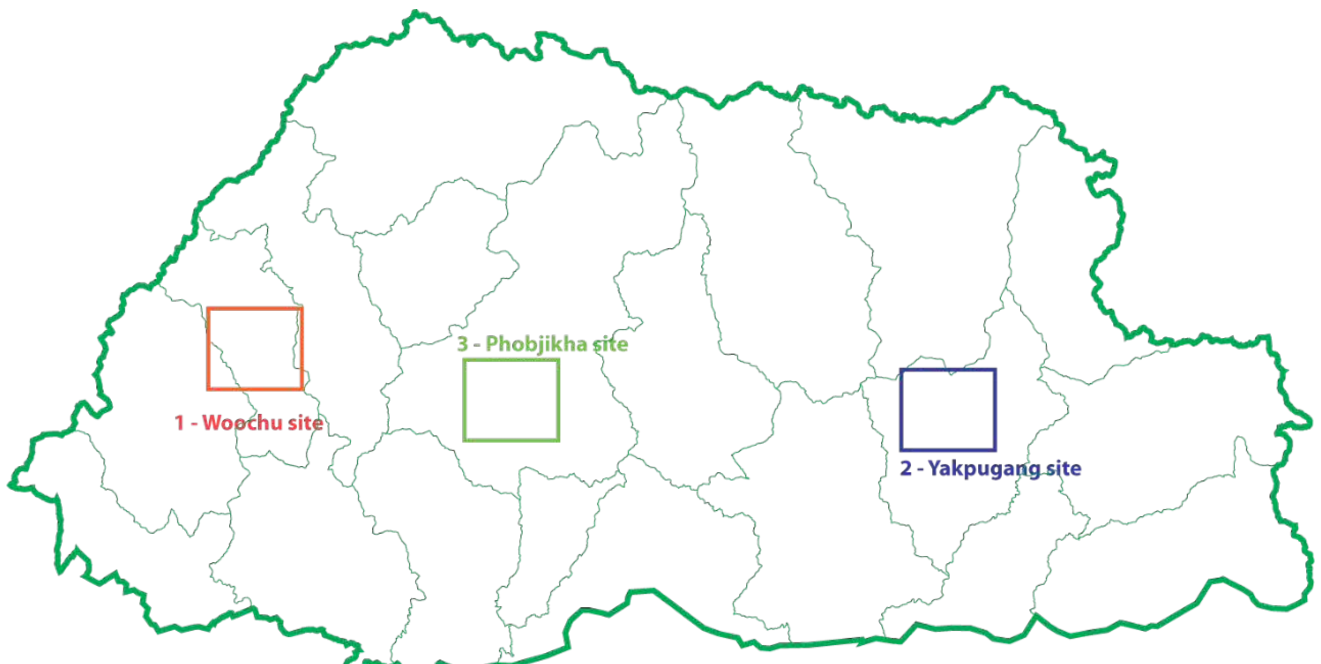


Figure 5. Pilot PES sites in Bhutan (WMD, 2015).

The Service providers comprising of 113 members of the Yakpugang Community Forestry Group were entrusted to protect the drinking water source of the Mongar town. In return the group was annually paid Nu. 52,000(equivalent to USD 750). The group carried out activities such as maintaining buffer area, limiting cattle grazing, reducing no. of cattle heads, plantations in the landslide & barren areas, cleaning of streams, monitoring from illegal extractions of forest, resources & against grazing by cattle other than Yakpugang community.

With its successful implementation in the three years the PES scheme in Yakpugang has been renewed and new buyers have also been brought in. The contract has now been renewed for another five years starting from January 2016. The CF group members are now paid Nu. 1,42,880 (2164 USD) annually for protection of the water source.

In 2016, two additional PES schemes for water supply were similarly established for 5 years' duration, in Pasakha, Chhukha district and Namay Nichu, Paro district. However, there is no progress on implementation of the other pilot sites due to various issues. For Phobjikha, collection of entry fees was not allowed for the fear of setting precedence as there was no similar systems of entry fee collections even in the National Parks at that time. A survey on willingness to pay was conducted among a few tourists who visited there but It was uncertain on how many would actually come back to visit although they were positive about the payment system. In the case of PES schemes for hydropower, there are no studies carried out to show the positive impacts of upstream watershed management to downstream hydropower production. There is need to generate data and information to take to hydropower plants and ask them to provide funds or take part in PES.

In the case of developing the PES for hydropower in Paro Woochu sub-watershed, there had been an effort to build capacity in SWAT modeling through the FAO project. However, the model results for the Woochu sub-basin were not used to develop a valuation of the services provided. There has not been much subsequent follow-on work and it appears that the local capacity is still lacking in this field. The results of this analysis using InVEST could be used to further underscore the need for building local modeling capacity in using both these tools effectively for doing detailed assessments of sediment retention and water yield service.

4. HYDROPOWER PERSPECTIVES ON WATERSHED MANAGEMENT

HYDROPOWER PLANS IN CHAMKHARCHHU SUB BASIN

There are 7 planned hydropower projects within the Chamkharchhu sub basin (PSMP, 2003). The detailed project report (DPR) for the first project Chamkharchhu-I has been completed and its construction is scheduled to begin within the 11th Five Year plan (2013-2018). Once completed, the projects would generate annual revenues of around Nu. 60 billion.

Sl.	Project	Installed Capacity (MW)	Annual Energy (MU)	Tariff (Nu/kWh)	Annual Revenue (Nu. Millions)	Remarks
1	Chamkharchhu-I	770	3344	4.78	15,984.32	DPR completed
2	Chamkharchhu-II	590	2420.28	3.87	9,366.48	PFR completed
3	Chamkharchhu-III	1217	4727.05	4.77	22,548.04	Desktop study
4	Chamkharchhu-IV	364	1491.87	4.65	6,937.20	PFR completed
5	Chamkharchhu-V	97	423	4.43	1,875.30	Desktop study
6	Gumthang	108	520	4.43	2305.33	Desktop study
7	Gizamchhu	53	241	4.43	1,068.43	Desktop study
	Total				**60,085.10**	

Table 1. Projected Hydropower Revenues from Chamkharchhu basin (Source: DGPC, 2015)

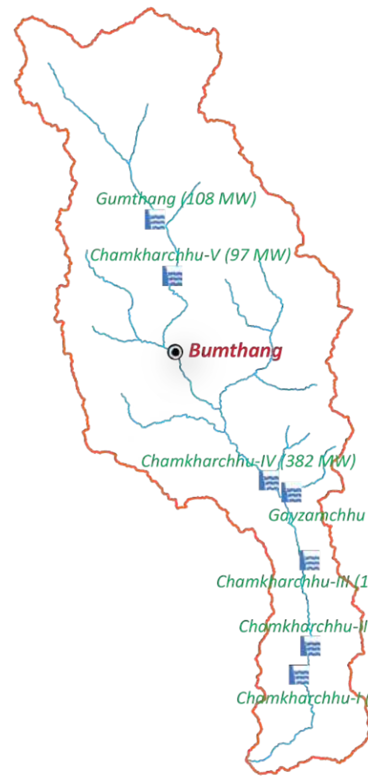


Figure 6. Chamkharchhu basin with proposed hydropower projects (DGPC, 2015).

Thus, the potential for PES based on benefits to hydropower is a highly viable proposition, as the costs of improved upstream management interventions would be affordable and also in the economic interest of the upcoming hydropower projects, as given below.

THE COSTS OF RIVER SEDIMENTATION FOR HYDROPOWER GENERATION

The added risks due to altered ecological conditions are well known by the hydropower sector in Bhutan. With growing infrastructure development (especially linear infrastructure including roads and transmission lines), some sparked by hydropower expansion, some catchment areas have experienced deterioration.

Despite existing rules requiring that infrastructure be built in the least disruptive manner possible, enforcement of such directives is insufficient, leading to some landscapes at certain road sites or dam sites becoming degraded. This in turn leads to increased erosion and siltation, which, in combination with lower flows in the dry season – takes a toll on hydro blades, which increases costs for the industry and shortens the lifespan of expensive hydro equipment.

Currently, DGPC hydropower generation plants are equipped with de-silting chambers and flushing mechanisms to deal with river sediment load (FAO & RGOB, 2011). There are two costs incurred to hydropower projects due to sedimentation of rivers caused by both anthropogenic and natural causes upstream of the dam:

• Incremental costs of sedimentation in construction costs

During the feasibility phase of hydropower project, DoE collects information on the sediment load and type of minerals to inform the design process on the:

- type of coating that the turbines and other exposed machinery must receive to increase their resistance to erosion caused by the hard minerals dissolved in the water.
- depth and length of the Desilting Chambers (DC)/ Settling basins to allow for sediment deposition and Silt Flushing Tunnels (SFT) to allow for settled sediment flushing.

The Desilting Chambers (DC)/Settling basins are built from the onset to allow the plant to deal with sediment in the water. According to the type and quantity of sediment, the construction costs of the desilting chambers may be affected- ie. larger chambers imply longer tunneling. However, this may not be a determining factor in the construction of the power plant, and any additional cost is likely to be recovered during operation.

• Incremental costs of sedimentation during operation

During operation, each chamber is cleaned once a year- the cycle takes approximately 18 hours. In extreme case with intense rainfall, additional measures may need to be taken. Since each power plant has several chambers, these can be cleaned alternately and production does not have to halt during this process. Thus, DGPC does not seem to incur in-production losses due to sediments in the river.

From the above, it may be seen that the design of the run-of-river projects such as the one to be built at Chamkharchhu-I site, has in-built measures to deal with sedimentation both at the design and operation phases. With additional insight into the sediment production mechanisms operating in the basin, it may be possible to improve the design of the other 6 upcoming projects. However, there are clearly benefits to the project from better management of the upstream catchments primarily from pro-longed life of turbines, as well as better regulated flows especially during the lean winter season. The challenge remains in how to quantify the causal relationships between the degradation of the upstream area and the increase in costs for the hydropower projects during both design and operation phases.

5. PES WITH HYDRO

A research published in the Environmental Science & Policy, shows that sediment flowing into rivers that feed hydropower projects could be cut roughly in half (44%), by paying people upstream to perform specific conservation activities in targeted areas. Bhutan's hydropower sector currently accounts for up to 40 percent of government revenue and has the potential to grow. Currently about 5% of potential capacity is being harnessed, and vision in 2020 is to do 10,000 mw.

With Hydropower being one of the highest contributor towards the country's economy, the rivers in the country are a major source for the sector. However, the geographical situation of the country also poses a challenge for the hydropower plants. With most of the hydropower plants designed as a run-of-river system, it becomes vulnerable to high sediment concentrations thus increasing the costs of operations. Certain problems of sedimentation can be addressed to a certain extent by investing in conservation activities up stream such as watershed management, sustainable land use practices etc.

Under the sustainable hydropower policy 2005 of Bhutan, 1% of the royalty collected from the hydropower plants are ploughed back to the Government revenue to meet the conservation costs. However, this does not mean that the money is put back directly upstream of the hydropower projects where conservation efforts are really necessary to address the sedimentation issues. Using the results of the SDR modelling, a PES plan can be

designed whereby areas of concern can be selected and targeted interventions can be planned accordingly. For this, the hydropower plant downstream can plough back some revenue for implementation of these specific activities. With further studies on seasonal water yield to support this study, hydropower projects can be convinced that the services they pay for are rightly being managed. However, more work will have to be done to come up with a more comprehensive plan for PES with the hydropower projects as it would entail discussions with various sectors in the Government. It would be the right time to initiate such a PES Scheme especially for the Chamkharchhu project as the project has just been initiated. If successful similar PES programs can also be designed for the other Hydropower plants.

Himachal Pradesh in India, with similar landscape like Bhutan, also has a number of hydropower plants designed as run of the river system. To address sedimentation issues caused by upstream land management practices, a study focusing on targeting investments in soil and water conservation to support base flow regulation and sediment retention in hydropower catchment facilities, and developing a framework for future work on economic valuation of these services was conducted with support from the Natural Capital Project. Using the results of the study, HP is currently in the process of developing a PES program around the ecosystem services that support hydropower production. Activities will be aimed at improving the condition of watersheds by implementing soil and water conservation practices.

EROSION RATES IN BHUTAN (NSSC, 2010)

With majority of the agricultural lands being on the steep slopes in Bhutan, erosion rates are relatively unknown as most of the research worldwide focuses on much gentler slopes. Many farmers have to cultivate land of more than 30 degrees and it is not rare to see farmers work on slopes of over 30 degrees.

To quantify soil erosion rates in Bhutan under different slope and agro-ecological conditions, 5 sites with 22 erosion plots were established by the National Soil Services Centre over 2008-2009 as part of the GEF funded Sustainable Land Management Project (SLMP). The first three sites were set up and in 2008 followed by another 2 sites in 2009. The erosion plots established varied between slopes of 9 to 30 degrees, and were considered to be a representative selection of SLMP geog conditions and indicative for overall Bhutanese conditions.

Figure 7. SLMP erosion plot sites (NSSC, 2010).

Each erosion site had plots with various Sustainable Land Management (SLM) treatments or practices which were used in the erosion plots to measure how effective these measures were in controlling soil erosion. The soil erosion measurements recorded indicated a clear trend. The bare reference plots for the year 2009 had on average the highest erosion rates (24.6 t/ha) followed by the traditional practice plots with an average rate of 6.42 t/ha. The SLM plots had an average soil erosion rate of 3.36 t/ha, whereas the SLM+ plots averaged 4.27 t/ha.

The results of the first two years of soil erosion plots in Bhutan showed that traditional land management practices produced moderate erosion rates, and without any land management (bare reference plots) the erosion rate was high (Table 1). It confirmed the urgent need for application of SLM or soil conservation measures to reduce the prevalent high erosion rates on the steep Bhutanese slopes and to make agriculture more sustainable and productive (NSSC, 2010).

Soil erosion rate Range (tonnes/ha/yr)	Soil erosion class
0-5	Slight
5-10	Moderate
10-20	High
20-40	Very High
40-80	Severe
>80	Very Severe

Table 2. Soil erosion classification, after Singh et al. (1992) as determined for India.

The above work on determining erosion rates for Bhutan is a very valuable one in that it provides a scientific basis and validation of the magnitude of the benefits of improved land management practices. This data would be useful for deriving improved estimates of the local biophysical values for improved practices in the conservation and restoration scenarios, which will be considered later in this report.

6. STUDY AREA

Chamkharchhu sub basin is located in central Bhutan, the basin is entirely located within the two districts of Bumthang and Zhemgang. It covers an area of 3,160 sq. km and stretches 130 km from the international boundary in the north, to the junction of the Chamkharchhu river with the Mangdechhu river to form the Manas river, which then enters India to the south. The variation in eco-regions is from alpine to sub-tropical; the altitudinal range is 250 masl to 6,458 masl with an average elevation of 3,606 masl. More than half (57.76 %) of the basin (1,825.4 sq.km) falls within the two protected areas viz. Wangchuck Centennial National Park and Phrumsengla National Park.

Figure 8. Location map of Chamkharchhu sub basin.

LAND COVER TYPES IN THE BASIN:

Given below are the various land cover types and their areal coverage for the Chamkharchhu sub basin. These figures are derived from the national land cover map of 2010 produced by the Ministry of Agriculture & Forest.

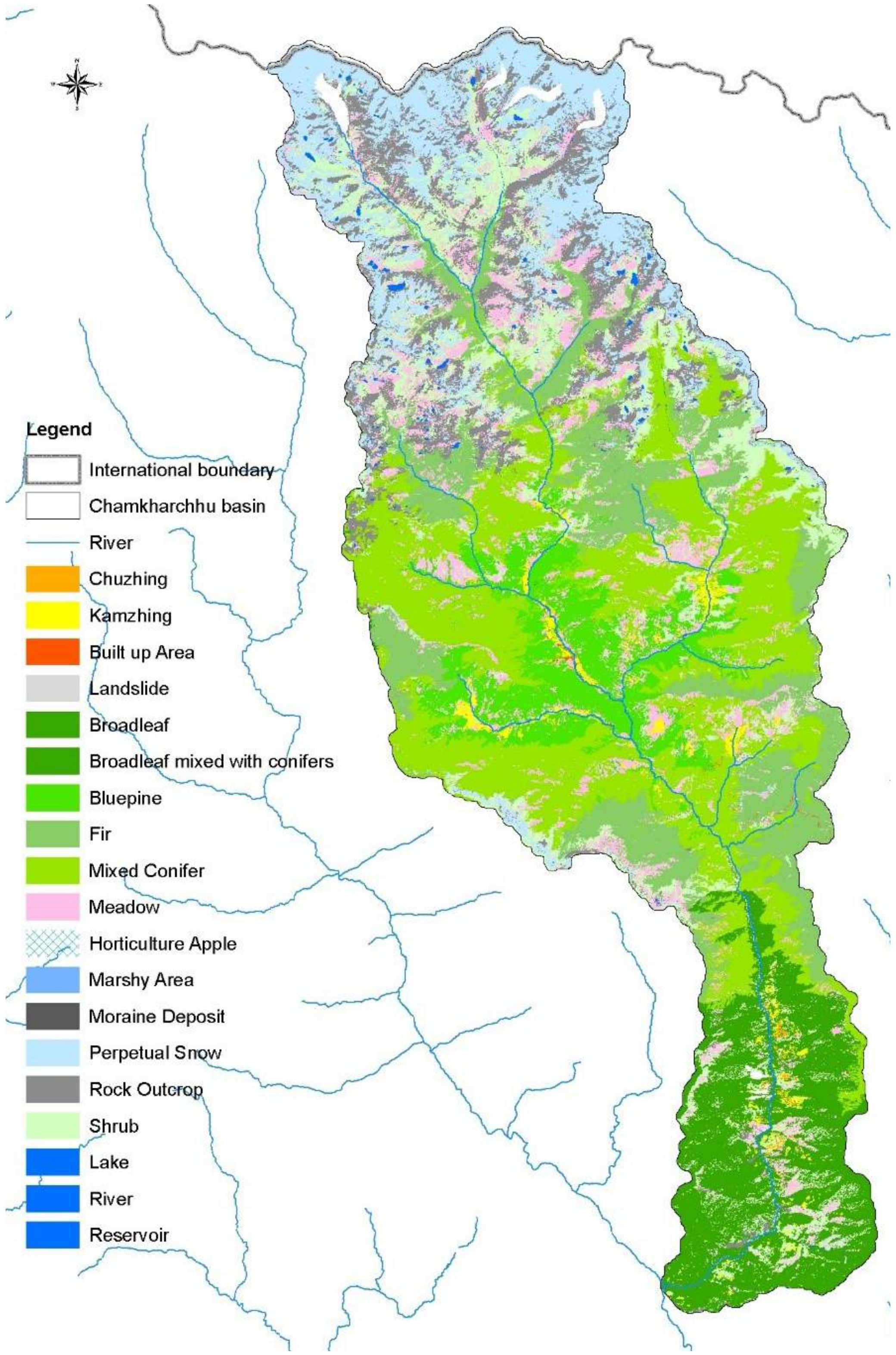
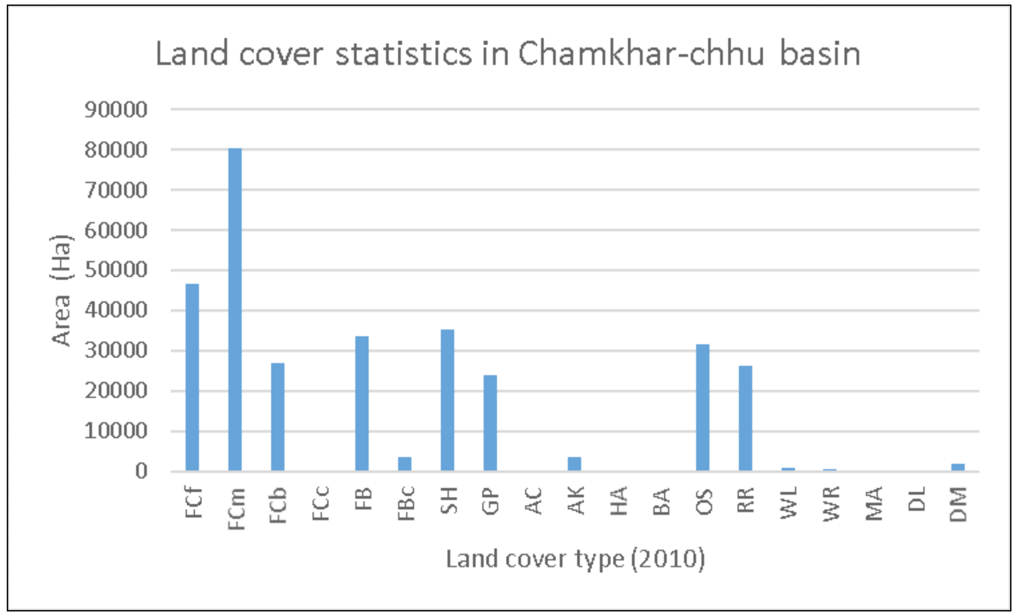


