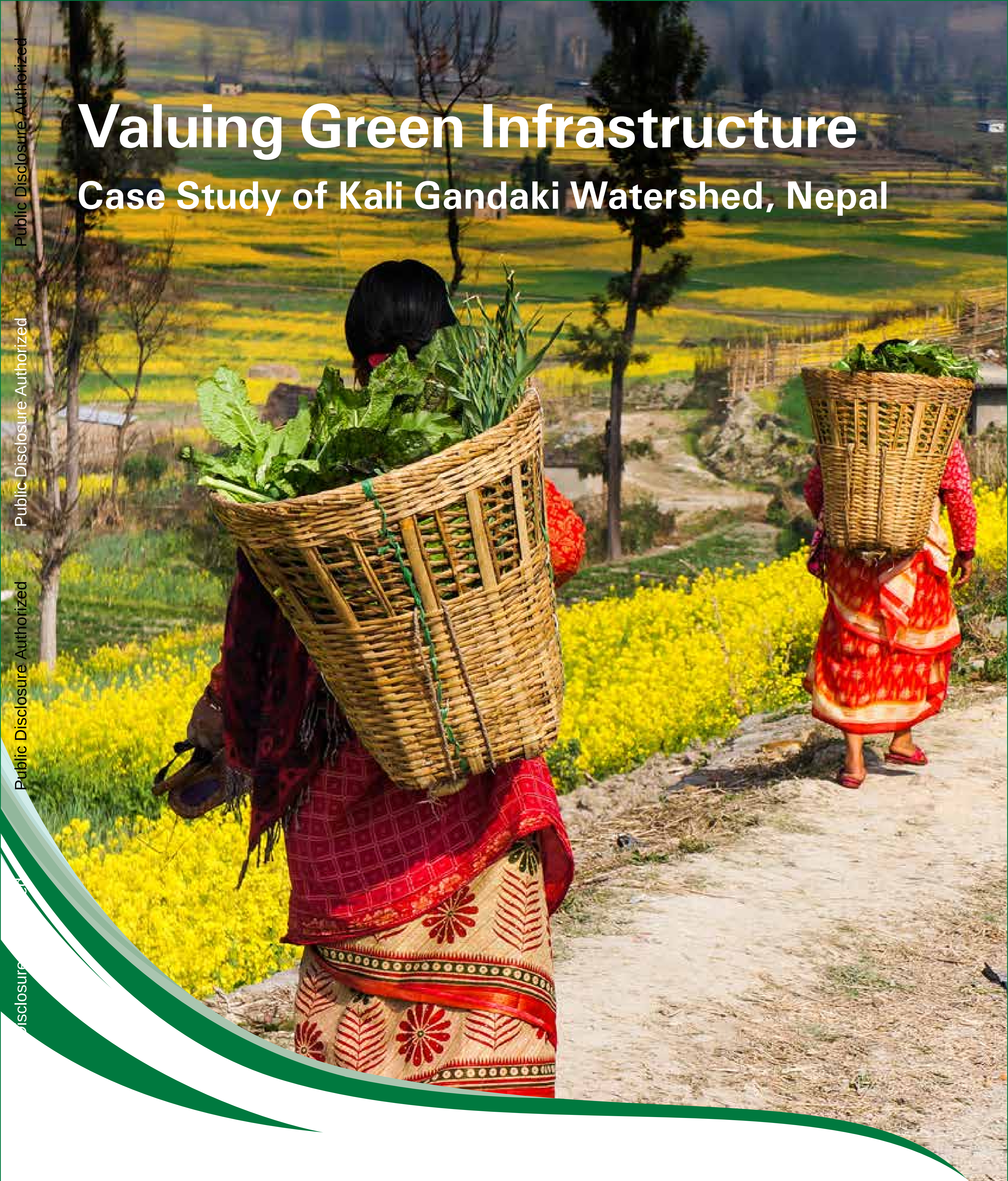
Valuing Green Infrastructure

Case Study of Kali Gandaki Watershed, Nepal



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CONTENTS

FIGURES

TABLES

BOXES

ACRONYMS

DEM	Digital elevation model
DoFSC	Department of Forests and Soil Conservation, Ministry of Forests and Environment, Government of Nepal
GoN	Government of Nepal
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
KGA	Kali Gandaki A Hydropower Plant
LSO	Landslide object (a group of connected pixels likely to form a landslide)
LULC	Land use/land cover
NEA	Nepal Electricity Authority
NPR	Nepalese rupee
NPV	Net present value
OSM	Open Street Map
PES	Payments for ecosystem services
ROOT	Restoration Opportunities Optimization Tool
RUSLE	Revised universal soil loss equation
SCC	Social cost of carbon
SDR	Sediment delivery ratio
SDU	Spatial decision unit
SOC	Soil organic carbon
UNEP	United Nations Environment Programme
USAID	United States Agency for International Development
USD	United States dollars
VSL	Value of a statistical life
WOCAT	World Overview of Conservation Approaches and Technologies

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EXECUTIVE SUMMARY

THE MULTIPLE BENEFITS OF WATERSHED MANAGEMENT

Watersheds are an appropriate and effective unit for managing ecological assets, given the interconnected nature of economic activities and their impacts within a watershed, locally and regionally, upstream and downstream. Watersheds are increasingly recognized as a critical form of green infrastructure that provides a flow of economic benefits. In mountainous countries like Nepal, watershed management can contribute to important development goals and increase resilience to climate change.

Watershed management refers to a wide variety of practices that fall under the umbrella of "investment in green infrastructure", such as slope correction using terracing, planting hedgerows and cover crops, using crop residues, cover crops, and mulches, trenching and bunding, re- and afforestation, and revision of grazing practices. Minimizing the loss of soil and downstream sedimentation is one of the most visible and immediate benefits of watershed management, the positive impact of which can be felt across many sectors of the economy, including agriculture, hydropower, and water. These practices also help to regulate water flows, stabilize soils, maintain soil fertility, improve soil water holding capacity, regulate water quality in downstream rivers, mitigate shallow to medium depth landslides, and sequester carbon. They generate other on-site benefits to landholders such as fuelwood and fodder for livestock. The multiple benefits of watershed management therefore accrue not only to the agriculture, energy, and water sectors, but also have implications for disaster risk reduction, transportation, and climate change mitigation.

Agriculture and rural development

Soils store nutrients on which crops depend, so preventing nutrient loss both increases their availability to crops being grown and reduces the necessity of applying other fertilizers. A number of studies have demonstrated that terraces, hedgerows, reduced tillage, and other practices that prevent soil erosion also prevent soil nutrient losses, thereby improving crop yields (see, e .g., Atreya et al. 2008; Das and Bauer 2012). Similarly, porous and absorbent soils retain more moisture, having the effect of making more water available to crops, and reducing the need to acquire and transport water from other places. Hedgerows and plantings may also be harvested for food, fodder, or other products. They may also serve as windbreaks, providing protection against the elements, and detaining or diverting floodwaters.

These physical effects translate into economic and societal benefits. The implications of higher soil fertility and more reliable water availability is that more food (or other crops) can be produced with fewer purchased inputs and/or farm labor. The latter consideration may be particularly significant from a broader societal perspective. Farm households may need to haul less water, fertilizer, and fodder, or spend less time herding their livestock in search of fodder (Pandit, Shrestha, and Bhattarai 2014). This may have substantial equity, as well as simply productive benefits, to the extent that women, children, the elderly, or other disadvantaged groups engage in these tasks.

Water supply

There is abundant evidence that healthy watersheds provide a suite of hydrologic ecosystem services, i.e., the benefits to people produced by ecosystem effects on freshwater systems (Brauman et al. 2007). These hydrologic services include water purification, seasonal flow regulation, flood mitigation, habitat protection, and provision of water-related cultural services (Brauman et al. 2007; Postel and Thompson 2005). As water moves through a landscape, the physical conditions that affect its flow and recycling are affected by the condition and structure of vegetation cover. Watershed management is therefore an important strategy for societies looking to meet the needs of growing populations for clean and reliable water supplies.

The water quality benefits of watershed management interventions (such as retention of sediment and other pollutants) are unambiguous, and there is strong evidence for the importance of preserving natural vegetation to maintain existing hydrologic regulation services (Brauman et al. 2007). However, the impacts on seasonal water flows and flood mitigation due to land management interventions such as reforestation, afforestation, and best management practices commonly adopted in croplands and rangelands varies with local conditions, and the mechanisms are still hotly debated in the literature (Dennedy-Frank 2018; Filoso et al. 2017).

Energy

Hydropower is a major source for strategic energy development in the Himalayan region, and a key sector to promote sustainable economies. However, the efficient operation of hydropower is hindered by excessive sedimentation that reduces the lifespan of reservoirs by decreasing storage capacity, while increasing short-term operations costs and reducing generation efficiency. Hydropower therefore relies heavily on ecosystem services from watersheds and the sector has already begun to recognize the need for managing sediment production from landscapes as an integrated part of a sediment management strategy (Annandale, Morris, and Karki 2016).

Roads

Well-managed watersheds can also contribute to maintaining infrastructure, particularly roads, by reducing risks from erosion, landslides, and flooding (Mandle et al. 2016). Well-anchored vegetation above roads can reduce the risk of landslides that cut off the flow of goods and people and result in significant costs for repairs. Preserving upstream catchments can mitigate flood risk, thereby reducing risk of road washout. Understanding and managing the benefits of watershed management for roads and other transportation infrastructure can reduce costs by, for example, reducing the need for more costly engineering solutions to manage sediment and other risks.

Disaster management and resilience

Landslides are both a major source of sediment in mountainous catchments and a major risk to life, property, and other assets that are located on unstable slopes. Landslides impose numerous social, environmental, and economic costs on affected areas, such as loss of life and property, damage to infrastructure, and economic impacts associated with loss of connectivity, particularly in remote areas with limited road networks.

The maintenance and improvement of vegetation cover can help to stabilize slopes, slough off rain before it infiltrates, channel water away from vulnerable slopes, and increase soil strength (Collison, Anderson, and Lloyd 1995; Vanacker et al. 2003). Reducing the risk of landslides through watershed management – where appropriate – can have downstream benefits, by reducing the amount of sediment reaching rivers, as well as local benefits, by avoiding loss of life and damages to infrastructure.

Climate change mitigation

Managing watersheds through interventions that involve the planting of trees (such as agroforestry), improving vegetation cover and soil health can increase both above- and below-ground carbon pools as well as soil organic carbon. Sequestering more carbon in landscapes is a clear win for watershed management activities, and also provides opportunities for co-financing from existing climate mitigation programs. More intense weather patterns due to climate changes have the potential to increase existing problems of sedimentation even further, affecting, in turn, development outcomes for multiple sectors. Greater investment in resource management, through integrated and targeted programs of watershed management, has the potential to address these challenges.

Understanding the multiple benefits of watershed management and how these benefits accrue to different sectors is fundamental to designing effective programs that maximize return on investment. However, many of the economic benefits are hidden, as these watershed services are not transacted in the market, which leads in turn to under-investment in watershed management. In order to efficiently and sustainably manage these important assets, it is critical to quantify and value the many services that watershed management can provide.

OBJECTIVES

The objectives of this study are to

1. Develop methodologies to value a range of ecosystem services that come from watershed management, and to demonstrate their application in the Kali Gandaki watershed to help create evidence on the value of green infrastructure.
2. Develop tools and demonstrate landscape-scale methods to help practitioners target watershed management interventions to improve effectiveness and reduce project costs.

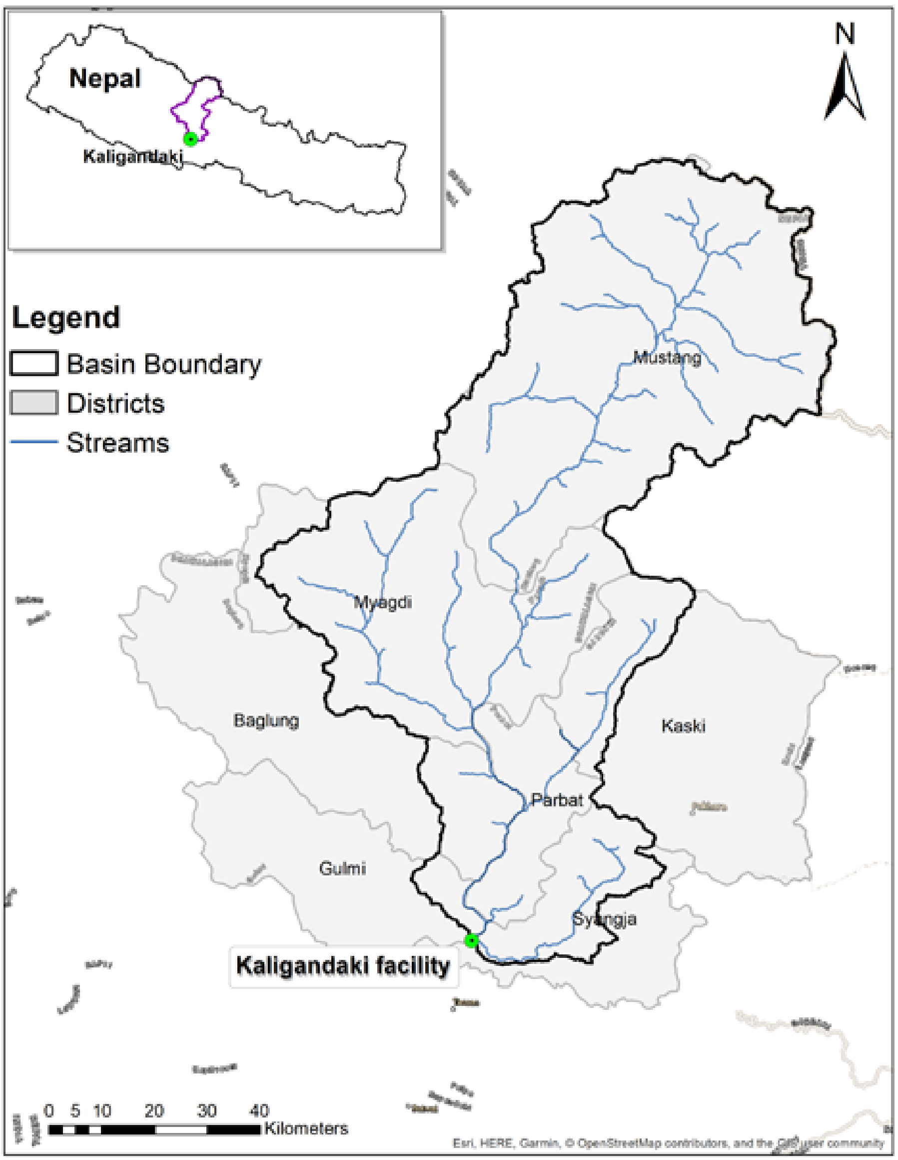
Since sediment retention is one of the most immediate and visible impacts of watershed management activities, this study focused primarily on benefits that result from avoided erosion and sedimentation and looked secondarily at some of the co-benefits arising from activities that are used to control sediment. While proper watershed management is essential to maintaining water flow and quality, the quantification and, particularly, valuation of these benefits requires greater detail of data than was available in this study. Those aspects are, therefore, left for future work.

STUDY AREA

This study focuses on the watershed area that drains to the Kali Gandaki A Hydropower Plant (KGA), located just below the confluence of the Kali Gandaki and Aadhi rivers (see Figure 1). KGA, operated by the Nepal Electricity Authority (NEA) and built at a cost of about US $350 M (ADB 2012), is currently the largest power plant in Nepal with an installed capacity of 144 MW. Since it became operational in 2002, the plant has experienced multiple issues caused by sedimentation, including turbine erosion due to the abrasion from inflowing sediment combined with cavitation, leading to frequent repairs (an overhaul every 3 years) and unplanned shutdowns. In addition, dead storage capacity in the reservoir (e.g. storage below the level of the lowest outlet, designed to trap excess sediment) was already filled by the time the plant was operational due to the small reservoir volume and large monsoon sediments, and live storage (storage above the lowest outlet) has also declined over KGA's operation (Morris 2014).

The Department of Forests and Soil Conservation (DoFSC), Ministry of Forests and Environment, Government of Nepal, has been investing in watershed management (referred to as "catchment area treatment") activities for decades. These investments typically involve practices to prevent erosion (such as cover cropping or inter-cropping with fruit trees in cultivated lands), to reduce overland flow, promote

Figure - 1: Study area - Kali Gandaki watershed, with location of hydropower facility



infiltration, and prevent or mitigate landslide damages (such as terracing, contour trenches, or tree planting), and to capture sediment in runoff (such as hedgerows or check dams). However, the DoFSC programs are focused on a single priority sub-watershed at a time, interventions are highly localized, and not targeted to maximize the flow of ecosystem services.

According to the 2011 national census, there are approximately 590,000 people living in the watershed area (Government of Nepal 2013). Cultivation is the main source of income for residents, and most agricultural activity occurs in the southern foothills of the watershed on very steep slopes, with the mean gradient of farmland being 41%, and little farmland on slopes with less than 5%. The steep slopes and high precipitation require that most croplands are converted to an elaborate system of terraces to control erosion and manage water on the hillslopes. Labor migration away from the hills is common (Jaquet, Kohler, and Schwilch 2019), often leaving behind terraces that are abandoned, and which may be more prone to erosion. Fragile geology, naturally high levels of erosion and mass movements make the issues of erosion and sedimentation of high priority and mean that this area is particularly vulnerable to impacts of land management.

ASSESSMENT APPROACH

The study presents a systematic approach to assess where, in what quantity, and through what processes sediment is being generated in the Kali Gandaki watershed, identify plausible interventions through investing in green infrastructure approaches for watershed management, and evaluate their impacts. The economic benefits of a targeted program of watershed investments are evaluated, and the results are used to develop cost-effective watershed management investment portfolios to achieve multiple ecosystem service objectives. Ecosystem services benefits analyzed included the following

Downstream benefits, with a focus on reduced sediment arriving at KGA:
- Reductions in damage to equipment, efficiency loss, and need for repairs
- Reduced costs of desanding and preventative measures
- Maintenance of storage capacity for peaking

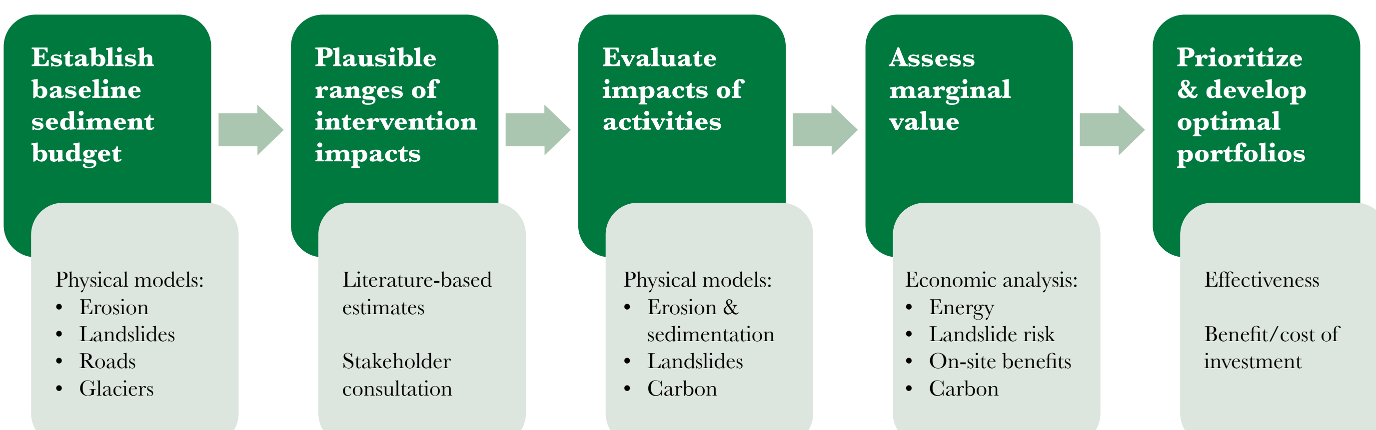
Local benefits, arising from the reduction in landslide risk:
- Avoided lives lost
- Avoided cost of replacing structures
- Avoided cost of road repairs

Global benefits:
- Carbon sequestration from improving or preserving vegetation cover and enhancing soil carbon

METHODS

Establish baseline sediment budget: A set of newly collected field data on sediment concentrations was used with an existing InVEST model for erosion and sediment transport, along with novel approaches to estimate the contribution of roads, landslides, and glacial erosion to total sediment loads.

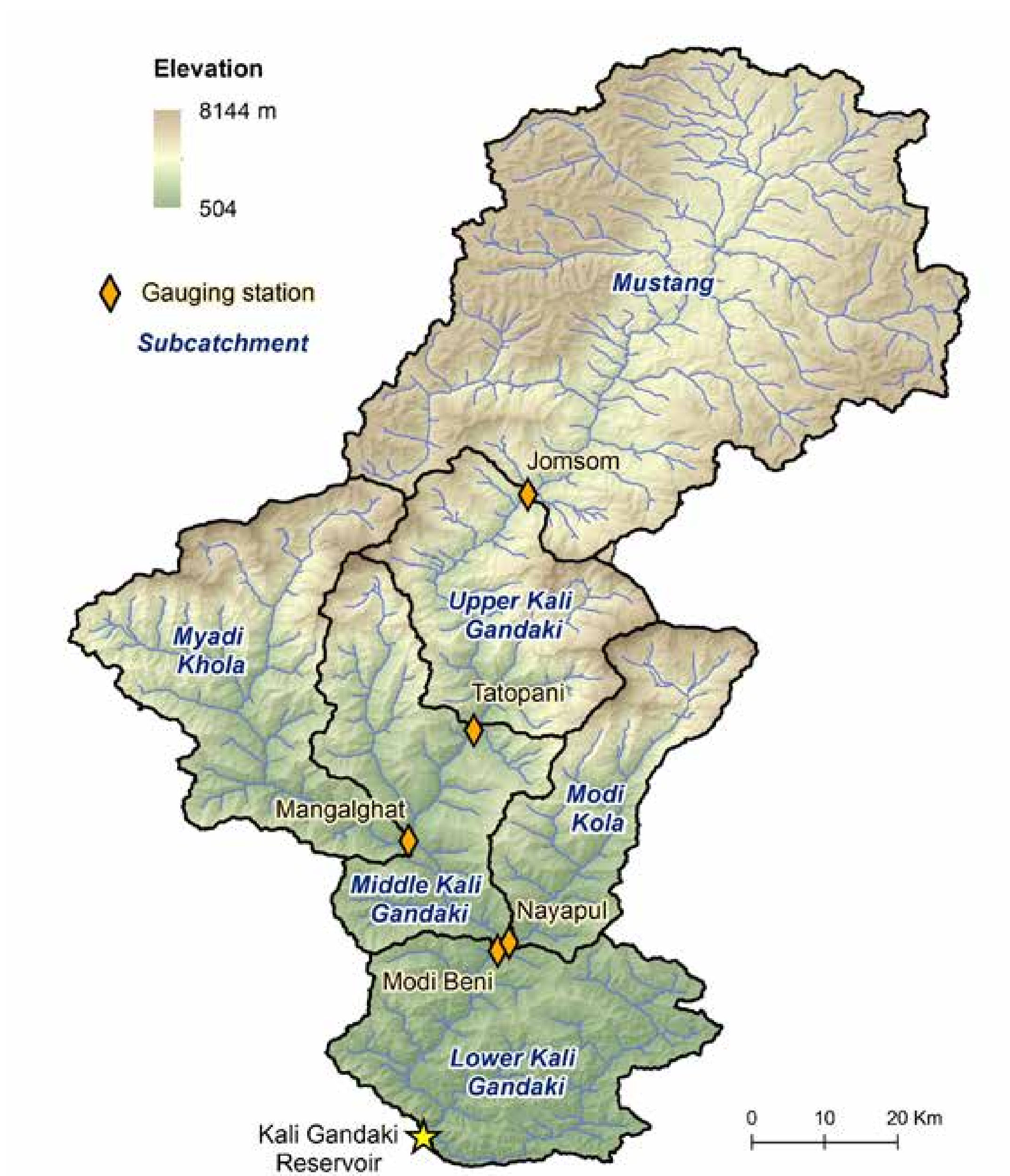
Figure - 2: Workflow used in this study to evaluate watershed management activities, value their impacts, prioritize intervention locations and estimate the benefit: cost at different levels of investment



To assist in developing the sediment budget, monitoring data at multiple locations in the watershed were collected over a period of one year. These data sets, along with flow data obtained from the Nepal Department of Hydrology and Meteorology, were used to develop a 5-year record of sediment contributions from the different sub-watersheds of the Kali Gandaki (Figure 3). Models were calibrated to this sediment record, and the resulting model performance was acceptable (Figure 4).

Identify plausible interventions and range of impacts: A combination of literature review and stakeholder consultation was used to select activities that are feasible and suitable to local conditions, and to provide estimates of their costs and effectiveness. Activities modeled include terrace improvements, soil and water conservation practices (such as hedgerows, cover crops, agroforestry), reclamation of degraded forests and rangelands, and landslide mitigation practices (such as revegetating denuded slopes and slope

Figure - 3: Topography of the Kali Gandaki watershed, location of gauging stations and their respective drainage area



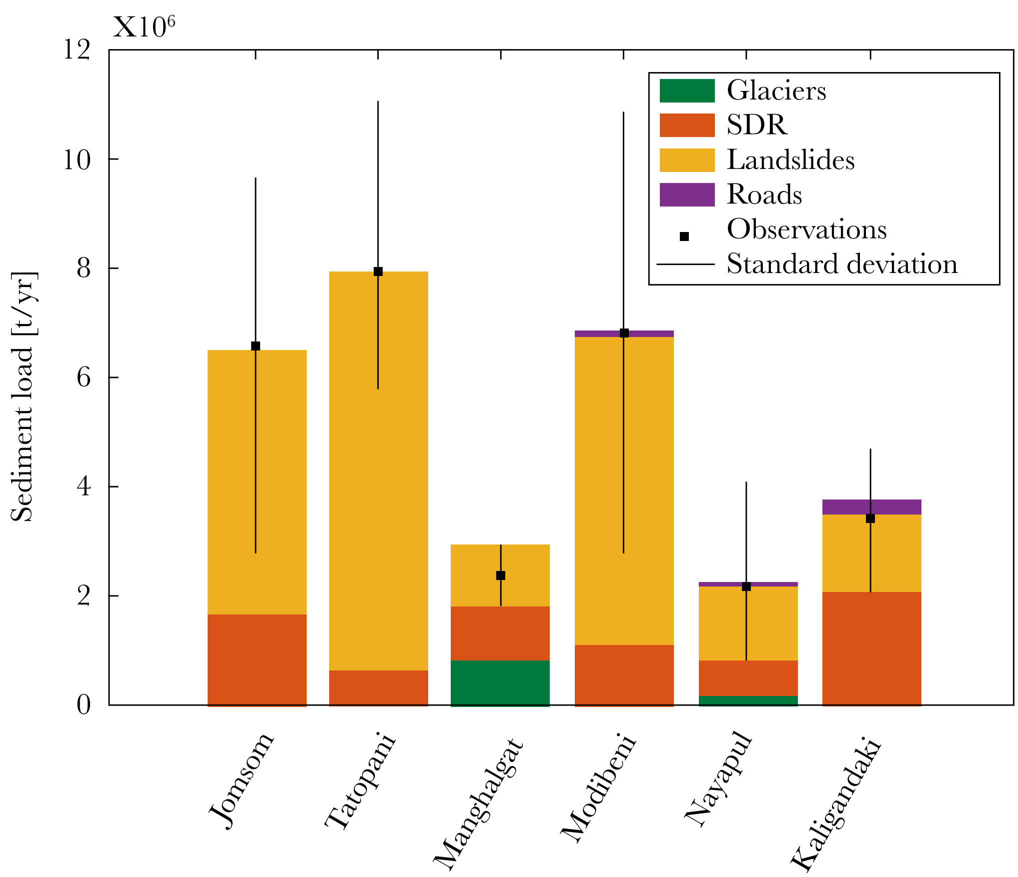
correction). While roads are included as a source of sediment in much of the study area, we do not model any interventions that affect road erosion, as the engineering solutions required to manage sediment from roads were outside the scope of what are normally considered "green infrastructure" interventions. Costs for interventions modeled range from about US $880 per hectare for rangeland rehabilitation to over $39,000 per hectare for mitigation of landslide-prone areas.

Evaluate potential impacts of activities: The impacts of activities on ecosystem services were evaluated using the biophysical models mentioned above, to determine the location-specific benefits of activities in every possible location. For each type of watershed management activity, impacts on hillslope erosion and landslide risks were evaluated. In landslide-prone areas that were treated, the impacts of treatment on the overall risk to lives, buildings, and roads was evaluated using data on the locations of infrastructure in the study area. Estimates of sediment generated in the watershed and impacted by watershed management interventions were adjusted to account for the balance of long-term sediment deposition and re-mobilization in stream channels and deposition in KGA's reservoir.

Assess marginal value of sediment reductions: A combination of micro-economic modeling, spatial overlays, and qualitative methods was employed to evaluate the value of implementing watershed management practices that reduce sediment and landslide risk, provide local benefits to landholders, and store carbon.

Reductions in sediment to the KGA facility were valued based on the avoided cost of damages, as well as measures to prevent damage and avoided loss of reservoir storage for generating electricity during peak times. This study does not attempt to quantify avoided cost of damages to the Modi Khola (14.8 MW) and the Lower Modi 1 (10 MW)

Figure - 4: Comparison of observed sediment load and results from the calibrated multi-model suite. Colors indicate the total sediment contribution from each component of the sediment budget (glaciers, hillslope erosion/SDR, landslides, and road erosion). Error bars indicate ± 1 standard deviation in observed loads



hydropower facilities, located upstream of KGA on the Modi tributary. The impacts of landslide mitigation were valued based on the avoided loss of lives (using a value of statistical life approach), avoided loss of structures (using average rental rates in rural areas), and avoided costs of road repair (using average road repair costs). The impacts on carbon storage were valued using the social cost of carbon; the benefits to local landholders (such as improved soil fertility, crop production, and water regulation) were valued based on the average cost-share reported for similar programs and locations.

Prioritize intervention scenarios: Estimates of implementation costs and modeled effectiveness of each activity/location were used to identify optimal portfolios of interventions at different budget levels. Objectives for prioritizing activities, the associated beneficiaries, and the valuation approaches employed are summarized in Table 1.

RESULTS

Results for watershed management portfolios ranging from US $500,000 to $50M show that such programs can have a significant, positive impact across many sectors. The benefits are driven largely by local benefits and the value of avoided lives lost in landslides, with the next highest beneficiary being downstream hydropower (Figure 5). At the $500,000 budget level, each $1 invested yields $4.38 in benefits, but this ratio drops as budgets are increased. However, even with an investment of $50M, the program still has a positive benefit: cost ratio, even without considering the carbon sequestration benefit.

Figure 6 shows the benefit: cost ratio of the modeled portfolios of interventions, including high and low bounds on the estimated total benefits. These bounds are based on potential values for each benefit stream using a range of parameter estimates in the economic valuation models.

Table - 1: Objectives used to prioritize watershed management activities and locations activities and locations

Objective	**Unit**	**Beneficiary**	**Valuation approach**
On-farm benefits of soil retention	Tons of sediment/yr	Local landholders	Revealed preference based on reported cost-share from similar programs
Avoided sediment reaching Kaligandaki reservoir	Tons of sediment/yr	KGA hydropower plant	Avoided damage Avoided costs of desanding Peaking capacity maintained
Avoided lives lost from landslides	USD	People at risk from landslides	Value of statistical life
Avoided damages to structures	USD	Communities at risk from landslide damages to structures	Rental rate
Avoided repairs to roads	USD	Dept of Roads, VDCs and communities at risk from landslide damages to roads	Avoided repair costs
Added carbon storage	Metric tons	National (e.g. REDD+ program), Global	Social cost of carbon in 2020

Figure - 5: The multiple values of watershed management. The benefits are driven largely by local benefits and the value of avoided lives lost in landslides, with the next highest beneficiary being downstream hydropower (KGA)

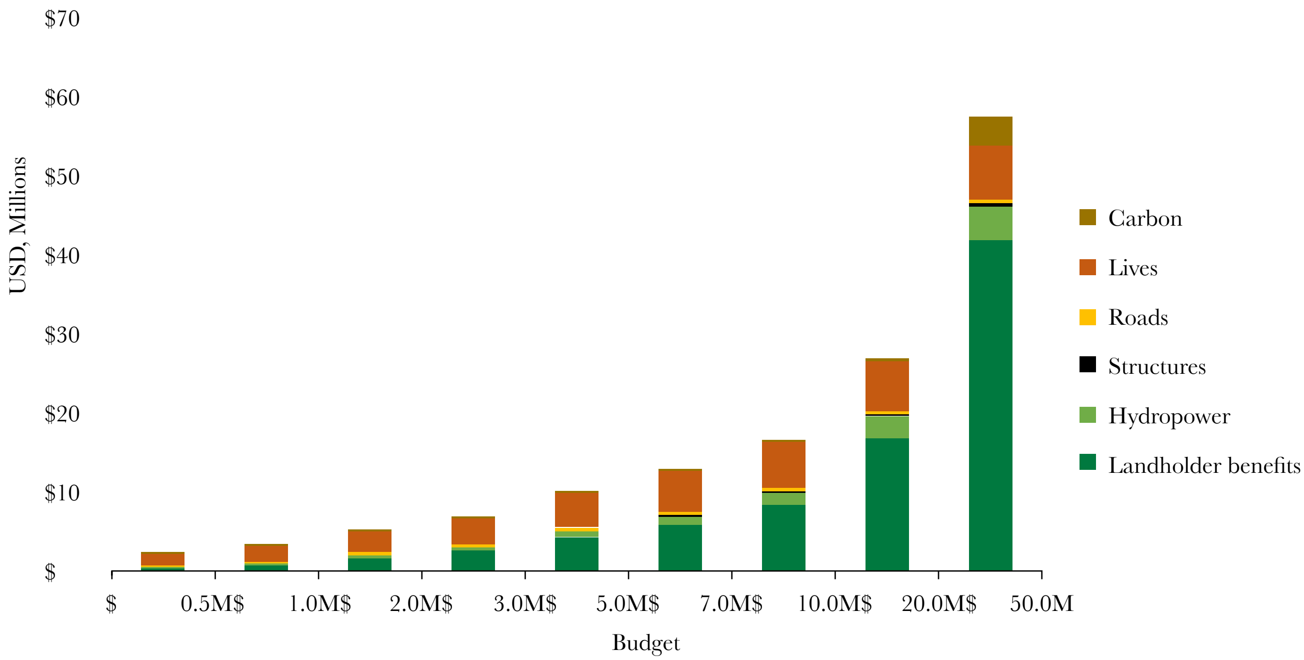
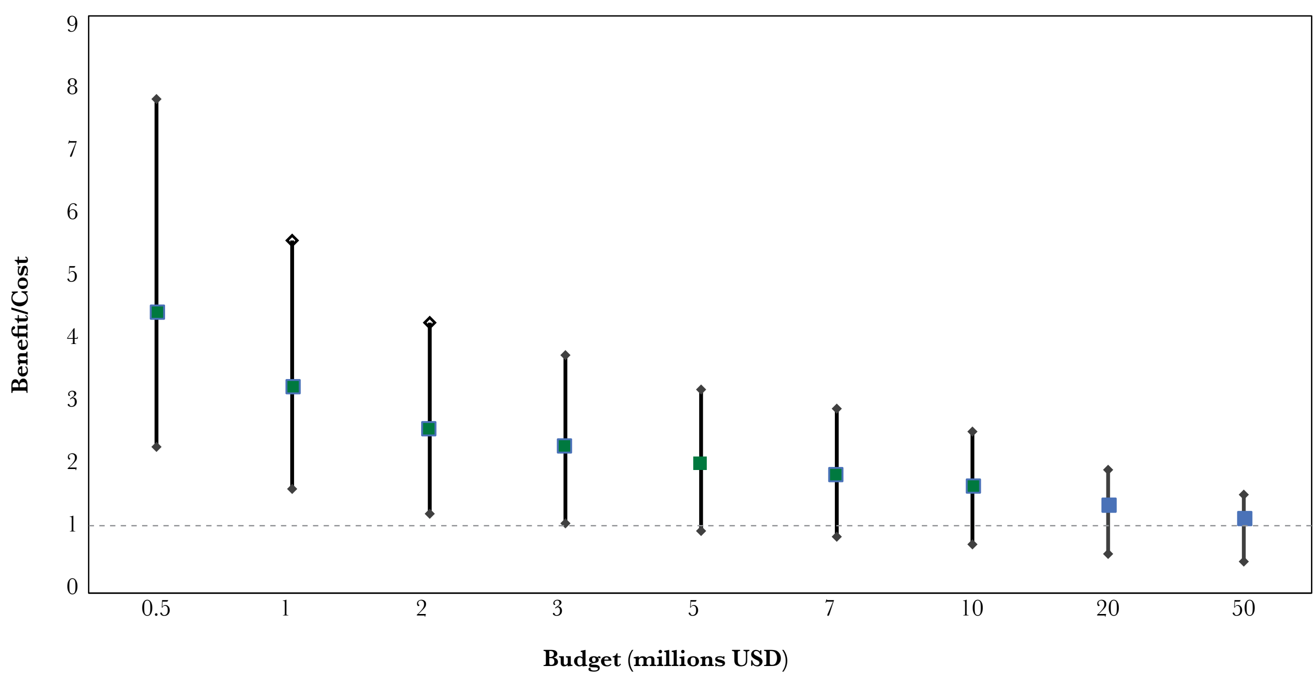


Figure - 6: Benefit/cost ratio of modeled portfolios (blue points), showing high and low boundaries on estimates (lines). High and low bounds are based on potential values for each benefit stream based on a range of parameter estimates as explained in the main report text. These ranges should be considered illustrative and are not to be interpreted as confidence intervals



These ranges illustrate that the positive economic benefit of watershed management interventions is relatively robust to model assumptions but should not be interpreted as confidence intervals.