Figure 9. Land cover types in Chamkharchhu sub basin (LCMP, 2010).

Sl.	Land cover type	Land cover code	Area in 2010 (Ha)	% Land cover (2010)
1	Forest Conifer - Fir	FCf	46699.92	14.78
2	Forest Conifer - Mixed	FCm	80271.72	25.40
3	Forest Conifer - Bluepine	FCb	27029.07	8.55
4	Forest Conifer - Chirpine	FCc	231.3	0.07
5	Forest Broadleaf	FB	33765.03	10.68
6	Forest Broadleaf with Conifer	FBc	3422.16	1.08
7	Shrubs	SH	35229.06	11.15
8	Meadows	GP	24032.88	7.61
9	Agriculture Wetland	AC	286.74	0.091
10	Agriculture Dryland	AK	3464.28	1.10
11	Horticulture - Apple	HA	3.51	0.001
12	Built-up Area	BA	92.52	0.03
13	Snow cover	OS	31666.32	10.02
14	Rocky outcrops	RR	26412.66	8.36
15	Water - Lakes	WL	966.33	0.31
16	Water - Rivers	WR	459.45	0.15
17	Marshy areas	MA	25.92	0.008
18	Degraded area - Landslide	DL	153.63	0.05
19	Degraded area - Moraines	DM	1814.4	0.57
	Total area of basin =		316,026.9	100



SEDIMENT OBSERVATIONS IN CHAMKHARCHHU SUB BASIN

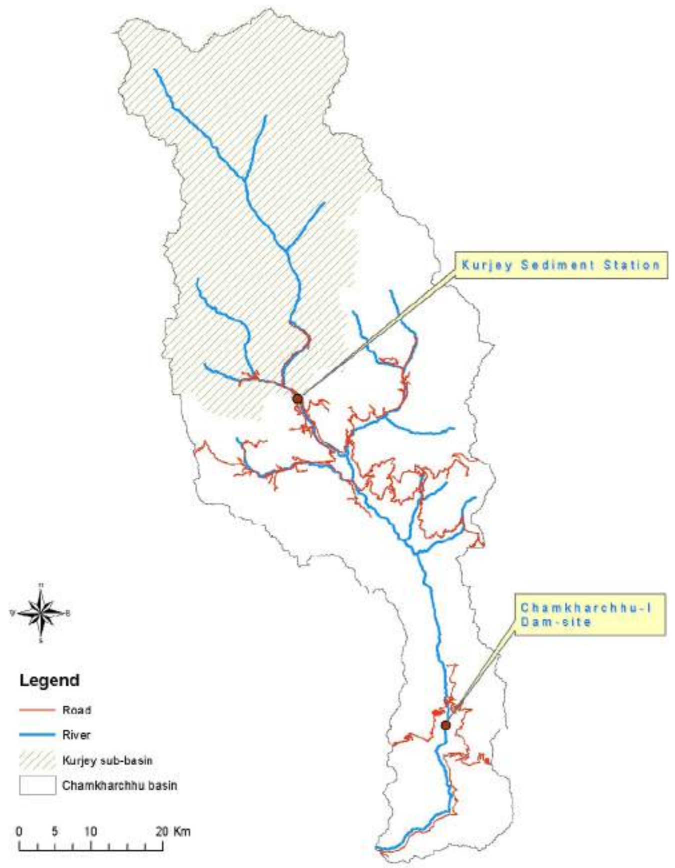
The nation-wide sediment sampling network comprises of 10 sediment sampling stations co-located with the Hydrological network of stream gauging station. The observation infrastructure is established and maintained by the Department of Hydromet Services (DHMS). Suspended sediment sampling is carried out by the use of depth integrating samplers. Sediment sampling frequency must be high in rivers. All samples are transported from the sampling stations to the sediment laboratory for analysis at the headquarters in Thimphu every 20 days or so. There is one sediment sampling station within the Chamkharchhu sub basin which is located at Kurjey, upstream of the Chamkharchhu-I dam site. Sampling data is available starting from August 2008 up to the present time. The main variables captured are the total suspended sediment load and estimates for bed load, which are used to estimate the total sediment load in tonnes as well as sediment yield in tonnes/sq. km.

Year	Estimated total sediment load for record period (tonnes):
2009	364,161.25
2010	241,830.80
2011	113,594.57
2012	51,341.67
2013	47,334.57
2014	91,661.04
Observed annual average sediment load	151,653.98

Name of station = Kurjey
Elevation = 2,600 masl
Type = Principal/Sediment Station
Established year = 28/05/1991 through NORAD project
Area of sub-basin = 1,360.75 sq.km
Sediment Yield = 2.70 tons/ha/year (2009)

Amount of sediment export delivery from InVEST model for the Kurjey sub-basin, which is upstream of the Kurjey sediment station location is equal to 113,072.47 tonnes (Baseline scenario in 2010) whereas the average observed annual sediment load is 151,653.98 tonnes per year (6 years time-series average).

Calibration was not done since the longer time series is not available and there is huge variation between the years. Only % changes in the sediment export and retention index are therefore considered in this report. With the availability of at least 10 years of observations, the calibration of the model could be undertaken in the future.



Location of sediment observation station in Chamkharchhu sub basin

7. SDR MODEL OUTPUTS

METHODOLOGY

The focus of the assessment is on generating proof-of-concept for how InVEST can model changes in ecosystem services (ES) which can impact hydropower facilities in the Chamkharchhu sub basin. The upcoming Chamkharchhu-I hydropower project is taken as the case study.

Since it is known that sediment is the primary concern of these hydropower facilities, we will use the InVEST Sediment Delivery Ratio (SDR) tool to model sediment production and retention in the basin. Understanding where erosion is being generated in the watershed, due to local land use, soils, climate and topography, is important for helping target restoration programs that can reduce erosion at its source. Similarly, knowing where existing vegetation is playing a role in retaining sediment in place, and keeping it from eroding, is also a key part of targeting conservation programs that can maintain the ecosystem services that are already being provided. Both of these types of programs can reduce the burden on turbines and other hydropower infrastructure.

To illustrate this, we will look at relative changes in ES under various hypothetical scenarios: one in which improvements are made to the areas in the watershed that generate high levels of sediment which flow downstream to the hydropower facility of interest (Restoration scenario), the other scenario is one in which areas currently providing high levels of sediment retention service upstream are allowed to degrade (Degradation scenario.)

This is done following the methodology given below:

1. The InVEST SDR model is run under current conditions, with a current land use/land cover (LULC) map. The available national land cover map of 2010 is used as the LULC in these scenarios, although ideally a more recent land cover map would be more representative. The particular areas of interest are the 23 sub-watersheds into which the Chamkharchhu sub basin has been delineated, for which statistics on the ecosystem services of interest (sediment export and retention) will be generated by the SDR tool. Overall figures are then obtained for all sub-watersheds constituting the upstream area of the dam site for the Chamkharchhu-I hydropower project as well as the whole Chamkharchhu watershed.

2. The resulting sediment export map produced by InVEST is examined to identify areas with high sediment delivery rates. The areas of the sediment export map with a value greater than 6.42 tonnes/ha/year are selected. This threshold is selected as it is the observed average erosion rate for the traditional agriculture practice plots in Bhutan, as given in the study carried out by the NSSC in 2009. This falls in the moderate erosion category according to the erosion rate classification for India as given in Table 1. The rationale being that areas producing moderate to high sediment would be good areas to target for restoration, to reduce the amount of sediment reaching the stream.

3. For developing a restoration scenario, the above high sediment export areas in the baseline scenario are changed to an improved land cover type, forest in this case; the assumption being made here is that restoration would involve reforestation. The broadleaf forest type (FB) is used as the improved land cover type since it shows a low level of sediment export.

4. The SDR model is run again, and the results are compared to the results with the current land cover map. In particular, the sub-watershed results that are aggregated across the basin shows the difference between how much erosion is produced in the current landscape vs. a landscape in which restoration is done. The percent change in the values of sediment export are reported, because the model has not been calibrated.

5. A similar process is followed with the sediment retention map produced by InVEST, in order to identify areas that are currently providing high levels of sediment retention service. The areas with a value of sediment retention index greater than 25 tonnes/pixel are selected; this threshold value is chosen based on a visual

examination of the amount of the landscape which falls in this category after considering various other threshold amounts. It was found that with this threshold, the area of high sediment retention index covers approximately 100 sq. km, which is similar in extent to the area which falls in the high sediment export category with the sediment export threshold of 6.42 tonnes per year. The selected areas are then changed to a degraded land cover type, shrubs in this case, since it is found that the shrubs make up most of the high sediment export areas. The SDR model is run again on this degraded scenario LULC map. The difference between the current land cover and this degraded land cover map shows the marginal benefit of protecting these areas and not letting them degrade.

DATA INPUTS

Please see the InVEST User Guide for additional information about data requirements and results of the SDR model.

Data	Description	Source
DEM	Digital Elevation model, with elevation values across the area of interest.	ASTER GDEM v2 was used.
Rainfall erosivity	A measure of the intensity of rainfall, such that stronger rains produce more erosion.	Erosivity(R) was derived using Worldclim current climate precipitation data (Hijmans et al, 2005). Roose's method (R= total annual rainfall X 0.5) was used as given in (FAO, 1996). Values for the basin were between 142 and 1779.5, with an average of 452.69.
Soil erodibility	Soil property indicating how easily each soil type detaches and becomes erosion.	ISRIC 1km resolution dataset was used. For the basin the values were between 0.006585 and 0.044778.
Land use land cover map	Location of different land uses and land covers in the area of interest.	National Land cover map of 2010 was used.
Watersheds	Basin that contributes to a point of interest where water quality will be analysed.	Watershed was delineated from the location of Chamkharchhu-1 dam and the outlet of the whole basin.
Biophysical table	Parameters required for the USLE corresponding to each of the land use classes.	Values were used from various sources as given in Appendix-2.
Threshold flow accumulation	The number of upstream cells that must flow into a cell before it's considered part of a stream, which is used to generate a river network from the DEM.	Value of 30,000 was used which matched closely the map of the river network.
SDR_{max} ,k_b,and IC_0	Three model calibration parameters. The default values are SDR_{max} =0.8, kb=2 and IC0=0.5.	Default values were used for SDR $_{max}$, ICO and kb.

Table 3. InVEST Sediment delivery ratio (SDR) model data requirements.

MODEL OUTPUTS AND DISCUSSION

Given below are the land cover statistics and maps obtained from the areas of interest in the basin, which are the areas having high sediment export and retention capacity as well as the three scenarios of interest viz. baseline, restoration and degradation scenarios as explained in the Methodology section given above. A description and analysis is presented for these outputs.

LAND COVER STATISTICS IN THE 3 SCENARIOS:

	Area of each land cover type (in Ha)				
Land cover type	Baseline scenario – 2010 (B)	Restoration scenario (R)	Difference (R-B)	Degradation scenario (D)	Difference (D-B)
Forest Conifer - Fir	46699.92	46576.80	-123.12	46,026.81	-673.11
Forest Conifer - Mixed	80271.72	80092.40	-179.32	78,672.69	-1,599.03
Forest Conifer - Bluepine	27029.07	27002.80	-26.27	26548.02	-481.05
Forest Conifer - Chirpine	231.30	223.38	-7.92	193.86	-37.44
Forest Broadleaf	33765.03	44097.20	10,332.17	29,524.77	-4,240.26
Forest Broadleaf with Conifer	3422.16	3368.88	-53.28	3061.98	-360.18
Shrubs	35229.06	28713.70	-6,515.36	43813.71	8,584.65
Meadows	24032.88	21806.90	-2,225.98	23385.33	-647.55
Agriculture Wetland	286.74	176.85	-109.89	241.47	-45.27
Agriculture Dryland	3464.28	2620.17	-844.11	3303.81	-160.47
Horticulture - Apple	3.51	2.79	-0.72	3.51	0
Built-up Area	92.52	80.55	-11.97	90.36	-2.16
Snow cover	31666.32	31849.7	183.38	31,841.19	174.87
Rocky outcrops	26412.66	26445.6	32.94	26,256.69	-155.97
Water - Lakes	966.33	965.52	-0.81	965.07	-1.26
Water - Rivers	459.45	459.09	-0.36	429.84	-29.61
Marshy areas	25.92	25.92	0	25.92	0
Degraded area - Landslide	153.63	7.47	-146.16	131.40	-22.23
Degraded area - Moraines	1814.40	1814.40	0	1813.59	-0.81
Total area of basin =	316,026.9	316,026.9		316,026.9	

Table 4. Overall land cover statistics in the 3 scenarios (Area in Ha).

	Area of each land cover type (in %)				
Land cover type	Baseline scenario (B)	Restoration scenario (R)	Difference (R-B)	Degradation scenario (D)	Difference (D-B)
Forest Conifer - Fir	14.78	14.72	-0.06	14.55	-0.23
Forest Conifer - Mixed	25.40	25.32	-0.08	24.87	-0.53
Forest Conifer - Bluepine	8.55	8.54	-0.01	8.39	-0.16
Forest Conifer - Chirpine	0.07	0.07	0	0.06	-0.01
Forest Broadleaf	10.68	13.94	3.26	9.33	-1.35
Forest Broadleaf with Conifer	1.08	1.06	-0.02	0.97	-0.11
Shrubs	11.15	9.07	-2.08	13.85	2.7
Meadows	7.61	6.89	-0.72	7.39	-0.22
Agriculture Wetland	0.091	0.06	-0.031	0.08	-0.011
Agriculture Dryland	1.10	0.83	-0.27	1.04	-0.06
Horticulture - Apple	0.001	0.0009	-0.0001	0.001	0
Built-up Area	0.03	0.03	0	0.029	-0.001
Snow cover	10.02	10.07	0.05	10.07	0.05
Rocky outcrops	8.36	8.36	0	8.30	-0.06
Water - Lakes	0.31	0.30	-0.01	0.31	0
Water - Rivers	0.15	0.15	0	0.14	-0.01
Marshy areas	0.008	0.008	0	0.01	0.002
Degraded area - Landslide	0.05	0.002	-0.048	0.05	0
Degraded area - Moraines	0.57	0.57	0	0.57	0
Total area of basin =	100%	100%		100%	

Table 5. Overall land cover statistics in the 3 scenarios (Percentage of Area under each land-cover class).

It is seen that the dominant land cover in the entire basin is Mixed Conifer Forest (FCm) which covers 25% in the baseline scenario. This figure does not change much in the other two scenarios, which is also true for most of the other land cover types.

The proportion of Broadleaf forest increases from 10.68% in the baseline scenario to 13.94% in the restoration scenario; and it decreases to 9.33% in the degradation scenario. This is owing to the fact that restoration activities in the high sediment export areas are assumed to be conversion to Broadleaf forest.

The other land cover type which exhibits some changes between the scenarios is the Shrubs class. The increase in shrubs from the baseline scenario of 11.15% to 13.85% in the degradation scenario is due to the assumption that the degradation scenario implies conversion of high sediment retention areas to shrubs. There is a decrease in the shrubs area from 11.15% in the baseline scenario to 9.07 in the restoration scenario, since a lot of the high sediment export area consists of shrubs, which is restored to forest within this scenario.