Some of the largest benefits valued in this study are those relating to landslide risk reduction. Figure 7 shows the results of the landslide risk model for an area in the central Kali Gandaki watershed, overlaid with data on the locations of structures and roads. Reddish areas show the parts of the hillslope that are prone to failure. The different shades of red indicate that different connected parts of a hillslope will fail with different probabilities. The brown cells indicate modeled runout paths that begin at the downslope end of each landslide. Runout paths are colored in different shades of brown, according to the failure probability of the landslide from which they originate. Note that many houses and roads are located in areas of medium risk of being impacted by a landslide or resulting runout. Overlaying the infrastructure at risk allows for an estimation of the total infrastructure at risk in the watershed, and the value of reducing that risk through watershed management activities. The combined values of avoided lives lost, avoided damages to structures, and avoided road repairs, comprise between 25 and 75% of the total value of benefits from the modeled watershed management interventions (depending on the budget level).

Finally, watershed management activities can be prioritized based on different objectives, which will impact where investments should be focused. Figure 8 illustrates the potential trade-off between prioritizing activities for local versus downstream benefits. Those portfolio maps show that when downstream sediment is the primary focus, reducing sediment through mitigating mass movement in landslides along the main stem and tributary channels are frequently the preferred options. However, when local erosion is the main concern, the focus shifts more toward terrace improvement, grazing land and forest rehabilitation in the middle hills area.

CONCLUSIONS

This study presents a novel attempt to generate a comprehensive valuation of the multiple benefits that can result from implementing a watershed management program to control erosion and sedimentation in the Kali Gandaki watershed. A physically-based modeling approach, in combination with micro-economic modeling of major benefit streams, was employed using watershed- and region-specific data to rigorously evaluate these benefits. In this way, our study goes beyond the often-used approach of simply transferring area-based estimates of the value of watershed benefits from one region to another, and represents a proof-of-concept for how such approaches may be applied in other contexts.

Conservative assumptions were applied throughout the economic analysis; even so, the results show that the aggregated benefits of such a program can greatly outweigh the costs. The benefits to cost ratio is highest at lower investment levels and decreases to 1.2 with a US $50M investment. There is both a physical limit and a feasibility limit as to how much can be achieved with watershed management alone, using the types of practices evaluated in this study. But as part of a comprehensive sediment strategy that includes land management improvements, structural sediment mitigation approaches, reclamation of degraded lands, and best practices for road engineering, our results show that a data-driven and targeted program of watershed management can contribute greatly to a broader social benefit through real and significant economic gains to society.

The results highlight the importance of considering multiple benefit streams and sources of value to make the case that investments in watershed services are sound. With the exception of the benefits from landslide mitigation[1], no one sector receives enough benefits to justify 100% of the investment cost, and in some cases targeting investments to benefit one sector will reduce the benefits accrued to other sectors. Mapping and quantifying the sources of sediment and benefit pathways will help policymakers to design equitable programs that distribute the costs of sediment management across different actors who receive benefits, and that address conservation and development goals as well as the need for sustainable energy and rural development.

As with any study that relies on physically-based models and extrapolates landscape-scale effects from local data, there are uncertainties inherent in the analysis. Every attempt has been made to use the best available data, vetted through a stakeholder engagement process. Errors in the underlying data on topography, historical climate, streamflow and sediment concentrations, and uncertainties about the costs and characteristics of watershed management practices

1. The total benefits from reducing landslide risks (value of avoided lives lost, avoided loss of structures and avoided road repairs) is greater than the cost of implementation only up to a budget of about US $5M.

Figure - 7: Results of the landslides risk and runout modeling for an area on the middle Kali Gandaki River (small cutout for location). Red colors indicate landslide probability, and brown colors indicate runout probability. The darkest colors show areas with the highest probability of failure. Green squares are structures and black lines are roads. This overlay reveals that many of these infrastructures are located in areas of medium landslide risk and/or high probability of being impacted by landslide runout

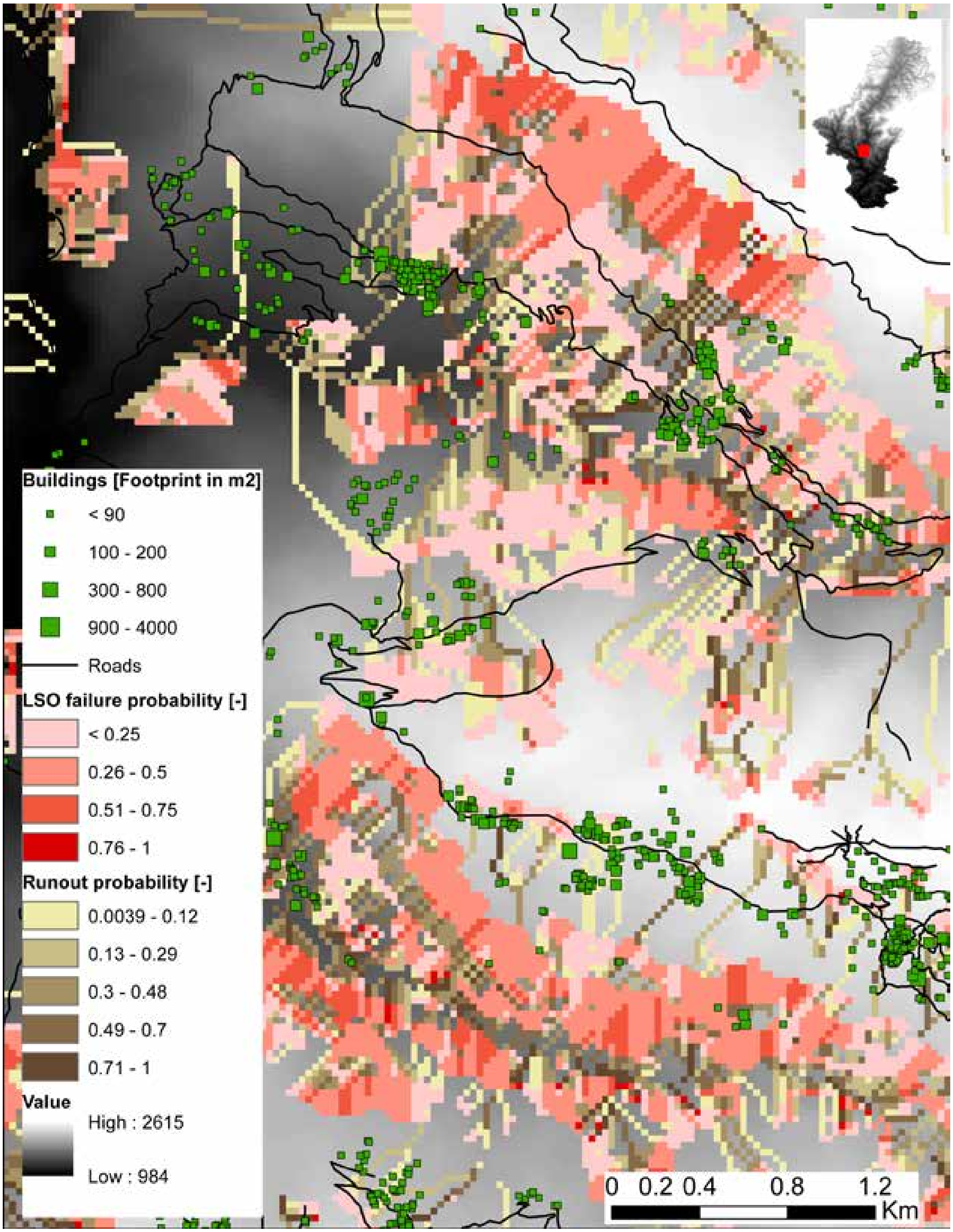
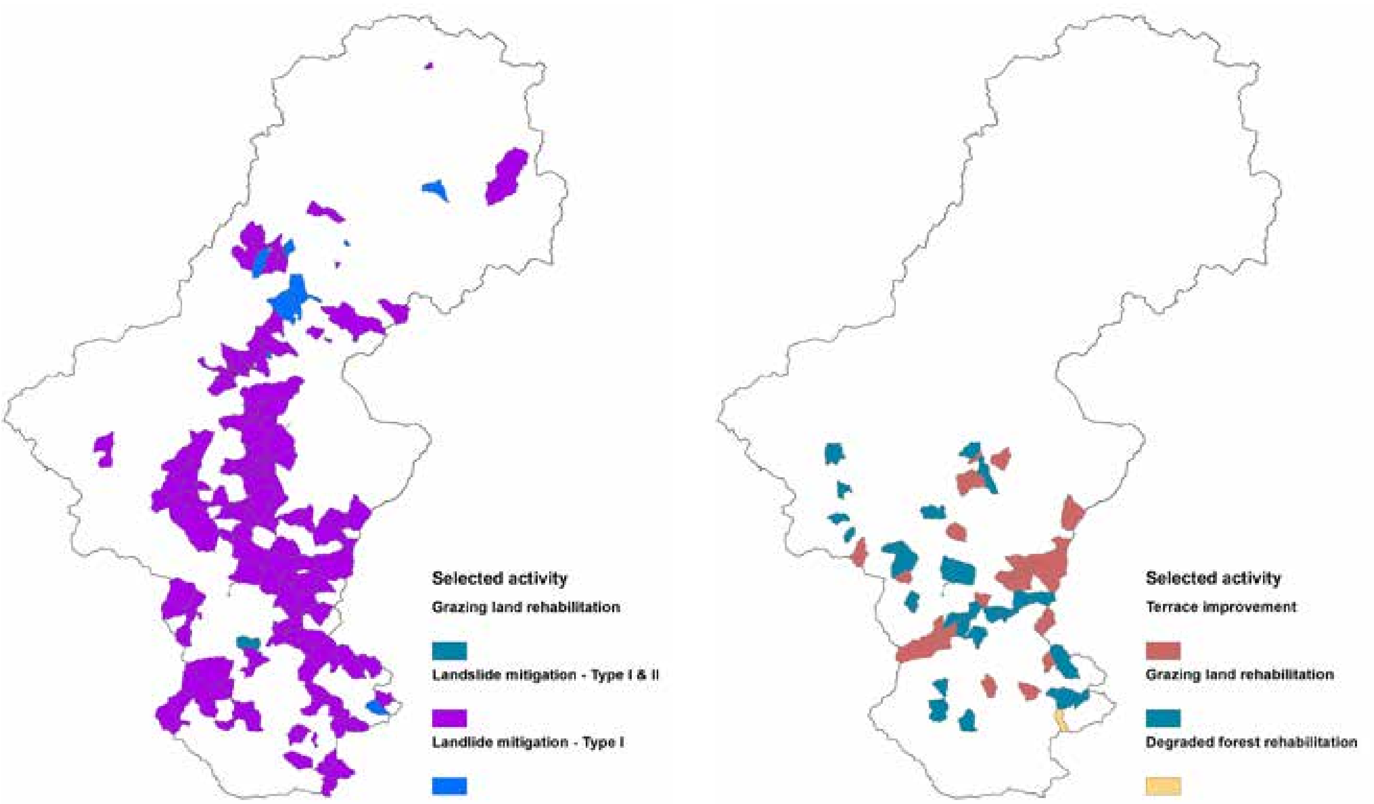


Figure - 8: Intervention portfolios at a budget of US $20M optimized for two competing objectives (left column: downstream sediment for hydropower and right column: local erosion reduction). Note that different activities and sub-watersheds are chosen for implementation to meet the different objectives in the two scenarios



US $20M portfolio, optimized to reduce sediment downstream

US $20M portfolio, optimized to reduce local erosion

as implemented in specific and varying locations on the ground means that the results of this study should be taken as demonstrative, rather than definitive. However, this study overall is conservative in its assumptions and thus provides evidence that watershed management can have positive economic benefits that greatly exceed the costs of its implementation.

It is worth noting that the benefits accruing to landholders are a large fraction of the total benefits. The assertion that better land-management practices might provide such benefits to the landholders implementing them may beg the question of why they have not already been adopted. Reasons for this can include lack of access to capital, lack of information, or the fact that the cost of implementing improvements may equal or exceed the private marginal benefit of their adoption. Aligning the incentives for landholders with broader societal goals for improving the value of ecosystem services from watersheds is therefore a policy challenge, and one that can be informed by the types of information provided by this study: e.g., where watershed management practices provide greatest overall economic benefits and how these benefits accrue to different sectors. Such a systematic approach allows for further engagement with different sectors to align interests and leverage resources.

The ***agriculture, forestry, and water sectors*** can use this valuation methodology to make a case for why watershed management programs are good investments. Understanding and quantifying the benefits that accrue to different sectors enables the design of more efficient and robust payments for ecosystem services (PES) schemes and can leverage investment from multiple actors. The ***transportation and disaster risk management sectors*** can apply the landscape-scale hazard mapping developed in this study to estimate the exposure of assets such as roads, at a finer spatial resolution than is currently available from landscape-scale screening analyses. Further, the prioritization tools can be used to identify areas of particular risk that may require a higher standard of impact assessment and/or consideration of cumulative (rather than project-specific) impacts on ecosystem services. The ***hydropower sector*** can use the valuation and prioritization methodologies to design PES schemes that more effectively control sediment from watersheds. The tools also have relevance for ***environmental and social safeguards***, by providing a data-driven and systematic way to incorporate ecosystem services impacts into environment management plans and to identify mitigation opportunities to offset project impacts to ecosystem services.

Overall, the methods and data resulting from this study demonstrate why effective and efficient targeting is key to achieving the greatest benefits at the lowest costs. Across all of these sectors, the use of watershed-scale tools to evaluate and integrate the multiple benefits of watershed management into sectoral and cross-sectoral policy and planning can be used as a strategic tool to build resilience as climate change impacts are increasingly felt. Further, the stakeholder-driven process employed here allows for more durable and sustainable solutions, and the science-based, landscape-level assessment uncovers the underlying drivers of problems instead of focusing only the individual, localized results of such problems.

1. INTRODUCTION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1.1. THE PROBLEM

Watersheds are an appropriate and effective unit for managing ecological assets, given the interconnected nature of economic activities and their impacts within a watershed, locally and regionally, upstream and downstream. Watersheds are increasingly recognized as a critical form of green infrastructure that provides a flow of economic benefits. In mountainous countries like Nepal, watershed management can contribute to important development goals and increase resilience to climate change.

Watershed management refers to a wide variety of practices that fall under the umbrella of "investment in green infrastructure", such as slope correction using terracing, planting hedgerows and cover crops, using crop residues, cover crops, and mulches, trenching and bunding, re- and afforestation, and revision of grazing practices. Minimizing the loss of soil and downstream sedimentation is one of the most visible and immediate benefits of watershed management the positive impact of which can be felt across many sectors of the economy, including agriculture, hydropower, and water. These practices also help to regulate water flows, stabilize soils, maintain soil fertility, improve soil water holding capacity, regulate water quality in downstream rivers, mitigate shallow to medium depth landslides, and sequester carbon. They generate other on-site benefits to landholders such as fuelwood and fodder for livestock. The multiple benefits of watershed management therefore accrue not only to the agriculture, energy, and water sectors, but also have implications for disaster risk reduction, transportation, and climate change mitigation, as described below.

Agriculture and rural development

Soils store nutrients on which crops depend, so preventing nutrient loss both increases their availability to crops being grown and reduces the necessity of applying other fertilizers. A number of studies have demonstrated that terraces, hedgerows, reduced tillage, and other practices that prevent soil erosion also prevent soil nutrient losses (see, e .g., Atreya et al. 2008; Das and Bauer 2012). Agricultural models then predict that future crop yields will be improved as a result (Das and Bauer 2012).