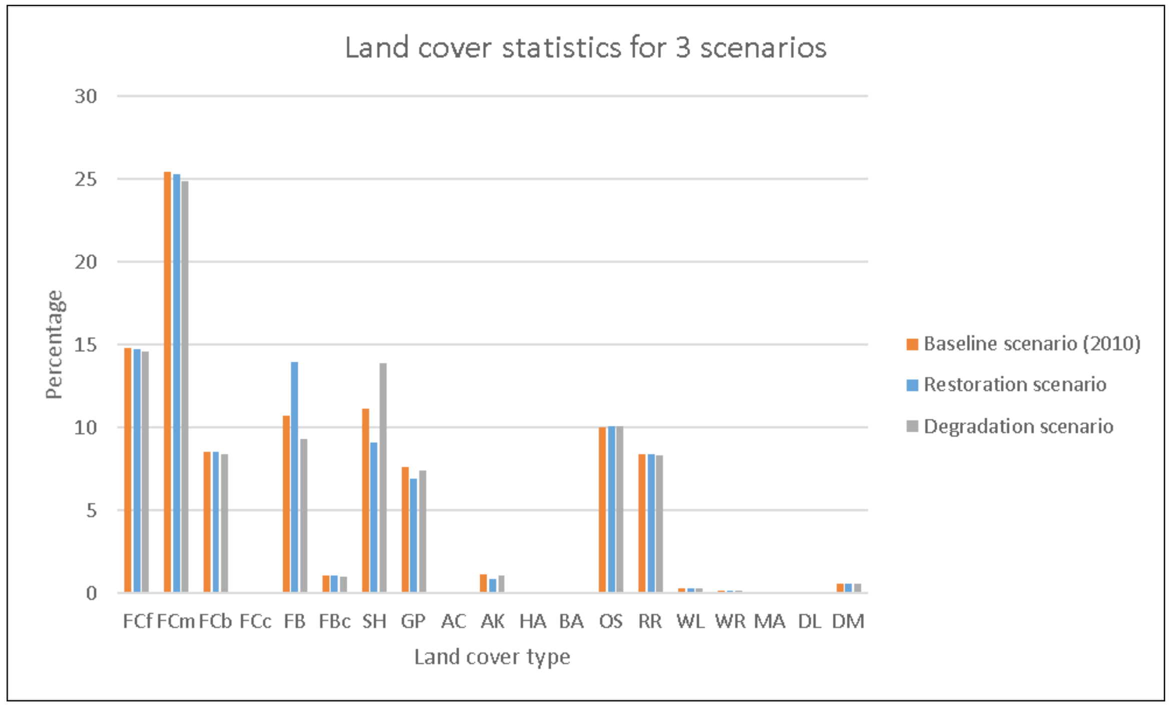


Figure 10. Land cover statistics for the 3 scenarios.

LAND COVER STATISTICS IN THE AREAS OF INTEREST

I) HIGH SEDIMENT EXPORT AREAS:

Land Cover type (Code)	Total annual sediment export (tons)	% of Total annual sediment export	Area (ha)	% of High sediment export area	Sediment export yield (tonnes/ha/year)
Forest Conifer - Fir (FCf)	146.70	0.03	15.57	0.143	9
Forest Conifer – Mixed (FCm)	1,839.76	0.35	152.10	1.397	12
Forest Conifer – Bluepine (FCb)	321.12	0.06	26.55	0.244	12
Forest Conifer – Chirpine (FCc)	165.99	0.03	7.92	0.073	21
Forest Broadleaf (FB)	10,141.50	1.94	679.50	6.242	15
Forest Broadleaf with Conifer (FBc)	823.72	0.16	58.86	0.541	14
Shrubs (SH)	361,271.00	69.14	6556.59	60.226	55
Meadows (GP)	76,683.60	14.67	2276.19	20.908	34
Agriculture Wetland (AC)	3,176.36	0.61	109.89	1.009	29
Agriculture Dryland (AK)	36,954.10	7.07	844.47	7.757	44
Horticulture – Apple (HA)	20.02	0.00	0.72	0.007	28
Built-up Area (BA)	959.25	0.18	12.15	0.112	79
Degraded area – Landslide (DL)	30,052.10	5.75	146.16	1.343	206
	522,555.21	**100.00**	**10,886.67**	**100.00**	

Table 6. Statistics of high sediment export areas (defined as >6.42 tonnes/ha/year) in the Chamkharchhu basin.

The above table shows the statistics of the areas which have a sediment export greater than 6.42 tons per ha per year. There is 10,886.67 ha (3.45%) which falls in this category out of the total area of the basin (316,026 ha). This relatively small area contributes 522,555 tons of sediment export every year, which is almost 82.81 % of the total sediment export produced by the entire basin of 631,045.3 tons per year. This shows that there would be considerable potential gains in reduction of sediment production, by investing in restoration of a relatively small proportion of the basin (3.45 %) which is responsible for a disproportionately high amount of sediment generation (82.81 %).

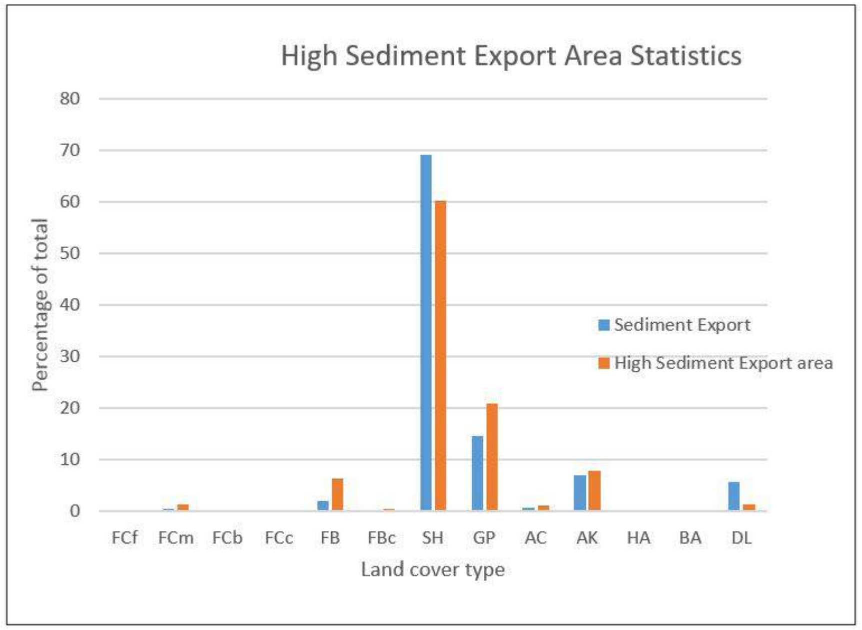
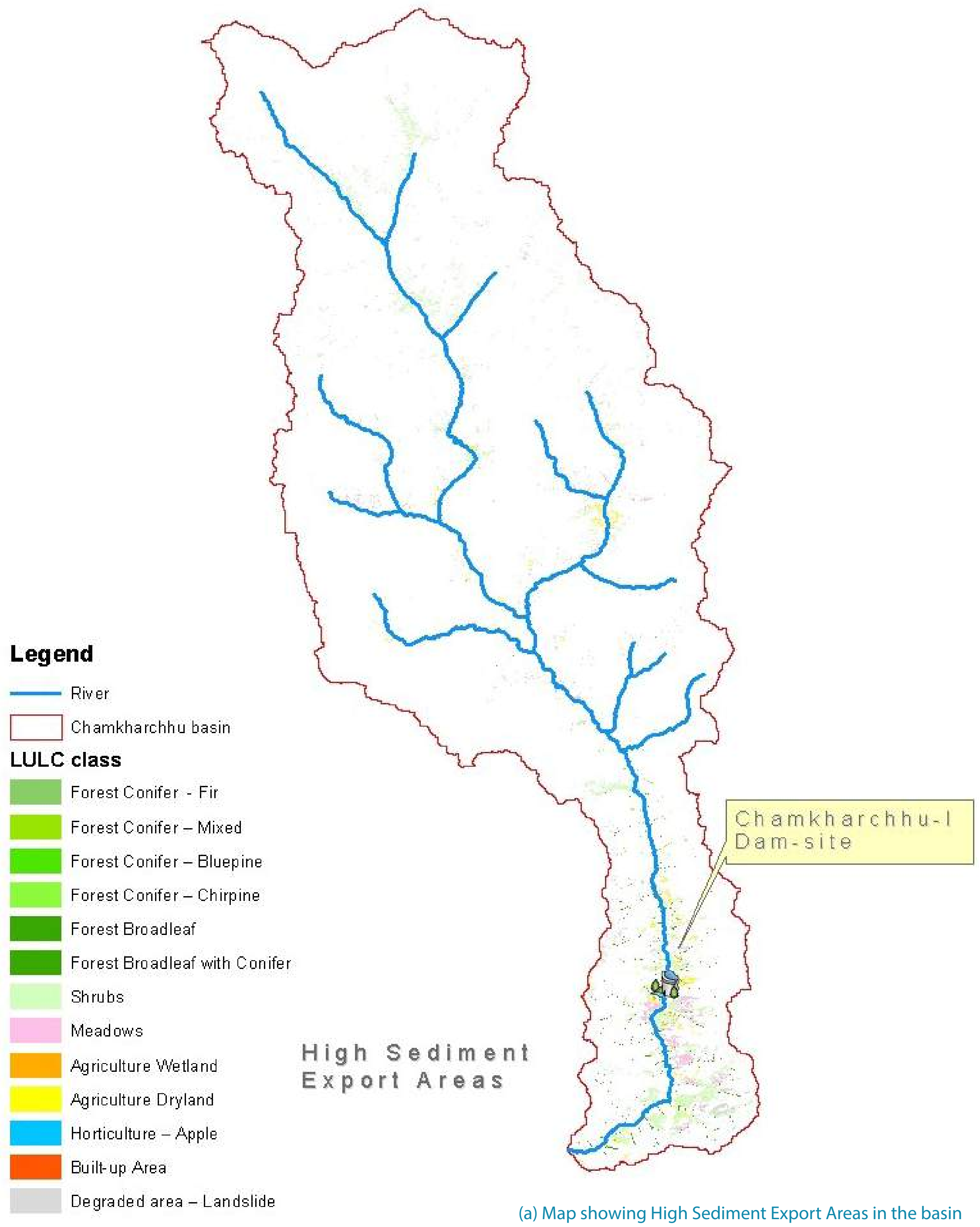


Figure 11. Statistics of the high sediment export areas (defined as >6.42 tonnes/ha/year).

From the above chart it is seen that the Shrub and Grassland land cover types have the highest contribution to sediment export at nearly 70 % and 15 % of the total sediment export amount. These two classes also cover almost 60% and 20% of the high sediment export area. Almost 6% is contributed by the DL (degraded landslide) class, which is covering only 1.3 % of the high sediment export area.

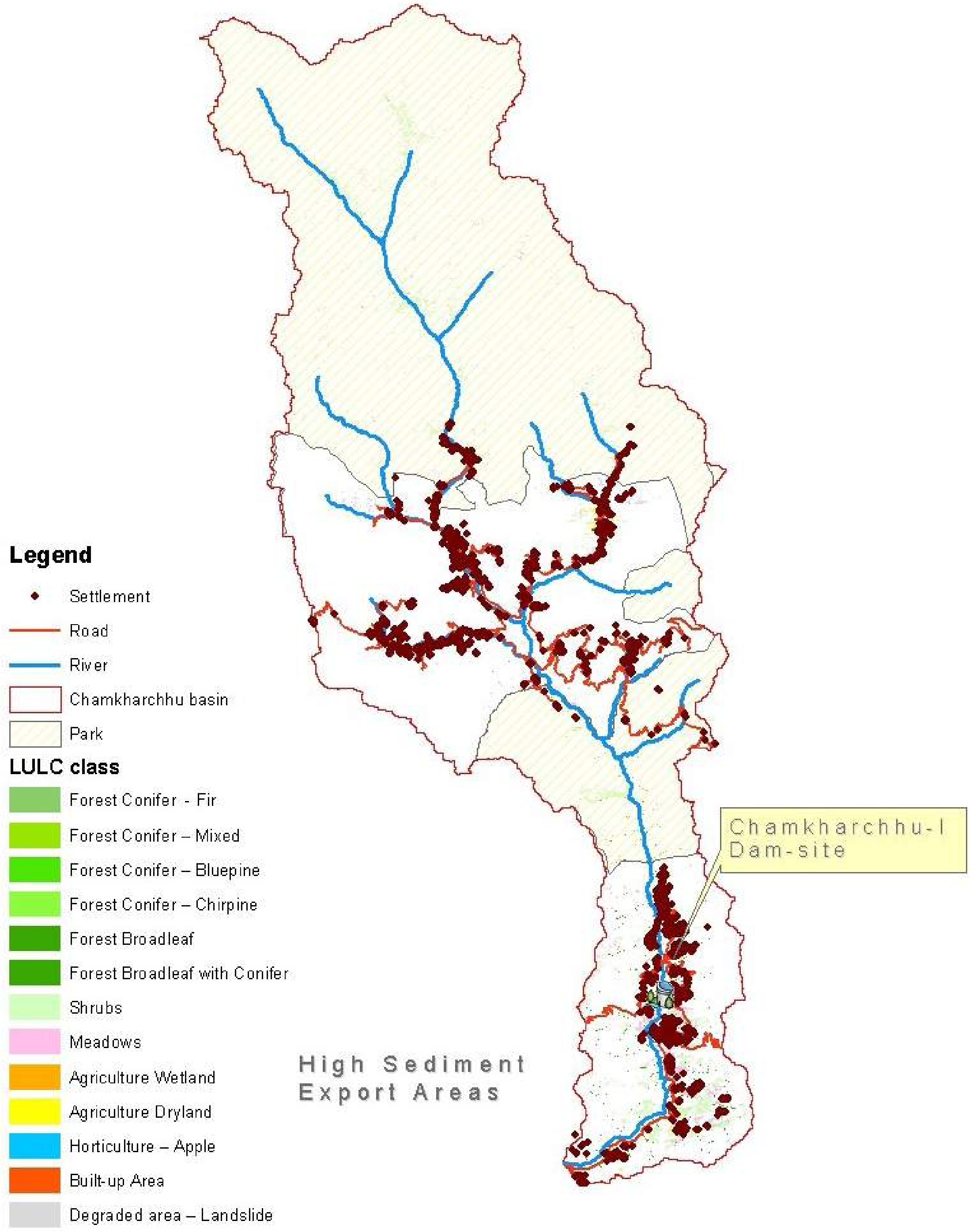
Thus, almost 91% of the sediment export is occurring from only these 3 land cover types, implying that any restoration scenario would have to prioritize these 3 land cover categories for future interventions. While land cover is a dominant driver of erosion in this model, slope also plays a major role in the amount of erosion predicted, with higher slopes likely to produce more erosion. Given the hilly nature of this watershed, further analysis is likely to show that interventions should also be prioritized, as feasible, based on slope.

Figure 12. Maps of high sediment export areas (defined as >6.42 tonnes/ha/year).



(a) Map showing High Sediment Export Areas in the basin

Figure 12. Maps of high sediment export areas (defined as >6.42 tonnes/ha/year).



(b) Map showing High Sediment Export Areas overlaid with road, settlements and Protected Area network

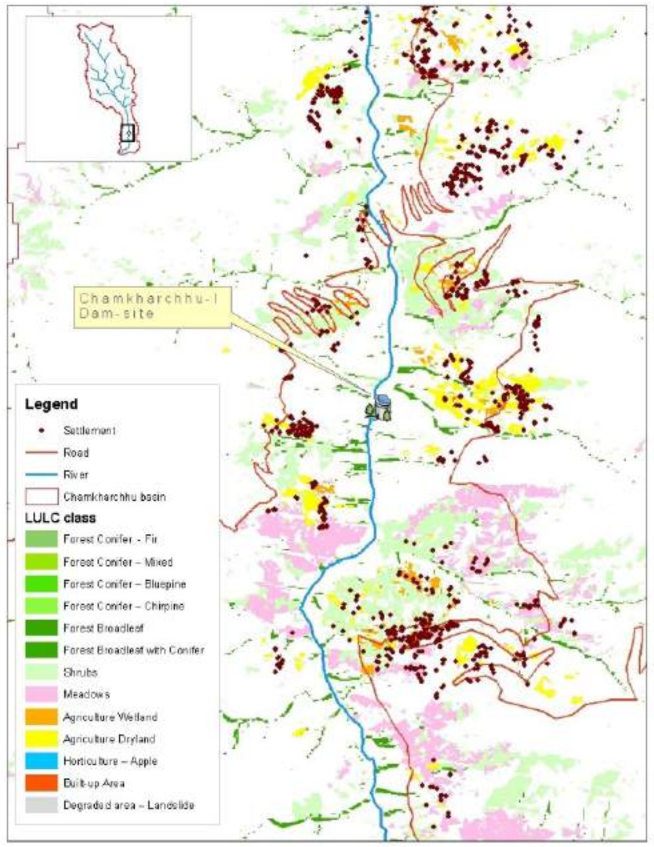
From the above map of the whole basin, the areas of high sediment export are seen to be in pockets which are predominantly in and around the around the catchment of the Chamkharchhu-I dam-site location (Fig 12). A few pockets of high sediment export are also seen above the dam site. (Figure 14). A closer view (Figure 14) shows that the main land-cover class responsible for high sediment export is grassland (GP) and shrub (SH) with some contribution from dryland agriculture (AK).

As expected, it is seen that the forested areas do not contribute much to high levels of sediment export in the basin, except for some forest areas which follow the drainage pattern; this could be the case, if the forest is right along a stream. There will be some erosion coming from forests, and if there's not much vegetation between the forest and the stream, it will still show up as sediment export. In the second map, Fig 12(b) the settlement pattern can be seen to be along the banks of the river where high sediment export can be seen. Also more settlement is also observed near the catchment of the Chamkharchhu – I dam site location.

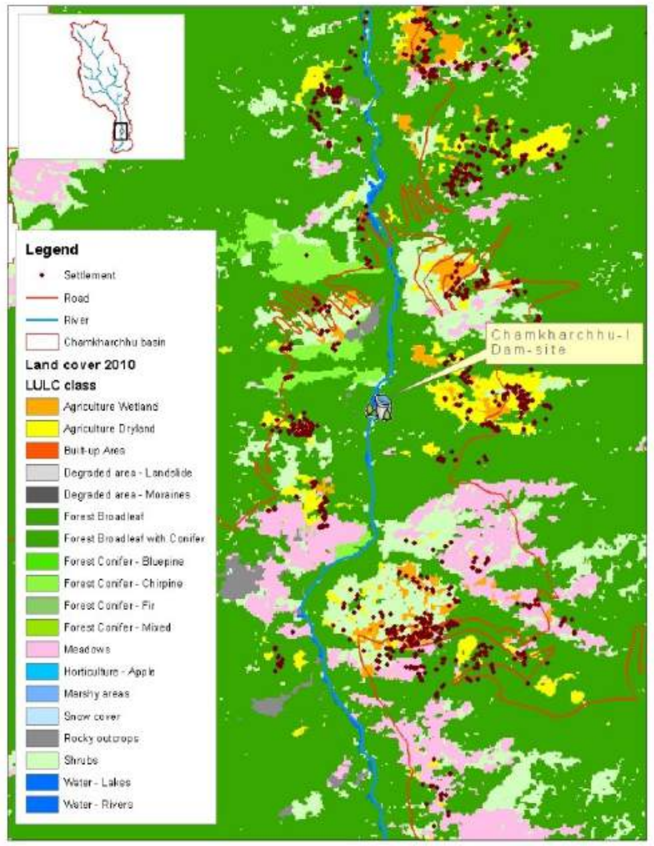
Sl.	Land Cover (Code)	Total annual sediment export (tons)	% of Total annual sediment export	Area (ha)	% of High sediment export area
1	Shrubs (SH)	361,271.00	69.14	6556.59	60.226
2	Meadows (GP)	76,683.60	14.67	2276.19	20.908
3	Agriculture Dryland (AK)	36,954.10	7.07	844.47	7.757
		474,908.70	**90.88**	**9,677.25**	**88.891**

Table 7. Top 3 sediment exporting land-cover types.

Figure 13. A closer view of the high sediment export areas.

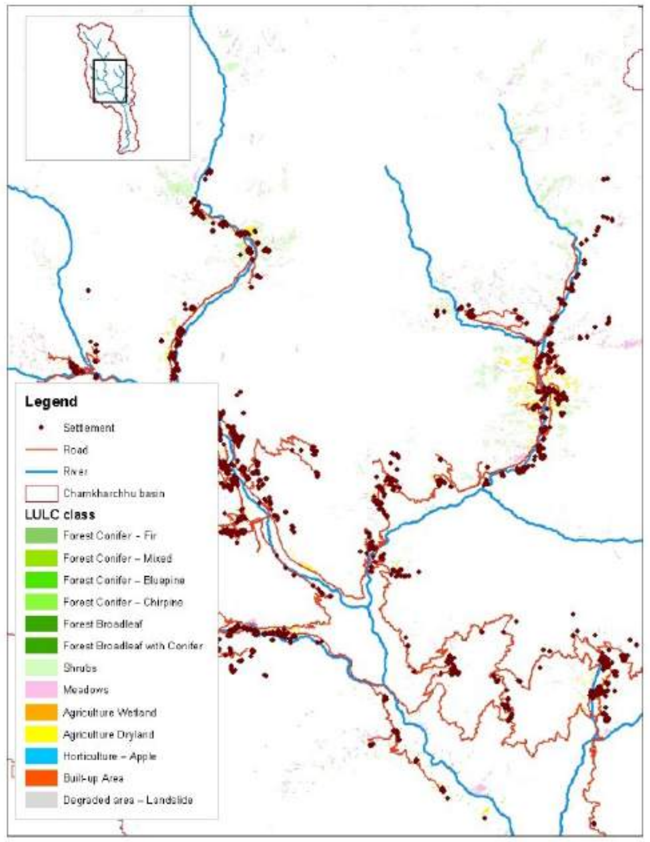


(a) High Sediment Export Areas near the Chamkharchhu-I dam-site with settlements and road layers.

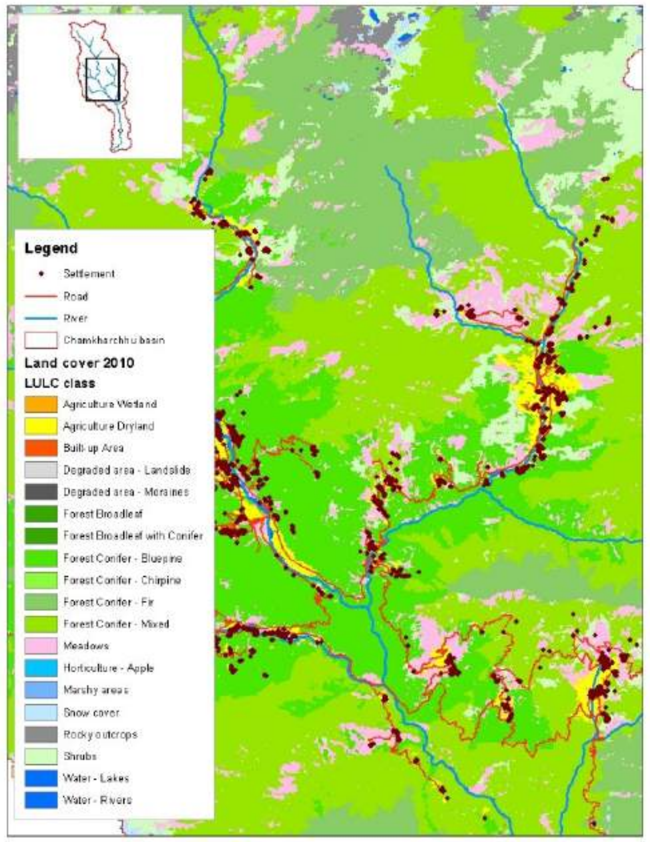


(b) Land cover map of the area near the Chamkharchhu-I dam-site with settlements and road layers.

Figure 13. A closer view of the high sediment export areas.



(c) High Sediment Export Areas upstream of the Chamkharchhu-I dam-site with settlements and road layers.



(d) Land cover map of the area upstream of the Chamkharchhu-I dam-site with settlements and road layers.

II) HIGH SEDIMENT RETENTION AREAS

Land Cover Code	Total annual sediment retention (tons)	% of Total annual sediment retention	Area (ha)	% of High sediment retention area
Forest Conifer - Fir (FCf)	6,284	1.13	565.56	5.85
Forest Conifer – Mixed (FCm)	34928	6.29	1571.76	16.24
Forest Conifer – Bluepine (FCb)	16044	2.89	481.32	4.97
Forest Conifer – Chirpine (FCc)	1664	0.30	37.44	0.39
Forest Broadleaf (FB)	242515	43.70	4365.27	45.11
Forest Broadleaf with Conifer (FBc)	24384	4.39	365.76	3.78
Shrubs (SH)	88,088	15.87	1132.56	11.71
Meadows (GP)	62024	11.18	697.77	7.21
Agriculture Wetland (AC)	4527	0.82	45.27	0.47
Agriculture Dryland (AK)	17870	3.22	160.83	1.66
Built-up Area (BA)	416	0.07	2.34	0.02
Snow cover (OS)	1692	0.31	8.46	0.09
Rocky outcrops (RR)	39881	7.19	188.91	1.95
Water – Lakes (WL)	110	0.02	0.45	0.005
Water – Rivers (WR)	7800	1.40	29.25	0.30
Degraded area – Landslide (DL)	6422	1.17	22.23	0.23
Degraded area – Moraine (DM)	252	0.05	0.81	0.008
	554,901.00	**100**	**9675.99**	

Table 8. Statistics for the high sediment retention index (>25 tonnes/pixel) areas in the Chamkharchhu basin.

The table shows the statistics of the areas which have a sediment retention index greater than 25 tons per pixel. There is 9,676 ha (3.06%) which falls in this category out of the total area of the basin (316,026 ha). This relatively small area contributes around 3.36 % of the total sediment retention index of the entire basin of 16.5

million tons per year. This shows that allowing the high sediment retention areas to degrade would not have as big an impact on the sediment retention index in comparison to the change in the sediment export amount when the high sediment export area is allowed to degrade. The sediment retention service provided by the landscape appears to be proportional to the area covered by a particular land-cover class.

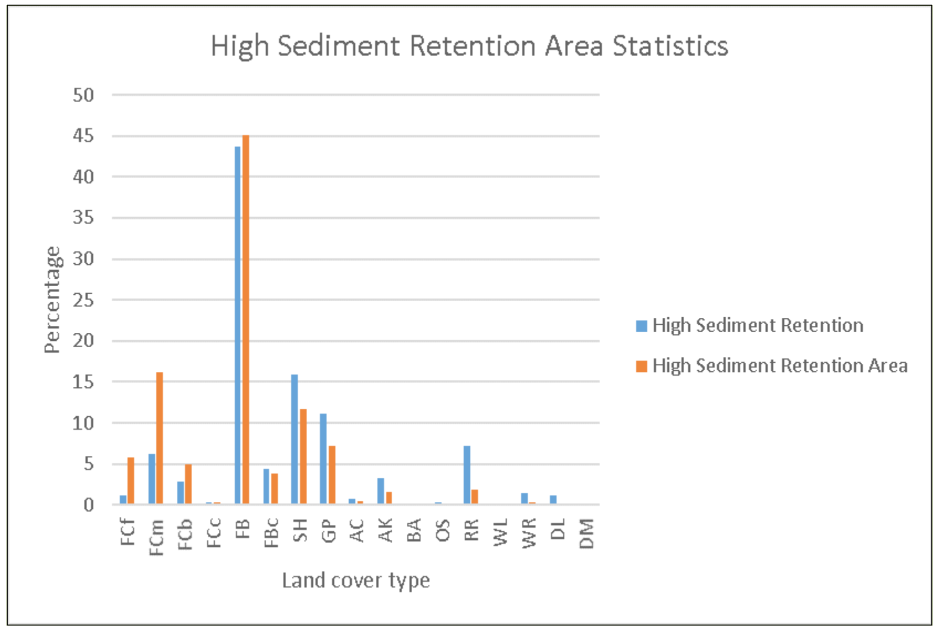
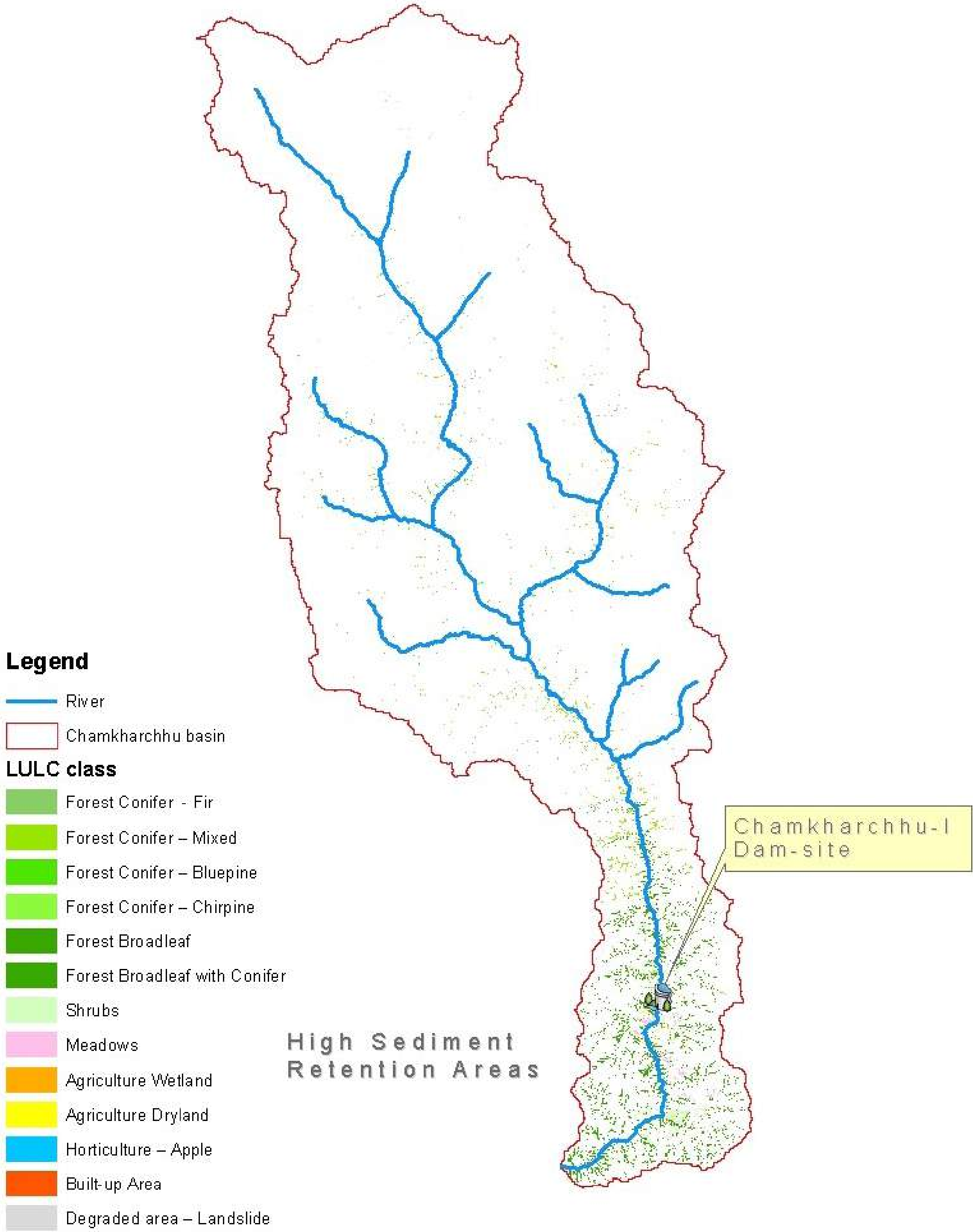


Figure 14. High sediment retention area statistics.

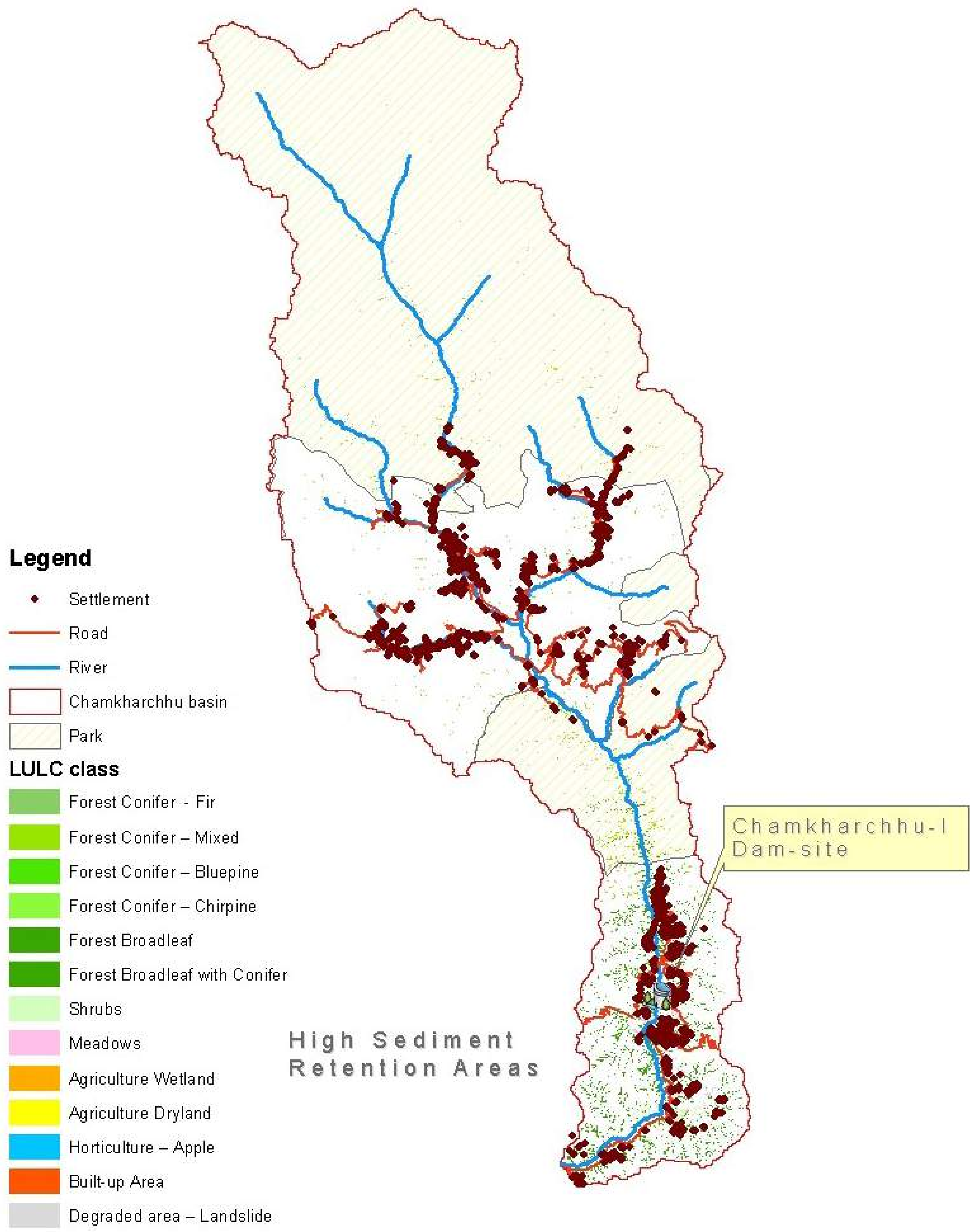
There is 9,675 ha of the basin which makes up the high sediment retention area within the basin. The land cover type with the highest contribution to sediment retention in the basin is the broadleaf forest (FB) class, which accounts for 43.70% of the total sediment retention in the basin; in terms of size, it covers 45.11% of the high sediment retaining areas of the basin.

Figure 15. Maps of high sediment retention areas.