Similarly, porous and absorbent soils retain more moisture, having the effect of making more water available to crops, particularly between rainfalls, and reducing the need to acquire and transport water from other places. Some measures that are put in place to retain soils also have beneficial side-effects. Hedgerows and plantings may be harvested for food, fodder, or other products. They may also serve as windbreaks, providing protection against the elements, and detaining or diverting floodwaters. Another reason for building terraces, as well as hedgerows, bunds, and other measures that may have the effect of establishing terrace-like features over time, is that they provide a more level surface that is more easily worked than a sloping one (Thapa and Paudel 2002; Bhattarai 2018)

These physical effects translate into economic and societal benefits. The implications of higher soil fertility and more reliable water availability is that more food (or other crops) can be produced with fewer purchased inputs and/or farm labor. The latter consideration may be particularly significant from a broader societal perspective. Farm households may need to haul less water, fertilizer, and fodder, or spend less time herding their livestock in search of fodder (Pandit, Shrestha, and Bhattarai 2014). This may have substantial equity, as well as simply productive benefits, to the extent that women, children, the elderly, or other disadvantaged groups engage in these tasks.

Water supply

There is abundant evidence that healthy watersheds provide a suite of hydrologic ecosystem services i.e., the benefits to people produced by ecosystem effects on freshwater systems (Brauman et al. 2007). These hydrologic services include water purification, seasonal flow regulation, flood mitigation, habitat protection, and provision of water-related cultural services (Brauman et al. 2007; Postel and Thompson 2005). As water moves through a landscape, the physical conditions that affect its flow and recycling are affected by the condition and structure of vegetation cover. Watershed management is therefore an important strategy for societies looking to meet the needs of growing populations for clean and reliable water supplies.

The water quality benefits of watershed management interventions (such as retention of sediment and other pollutants) are unambiguous, and there is strong evidence for the importance of preserving natural vegetation to maintain existing hydrologic regulation services (Brauman et al. 2007). However, the impacts on seasonal water flows and flood mitigation due to land management interventions such as reforestation, afforestation, and best management practices commonly adopted in croplands and rangelands varies with local conditions, and the mechanisms are still hotly debated in the literature (Dennedy-Frank 2018; Filoso et al. 2017).

Energy

Hydropower is a major source for strategic energy development in the Himalayan region, and a key sector to promote sustainable economies. However, the efficient operation of hydropower is hindered by excessive sedimentation that reduces the lifespan of reservoirs by decreasing storage capacity, while increasing short-term operations costs and reducing generation efficiency. For reservoir-based hydropower projects, excessive sedimentation causes a loss of storage capacity and reduces the effective lifespan of the reservoir or increases operations costs by requiring expensive dredging to be carried out. Run-of-river, or diversion, hydropower projects are also common in this region. These projects face increased wear and tear of electro-mechanical as well as structural components when incoming sediment levels are too high. Hydropower therefore relies heavily on ecosystem services from watersheds and the sector has already begun to recognize the need for managing sediment production from landscapes as an integrated part of a sediment management strategy (Annandale, Morris, and Karki 2016).

Roads

Well-managed watersheds can also contribute to maintaining infrastructure, particularly roads, by reducing risks from erosion, landslides, and flooding (Mandle et al. 2016). Well-anchored vegetation above roads can reduce the risk of landslides that cut off the flow of goods and people and result in significant costs for repairs. Preserving upstream catchments can mitigate flood risk, thereby reducing risk of road washout. Understanding and managing the benefits of watershed management for roads and other transportation infrastructure can reduce costs by, for example, reducing the need for more costly engineering solutions to manage sediment and other risks.

Disaster management and resilience

Landslides are both a major source of sediment in mountainous catchments and a major risk to life, property, and other assets that are located on unstable slopes. Landslides impose numerous social, environmental, and economic costs on affected areas, such as loss of life and property, damage to infrastructure, and economic impacts associated with loss of connectivity, particularly in remote areas with limited road networks.

The maintenance and improvement of vegetation cover can help to stabilize slopes, slough off rain before it infiltrates, channel water away from vulnerable slopes, and increase soil strength (Collison, Anderson, and Lloyd 1995; Vanacker et al. 2003). Reducing the risk of landslides through watershed management – where appropriate – can have downstream benefits, by reducing the amount of sediment reaching rivers, as well as local benefits, by avoiding loss of life and damages to infrastructure.

Climate change mitigation

Managing watersheds through interventions that involve the planting of trees (such as agroforestry), improving vegetation cover and soil health can increase both above- and below-ground carbon pools as well as soil organic carbon. Sequestering more carbon in landscapes is a clear win for watershed management activities, and also provides opportunities for co-financing from existing climate mitigation programs. More intense weather patterns due to climate changes have the potential to increase existing problems of sedimentation even further, affecting, in turn, development outcomes for multiple sectors. Greater investment in resource management, through integrated and targeted programs of watershed management, has the potential to address these challenges.

Understanding the multiple benefits of watershed management and how these benefits accrue to different sectors is fundamental to designing effective programs that maximize return on investment. However, many of the economic benefits are hidden, as these watershed services are not transacted in the market, which leads in turn to under-investment in watershed management. In order to efficiently and sustainably manage these important assets, it is critical to quantify and value the many services that watershed management can provide.

This study presents a novel approach to comprehensively value a variety of benefits that can be achieved with a watershed management program aimed to reduce erosion and sediment loss. The analysis shows that even under conservative assumptions, the benefits of a data-driven and targeted program of watershed management can outweigh the costs.

1.2. PURPOSE AND OVERVIEW OF THIS STUDY

The objectives of this study are to

1. Develop methodologies to value a range of ecosystem services that come from watershed management, and to demonstrate their application in the Kali Gandaki watershed to help create evidence on the value of green infrastructure.
2. Develop tools and demonstrate landscape-scale methods to help practitioners target watershed management interventions to improve effectiveness and reduce project costs.

Since sediment retention is one of the most immediate and visible impacts of watershed management activities, this study focused primarily on benefits that result from avoided erosion and sedimentation and looked secondarily at some of the co-benefits arising from activities that are used to control sediment. While proper watershed management is essential to maintaining water flow and quality, the quantification and, particularly, valuation of these benefits requires greater detail of data than was available in this study. Those aspects are, therefore, left for future work.

This report begins with a systematic, watershed-level assessment of sediment sources in the Kali Gandaki catchment area. We use newly available data and models to consider not only sources of sediment but also how sediment moves across the landscape and in rivers and is finally deposited into the reservoir. We present a novel method for assessing sediment contribution from landslides, and the potential for watershed management activities to mitigate the risk of landslides to lives, roads and built structures. We then assess the potential for watershed management to mitigate sediment sources and present an economic valuation of the benefits of such activities in terms of carbon sequestration, energy generation, reservoir storage capacity, operations and maintenance costs, the avoided loss of lives and the avoided costs of replacing structures and repairing roads due to landslide risk mitigation. Further, we discuss the potential for additional co-benefits that can accrue locally, such as improved soil fertility and soil moisture, local water regulation, and crop productivity.

Every attempt has been made to use the best available data, vetted through a stakeholder engagement process. As with every modeling study, necessary assumptions and simplifications are made to enable analysis at a watershed scale. Errors in the underlying data on topography, historical climate, streamflow and sediment concentrations, and uncertainties about the costs and characteristics of watershed management practices as implemented in specific and varying locations on the ground means that the results of this study should be taken as demonstrative, rather than definitive. However, this study is overall conservative in its assumptions and, thus, provides evidence that watershed management can have positive economic benefits that greatly exceed the costs of its implementation.

The rest of the report is organized as follows: chapter 2 provides information about the Kali Gandaki watershed. Next, in chapter 3, methods are presented to (1) develop a detailed sediment budget for the watershed; (2) model benefits and values of watershed management to a suite of ecosystem services; and (3) prioritize where, in a watershed, activities should be focused to maximize impacts while minimizing cost. Chapter 4 presents the results of the analysis, in terms of both physical changes brought about by implementing watershed management as well as the economic benefits that accrue to different sectors at a range of budget levels. The implications of prioritizing activities to achieve different objectives are discussed with some illustrative examples. Finally, chapter 5 draws out the main findings of the study and makes recommendations as to how the findings can be used by the different benefiting sectors – agriculture, roads, hydropower, disaster management – and outlines future work to improve the data and technical basis of these estimates.

Box 1.1: Sedimentation issues and approaches in the Kali Gandaki watershed

The Kaligandaki A Hydropower Plant (KGA), operated by the Nepal Electricity Authority (NEA) and built at a cost of about US $350 M (ADB 2012), is the largest power plant in Nepal with an installed capacity of 144 MW. Since its opening in 2002, KGA has been the largest single generator in the country, providing a quarter or more of the power generated by NEA assets (NEA 2013; NEA Annual Reports 2009–18).

The steep-sided gorge of the Kali Gandaki river afforded a good site for locating a hydroelectric facility (World Bank 2013), but the need to control sediment was recognized from the earliest planning stages (ADB 2012). KGA's design incorporated two large desanding basins that were intended to remove most of the coarse, abrasive sediment that could damage turbines and other equipment (ADB 2012; IHA 2017). However, KGA has suffered greater losses in terms of damage to equipment, loss of efficiency, and more frequently required maintenance than had been anticipated (ADB 2012; World Bank 2013; Morris 2014). Since it became operational in 2002, the plant has experienced multiple issues caused by sedimentation, including turbine erosion due to the abrasion from inflowing sediment combined with cavitation, leading to frequent repairs (an overhaul every 3 years) and unplanned shutdowns. In addition, dead storage capacity in the reservoir (e.g. storage below the level of the lowest outlet, designed to trap excess sediment) was already filled by the time the plant was operational due to the small reservoir volume and large monsoon sediments.

Sediment accumulation affects operations by restricting the plant's ability to meet peak demand. KGA was designed with over 3 million cubic meters of live storage volume in the reservoir behind the dam (Morris 2014). From roughly June through October, monsoon rains and melting snow and ice from the high Himalayas generate water flow in the Kali Gandaki much greater than needed to generate at full power. From November until May, however, the flow declines to a relative trickle. As each kilowatt hour is more valuable during periods of peak, as opposed to off-peak, demand, the water in storage is used to generate more power during those hours of the day when it is most valuable.

Box 1.1 (Contd.): Sedimentation issues and approaches in the Kali Gandaki watershed

Sedimentation also results in loss of reservoir volume (Word Bank 2013; Morris 2014; more generally, see Førsund 2009). NEA officials have estimated that, at times, as much as half of designed peaking capacity may have been lost. Capacity losses may be reduced and, in some instances, reversed by management measures such as maintaining lower water heights, and hence a lower residence time in the reservoir, during high flow periods, or flushing by opening the floodgates (Morris 2014; World Bank 2013). Such measures, however, also impose costs. A lower operating level implies loss of hydraulic head and, consequently, lower power production; flushing implies forgone power production during the period that water is diverted through the floodgates.

In an effort to address the issue of sedimentation, the World Bank initiated a US $30M project in 2013 to revamp the civil and electro-mechanical works at the plant, as well as to provide technical assistance and build capacity. As part of that project, funding was provided to consider whether and how changes in land management in the watershed might affect sediment delivery (World Bank 2018b). That study made recommendations for priority locations to invest in various sediment management practices, including land management interventions, structural interventions, and mitigating impacts from road construction. The current study goes a step further in developing a rigorous cost-benefit analysis to understand the economic value of sediment reductions to KGA, among other benefits.

The Department of Forests and Soil Conservation (DoFSC), Ministry of Forests and Environment, Government of Nepal, has been investing in watershed management (referred to as "catchment area treatment") activities for decades. Management practices employed in the study area (Figure 2.1) typically involve practices to prevent erosion (such as cover cropping or inter-cropping with fruit trees in cultivated lands), to reduce overland flow, promote infiltration, and prevent or mitigate landslide damages (such as terracing, contour trenches, or tree planting), and to capture sediment in runoff (such as hedgerows or check dams). However, the DoFSC programs are focused on a single priority sub-watershed at a time, interventions are highly localized, and not targeted to maximize the flow of ecosystem services.

The watershed management personnel of DoFSC and the District Soil Conservation Offices have a deep knowledge of on-the-ground issues with sediment management, and they have detailed norms for designing and implementing watershed management interventions to address specific problems. The recently formed Gandaki Basin Management Centre aims to provide a centralized knowledge platform for data, guidance, and best practices on watershed management in this region, but they currently lack a systematic approach to model and assess impacts of potential activities at the scale of this study. Such a landscape-scale approach to assessment and targeting would make the best use of the in-depth knowledge that does exist on how to design and implement effective interventions.

Further, the DoFSC's current expenditure (less than US $100,000 allocated each year) is extremely small compared to the scale of the problem (over 30 million tons of sediment coming down the Kali Gandaki River, on average, each year), as is demonstrated later in this report.

2. STUDY AREA

2.1. SOCIO-ECONOMIC CHARACTERISTICS

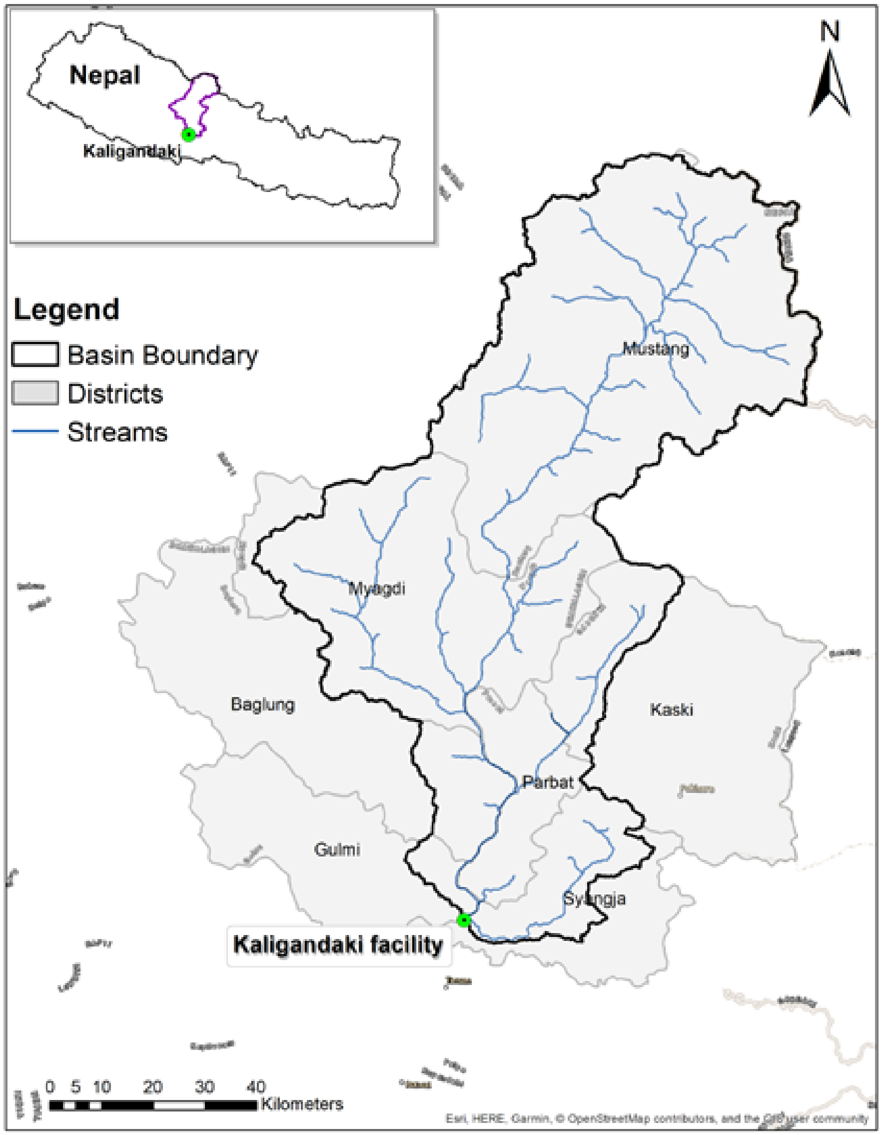
This study focuses on the watershed area that drains to the Kali Gandaki A Hydropower Plant (KGA), located just below the confluence of the Kali Gandaki and Aadhi rivers (Figure 2.1).

The distribution of settlements, livelihoods and infrastructure in the Kali Gandaki watershed reflects the geographic variability of the area. Cultivation is the main source of income for residents and most agricultural activity occurs in the southern foothills, where a majority of the roads and villages are also located (Figure 2.2). Agriculture is the dominant land use for the lower elevation range (500 to around 1200 m) but also occurs up to 2000 m on the southern slopes of the Himalayas.

Higher altitudes show a transition to forest, bushland, and grassland that is used for grazing and collection of fuel wood. Agriculture takes place on very steep slopes, with the mean gradient of farmland being 41%, and little farmland on slopes with less than 5%. The steep slopes and high precipitation require that most croplands are converted to an elaborate system of terraces to control erosion and manage water on the hillslopes, as shown in Figure 2.3.

On the northern side of the Himalayas, agricultural activity is limited to small pockets of farming on the alluvial plains of the Mustang plateau as a result of very high altitude and

Figure - 2.1: Study area - Kali Gandaki watershed, with location of hydropower facility



low rainfall. The valley bottom of the Mustang Plateau is covered in grassland, supporting grazing in many areas, which is a primary source of income in the high mountains (Aryal, Maraseni, and Cockfield 2014). This grassland reaches up to about 4500 m.

According to the 2011 national census, there are approximately 590,000 people living in the watershed area (Government of Nepal 2013). Most settlements are located at lower elevations to the south, and there are a few small villages in the Mustang area. Villages in the lower watershed are connected with a dense network of roads, while several major highways follow the course of the Kali Gandaki river (Figure 2.4).

Labor migration away from the hills is common (Jaquet, Kohler, and Schwilch 2019), often leaving behind terraces that are abandoned, which may be more prone to erosion. Naturally high levels of erosion in the Himalayas are compounded by a lack of integrated spatial planning and development, leading to widespread degradation of forest cover and loss of fertile soils. Extreme topography and climate also contribute to erosion where terraces are managed in a sub-optimal way. In addition, rural road-building has increased, expanding transportation options and accessibility. But often these roads are built hastily, using cut and throw practices, on steep slopes and without stabilization methods (Figure 2.5), and this is reported to be another major source for sediment through thrown soil and resulting landslides (Shrestha 2009).

Figure - 2.2: Department of Survey land use/land cover map from year 2000, also showing the locations of settlements

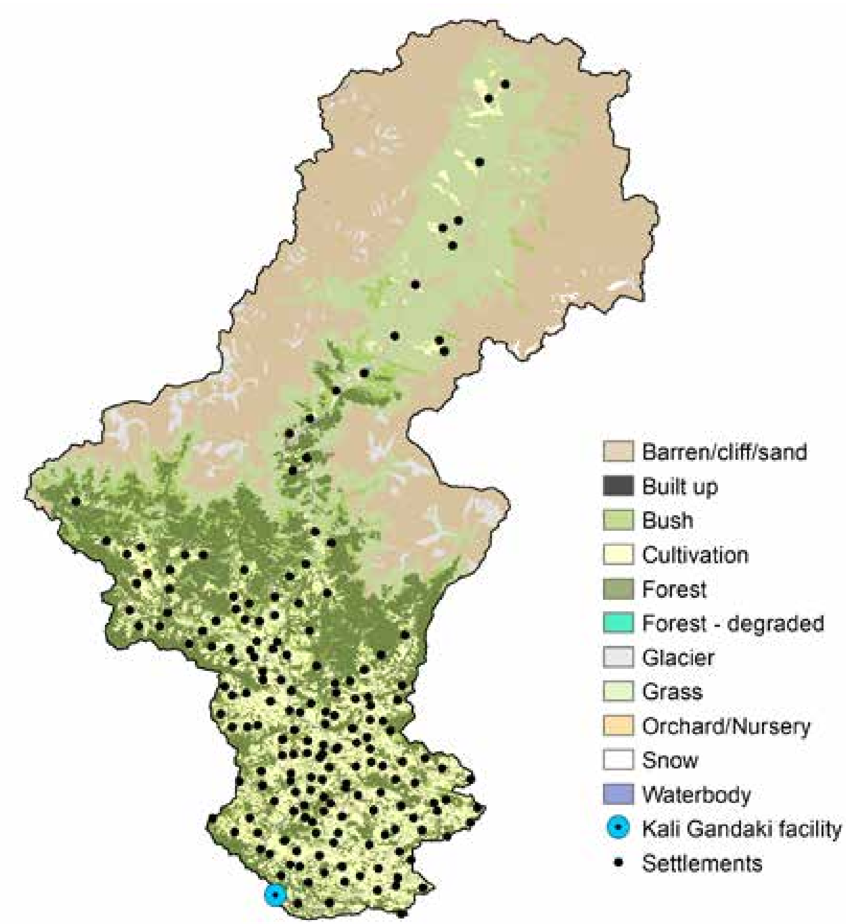
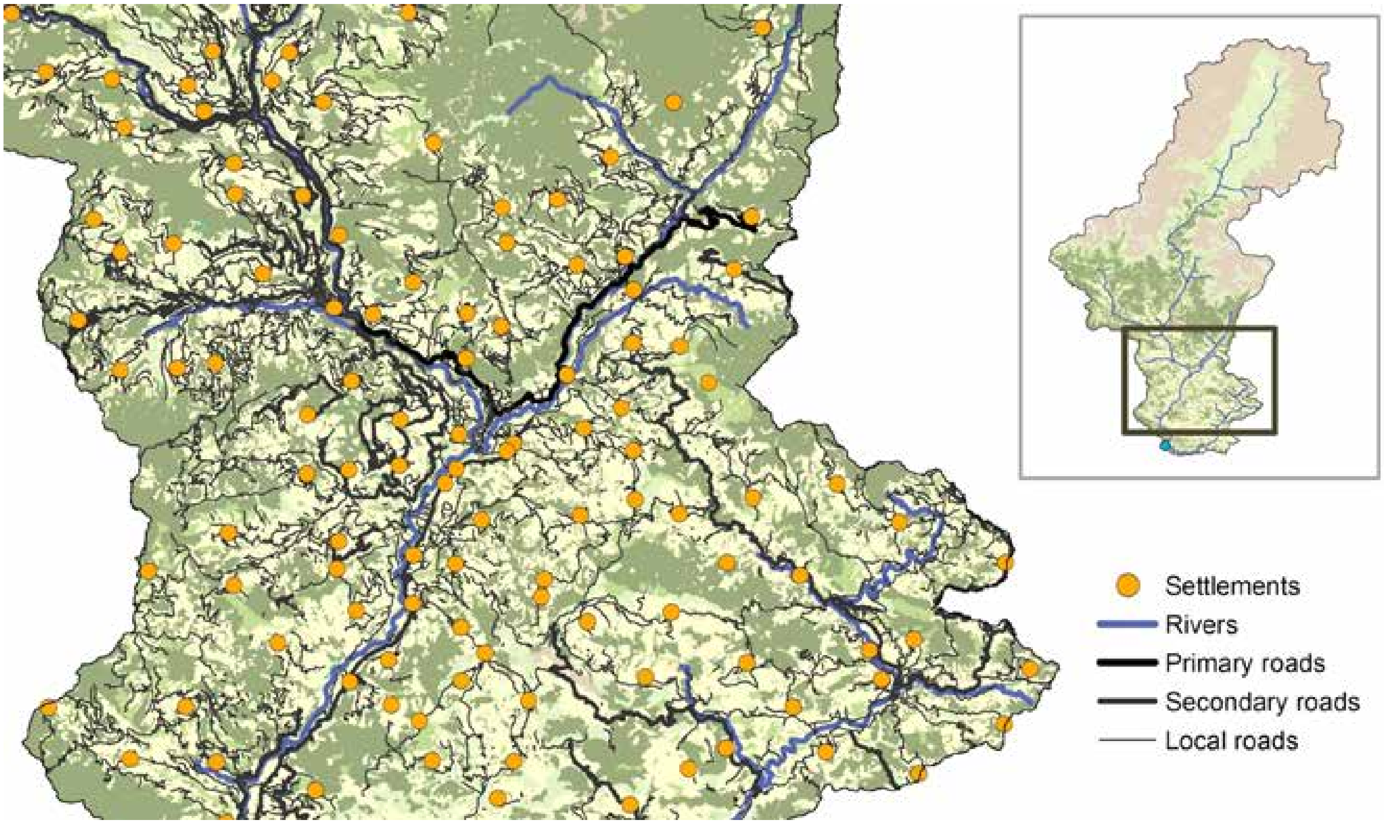


Table - 2.1: Land uses and their total areas found in the Kali Gandaki watershed

Land use	Area (ha)	Percent of total
Barren/Cliff	268,100	35.4
Sand	9,900	1.3
Built up	300	< 1.0
Bush	36,700	4.8
Cultivation	106,100	14.0
Forest	155,300	20.5
Glacier	17,300	2.3
Grass	156,700	20.7
Orchard/Nursery	1,100	< 1.0
Snow	1,100	< 1.0
Waterbody	4,300	< 1.0
TOTAL	**756,900**	**100%**

Figure - 2.3: Example of agricultural terracing on a steep slope in the Kali Gandaki watershed

Figure - 2.4: The lower Kali Gandaki watershed, where many settlements are connected by a network of rural roads



2.2. WATERSHED CHARACTERISTICS

The watershed of KGA covers 7600 km^2 and is characterized by a very high spatial variability of geology, climate, and altitude (ranging from 8144 m - 525 m) resulting in variable geomorphic and hydrologic processes. The Kali Gandaki river originates from the Mustang Plateau on the Chinese-Nepali border (Figure 2.1). The river flows southwards through the Mustang Plateau, which is characterized by its high altitude (> 4000 m) and very low precipitation. At the southern end of the Mustang Plateau, the Kali Gandaki cuts through the main range of the Himalayas, in between the Dhaulagiri and Annapurna massifs, forming a deep and narrow gorge between the two rapidly uplifting mountain ranges. This part of the watershed is herein referred to as Upper Kali Gandaki. On the southern, and specifically south-eastern slopes of the Himalayan main range, referred to as Middle Kali Gandaki, very high annual rainfalls are observed reaching up to 5000 mm/yr.

From these southern slopes, the river, referred to as Middle Kali Gandaki from here on, flows through lesser Himalayas.

Figure - 2.5: Example of rural road construction, cut into steep hillsides without mitigation measures, increasing the chance of erosion and landslides.

The Middle Kali Gandaki receives one major tributary, the Myagdi River, which drains from the Dhaulagiri massif to the west. The lower Kali Gandaki River is delineated upstream by the confluence of the Middle Kali Gandaki with the Modi River, which drains the Annapurna massif to the east, and downstream by the KGA reservoir, located just below the confluence of the Kali Gandaki and Aadhi Rivers. Hence, six distinct sub-watersheds can be delineated within the Kali Gandaki watershed, each with a gauging station at its outlet (see Figure 2.6 and Table 2.2).

2.3. BASELINE SEDIMENT MONITORING

To model where and how sediment is generated, sediment monitoring data at multiple locations throughout the watershed are needed. Such data sets are not available in Nepal, and therefore the study included a sediment monitoring campaign. Specifically, sediment delivery from the sub-watersheds was monitored by a team from Kathmandu University over a period of one year in 2018 – 2019 (Kafle and Bhandari 2019). Samples of suspended sediment, i.e., sand, silt and clay, were taken every two weeks at the gauging stations in each sub- watershed, except for the station at the reservoir of KGA itself (Figure 2.6 and Appendix 1). Monitoring the bedload of gravel and coarser fractions was not part of the sampling campaign, so estimates given below are for fine sediments (sand and finer). Results allow to determine the sediment load from the sub-watersheds of the Mustang Plateau, the Upper Kali Gandaki, the middle Kali Gandaki, and the Myagdi Khola and Modi Khola tributaries. The characteristics of the area draining to each gauging station are shown in Table 2.2, and the sampling locations and sub-watersheds are identified on the map in Figure 2.6. We used a rating curve approach to develop a longer-term sediment budget for the Kali Gandaki watershed covering 2009-2015 (see Box 2.1). This approach is useful to understand if the results derived for 2018-2019 can be generalized for a longer time period.

In terms of total contribution, the biggest fraction of sediment originates from the Upper Kali Gandaki, upstream of Jomsom (7.9 Mt/yr), followed by the Middle Kali Gandaki (6.8 Mt/yr) and the Mustang Plateau (6.6 Mt/yr; Figure 2.7). The tributaries and the lower Kali Gandaki watershed each contribute only around 2 – 3 Mt/yr. It should be noted that the yield (sediment generation per drainage area) from the Upper Kaligandaki and the Middle Kaligandaki is extremely high (around 10,000 t/km^2/yr). The yields for the remaining sub-watersheds (i.e., Myagdi Khola and Modi Khola and lower Kali Gandaki) are all in the range of 2000 – 3000 t/km^2/yr. This means that a square kilometer of land in the Upper or Middle Kali Gandaki will in average produce five times more sediment than a square kilometer of land in the Mustang Area. The spatial heterogeneity in sediment yield is the results of differences in geology, uplift rates, and precipitation between sub-watersheds.

These findings also highlight the need for spatially distributed sediment measurements to determine sediment origins in the watershed, and the need for adopting a landscape-scale perspective on sediment management supported by such measurements. For example, most of the sediment load arriving in KGA is derived from areas that are relatively far away from KGA (Figure 2.6 and Figure 2.7). Information on sediment yield cannot easily be inferred nor generalized from readily available (e.g., global) data. For example, the sub-watersheds of Modi and Myagdi Rivers cover a similar area and elevation range than the middle Kali Gandaki but contribute less than half of the sediment of the middle Kali Gandaki.

Results also allow for estimation of the total sediment delivery to KGA. The sampling results show that the total load of suspended sediment, i.e., sand and finer, arriving at KGA is 31.7 ± 4.9 Mt/yr, similar to what is reported based in other studies (Struck et al. 2015). The current sampling only considered fine sediment transported in suspension (i.e., sand and finer). The Kali Gandaki River also transports a significant amount of coarse material (pebbles, cobbles, boulders) as bed load, which is likely in the range of 10 – 20 % of the fine load (Turowski, Rickenmann, and Dadson 2010). Unmonitored bed load thereby adds another 3.1 to 6.2 Mt/yr to the sediment budget at KGA. What cannot be determined from the derived suspended load measurements is which processes, e.g., landslides, road erosion, or glaciers, generated the sediment loads in different areas.

The team also analyzed the mineral composition of suspended sediment at selected stations (Kafle and Bhandari 2019) which can give some hints about sediment generating processes and their impacts on equipment. Sediment composition was analyzed with regard to four minerals: Quartz, Feldspar, Muscovite, and Tourmaline. Amongst these minerals, Quartz (Mohs hardness 7) and Tourmaline (Mohs Hardness 7 – 7.5) are hardest and Muscovite (Mohs hardness 2 – 3) is softest. All except Muscovite are harder than chrome-nickel steel commonly used for turbine parts (Mohs hardness around 4) (Felix et al. 2016). The other, harder minerals will be highly abrasive on the softer turbine material.

Figure - 2.6: Topography of the Kali Gandaki watershed, location of gauging stations and their respective drainage area. Note that no sampling was taken at Kali Gandaki Reservoir during this period, rather values were interpolated from upstream observations

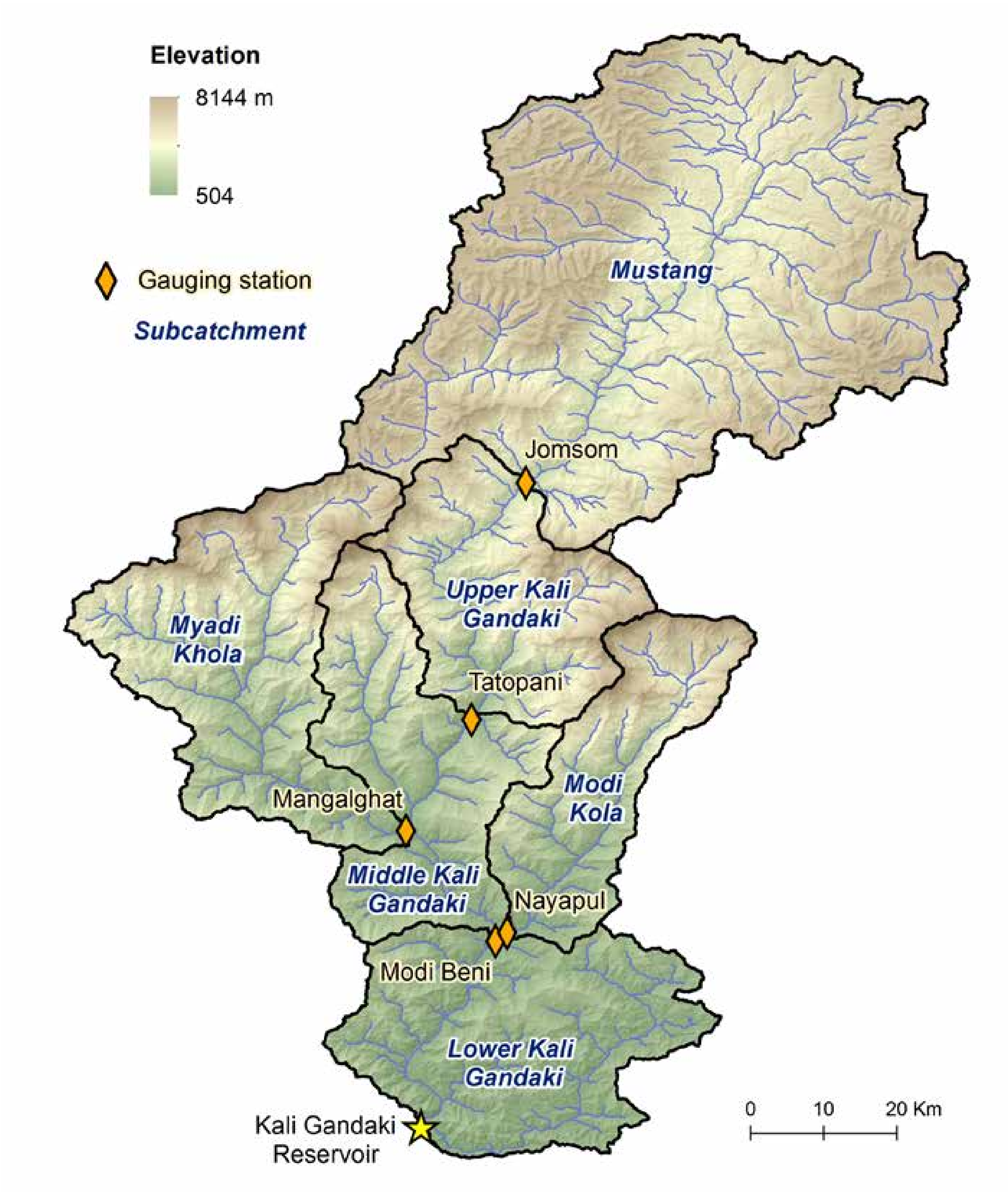


Table - 2.2: Gauging stations used in this study and overview of sub-watershed characteristics

Gauging station	Sub-watershed	Drainage area [km^2]$^+$	Elevation: Mean [m]$^+$	Elevation: Standard deviation [m]$^+$	Glacier-covered Area [% of total]*	Mean annual precipitation [mm]$^\#$
Jomsom	Mustang	3165	4786	845	7.9	426.0
Tatopani	Upper Kali Gandaki	782	3946	1251	9.8	1191.1
Manghalghat	Myagdi Khola	1095	3357	1509	12.6	2260.3
Modi Beni	Middle Kali Gandaki	840	2405	1092	1.5	2076.1
Nayapul	Modi Khola	648	3192	1645	11.8	2988.0
Kaligandaki Reservoir (not covered by current sampling campaign)	Lower Kali Gandaki	1034	1245	365	0.0	2394.7