(a) Map showing High Sediment Retention Areas in the basin

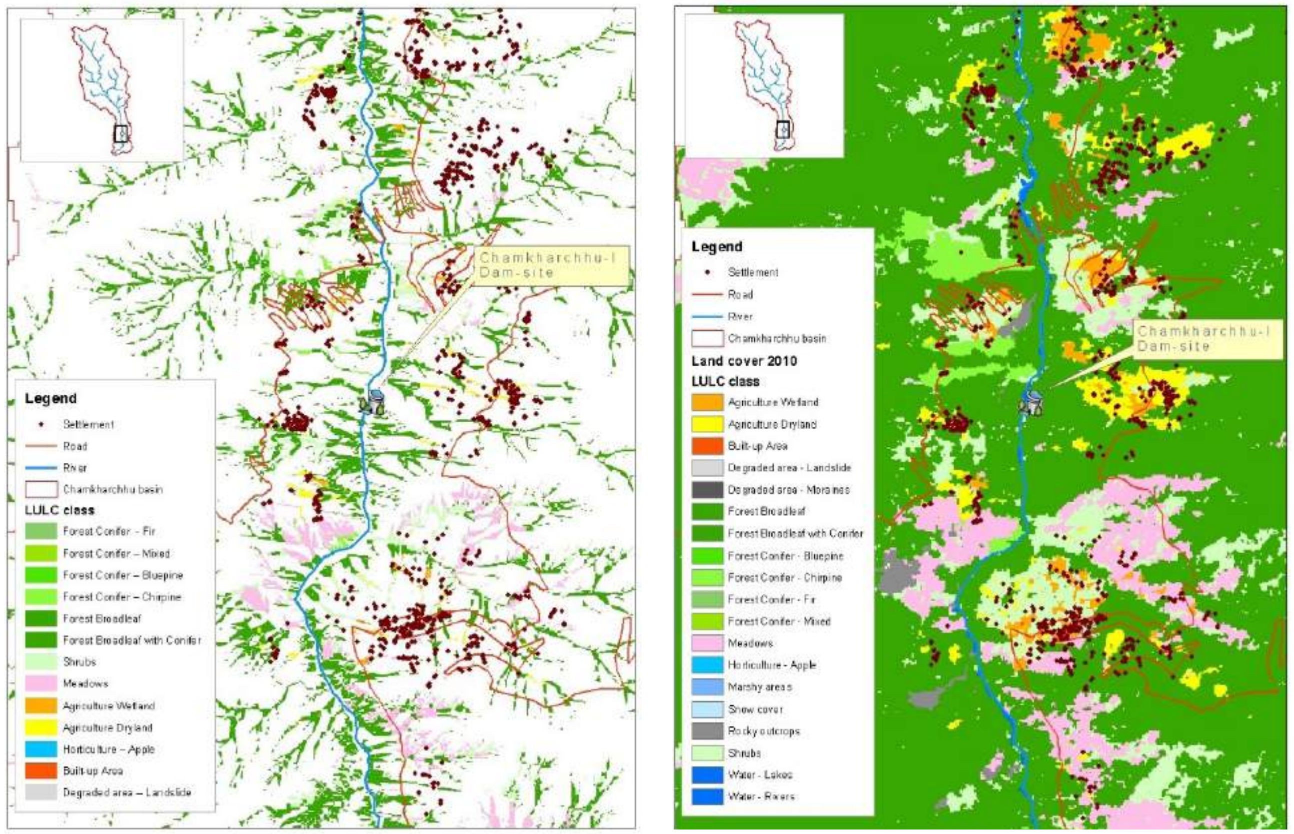
(b) Map showing High Sediment Retention Areas overlaid with road, settlements and Protected Area network



Sl.	Land Cover Code	Total annual sediment retention (tons)	% of Total annual sediment retention	Area (ha)	% of High sediment retention area
1	Forest Broadleaf (FB)	242515	43.70	4365.27	45.11
2	Shrubs (SH)	88,088	15.87	1132.56	11.71
3	Meadows (GP)	62024	11.18	697.77	7.21
		392,627	**70.75**	**6,195.6**	**64.03**

Table 9. Top 3 sediment retention land-cover types.

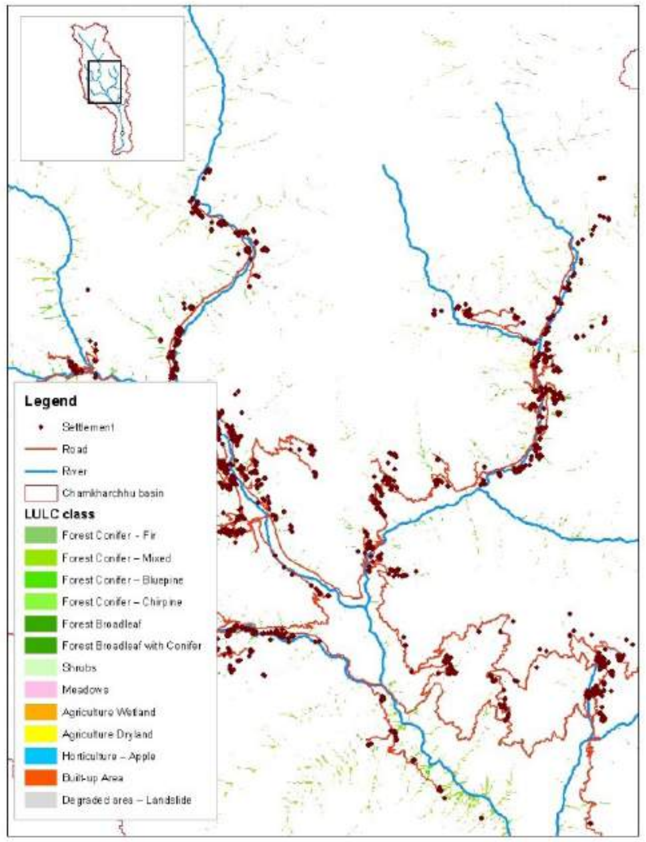
Figure 16. A closer view of the high sediment retention areas



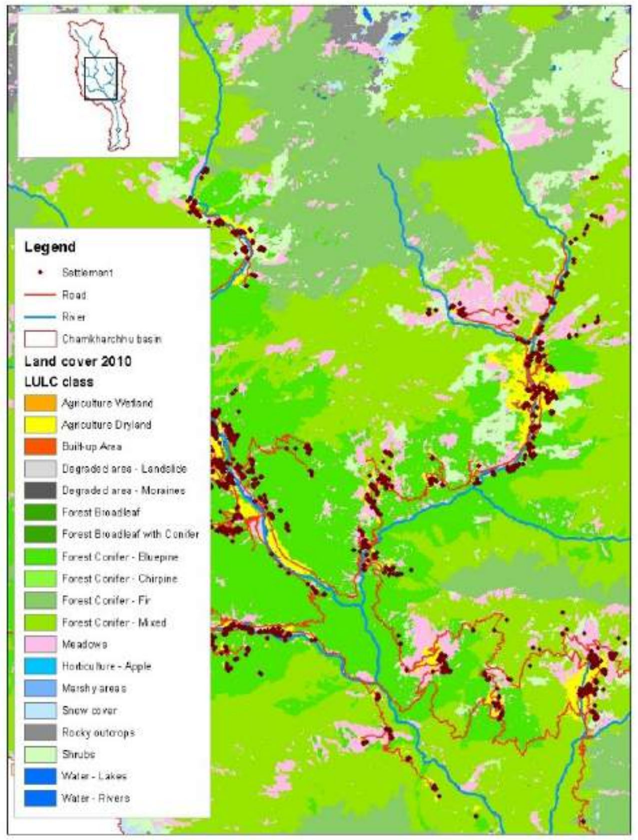
(a) High Sediment Retention Areas near the Chamkharchhu-I dam-site with settlements and road layers.

(b) Land cover map of the area near the Chamkharchhu-I dam-site with settlements and road layers.

Figure 16. A closer view of the high sediment retention areas



(c) High Sediment Retention Areas upstream of the Chamkharchhu-I dam-site with settlements and road layers.



(d) Land cover map of the area upstream of the Chamkharchhu-I dam-site with settlements and road layers.

SEDIMENT EXPORT AND RETENTION SERVICES

To see how land use change can impact sediment delivery, we will compare the sediment export and retention outputs from the SDR model under the baseline condition (current land cover), Restoration scenario and Degradation scenario, for both the watershed feeding Chamkharchhu-I dam, and the whole Chamkharchhu sub basin.

Sediment export is expressed in tonnes/year, and sediment retention should be taken as an index, not a precise measurement of the amount of sediment retained by the landscape. Because this model has not been calibrated, it is appropriate to look at percent change between scenarios. Area of interest (AOI) watershed sub-totals are given first, and then the maps showing the sediment export for the three scenarios are given below.

Area of Interest (AOI)	Baseline scenario	Restoration scenario			Degradation scenario		
	Amount (tonnes per year)	Amount (tonnes per year)	Percent change (%)	Absolute change (tonnes per year)	Amount (tonnes per year)	Percent change (%)	Absolute change (tonnes per year)
Sediment export for Whole basin	631,339.62	101,324.58	**-83.95**	-530,015.04	3,459,594.36	**447.97**	2,828,254.74
Sediment export for Dam basin	300,249.44	78,543.48	**-73.84**	-221,705.96	1,635,185.97	**444.61**	1,334,936.53
For Kurjey basin	113,072.47	33,211.40	-70.63	-79,861.07	251,893.01	122.77	138,820.54
Sediment retention index for Whole basin	82,938,210.75	83,471,276.94	**0.64**	533,066.19	80,113,007.17	**-3.41**	-2,825,203.58
Sediment retention index for Dam basin	47,774,413.49	47,999,218.32	**0.47**	224,804.83	46,442,575.84	**-2.79**	-1,331,837.65
For Kurjey basin	1,965,517.29	1,856,103.68	-5.57	-109,413.61	2,056,432.86	4.63	90,915.57

Table 10. SDR Model results

i. Restoration scenario:

The modelling results indicate that most of the highly erodible areas are concentrated in two specific areas highlighted in Figure 13. The presence of settlements (agricultural land use patterns) and road infrastructure could be some of the factors contributing to the erosion but this needs to be further validated. While we did not look at improved agricultural practices in this study, with correct targeting, investing in this type of activity could benefit both water quality and the fertility and productivity of farmers' land. Doing reforestation and improving land use in these highly erodible areas is predicted to reduce sediment reaching the outlet of the whole basin by 83.95% annually. The amount of sediment reaching the Chamkharchhu-I dam site is predicted to reduce by 73.84% annually. This is a significant value when taken over the lifetime of the hydropower plant, and can be used to determine how much of the basin might need to be restored in order to achieve a particular amount of reduction in sediment reaching the hydropower dam.

There is not much relative change in the sediment retention index for both the basin as a whole (+0.64%) and the basin above the Chamkharchhu-I dam site (+0.47%). However, in absolute terms, the sediment retention index increases by 533,066.19 tonnes per year for the whole basin and by 224,804.83 tonnes per year for the dam basin. This is a significant figure which corresponds closely with the sediment export change between the baseline and restoration scenario, of 530,015.04 tonnes per year for the whole basin, and 221,705.96 tonnes per year for the dam basin.The values of sediment export for the Kurjey basin (upstream of the sediment observation station located at Kurjey) is expected to decrease by 70.63% (or 79,861.07 tonnes) per year in the restoration scenario. In the degradation scenario it is expected to increase by 122.77% (or 138,820.54 tonnes) per year. Amount of sediment export delivery from InVEST model for the Kurjey sub-basin, which is upstream of the Kurjey sediment station location is equal to 113,072.47 tonnes (Baseline scenario in 2010) whereas the average observed annual sediment load is 151,653.98 tonnes per year (6 years' time-series average).

ii. Degradation scenario:

It provides a way of quantifying the marginal change in service that could result from preserving the existing landscape, and not letting it degrade. Results indicate that if the areas that are currently providing high levels of sediment retention service are allowed to degrade, there could be an increase in the amount of sediment reaching the outlet of the whole basin by 447.97%. The amount of sediment reaching the Chamkharchhu-I dam site is predicted to increase by 444.61%. Hence there is a huge change in the sediment export for both the areas of interest, if the degradation scenario were to occur. During earlier runs of the model using a slightly different set of biophysical coefficients (different from that given in Appendix 2), there was an increase in the sediment export by approximately 100%.

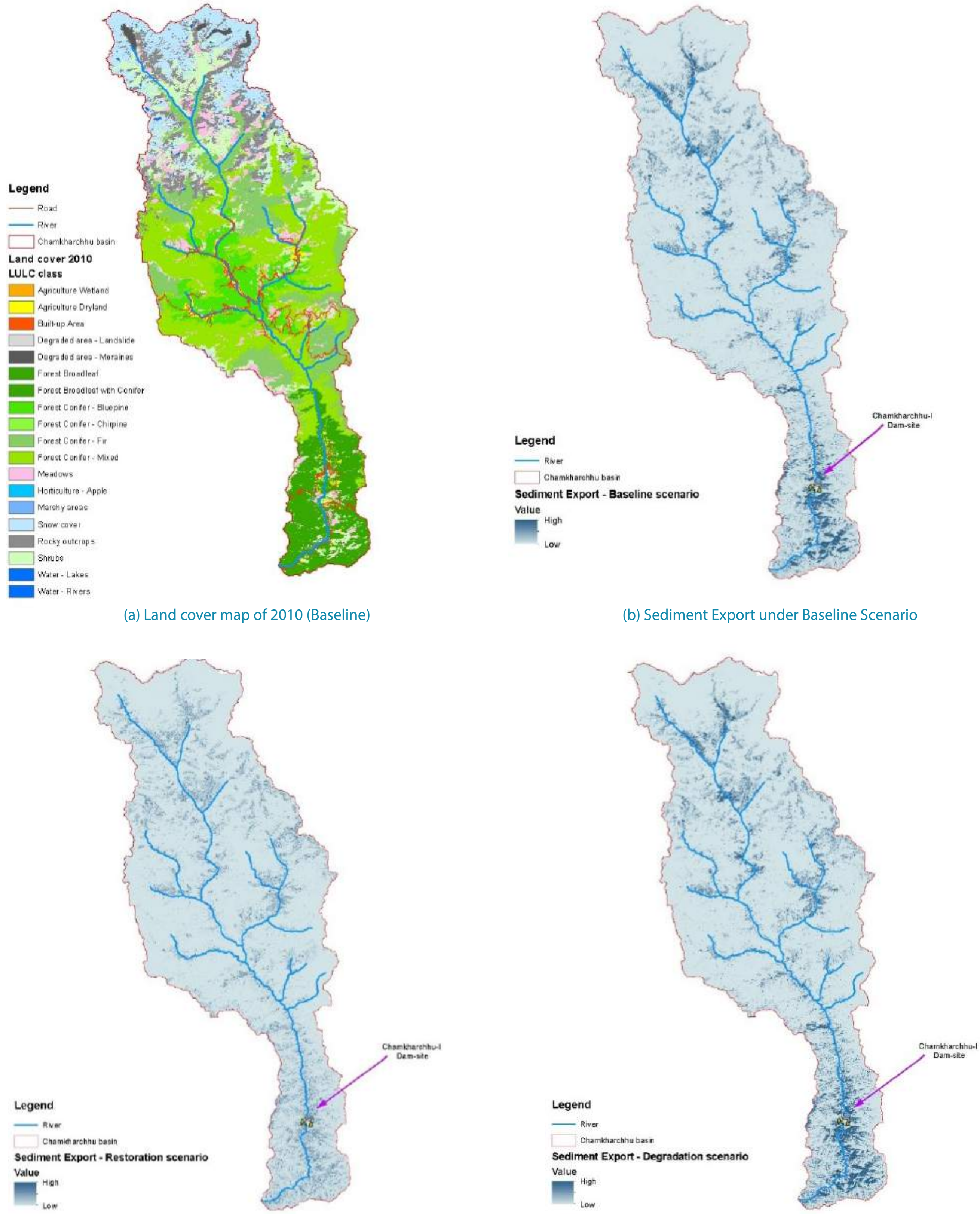
Hence, it appears that the model outputs are highly sensitive to the values of the coefficients used in the biophysical table, which are mostly global or regional values derived from literature sources. Availability of localized parameter values in the future, would further enhance confidence in the outputs of the model.

There are only marginal relative changes (less than -3.41%) in the sediment retention index in both the basins of interest if the degradation scenario were to occur. However, in absolute terms, the sediment retention index decreases by 2,825,203.58 tonnes per year for the whole basin and by 1,331,837.65 tonnes per year for the dam basin. This is a significant figure which corresponds closely with the sediment export change between the baseline and degradation scenario, of 2,828,254.74 tonnes per year for the whole basin, and 1,334,936.53 tonnes per year for the dam basin. Knowing the sites where particularly high levels of sediment retention service are currently being provided can help target conservation programs, to avoid degradation in the future. The values of sediment retention index for the Kurjey basin (upstream of the sediment observation station located at Kurjey) is expected to decrease by 5.57% (or 109,413.61 tonnes) per year in the restoration scenario. In the degradation scenario it is expected to increase by 4.63% (or 90,915.57tonnes) per year.

OUTPUT MAPS:

Spatial results from the SDR model show which areas in the basin are contributing different levels of sediment export and retention. These types of spatial results can help inform PES programs, providing additional guidance about where payments could be best spent to get the largest return on investment, when taken together with locally-important factors such as population centers, poverty alleviation and livelihoods. Appendix 3 contains additional maps illustrating the sediment export and retention in the areas of interest under the various scenarios.

Figure 17. Overall Sediment export of whole basin for the 3 scenarios.