$^+$ Derived from the DEM (30 m resolution)
* ICMOD glacier dataset
$^\#$ Interpolated from DHM rain gauges using Kriging

Box 2.1: Methods used for converting observed sediment data to longer-term sediment load

Methods & Tools 2.1: Rating curves for long term sediment budgets. Sediment rating curves were fitted to the observations at each sampling location to convert sediment observations, which cover only a single year, to a baseline annual sediment load that is representative for a longer time period. These rating curves of the form

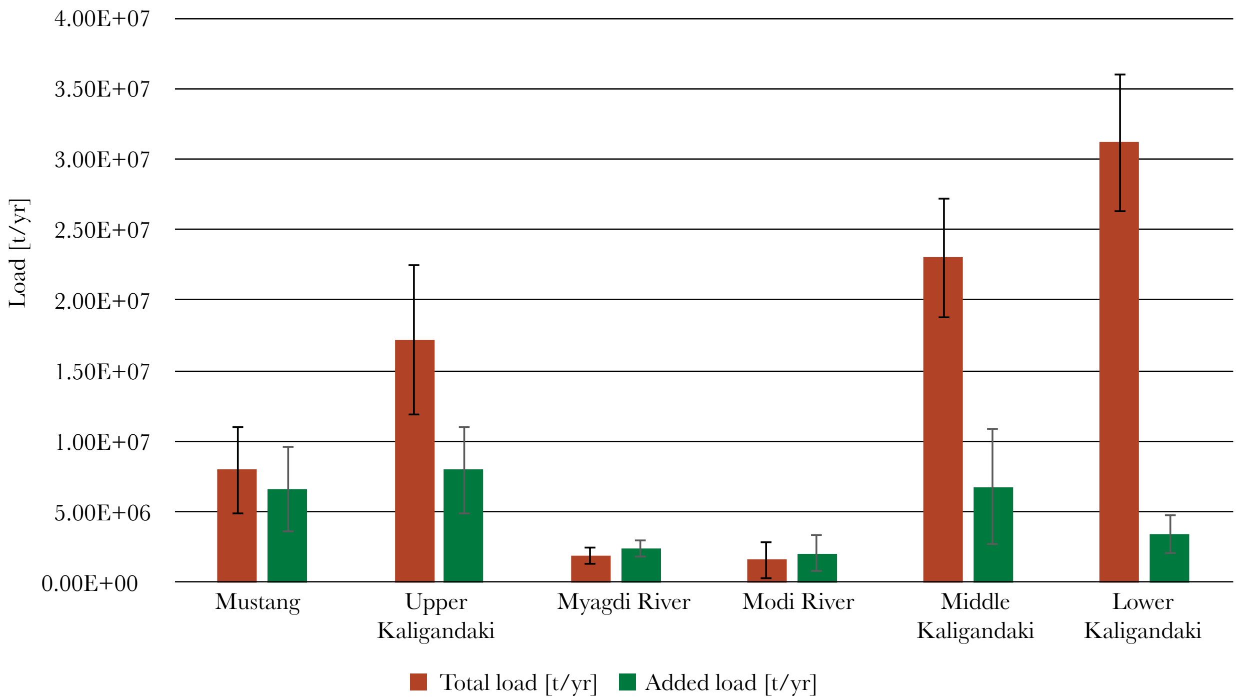
$$C_S = a * Q^b$$

where C_S is the sediment concentration in gram/m^3, Q is the discharge in m^3/s and a and b are location-specific scaling parameters. Rating curves relate water discharge to sediment concentration, which is useful in areas like the Kali Gandaki watershed, where a much longer-term record is available for discharge than for sediment. Rating curves can then be used to reconstruct past, unmonitored sediment concentrations and loads from discharge observations, as long as there is sufficient confidence that the processes linking the generation and transport of sediment have not changed significantly over the time horizon on which the rating curve method is applied.

Using this approach, the total load reaching KGA can be attributed to the various sub-watersheds. Figure 3.2 reports the total annual sediment load estimated at each station, as well as how much the corresponding sub-watershed adds to the total sediment load, over a roughly 5-year time period for which flow data were available. For more details on input data and limitations of this approach, see Appendix 1.

This analysis helps to understand possible differences and similarities in sediment generating processes between sub-watersheds. Sediment from different sources (in terms of location and process) can have different impacts on hydropower. For example, sediment derived from glacial erosion is often particularly damaging to hydropower plants. This is because glaciers can scour hard bed-rock creating fine sediment that is difficult to remove in desanders and is very abrasive. In Kali Gandaki, parts of the watershed are glaciated and glacial erosions cannot be controlled by watershed management. A large sediment contribution from glaciers would hence limit opportunities for such interventions.

Figure - 2.7: Total load and contribution of sub-watersheds draining to KGA. The total load describes the total amount of fine sediment transported at the outlet of each sub-watershed. The added load indicates how much of that load originates within a sub-watershed. Loads are calculated using a rating curve approach using results from the 2018 – 2019 sediment monitoring campaign by Kathmandu University and past discharge data from 2009 – 2015 (See Box 3.1). Error bars indicate the standard deviation of total and added load over this time period. Note that there were no measurements for the Lower Kali Gandaki, and therefore data are derived from various data sources



However, the analysis concluded that even sediment from little-glaciated sub-watersheds consists mostly of very hard minerals (only around 10% of the sediment consists of Muscovite). The mineral composition of sediment from Myagdi and Modi (the sub-watersheds with most glaciers) is not significantly different from the others. This also implies that managing sediment from the non-glaciated areas, and mitigating processes such as landslides, might be an effective strategy for reducing the load of hard sediment to KGA.

3. METHODS AND TOOLS

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3.1. OVERVIEW OF ASSESSMENT APPROACH

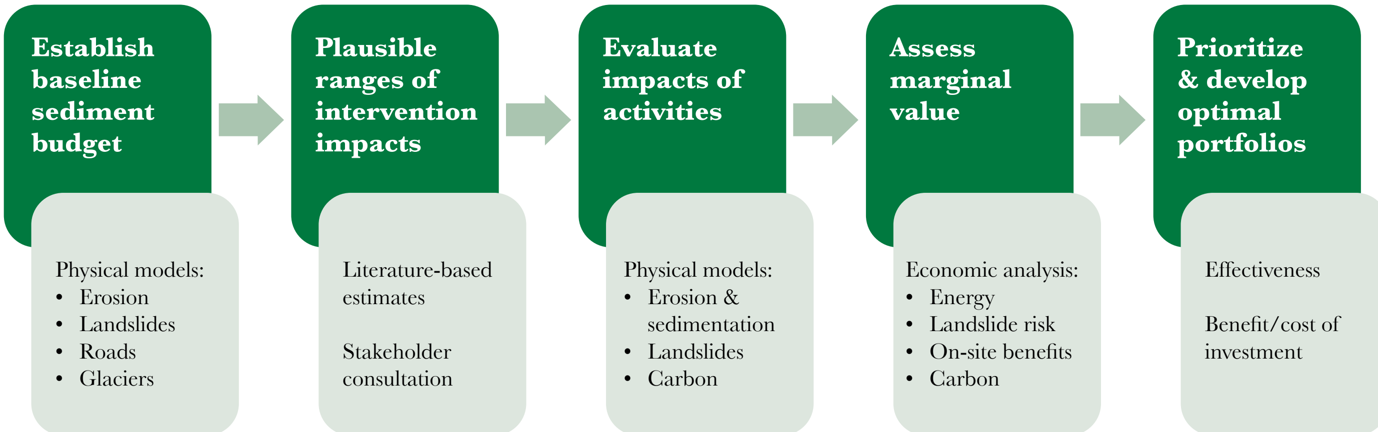
The study presents a systematic approach to assess where, in what quantity, and through what processes sediment is generated in the Kali Gandaki watershed, identify plausible interventions through investing in green infrastructure approaches for watershed management, and evaluate their impacts. Activities and locations based on the potential for achieving multiple ecosystem service objectives are then prioritized, and finally the economic benefits of a targeted program of watershed investments are evaluated, to develop a cost-effective watershed management investment portfolio (see Figure 3.1 for general workflow).

Through a series of consultative workshops with stakeholders from six departments representing four government ministries, the cross-cutting Water and Energy Commission Secretariat, as well as NGOs, consultants, and researchers, we identified the following ecosystem service benefits of watershed management of importance in the Kali Gandaki watershed:

Downstream benefits, arising from reduced sediment arriving at KGA:

- Reductions in damage to equipment, efficiency loss, and need for repairs
- Reduced costs of desanding and preventative measures
- Maintenance of storage capacity for peaking.

Figure - 3.1: Workflow used in this study to evaluate watershed management activities, value their impacts, prioritize intervention locations and estimate the benefit: cost at different levels of investment



Local benefits, arising from the reduction in landslide risk:

- Avoided lives lost
- Avoided cost of replacing structures
- Avoided cost of road repairs.

Global benefits:

- Carbon sequestration from improving or preserving vegetation cover and enhancing soil carbon

Other benefits that were mentioned in our stakeholder consultations, but not quantified in this study, include water quality and water flow in streams for drinking water and irrigation, improved water infiltration and regulation for local springs, water flows for downstream fisheries, and biodiversity. We discuss the potential benefits for water regulation and water quality later in this report, but due to data limitations we were not able to quantify nor value these in this study. Further, the study focuses on the value of reducing sediment reaching KGA and does not attempt to quantify these values for the Modi Khola (14.8 MW) and Lower Modi 1 (10 MW) hydropower facilities, located upstream of KGA on the Modi tributary.

Existing watershed-scale models for erosion and sedimentation were combined with newly-developed modeling and economic approaches to address each stage of analysis, as follows:

- **Establish sediment budget:** A set of newly collected field data on sediment concentrations was used with an existing InVEST model for erosion and sediment transport, along with novel approaches to estimate the contribution of roads, landslides, and glacial erosion to total sediment loads.
- **Identify plausible interventions and range of impacts:** A combination of literature review and stakeholder consultation was used to select activities that agencies are currently engaged in and provide estimates of their effectiveness.
- **Evaluate potential impacts of activities:** The impacts of activities on ecosystem services of interest were evaluated using the biophysical models mentioned above, so as to determine the location-specific benefits of activities in every possible location.
- **Assess marginal value of sediment reductions:** A combination of micro-economic modeling, spatial overlays, and qualitative methods was employed to estimate the value of implementing watershed management practices that reduce sediment and landslide risk, provide local benefits to landholders, and store carbon.
- **Prioritize intervention scenarios:** An optimization tool (ROOT), which uses estimates of implementation costs and modeled effectiveness of each activity/location was applied to identify optimal portfolios of interventions at different budget levels.

Stakeholder input was solicited at each of these stages, to provide data on sediment concentrations in the Kali Gandaki watershed, data on physical and economic considerations, to define feasible activities, and to vet the analytic approaches. More details on each of these steps are provided in the following sections.

3.2. DEVELOPING A SEDIMENT BUDGET

In brief, sediment budgets represent a framework to organize and analyze information on sediment processes and their possible response to human interventions (Reid and Dunne 2016). Sediment budgets are crucial tools for watershed-level sediment management as they identify the dominant source processes that contribute to the sediment load at specific locations (Reid and Dunne 2016). Creating a sediment budget can help, for example, to understand which processes result in the observed sediment load in a specific part of a watershed.

Sediment budgets cover various erosion processes that generate sediment (sources), as well as sinks where sediment is deposited. Different sources generate sediment at different rates, and with variable timing and characteristics in terms of grain sizes. Locations of sediment generation are then connected to sediment sinks in downstream areas via processes of sediment transport, first on hillslopes and then in river channels (Downs et al. 2018).

Hence, location matters, and sediment budgets are ideally derived in a spatially distributed manner to account for the impacts of processes along the transport pathway between specific sediment sources and downstream sinks (Wasson 2003). The dominant processes generating sediment will depend strongly on the geographic setting, hydro-climatic conditions, and the legacy of human interference (Piégay 2016).

For Himalayan watersheds, relevant processes of sediment generation typically include glaciation, mass-movement (such as landslides and rockfalls), sheet and rill erosion from natural hillslopes and agricultural areas, as well as erosion in river channels (Wasson 2003) either from eroding bedrock or alluvial sediment (Fort, Cossart, and Arnaud-Fassetta 2010). All of these processes are subject to anthropogenic alteration ranging from local scales to global scales. In addition, purely man-made processes such as erosion from roads or mining can contribute significantly to a watershed's sediment budget (Sidle and Ziegler 2012).

This section gives a brief overview of relevant processes for the sediment budget of the study area, including their prevalent location, possible alteration by humans, and modeling approaches to quantify their contribution to the total sediment budget, for both the baseline and future management scenarios.

In brief, sediment sources (sheet and rill erosion, glacial erosion, landslide-mobilized sediment, and road-induced erosion) are modeled in a spatially-distributed way across the landscape. In each case (excluding glacial erosion), the estimates of local erosion are modified by a sediment delivery ratio to account for sediment retention on the landscape. The total sediment from all four sources is then modified to account for sediment deposition in stream channels between the source and KGA's reservoir. Each of these analytical steps is described below and further elaborated in Appendices 1 through 3. Further, the economic analysis (Section 3.3.5) also accounts for the fact that not all sediment that reaches KGA's reservoir will end up being diverted for power generation.

3.2.1. Sheet and rill erosion

Sheet and rill erosion (abbreviated as sheet erosion hereafter) occurs when soil particles are detached and transported downslope by the force of rain impact and shallow overland flow. Sheet erosion depends on the balance of forces protecting topsoils from being eroded, such as cohesion of the soil matrix or vegetation, as well as on the erosive forces exerted by rainfall. Eroded and transported particles are typically fine (fine sand and finer) and contain organic material from the topsoil.

Sheet and rill erosion will occur naturally on most hillslopes but can be greatly magnified by loss of vegetative cover and degradation of soils. In the Kali Gandaki watershed, sheet erosion is the dominant process on the slopes of the lower watershed. Here, slopes are steep and particularly susceptible to the erosive forces exerted by strong monsoonal rainfall. Farmers in this area have traditionally adopted farming practices that minimize soil erosion, such as the construction of terraces along the slope contours. Sediment yield from terraces in Nepal has been observed to vary by around one order of magnitude as a function of the adopted management practice (Chalise and Khanal 1997). Hence, abandonment or neglect of these terraces because of outmigration might increase erosion from terraces.

On higher slopes, remaining natural forests likely protect soils from strong erosion. However, very little vegetation exists in the Mustang area. Very low precipitation limits sediment mobilization on these slopes and soil erosion is typically limited to areas disturbed by human activities, e.g., cattle grazing (Fort, Cossart, and Arnaud-Fassetta 2010).

It should also be noted that part of the sediment that reaches the stream network might be deposited in the river channel downstream, and therefore might not reach the KGA reservoir or other downstream point of interest (see Section 3.2.5 for a discussion of channel transport).

Box 3.1: Methods used for modeling hillslope erosion

Methods & Tools 3.1: Modeling hillslope sheet and rill erosion. This study modeled sheet and rill erosion on hillslopes using the InVEST model for sediment retention (SDR; Hamel et al. 2015). This model is based on two separate components, accounting first, for soil erosion on single land parcels and second, for the subsequent sediment transport from a land parcel to the next downhill river channel. The first component is based on the Revised Universal Soil Loss Equation (RUSLE; Wischmeier and Smith 1978), according to which erosion can be calculated from

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

where

- E is erosion in t/ha/yr
- R is rainfall erosivity (units: MJ·mm/(ha·hr))
- K is soil erodibility (units: ton·ha·hr/(MJ·ha·mm)
- LS is a slope length-gradient factor (unitless)
- C is a cover management factor (unitless)
- P is a support practice factor

In the above equation, erosivity and erodibility are derived from gridded global data sets. The C values for different land use types (e.g., pasture vs. forests; derived from Nepal-specific land use maps) are derived from C values tabulated in relevant literature. The P factor can be used to parametrize the effectiveness of soil conservation practices to avoid soil runoff from a parcel (P=1: no effective erosion prevention, P=0: support practices fully stop soil runoff). A combination of C and P factors are used to describe the impact of a specific land use (e.g., growing corn) under different conservation practices (e.g., growing corn on a degraded, downslope-tilled plot vs. growing corn on a terraced plot with hedgerows).

RUSLE was developed for agricultural plots in the United States, making location specific calibration as well as a consideration of larger-scale topographic complexity via the SDR factor a necessity for landscape scale-applications. This is especially true in places where topographic and climatic conditions are much more extreme than in the locations where the RUSLE equation was developed, such as Kali Gandaki (Benavidez et al. 2018). Therefore, the model suite was calibrated to match average annual sediment loads derived from observed data (Box 2.1)

Eroded sediment will be transported downslope but a portion is deposited along the transport pathway. In InVEST, this retention of sediment on the slopes is modeled using a conceptual factor, commonly referred to as sediment delivery ratio (SDR), which is calculated for each pixel as a function of the area upslope of a pixel and the topography of the flow path between the pixel and the nearest stream (Cavalli et al. 2013). With the SDR applied, the final sediment delivery to the streams is

$$Q_{S,sheet} = E * SDR$$

Note that the SDR factor is calculated on a pixel-by-pixel basis (not a single value applied to the entire area), taking into account the landscape context of all upslope and downslope pixels.

3.2.2. Glacial erosion

Glacial erosion occurs as the glacial ice mass moves over the underlying bedrock and scours it. As it scours into bedrock, glacial erosion can mobilize significant amounts of fine and abrasive particles that are easily transported in a river, are hard to remove in a desander and have the potential to cause significant damage to hydro-electric facilities downstream.

Glacial erosion is limited to high, glaciated parts of the watershed, in this case the Dhaulagiri/Annapurna range and along the rim of the Mustang plateau. Some of these glaciers erode bedrock of great hardness, such as the Leucogranites (a type of granitic igneous rock) of the North-Eastern Mustang plateau, while most glaciers along the southern slopes of the main chain are located on sedimentary rocks (sandstone and schist) which might create less abrasive sediment particles (Parsons et al. 2016).

Box 3.2: Methods used for modeling glacial erosion

Methods & Tools 3.2: Modeling glacial erosion. The sediment load generated by glacial erosion is a function of the run-off from the glacier, which mobilizes sediment at the glacier toe, the size of the glacier, and the properties of the underlying bed-rock, which typically results in a non-linear relationship between the sediment generation of a glacier and the produced melt water discharge (Hallet et al. 1996). There are no specific measurements available for glaciers in the study area. However, for the Gangotri glacier in western Nepal Haritashya et al. (2006) propose a power law of the form

$$\log(C_{SS}) = 1.0862 * \log(Q_g) + 1.3141$$

where

C_{SS} Suspended sediment concentration in g/m^3
Q_g Discharge from a glacier in m^3/s

To determine discharge, we assume that the discharge can be determined from a steady state mass balance

$$\underline{Q_g} = \underline{P_g} - \underline{ET_g}$$

Where

$\underline{Q_g}$ mean discharge in m^3/s
$\underline{P_g}$ mean precipitation over a glacier in m^3/s
$\underline{ET_g}$ mean evapotranspiration from the glacier surface in m^3/s

This notably assumes that glaciers are not losing any mass, an assumption which might become more inaccurate as climate changes, resulting in faster glacier melt and hence an exponential increase in sediment generation. In this study, P_g is interpolated from available rain gauge observations (see Appendix 2: Modeling Landslides) and ET_g is derived from global data sets (WorldClim Version 2).

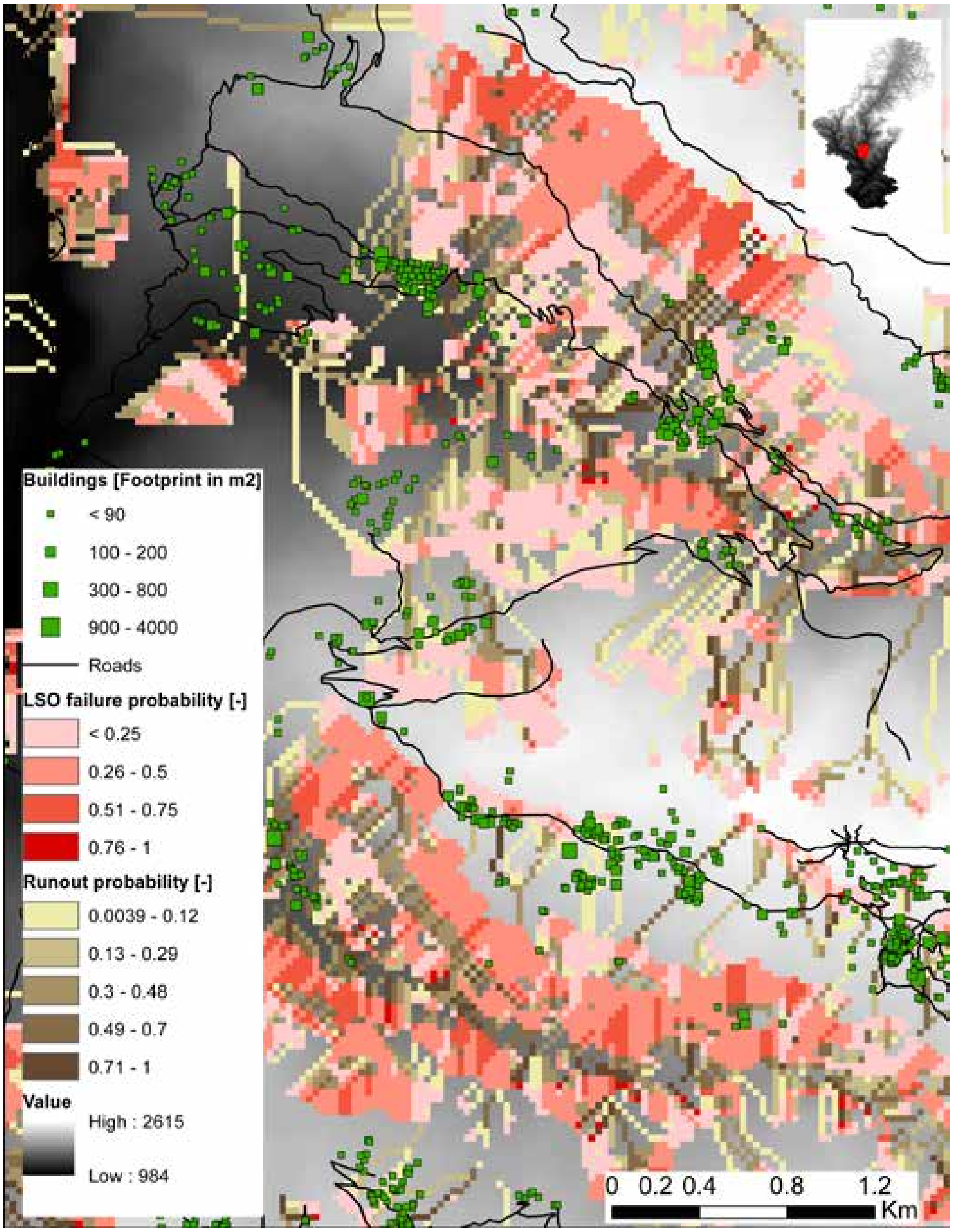
3.2.3. Mass movements: Landslides and rockfalls

Landslides are a significant and possibly even the dominant source of sediment in the Kali Gandaki watershed (Struck et al. 2015). Landslides occur where the forces retaining soil and the fractured bedrock are exceeded by the downslope force. In Nepal, this commonly occurs because of rain-induced changes in slope water saturation as heavy storms hit slopes that are already saturated by monsoonal rainfalls (Gabet et al. 2004). In the Kali Gandaki watershed, there is strong evidence that landslides are most prevalent along the southern slopes of the Annapurna and Dhaulagiri and in the Kali Gandaki Gorges in the Upper Kali Gandaki sub-watershed (Struck et al. 2015; Figure 2.6). These parts of the watershed receive high amounts of precipitation, slopes are extremely steep and rapidly uplifting, and might be weakened by tectonic activities along fault lines (Parsons et al. 2016). Landslides can damage assets such as roads, fields, or structures that are built on a failing slope, as well as when mobilized sediment travels downslope (referred to as "runout").

The landslide model gives four key outputs. First, connected areas of a hillslope that are prone to slope failure and that might form a landslide (referred to as landslide objects, or LSOs). Second, the mass of sediment mobilized from an LSO. Third, the probability with which an LSO will fail, given locally prevailing rainfall conditions. Fourth, the runout path originating from an LSO which might affect assets (building and infrastructure) outside of the immediate landslide area. The model intersects LSOs and runout paths with known locations of assets to derive a stochastic measure for the exposure of assets to landslides. The outputs are: (1) identification of the spatial extent of possible landslides (LSOs) and their runout, (2) the probability of failure for specific LSOs, (3) the amount of sediment mobilized from a potential slope failure, and (4) an estimate for hazards to specific assets given implementation of different landslide mitigation activities.

This approach goes far beyond common landslide vulnerability maps, in which a factor of safety is calculated for a single rainfall intensity pixel by pixel. While such approaches allow to qualitatively describe which parts of a landscape are relatively more or less prone to slope failure, they do not allow to derive any of the information listed in points (1) – (4) above, which are critical to understanding the value of landslide mitigation measures as part of a watershed management program. The novel approach

Figure - 3.2: Results of the stochastic connectivity of landslides and runout tool for an area on the middle Kali Gandaki River (small cutout for location). Red colors indicate landslide probability and brown colors indicate runout probability



used in this study allows for estimation of how watershed management interventions can change the probability of slope failure for a range of precipitation events. For a high-level overview, see Box 3.3: *Methods used for modeling landslide locations and probabilities.* Appendix 2 provides more details on the functioning of the model, its assumptions, the required inputs, and the multiple types of spatially distributed information it provides. Appendix 2, Table 4 lists specific data sources and values for model parameters.

Nearly all parameters in this model (which includes sediment delivery from landslides, runout and landslide location) can be derived from global datasets (DEMs, soil depth) or are interpolated from location-specific observations (extreme rainfall probabilities based on observed rain gauge data). Some geotechnical parameters, such as soil cohesion and internal angle of friction, are not commonly available at watershed scales, and even Nepal-specific observations are rare or absent, requiring to fall back on global data

(Appendix 2, Table 4) and watershed specific calibration of landslide-related sediment loads (Appendix 2, Section 3.3).

In the Himalayas, and specifically in Nepal, a significant loss of life and damage to infrastructure such as roads and hydropower plants is related to landslides associated with seismic events (Kargel et al. 2016; Schwanghart, Ryan, and Korup 2018). Co-seismic landslides were not included in this study because no spatially distributed information on ground acceleration with different return periods was available. However, for future studies that focus more on infrastructure risk, the landslide model presented here could be readily adopted to calculate failure probabilities for different ground accelerations with different return periods and estimate the resulting hazards.

It should also be noted that roads and other infrastructure (e.g., irrigation canals along steep hillslopes) can trigger landslides via a plethora of mechanisms that change hillslope hydrology and force balances (e.g., weakening of the cutslope, overloading of the hill slope, increased infiltration from poorly executed cut slope ditches, or increased saturation from road drainage pipes). All these factors impact slope stability on scales much smaller than the model resolution employed here, therefore modeling road-induced slides is not part of this study. However, the appendix provides a more detailed discussion of the topic (see Section 3.3 and Figure 9 and 10 in Appendix A2).

Figure 3.2 shows the results of the landslide model for an area in the middle Kali Gandaki sub-watershed. Locations of roads and houses are derived from the Open Street Map dataset. Reddish areas show the parts of the hillslope that are prone to failure. The different shades of red indicate that different connected parts of a hillslope (LSOs) will fail with different probabilities. The brown cells indicate modeled runout paths that begin at the downslope end of each LSO. Runout paths are colored in different shades of brown, according to the failure probability of the LSO from which they originate. Note that many houses and roads are located either on LSOs or on runout paths from upslope LSOs.

Box 3.3: Methods used for modeling landslide locations and probabilities

Methods & Tools 3.3: Modeling landslide locations and probabilities

If a specific part of a hillslope is prone to failure is commonly described by a factor of safety of the form

$$FS_i = \frac{c_i+\delta c_i+(\gamma_s-\gamma_w*m_i)*z_i*\alpha_i*\tan\phi_i}{\gamma_s*z_i*\sin\alpha_i*\cos\alpha_i}$$

The equation is based on the following input variables:

- c_i soil cohesion [kPa]
- δc_i added cohesion because of plant roots or slope engineering [kPa]. Root cohesion is set to 12 kPa on forested cells (derived from land use; Table 3.6; Vanacker et al. 2003).
- γ_s unit weight of soil [kN/m^3]
- γ_w unit weight of water [kN/m^3]
- m soil water saturation [-]
- z_i soil depth, assumed to be the depth of a potential failure plane [m]
- α_i slope angle [deg]
- ϕ_i soil internal angle of friction [deg]

This factor of safety is calculated on the scale of single cells of a digital elevation model. However, the volume of sediment mobilized by a landslide will depend on the overall size of a landslide, expressed by the relation

$$E_{LS} = 7.24A_{LS}^{1.322}$$

Where E_{LS} is the mobilized sediment volume in m^3 and A_{LS} is the area of the landslide in m^2 (Larsen et al., 2010). It should be noted that while this equation is empirical, there is a very good fit between the more than 4500 global observations in the original area and volume data set (R^2=0.95; Larsen et al., 2010). To determine the area of a potential landslide, one first determines the maximum extent of slope failure for very wet, fully saturated conditions. Then all parcels on a slope that are topographically connected based on flow paths are grouped into multi-cell landslide objects (LSOs). The threshold

Box 3.3 (contd.): Methods used for modeling landslide locations and probabilities

precipitation required to make each LSO fail (m*) and the probability p* with which m* is exceeded at the specific location of a landslide are determined. This information is derived from a spatially generalized probabilistic analysis of extreme rainfall based on available gauge data obtained from Nepal Department of Hydrology and Meteorology (DHM; See Appendix 2). The model resolution is identical to the resolution of the underlying DEM (30m for this study). Appendix 2, Table 4 lists case-study specific data sources and typical parameter values and data sources and to Appendix 2 for detailed model formulation. Finally, the sediment delivery rate to the streams from a specific landslide object can be calculated as

$$Q_{S,Landslides} = E_{LS}\rho_S\ p^{*}SDR$$

which considers the hillslope connectivity between the location of the landslide and the next downslope stream and the density of mobilized sediment (ρ_S in [t/m^3], herein assumed to be 1.6). Lastly, the empirical method proposed by Rickenmann (2005) is used to identify which downslope cells might be impacted by the runout of a specific landslide (see Appendix 2).

Box 3.4: Different approaches for large-scale landslide hazard assessments

Methods & Tools 3.4: Approaches for landslide modeling and susceptibility assessment

Evaluating landslide hazards on watershed scales is an area of ongoing research. This is because of the complexity of underlying physical processes, the importance of small-scale heterogeneity, e.g., in soil properties, and also because relevant data is rarely available at large landscape scales. For single slopes or small watersheds, tools such as CHASM or Step-TRAMM can be used for detailed assessments of slope stability. However, such tools cannot be applied for a landscape-scale screening of landslide hazards because of their high computational demands and the above-mentioned data limitations.

At the watershed scale, various geospatial assessment approaches are commonly used, typically using raster-based data to represent the study area. The area of interest is represented as a set of cells, and each cell has certain parameters assigned to it. Broadly, there are three approaches that are commonly applied: (1) qualitative susceptibility assessments, (2) quantitative susceptibility assessments, and (3) factor of safety assessments (the approach used in this study). All three methods can be applied to larger areas. Some characteristics of each approach are given in the table below. Ideally, all methods will be validated with geo- and time-referenced observations of landslides, whereas approach 2 (quantitative susceptibility) requires such data up front.

	1. Qualitative susceptibility	2. Quantitative susceptibility	3. Factor of safety
In a nutshell	Expert based ranking of different driving factors possibly related to landslides.	Data-driven approach to link observed landslides to specific local factors.	Physically based method considering drivers of slope stability.
Results	Qualitative hazard ranking, i.e., maps identifying higher or lower landslide risk.	Map of cells where landslides can occur for certain conditions.	Map of cells where landslides can occur for certain conditions, or probability of landslide occurrence (this study).
Pros	+considers local expert knowledge + include factors that cannot easily be integrated in physically based approaches + does not require training data	+ data driven method for a specific geography + include factors that cannot easily be integrated in physically based approaches + results in a quantitative risk assessment	+ allows modeling of interventions (if their impact on physical parameters is known) + results in a quantitative risk assessment + does not require training data + transferable between locations

	1. Qualitative susceptibility	2. Quantitative susceptibility	3. Factor of safety
Cons	- results in a ranking rather than a quantitative measure of landslide hazard - based on local knowledge, not easily transferred between settings.	- Requires training data, e.g. georeferenced data on timing and magnitude of landslides, that are not commonly available. - trained for specific locations, not easily transferable	- only applicable to small and shallow landslides - significant model uncertainty - complex changes in slope stability, e.g., because of human disturbance, cannot easily be integrated

Herein, we propose a geospatial analysis to identify connected areas of possible landslides. The motivation for this analysis is that the hazard created by a landslide will exponentially increase with its area, hence it is of utmost importance to understand if a number of failure-prone cells will all fail together as a large slide, or rather as single small events. Our connectivity assessment also allows us to determine the runout path and possible additional infrastructure at risk along that runout path. The proposed approach for hillslope connectivity is compatible with all approaches described above; that is, results from any of the above-listed methods could undergo post-processing to evaluate the risk of connected cells failing together.

3.2.4. Road induced erosion

Roads contribute to the sediment budget via three main processes. First, most roads in the Kali Gandaki watershed are unpaved, and rain erodes unpaved road surfaces and de-vegetated or unstabilized cut slopes associated with them. Second, sediment that is cut during the road building processes is often not hauled away but disposed of on the valley side of the road (fill slope). Without proper stabilization, this sediment is prone to be remobilized and delivered to the streams, a process commonly observed in the study area. Third, roads change the subsurface hydrology of slopes and increase the landslide risk. The model developed here covers the first two processes for road-induced sediment generation (see Box 3.5 and Box 3.6). Modeling the link between roads and landslides in a mechanistic manner would require detailed information on road design and geotechnical parameters which is not available at a watershed scale for this area.

Road erosion is a function of the terrain on which a road is built. Roads with steeper gradients will erode faster and cutting a road in a steeper hillslope will mobilize more material than cutting on a gentle slope. Road induced erosion is likely most prevalent in the lower parts of the watershed, where population centers are located on very steep slopes. There is likely much less erosion from roads in the Mustang region, where there are less roads, slopes are gentler, and there is lower population and infrastructure. Road-induced erosion is likely to increase in the future, as more settlements strive for road access to markets and infrastructure. Implementing best practices for road construction, including a strategic planning process to avoid steepest and least stable slopes could present an opportunity to reduce future erosion, but this strategic infrastructure planning process is not part of this modeling study.

The model for road surface erosion is based on empirical observations from the Virgin Islands, one of the few empirical models available (Ramos-Scharrón and MacDonald 2007). Applying such a location specific model to a different geography introduces significant uncertainty. Building a Nepal or Kali Gandaki specific model would be relatively straight forward using sediment traps and other low-tech equipment to measure sediment delivery from road segments with different characteristics (slope, precipitation, surface treatment, traffic rates; see Ramos-Scharrón and MacDonald (2007) for a description of the required equipment).

Erosion from the road cut is modeled separately. Uncertainty is lower for this model, as most parameters can be derived from available topographic data. Some details on the design of roads in the study area are derived from photographic evidence (Appendix 3).