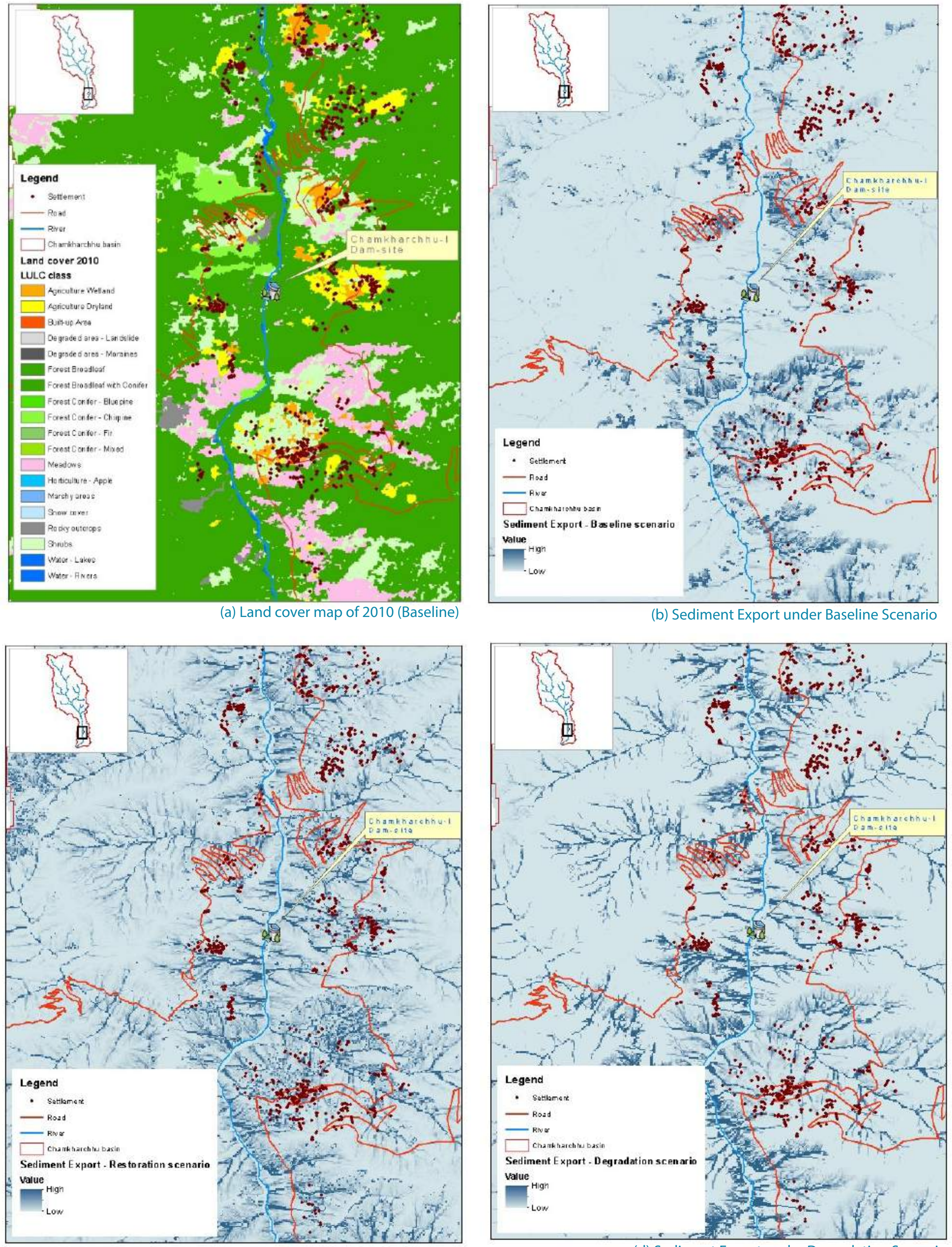
(a) Land cover map of 2010 (Baseline)

(b) Sediment Export under Baseline Scenario

(c) Sediment Export under Restoration Scenario

(d) Sediment Export under Degradation Scenario

Figure 18. Closer view of Sediment export near the dam-site under the 3 scenarios.



(a) Land cover map of 2010 (Baseline)

(b) Sediment Export under Baseline Scenario

(c) Sediment Export under Restoration Scenario

(d) Sediment Export under Degradation Scenario

HUMAN IMPACTS IN THE CHAMKHAR CHHU BASIN

Hemeroby index

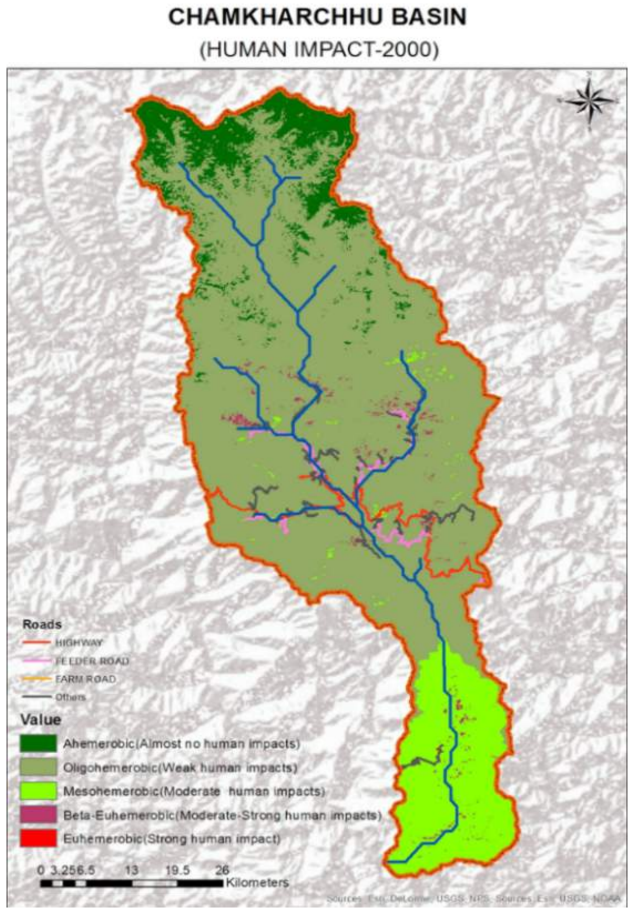
The concept of hemeroby was originally developed for measuring human impacts on flora and vegetation. The term hemeroby, which was introduced by the botanist Jalas (Jalas 1955), is derived from the Greek words hémeros (tamed, cultivated) and bíos (life). Later this concept was applied on whole ecosystems (Blume & Sukopp 1976: p. 83; Sukopp 1972: p. 113ff). According to this, hemeroby can be understood as an integrative measure of the impact of all human intervention on ecosystems (Kowarik 1988; Sukopp 1976: p. 21).

In analyzing current forms of land use in regard to human impact, hemeroby measures the distance between the current vegetation and a constructed final state of self-regulated vegetation in the complete absence of human intervention (so called potential natural vegetation (PNV)). Hence, it is as an inverse measure of the closeness to nature, if anthropogenic interventions are reversible (Kowarik 2006: p. 8). The concept of “closeness to nature”, in contrast, takes the original natural vegetation as a reference (Kowarik 2006: p. 4, see Fig. 1). While the original natural vegetation rep -resents the reconstructed vegetation which existed before the settlement of man, PNV describes the vegetation that would appear naturally if human impact is removed (Tüxen 1956).

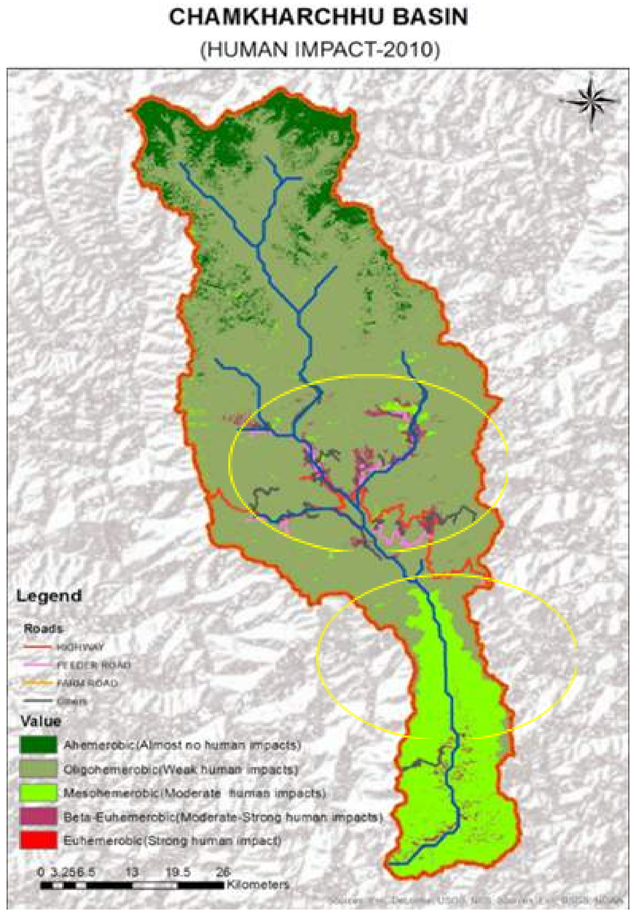
While reviewing the SDR modelling results from InVEST, most of the areas under high exports of sedimentation were observed where high settlements are seen (Population and Housing Census 2005). Thus to compare and analyze the extent of human impacts in the basin, a study conducted by the Living Himalayas Initiative in the Eastern Himalayas was used for the basin. Human impacts were compared across the time series of 2000 and 2010 based on the LULC maps.

The results of the Hemoroby index shows that the areas of concern are those areas that show the maximum change which in this case is seen as changes from weak human impact to moderate human impact and from moderate human impacts to high human impacts. These areas where maximum change has taken place overlap with the areas from the InVEST modelling results which show high sediment exports and retentions. Although more detailed studies would be needed to validate this, both these analyses give us some indication that areas of concern identified under the two different models are the same and would need further interventions.

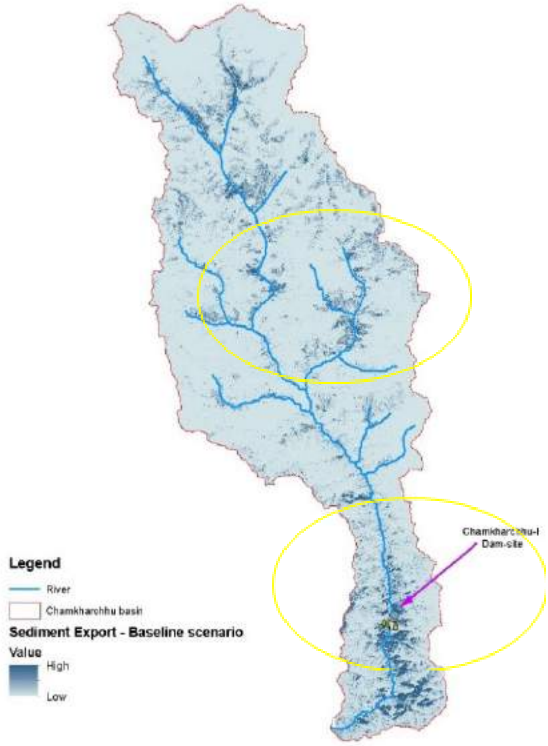
Figure 19. Priority areas identified from Hemeroby analysis and SDR scenarios (in yellow circles).



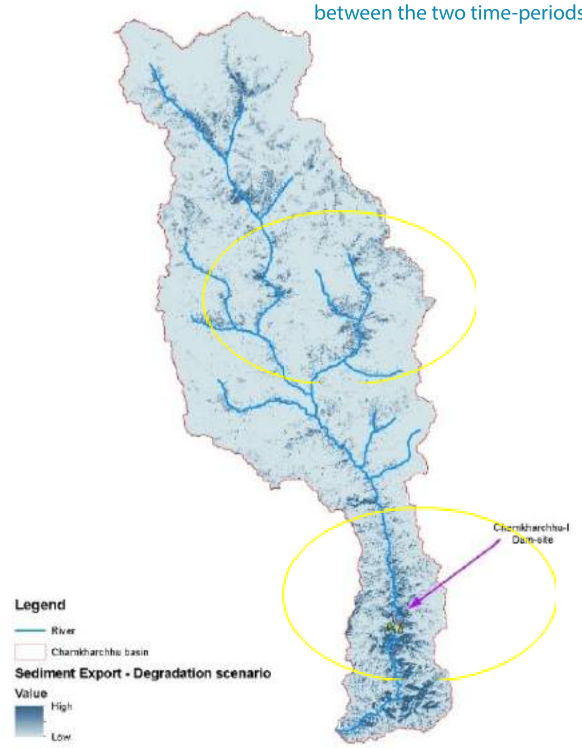
(a) Hemeroby index map of Chamkharchhu basin for the year 2000



(b) Hemeroby index map of Chamkharchhu basin for the year 2010. Area highlighted by yellow circles shows visible changes in the index between the two time-periods.



(c) Map showing Sediment export for the Baseline scenario taken to be the year 2010.



(d) Map showing Sediment export for the hypothetical Degradation scenario

8. DISCUSSIONS

Bhutan still has relatively high level of poverty in the country, more than 60% of the population lives in rural Bhutan and an estimated 12 percent of the country's total population live below the national poverty line. Impoverished communities if not provided with livelihood and income-generating opportunities are prone to engage in activities, such as illegal extraction of forest resources, that contribute to land degradation and increased sedimentations. On the other side, sustainable land management activities – for instance, agro-forestry, Improved agricultural practices – can help the poor to enhance their livelihoods and break away from the poverty cycle but also would contribute towards rehabilitation of degraded land. Furthermore, the poor are directly dependent on a wide range of natural resources and ecosystem services for their survival and well-being. Therefore, when soil erosion, forest degradation, and decline in biodiversity occur, it is generally the poor who are most severely affected. Further government effort to provide market access through improving rural transportation system pose another set of problem due to country's rugged topography. Building road and other market infrastructure development is costlier and trigger more severe soil erosion through landslides and other forms as compared to flatter landscapes.

The InVEST SDR modeling results for Chamkharchhu sub basin, appear to indicate that the sediment production processes in the Chamkharchhu sub basin are quite sensitive to changes in the land cover. In this study we talk about shrub lands and meadows and forested lands. This could also indicate that human interferences are directly related to the sediment production. Although a relatively small portion of the basin, (10886 ha, 3.45%) is identified to be responsible for a high proportion of the high sediment export areas (those having sediment export greater than 6.42 tons per ha per year), the areas show high sediment levels which would need to be addressed. This relatively small area out of the entire basin, contributes 522,555 tons of sediment export every year, which is almost 82.81 % of the total sediment export produced by the entire basin of 631,045.3 tons per year. With additional verification, the result from this model can be used in directing investments and interventions focused on increasing the sediment retention in this targeted areas (in this case it would mean rehabilitation of shrub land and meadows, with activities as community forests, agroforestry, sustainable land management to reduce soil loss and degradation).

The information could also be used to design PES programs targeted at watershed protection and sustainable land management practices to benefit communities and engage them in conservation related activities and at the same time help them improve their livelihoods. Such interventions will directly benefit the hydropower plants downstream and the economy in general but will also improve the livelihoods of the communities living in the basin. PES currently established in the country have been targeted only for smaller drinking water schemes and have benefitted smaller communities. However, the program can be expanded for larger watershed and land management programs to ensure both quality and quantity of water and targeting more beneficiaries.

Countries in Latin America have established Water funds similar to PES, but targeted for watershed management to gather investments for conservation activities. This has been successful and 16 water funds are already being implemented and many more are in the pipeline. These water funds have been established at large scale benefitting millions of people. RIOS (Resource Investment Optimization System), a specialized water fund tool developed by the Natural Capital Project, to design cost-effective investments in watershed services was used in Latin America to develop these water funds. RIOS uses InVEST software to estimate how much return is expected for commonly desired water benefits such as erosion control, water quality purification, and flood mitigation. With additional analysis on studies on water yield using InVEST, RIOS could be used to design similar water fund schemes for the ChamKharchhu basin as well as for the whole country in the near future.

Bhutan's hydropower sector currently accounts for up to 40 percent of government revenue and has the potential to grow even further. Currently about 5% of potential capacity is being harnessed, and vision in 2020 is to expand to 10,000 MW. 1% of revenue from hydropower plants are being marked in sustainable hydropower policy 2005 as plough back for conservation activities. Besides efficient hydropower generation, due to cost reduction in desilting there are other global benefits that can be derived from restoration activities e.g. carbon sequestration, biodiversity, and other forest ecosystems. These services could provide opportunities for Bhutan to derive payment for ecosystem services from the global community.

The InVEST results show that in these highly erodible areas is predicted to reduce sediment reaching the outlet of the whole basin by 83.95% annually if restoration is done. Watershed management, soil conservation activities such as agroforestry, terracing for improved agriculture can be some of the restoration activities that can be carried out to reduce the sediment load to the basin outlet.

Similarly, the amount of sediment reaching the Chamkharchhu-I dam site is predicted to reduce by 73.84% annually under the restoration scenario. This is a significant value when taken over the lifetime of the hydropower plant, and can be used to determine how much of the basin might need to be restored in order to achieve a particular amount of reduction in sediment reaching the hydropower dam. Taking this value and with further studies and economic valuation on the benefit of reducing the sedimentation vs maintenance of the turbines, PES programs can be designed for upstream watershed conservation activities.

Results indicate that if the areas that are currently providing high levels of sediment retention service are allowed to degrade, there could be an increase in the amount of sediment reaching the outlet of the whole basin by 447.97%. The amount of sediment reaching the Chamkharchhu-I dam site is predicted to increase by 444.61%. Hence there is a huge change in the sediment export for both the areas of interest, if the degradation scenario were to occur.

The sediment retention index does not show marked changes between the scenarios considered in the basin and appears to be less sensitive to changes in land cover than the sediment export parameter. The results (Table 10) indicate only relative marginal responses to both of the land cover change scenarios considered for the whole basin viz. restoration (+0.64%) and degradation (-3.41%). However, in absolute terms, the sediment retention index for the entire basin increases by 533,066.19 tonnes per year for the restoration scenario, and decreases by 2,825,203.58 tonnes per year in the degradation scenario. This is a significant figure which corresponds closely with the sediment export change between the baseline and restoration scenario of 530,015.04 tonnes per year; and baseline and degradation scenario of 2,828,254.74 tonnes per year and helps validate the sediment export figures. The change of sediment retention index in the degradation scenario is almost 6 times the change in the restoration scenario because of the specific targeting of high sediment retention areas in order to construct the degradation scenario.

CONSTRAINTS

Data and model limitations exist as there are still gaps in scientific understanding of watershed processes, gaps in basic data related to water quality and flows, and gaps in the capabilities of simulation modeling and decision support systems. In this modelling exercise, global data on soils were used due to unavailability of local data. Adequate information on rainfall, snow, climate and land use were also some limitations faced for this analysis.

The InVEST SDR model only considers the sheet erosion component. Therefore, the erosion components due channel, streambank and mass erosions have not been accounted for. These sources of erosion may be important in the context of Bhutan, due to the rugged topography, unstable slopes and the heightened construction of basic access roads (so called "farm roads"). These roads are not very well designed and engineered, in fact many are not passable during the rainy season due to inadequate drainage systems and lack of proper soling (asphalt).

The values used in the biophysical table also have high levels of uncertainty since they are derived from the literature for other regions of the world. As given in Appendix 2, a variety of sources were used. The values used or derived in studies conducted in the region, especially India were mainly used. However, for some land cover types, the other sources were used as well.

Since this is a small project to demonstrate proof of concept only, there were time and resource constraints. Therefore, the scenarios constructed were also kept simple to facilitate derivation of a first order estimate. Future assessments could use more realistic future scenarios which could be constructed after consultations with the stakeholders in the basin and other concerned partners.

Use of other models like SWAT in conjunction with InVEST would help to validate the modeling results, and more complex models like SWAT would provide more detailed information (such as results given on a daily time-step) that could be valuable to hydropower facilities. Doing calibration of the models, and improved parameterization of the model with more accurate parameter values, along with a better understanding of field conditions existing in the whole basin will help provide more precise results and better interpretation of the model outputs.

Furthermore, there may be some limitations while comparing the results over the different time series while using the LULC maps since the methodology involved in the development of the maps may vary between the time series.

CONCLUSIONS AND NEXT STEPS

The accuracy of all modeling is further improved by calibrating the model results to observed data. In the case of the SDR model, this requires having long-term annual sediment load observations at the outlet of the basin. SDR provides several parameters that can be used to calibrate the results to observed data, where the result will be more accurate absolute values of sediment export, and an understanding of how well the model represents the processes in the basin itself. When comparing the results with observed data, it is important to know that SDR only models sheet erosion, so it will not represent all of the erosion that is produced in the basin (by landslides, stream channels, etc.).

Potential future work could incorporate sub-annual hydrologic models, such as SWAT, along with economic data on equipment and facilities maintenance costs and the price of hydropower, in order to evaluate returns on investment at a temporal scale appropriate for the run-of-river hydropower facilities common in Bhutan. In the case of ES impacting hydropower production, to do robust economic valuation requires accurate, calibrated modeling, and input from hydropower producers regarding cost of increased maintenance, shutdown days, cost of power produced, etc.

The valuation could be expressed in terms of the economic impact of improved ecosystem services on hydropower production during low flow season, as well as avoided costs for damage due to excess sediment. Such an analysis could provide a quantitative estimate of ecosystem services value for hydropower that can directly inform the development of natural capital accounts (WAVES, 2015).

The process must be taken forward with close involvement of relevant sectoral partners especially for calibration, economic valuation and PES development phases. These stakeholders include: the hydropower sector, watershed management agency, National Environment Commission (NEC), and the National planning agency (GNHC). These later studies may consider how to perform economic valuation of ES for hydropower, do more robust targeting of PES, and create methods for incorporating ES into national planning. Further the results of the SDR model clearly indicates two possible areas of interest where interventions can be targeted, one being the catchment around the planned hydropower and the other upstream of the basin. The reasons for the high sedimentation could be attributed to the existing land use cover as well as the impacts of settlements and infrastructure development in that area.

However, this will have to be further validated with physical verification as well as stakeholder consultations. Targeted interventions such as, sustainable land management practices, watershed protection activities could be introduced in these areas with communities implementing them. The already high sedimentation, would be a concern for the upcoming hydropower plant and the additional infrastructure development could lead to

increased sedimentation load. PES programs can be designed focused around soil and water conservation once more detailed study on seasonal water yield as well as some physical verification in the ground level has been done.
Some activities for PES programs as well as for restoration and conservation could include

a. Reforestation/Afforestation programs in degraded lands/Shrub lands
b. Sustainable land management in steep agricultural fields as well as in fallow lands.
c. Promote cash crops for increased income and sustainable land management.
d. Protection of watersheds through monitored grazing practices, reduced felling
e. Improved rangeland/grazing in pastures and meadows.

The current study in Chamkharchhu sub basin has already provided us a lot of information on the ecosystem services related to Sediment Delivery and retention. With further studies, stakeholder consultation and field work, we could use this information to plan soil and water conservation activities in the targeted areas. If such studies are up scaled to a national level, the information would be pertinent for policy interventions required for conservation as well socio economic development plans.

WWF and Natural Capital project has worked with countries like Myanmar and Mozambique in conducting the Natural Capital valuation for the whole country to take stock of their natural resources. Myanmar is now using this information towards development of a green economy approach for sustainable use of natural resources integrated into the country's plans and policies. Indonesia and Mozambique has also embarked towards spatial planning for some of their critical landscapes to protect key species and landscapes and for watershed protection. The Natural Capital valuation is also used for development of PES mechanisms for watershed protection in Himachal Pradesh in India, Nepal, Africa etc.

Natural Capital valuation can also be used for spatial planning, Strategic Environment Planning, designing payment for ecosystem services, understand the development impacts and preparation of development plans for selected areas focused on targeted interventions. These can be integrated to develop a green economy plan.

Conservation is a high priority in Bhutan but increasing developmental activities and demand for natural resources is threatening the country's rich bio-diversity. It has therefore become essential to educate people on how valuable our natural capital is and the essential services it provides.

This valuation of ecosystem services will go a long way in developing and managing the natural capital of Bhutan as it will work with all stakeholders for sustainable use of natural capital which is very important. Accounting for Ecosystem services reveals the diverse benefits provided by nature and clarifies tradeoffs between alternative development scenarios and helps people make more informed decisions about how to use land and water resource. Although the existing polices on conservation have played a crucial part in maintaining our forest cover, this valuation exercise can add value for development of strategic environmental plans, spatial planning and also towards the development of a green economy plan for the whole country. This would be imperative for a small developing country like Bhutan with rich biodiversity to balance sustainable use of natural resources and growing economy.

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APPENDIX 1: LAND COVER CLASSIFICATION SYSTEM OF NLCM, 2010

The classification system used in the National Land Cover Map of 2010 has eleven main classes with fifteen sub-classes. The sub-classes are further divided into categories for more detailed mapping. Table 1 lists the various land cover classes, which are further described below.

Table 1: The Land Cover Classes

CLASS	SUB-CLASS	CATEGORY	SYMBOL
FORESTS	Conifer Forest(FC)	Fir Forest	FCf
		Mixed Conifer Forest	FCm
		Blue Pine Forest	FCb
		Chir Pine Forest	FCc
	Broadleaf Forest (FB)	Broadleaf Forest	FB
		Broadleaf & Conifer Forest	FBc
SHRUBS	-		SH
MEADOWS	-		GP
CULTIVATED AGRICULTURE LAND	Chhuzhing Land		AC
	Kamzhing Land		AK
	Horticulture Land	Apple Orchard	HA
		Citrus Orchard	HC
		Areca nut Plantation	HAa
		Cardamom Plantation	HCo
		Others	HO

Agriculture Kamzhing (AK)	10	0.18	Dabral, 2008	1	Dabral, 2008
Apple (HA)	11	0.8	Panagos, 2015	1	Dabral, 2008
Built-up Area (BA)	16	0.25	Teh, Soo Huey, 2011	1	Dabral, 2008
Snow (OS)	18	0.001	WAVES, 2015	1	Dabral, 2008
Rock out crops (RR)	19	0	Panagos, 2015	1	Dabral, 2008
Lake (WR)	22	0	Dabral, 2008	0	Dabral, 2008
Reservior (WRe)	23	0	Dabral, 2008	0	Dabral, 2008
Rivers (WR)	24	0	Dabral, 2008	0	Dabral, 2008
Marshey area (MA)	25	0.001	Verma, 2015	1	Dabral, 2008
Degraded Landslide (DL)	26	0.5	WAVES, 2015	1	Dabral, 2008
Moraine (DM)	28	0.001	WAVES, 2015	1	Dabral, 2008

Description of the Land Cover Classes

1. FORESTS

The "Forests" refer to a minimum area of land of 0.05-1.0 hectare with tree cover (or equivalent stocking level) of more than 10-30 percent with trees with the potential to reach a minimum height of 2-5 meters at maturity in situ (FRDD, DoFPS). The "Forests" is divided into two sub-classes which are then further classified into six categories.

1.1 Coniferous Forest (FC)

The Coniferous Forest is broadly sub-divided in four categories i.e. Fir Forest; Mixed Coniferous Forest; Blue Pine Forest and Chir Pine Forest.

1. Fir Forest (FCf)

The "Fir Forest" consists either of largely pure stands of Abies densa, or few stands of other species such as Junipers, taxus and larch. This category occurs mostly above 3000m asl.

2. Mixed Conifer Forest (FCm)

The "Mixed Conifer Forest" includes mixed stands of spruce, hemlock, juniper, fir, larch, taxus and blue pine. Some broadleaf inclusions are also common particularly oaks, rhododendron, maple and birch. It usually occurs between 2500m and 3500m asl.

3. Blue Pine Forest (FCb)

The "Blue Pine Forest" consists of pure or dominant stands of blue pine, usually at altitudes between 1500m and 3200m asl. Smaller areas of mixed conifers and broadleaf forest may occur interspersed in the blue pine mapping unit, but because of their small areas they are often left unrecorded.

4. Chir Pine Forest (FCc)

The "Chir Pine Forest" consists normally of pure stands of chir pine, usually at altitudes between 700m and 2000m asl at relatively dry areas. However, in depressions and water courses, broadleaf might occur but these areas are usually small and included within the chir pine mapping unit.

1.2 Broadleaf Forest (FB)

The "Broadleaf Forest" is divided into two categories i.e. Broadleaf Forest and Broadleaf mixed with Confers. Broadleaf Forest consists of pure broadleaf trees and may occur up to 4000m asl, but are more commonly found below 3000m asl.

1. Broadleaf Forest (FB)

The "Broadleaf Forest" consists of dominantly broadleaf trees.

2. Broadleaf mixed with Conifer (FBc)

The "Broadleaf mixed with Conifer" consists of dominantly broadleaf trees with few stands of blue pine and chir pine.

2. SHRUBS

Shrubs are woody perennial plants with persistent and woody stems and without any defined main stem. It includes natural scrubland at high elevations consisting of dwarf rhododendron, dwarf bamboo etc., as well as human-induced scrubland such as abandoned agricultural fields with overgrown bushes and other young regeneration in other disturbed areas.

3. MEADOWS

"Meadows" include any areas dominated by grasses without or with few scattered trees or shrubs on it. It occurs at all elevations, but is relatively more common at higher elevations.

4. CULTIVATED AGRICULTURAL LAND

The cultivated agricultural land includes only those agricultural land that are cultivated at the time of land cover assessment. It is divided into three main sub-classes i.e. Chhuzhing Land; Kamzhing Land and Horticulture Land.

4.1 Chhuzhing Land (AC)
The "Chhuzhing Land" refers to terraced fields that are usually used for irrigated paddy cultivation. The terraced paddy fields are usually inundated some part of the year through retention of rainwater or through irrigation.

4.2 Kamzhing Land (AK)
The "Kamzhing Land" refers to cultivated rain-fed areas (dry land). Some Kamzhing lands have certain level of land shaping.

4.3 Horticulture Land
The "Horticulture Land" includes orchards and plantation of cash crops. It is further divided into five sub-classes i.e. Apple orchard; Citrus orchard; Areca nut plantation; Cardamom plantations and Others.

1. Apple Orchard (HA)
This category includes areas under apple trees and occurs usually between 1800m to 2600m asl.

2. Citrus Orchard (HC)
This category includes areas under citrus (orange) trees. It is normally located between 400m to 1400m asl.

3. Areca nut Plantation (HAa)
This category includes areas under Areca nut plantation and is mostly situated below 400m asl.

4. Cardamom Plantation (HCo)
This category includes cardamom plantation in open areas.

5. Others(HO)
This category includes areas under mixed fruit trees or mixed plantation of different horticulture crops.

5. BUILT UP AREAS (BA)
This category describes built-up areas where artificial constructions cover the land with an impervious (e.g. concrete, CGI sheet, thatch) surface. It includes airport, rural settlements, urban areas, schools & institutes, industrial areas, hospital premises, sewage treatment plant, sports and leisure facilities and roads.

6. NON-BUILT UP AREAS (NB)
This class is defined by absence of the original (semi-) natural cover mainly due to anthropogenic factors. It includes waste dump sites, mines, stone quarries and other extraction sites.

7. SNOW COVER (OS)
This class includes both perpetual and seasonal snow cover. In general, it occurs above 3500m asl.

8. BARE AREAS
This class describes areas with natural or human induced land cover with less than 4% vegetation cover. It is further sub-divided into three categories i.e. Rock Outcrops; Scree and Bare Soils.

8.1 Rock Outcrops (RR)
This sub-class includes natural cliffs and rocky areas with less than 4% vegetation cover.

8.2 Scree (RS)
This sub-class includes areas with deposits of small to large, very hard and angular gravels and stones from the mountain tops mostly due to extreme physical weathering (freeze and thaw) of rocks. It is generally located above the natural tree line.

8.3 Bare Soils (BS)
This sub-class includes non-agricultural areas (marginal land) with very limited vegetation and rock outcrops (<4%) either due to natural processes (surface erosion) or human interventions (e.g. overgrazing, forest fire, etc.).

9. WATERBODIES
This class includes both natural and artificially created water bodies. It is further divided into three categories i.e. Lakes, Reservoirs and Rivers.

9.1 Lake (WL)
This sub-class includes perennial and natural water reservoirs such as glacial lakes.

9.2 Reservoirs (WRe)

This sub-class includes storage of water artificially through construction of dams e.g. Hydropower dam.

9.3 River (WR)
This sub-class includes perennial flow of water and the river bed.

10. MARSHY AREAS (MA)
The class includes areas that are either permanently or semi-permanently waterlogged (poorly drained) throughout or some part of the year. It includes swamps and marshy areas. It occurs mostly in depression areas (valley floors) where there is no proper outlet to drain out the excess water.

11. DEGRADED AREAS
This class includes areas that are permanently or semi-permanently degraded either due to natural processes or human interventions. It is further sub-divided into four sub-classes i.e. Landslides; Gullies; Ravine and Moraines.

11.1 Landslides (DL)
This sub-class includes mass movement (wasting) of soils debris due to gravitational force triggered by other factors such as rainfall and earthquakes.

11.2 Gullies (DG)
This sub-class includes huge channels (> 1m wide) formed through removal of soil and other materials by concentrated overland flow. It is an advanced stage of rill erosion and it cannot be obliterate through normal tillage operations.

11.3 Ravine (DR)
This sub-class includes areas with advanced stage of gully erosion (> 10m wide) and landslides.

11.4 Moraines (DM)
This sub-class includes areas with glacial deposits and they are mostly found in high altitude areas.

APPENDIX 2: SOURCES OF MODEL PARAMETERS USED IN THE BIOPHYSICAL TABLE

The parameters required for SDR are a unitless crop-management factor (usle_c) and support practice factor (usle_p) used in the USLE equation. The cropping factor refers to soil loss under a particular crop and management system, vs fallow/tilled land. The practice factor refers to soil loss under practices that are done specifically to reduce runoff and erosion, vs straight-row farming up and down the slope.

Land-use & Land-cover (LULC code)	Lucode used	Parameter: usle_c	Source:	Parameter: usle_p	Source:
Fir (FCf)	1	0.004	Dabral, 2008	1	Dabral, 2008
Mixed conifer (FCm)	2	0.004	Dabral, 2008	1	Dabral, 2008
Bluepine (FCb)	3	0.004	Dabral, 2008	1	Dabral, 2008
Chirpine (FCc)	4	0.004	Dabral, 2008	1	Dabral, 2008
Broaddleaf (FB)	5	0.004	Dabral, 2008	1	Dabral, 2008
Broadleaf with Conifer (FBc)	6	0.004	Dabral, 2008	1	Dabral, 2008
Shrubs (SH)	7	0.22	WAVES, 2015	1	Dabral, 2008
Pasture (GP)	8	0.1	Panagos, 2015	1	Dabral, 2008
Agriculture Chhuzhing (AC)	9	0.28	Dabral, 2008	0.28	Dabral, 2008
Agriculture Kamzhing (AK)	10	0.18	Dabral, 2008	1	Dabral, 2008
Apple (HA)	11	0.8	Panagos, 2015	1	Dabral, 2008
Built-up Area (BA)	16	0.25	Teh, Soo Huey, 2011	1	Dabral, 2008
Snow (OS)	18	0.001	WAVES, 2015	1	Dabral, 2008
Rock out crops (RR)	19	0	Panagos, 2015	1	Dabral, 2008
Lake (WR)	22	0	Dabral, 2008	0	Dabral, 2008
Reservior (WRe)	23	0	Dabral, 2008	0	Dabral, 2008
Rivers (WR)	24	0	Dabral, 2008	0	Dabral, 2008
Marshey area (MA)	25	0.001	Verma, 2015	1	Dabral, 2008
Degraded Landslide (DL)	26	0.5	WAVES, 2015	1	Dabral, 2008
Moraine (DM)	28	0.001	WAVES, 2015	1	Dabral, 2008

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APPENDIX 3: OUTPUT MAPS

Figure 20. Sediment export under baseline scenario (2010)

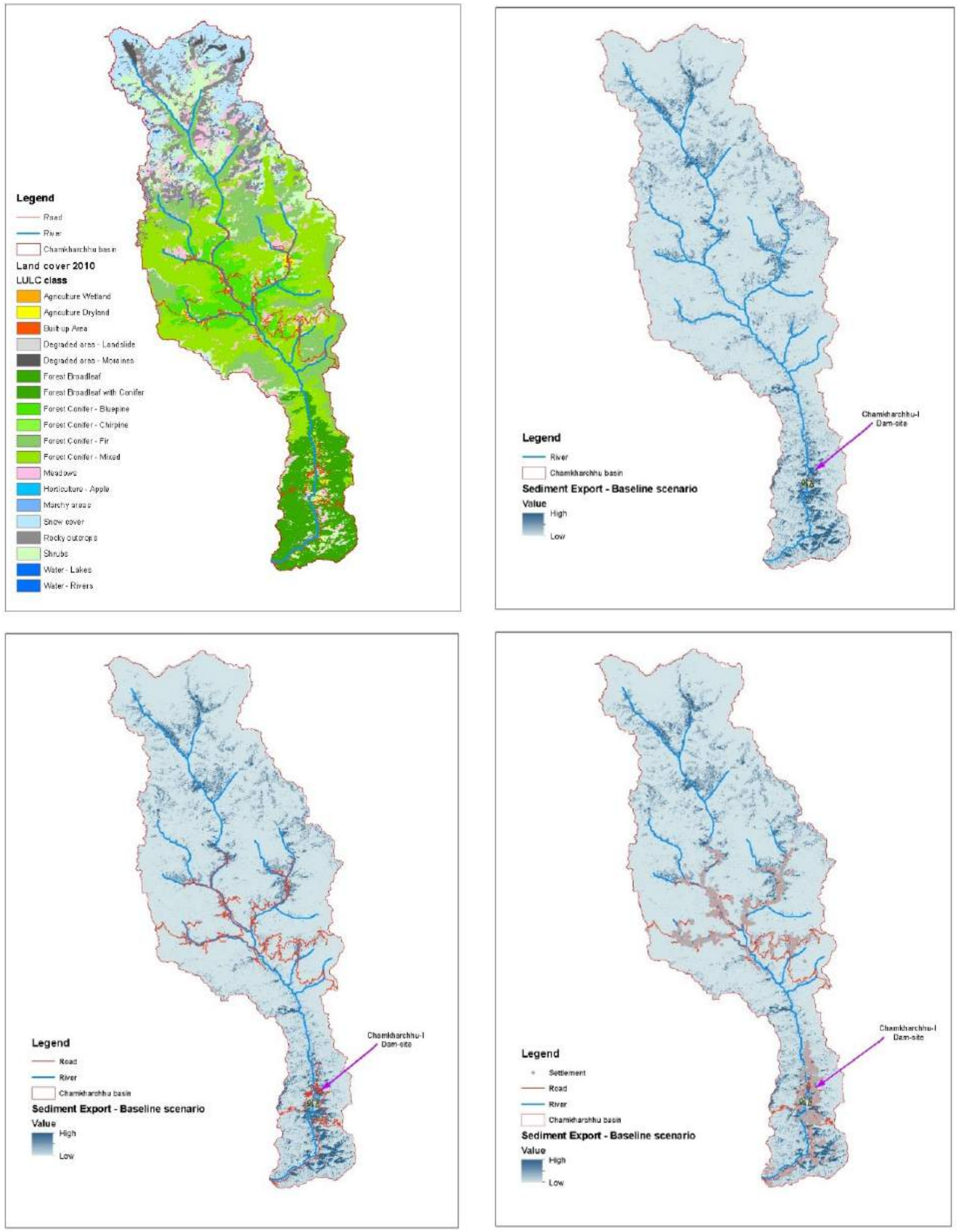

Figure 21. Closer view of baseline scenario.

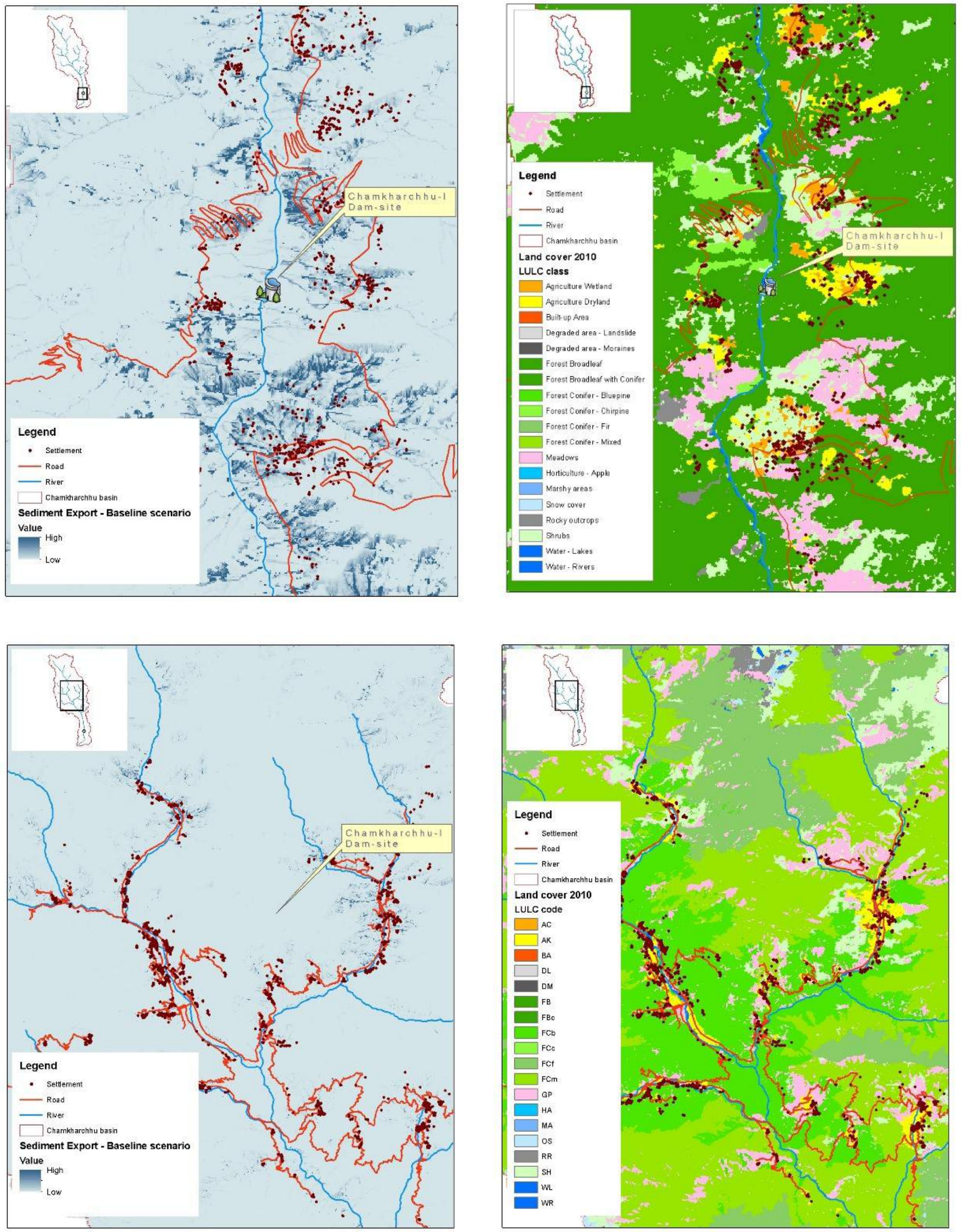

Figure 22. Sediment export under restoration scenario.

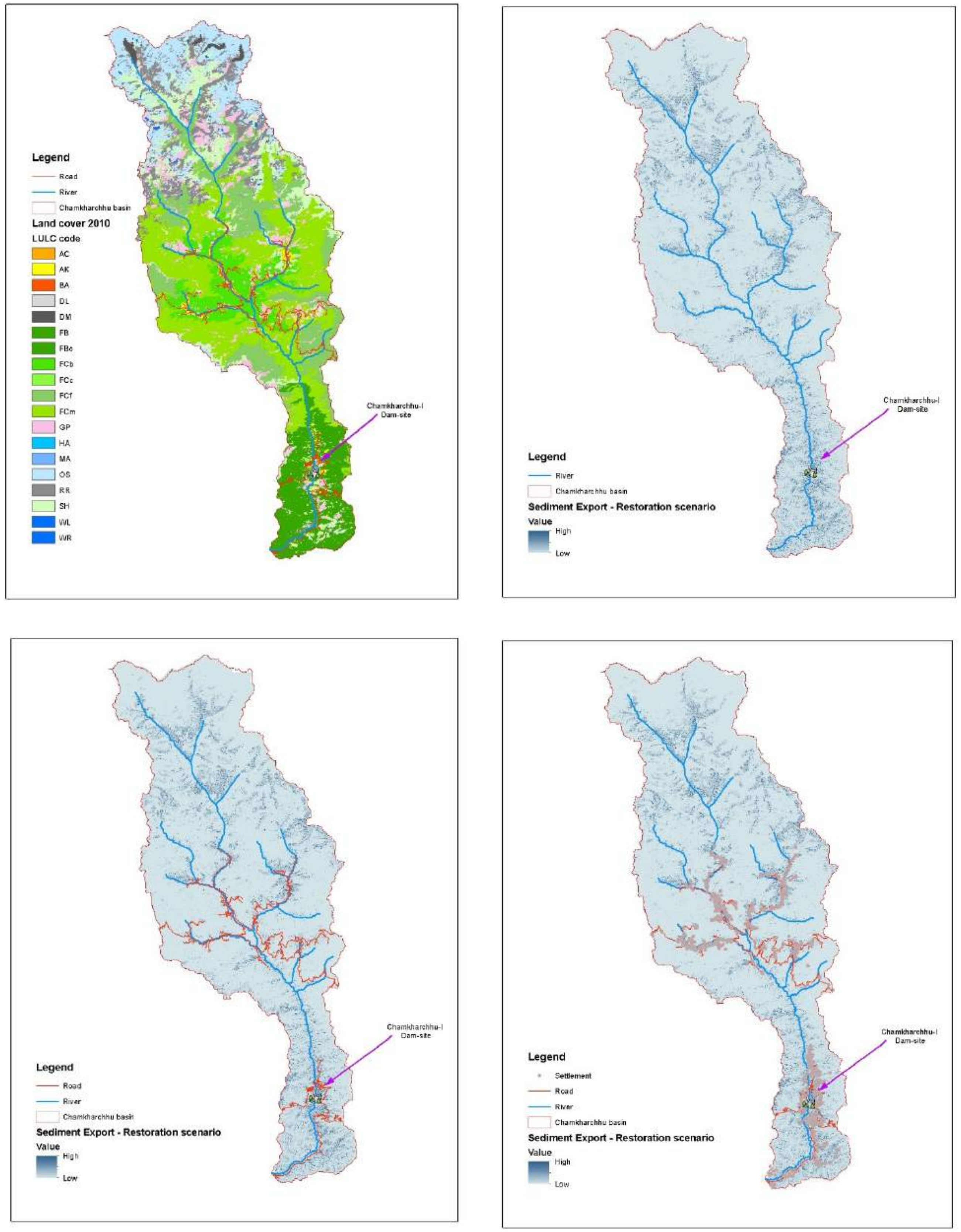

Figure 23. Closer view of restoration scenario.

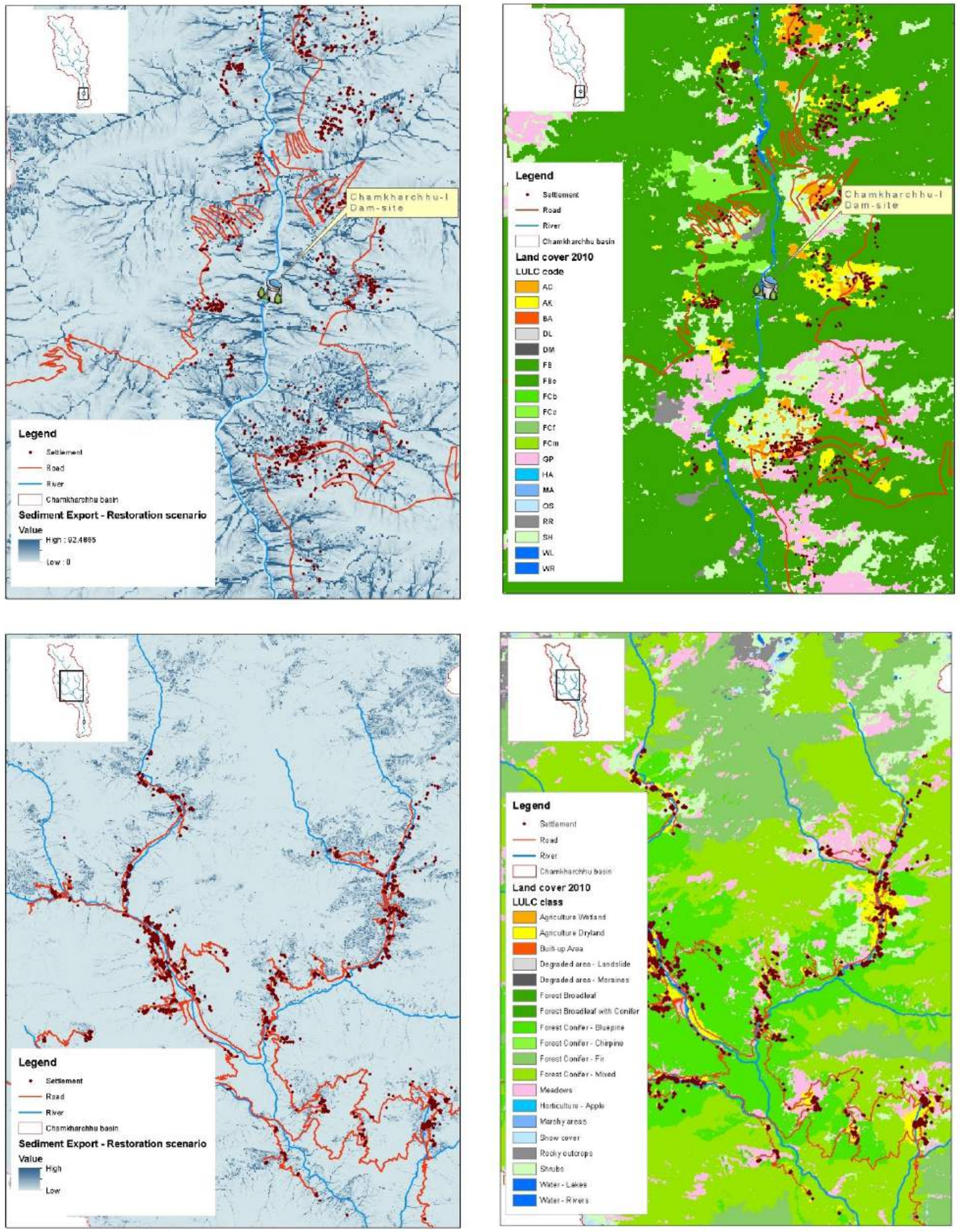

Figure 24. Sediment export under degradation scenario.

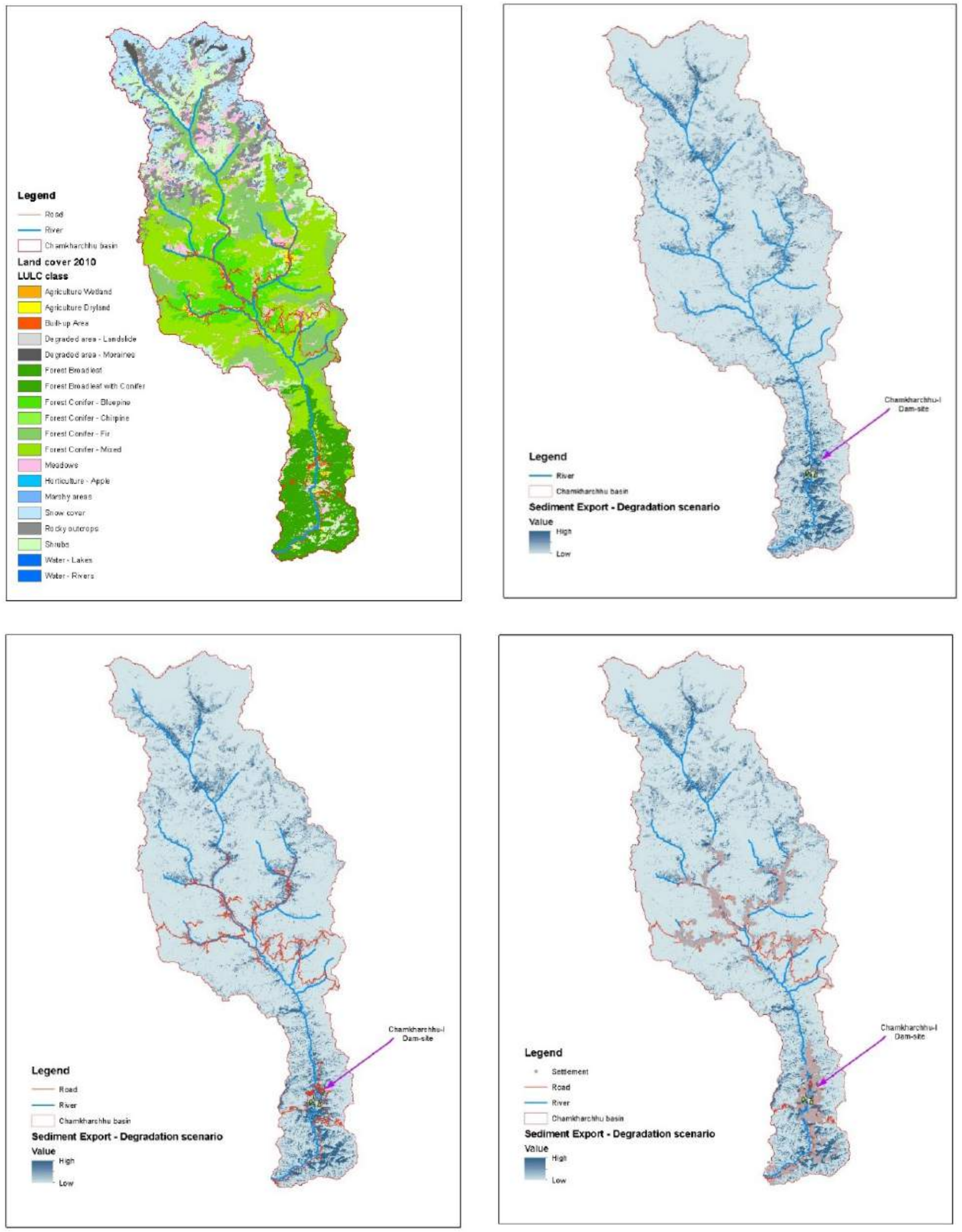

Figure 25. Closer view of degradation scenario.