Otherwise, all data for the road model are derived from global data sources. Open Street Map (OSM) data provide the location of the roads and define different categories of roads and tracks. A typical width is assigned to each type. Notably, this approach introduces uncertainty regarding the actual cut volume of roads and the OSM data is by no means comprehensive for all roads in the area. Mean annual rainfall is interpolated from DHM gauge data. Road gradients and hillslope angles are derived from the DEM.

Box 3.5: Methods used for modeling erosion from road surfaces

Methods & Tools 3.5: Modeling erosion from road surfaces

Erosion from road surfaces is modeled for each road segment using an empirical equation

$$E_R=(E_{RS}+E_{CS})*\rho_S$$

$$E_{RS}+E_{CS}=1.09*\left(-0.432+f_g\,(S^{1.5}\,P)\right)*L*W$$

Variables are:

- E_R Total erosion from a road segment in t/yr
- E_{RS} Erosion from the road surface in t/yr
- E_{CS} Erosion from the cut slope in t/yr
- ρ_S Sediment density in t/m^3
- f_g Grading factor 4.73 for freshly graded roads, 1.88 for ungraded road. Average (3.305) was used for this study
- S Gradient of road segment
- P Precipitation in cm/yr
- L Length of road segment m
- W Width of road segment m

It should be noted that this specific model was derived for roads in the tropical US Virgin Islands (Ramos-Scharrón and MacDonald, 2007; Ramos-Scharrón and MacDonald, 2005), the use of this model for Nepal is motivated by the absence of Nepal-specific data on road erosion. The precipitation in this study area is similar or higher than on the Virgin Islands for some parts of the watershed, but much lower in others, while slopes throughout the watershed are likely much higher than in the Virgin Islands. It is hence difficult to assign a specific positive or negative error to the use of such a location-specific empirical model to the Kali Gandaki watershed.

The analysis assumes that part of the sediment running off a road at its lowest point is retained on the landscape before reaching the stream. This retention is modeled using the same per-pixel SDR factor as used in the sheet erosion model (Box 3.1) so that the final sediment delivery to streams is

$$Q_{S,Roads} = E_R * SDR$$

Box 3.6: Methods used for modeling sediment delivery from road cuts

Methods & Tools 3.6: Modeling sediment delivery from road cuts

The sediment mobilized from the road cut material is calculated based on the width of a road, the local gradient of the hillslope into which the road is cut and by making some assumptions on the cutslope angle (See Appendix 3). These parameters then allow us to calculate the cross-section of the road cut on a specific slope, so that the total cut material from a specific road segment is

$$E^*_{Cut}=A_C\,L\,\rho_S$$

Where

- E^*_{Cut} Mass of cut material in t
- A_C cross sectional area of the road cut in m^2
- L length of the road segment in m
- ρ_S sediment density in t/m^3

Box 3.6 (contd.): Methods for modeling sediment delivery from road cuts

Note that this equation yields the instantaneous sediment in tons mobilized when the road is cut (or when it needs to be cleared after a landslide). To calculate a rate of annual sediment delivery, the analysis assumed that sediment from the road cut is mobilized over a 25-year time horizon, so that the annual delivery is

$$E_{Cut} \quad \frac{E^*_{Cut}}{25}$$

Sediment delivery from the cut material to the stream is calculated using the pixel-specific SDR factor (Box 3.1) so that

$$Q_{S,Cut} = E_{Cut} * SDR$$

In this study, changes induced in the factor of safety due to a road intersecting the LSO are not included, but road-induced landslides are an area of great interest and could be pursued in future work (see Appendix 3 for more discussion on this topic).

Box 3.7: Road construction practices and standards in Nepal

The Government of Nepal targets call for the country's road network to nearly quadruple, from about 65,000 km (0.44 km/km^2) to 220,000 km (1.5 km/km^2) by 2030 (NPC 2015). While there are benefits to be realized from better linking rural areas of the country, Nepal's steep slopes, fragile geology, and climatic conditions pose challenges for building roads that will be durable and minimize impacts on the environment. The planned increase in road construction, especially of earthen roads in rural areas, is expected to increase sediment generation substantially. This would impact water sources, agriculture, vegetation, hydropower operations, and other ecosystem services. As a secondary effect, roads might open access to areas that so far have seen little disturbance from activities such as logging.

Such negative impacts may be especially severe if current practices are not reformed. Rural roads are often built using heavy equipment, but with otherwise low budgets, little technical expertise, or best-practice design principles to reduce environmental impacts. Construction of local roads is often politically driven, and may reflect the interests of elite groups, while other actors are often the ones to experience the negative impacts from landslides, vegetation loss, and sediment generation from new roads. Extreme erosion from roads can be reduced during different steps of construction. First, strategic planning of road networks can help identify road networks that minimize the road length required to connect a maximum number of villages. Second, best practices can be adhered for the engineering design of roads and slopes. Last, proper environmental safeguards are required to ensure proper disposal of cut material.

There are a number of existing standards for road construction in Nepal. Nepal Road Standards, most recently revised in 2013-2014, provide design parameters for the design of strategic and local road networks based on administrative classification, technical/functional classification, side slopes of embankment, gradients, traffic characteristics, terrain, sight distance and slopes, and other factors. More than a dozen standards and frameworks have been formulated and implemented in road construction and management, such as: Rural Road Standards 1998, Standard Specifications for Road and Bridge Works 2014, Bridge Standards for Strategic Road Network 2009, Environmental and Social Management Frameworks for road management practices in Nepal. Furthermore, bio-engineering techniques for slope and soil protection (e.g., planting local deep-rooted species on bare roadside embankments to reduce soil erosion and stabilize slopes; Howell 1999) are well-known by government officials and are sometimes practiced, but not systematically implemented, for new roads. These standards also state that all roads should be designed and constructed with proper assessment of environmental and social aspects and their impacts as per the umbrella Environmental Protection Act (EPA 1997, currently being amended). However, poor governance means that these requirements are not consistently observed, especially in more rural areas, where funding and technical capacity for improved road building and planning are not available.

3.2.5. Sediment transport in river and fluvial erosion

Fluvial processes impact sediment budgets in two main ways. First, sediment eroded from beds and banks can be a relevant source of sediment in mountain rivers (Wasson 2003). Second, transport processes in rivers are responsible for transporting sediment from the location where it enters the river network to a downstream location. A significant part of the sediment entering a stream can be deposited on floodplains or on sediment bars (Fryirs et al. 2007). Having such areas of deposition will change the impact hillslope management measures will have on sediment transport at a downstream location.

For this study, only fluvial sediment connectivity is evaluated. This is because modeling bank and bed erosion in rivers would require more detailed information on bed-material composition. Also, bank and bed erosion cannot be mitigated with common watershed management techniques

To estimate which amount of sediment can be delivered from each part of the watershed to KGA, the study used the CASCADE model to quantify sediment transport capacity in the river network (Schmitt et al. 2018; Schmitt, Bizzi, and Castelletti 2016). The CASCADE model is based on a statistical application of a common sediment transport formula (Wilcock and Crowe 2003) on a whole network-scale.[2]

While the model allows for considering many grain sizes, the model in the analysis is set up to consider only for a single grain size of medium sand (0.5 mm). This assumption is used as most processes typically targeted by hillslope management (i.e., sheet and rill erosion) will deliver relatively fine sediment. Landslides instead would mobilize both coarse and finer sediment fractions. However, for landslides that do not directly run-out into the rivers, fine sediment will be washed out preferentially from the landslide debris on the hillslopes. However, mechanisms and magnitudes of coarse sediment delivery to streams from landslides would merit further examination and is left for future work.

The CASCADE model yields two main types of information. The first is the transport capacity of the river network, which indicates how much sediment of a certain grain size could be transported in the rivers. The second information is actual sediment transport. Actual sediment transport at any location will depend on how much sediment is actually supplied to the network. If the transport capacity is lower than what is supplied, deposition of sediment will occur. The model was calibrated by varying the supply from the different sub-watersheds until model results were in agreement with the observed sediment data.

For the Kali Gandaki watershed, the analysis shows that most of the rivers allow for a great amount of sediment transport (Figure 3.3, left panel). For fine sand, most rivers have a much greater capacity to transport sediment than what is supplied from upstream (Figure 3.3, left panel). Especially rivers in the upper and middle Kali Gandaki and tributaries along the southern slopes of the Dhaulagiri / Annapurna range have a very high transport capacity (several thousand Megatons of sediment per year, Figure 3.3, red colors in left panel). The only rivers that are possibly transport limited (i.e., receive more sediment then what they can transport) are rivers in the Mustang area. This could be because the hillslopes in the area are not stabilized by vegetation, so that even the small amounts of precipitation in the Mustang area can lead to significant sediment supply. However, because of the low precipitation, the discharge in the rivers is very low and only a limited amount of sediment can be conveyed downstream.

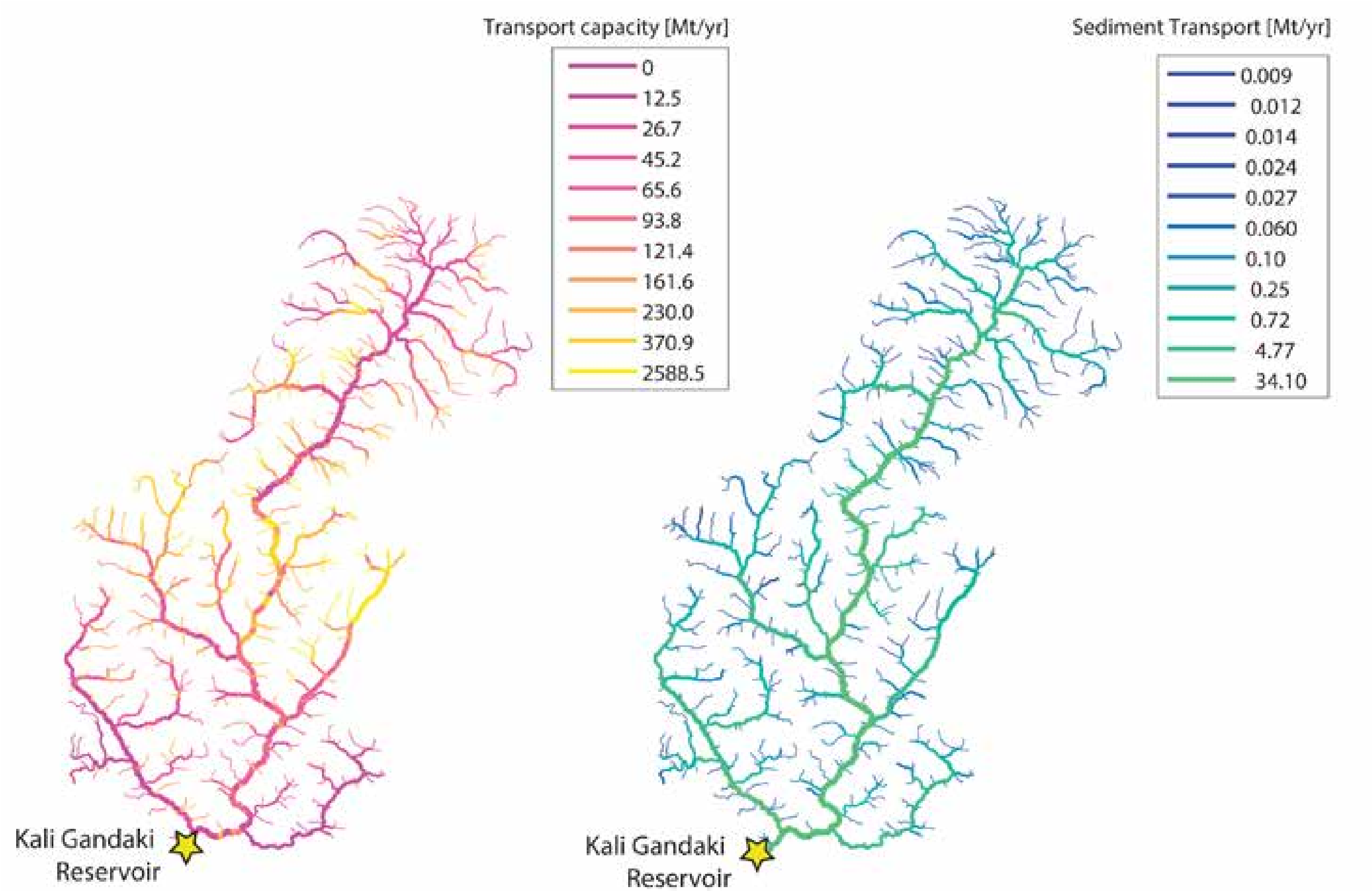
Results of this analysis show that around 95% of sand and finer material entering rivers will be delivered to KGA, a finding which is in line with field observations that rivers in this watershed are mostly supply limited (i.e., can transport all sediment entering the channels; Morris 2014). This also implies that sediment reductions due to watershed management activities, even in the upper watershed, could be felt far downstream, reducing sediment delivery to KGA. The sediment transport in the river network as a function of supply and transport capacity is shown in Figure 3.3 (right panel).

3.3. MODELING BENEFITS OF WATERSHED MANAGEMENT

This section describes the watershed management activities that are modeled in this study, along with how estimates of their costs are derived. Next, the methods used to evaluate the impacts of these activities on sediments generated from hillslope erosion, on landslide-related sediment and associated risks are detailed, followed by the methods used to estimate impacts on carbon storage. The valuation methods applied to estimate the economic values of each benefit stream are summarized (Appendices 2 through 4 provide more detailed treatment).

2. The functioning of the model is shown for the Red River Basin in Vietnam in this video https://www.youtube.com/watch?v=S_EYxK4tRlc

Figure - 3.3: Transport capacity for medium sand (0.5 mm diameter) (left panel) and actual sediment transport for the same grain size (right panel). Note the difference in scales between the two figures



3.3.1. Activities & costs

Several categories of watershed management activities in this analysis are used. The categories were selected as a representative sample of management actions that could be taken to improve landscape condition and control sediment. Potential activities to be analyzed were chosen for their feasibility and suitability to the local conditions, based on a review of relevant literature (Dahal and Bajracharya 2013; Paudel et al. 2017; S. B. Shrestha 2016; Atreya et al. 2008; ICIMOD 2007) and guidance documents provided by the Nepal Department of Forests and Soil Conservation (DoFSC), and refined through stakeholder consultation during two workshops held in October 2017 and January 2019 in Kathmandu. Based on the input received during these workshops from representatives of DoFSC, Nepal Electricity Authority, Kathmandu University, Department of Roads, Department of Survey, Ministry of Agriculture Development, Water and Energy Commission Secretariat, Basin Management Center Gandaki, Provincial Forest Directorates, the World Bank, Paani Program of USAID, District Soil Conservation Offices, and World Wildlife Fund, 7 intervention types (4 on croplands and degraded lands, plus 3 on landslide-prone areas) were selected and are shown in Table 3.1.

The selected categories of activities are applicable to different land areas based on their current land management and physical characteristics. For example, it is assumed that cultivated land above 5% slope could be treated with one or more of the techniques in the category Hill terrace improvement.[3] Depending on local conditions, this

3. Our modeling does not assume that all of the activities listed under each intervention are implemented; rather we model the average effectiveness of the types of activities (based on literature-based estimates of their impacts on model parameters). We assume that upon implementation, the best activity or combination of activities from the list would be selected by local experts to maximize the potential reduction in sediment.

could include techniques such as terrace improvements, hedgerows, and/or agroforestry (planting fruit or other trees among crops). The impact and effectiveness of the modeled activities was assumed to reflect an average change that such interventions would cause in the landscape. For example, while there are many different types of terracing possible (e.g. terracing with hedgerows, bench terraces, cut-and-fill), the actual impacts of activities and their implementation cost will vary depending on site-specific conditions upon implementation. Therefore, the modeling assumes that the specific activities selected to implement "terrace improvement" in a given location would reflect best practices based on the local site conditions.

For interventions aimed at preventing or mitigating the risk of landslides, this study uses data reported by Dahal and Dahal (2017). From the methods reported therein, we focus on two types: tree and bamboo plantation, and installation of subsoil drains. Such low-cost engineering measures are not suitable, however, to address very large landslides with deep-seated failure planes. Landslide-prone areas are, therefore, classified into four groups with increasing magnitude, and a prototype portfolio of measures are developed that can be applied for the mitigation of types 1 through 3. Specifically, the following classification is proposed:

1. Shallow landslide (<1.5m) in the topsoil (i.e., landslide depth < soil depth). The minimum depth of an LSO is given by the cell size and is around 1.4 m. The 1.5 m threshold implies that the failure plane is in the range of deeper rooting plants and trees.
2. Landslide depth > 1.5 m but still in the topsoil. Failure plane in the range of deep rooting trees.
3. Landslide depth > depth of the topsoil, but less than 3 m. Failure plane in the bedrock (i.e., can't be reached by roots quickly) but still possibly in the range for soft / grey-green engineering.
4. Landslide depth > 3 m. Deep seated landslides which would require massive engineering for mitigation.[4]

Landslide interventions are assumed to be only feasible on hillslopes not more than 1 km away from a road, as they might require transport of large equipment and material. All agricultural land is also considered, assuming that there will always be some sort of access, even if it does not show up in the road data-set. It should also be noted that interventions might reduce the risk of smaller co-seismic landslides. This effect was not analyzed in this study but should be evaluated in future work.

Furthermore, we do not model any interventions that affect road erosion, as the engineering solutions required to manage sediment from roads were outside the scope of what are normally considered "green infrastructure" watershed interventions. We also assume that glacial erosion will not be the target of any land management interventions, as most glacial areas are extremely remote with limited potential for improving vegetation cover.

Implementation Costs

Costs for each activity were based on a review of literature on implementation of similar activities in the Himalayas (Nepal, India, and Bhutan). Studies were chosen that contain a detailed and well-documented explanation of costs. Costs given in the studies were broken out into establishment and maintenance costs for materials and labor, and many included the fraction of both initial establishment and maintenance costs borne by the landholders adopting the practice. Labor costs were calculated using the reported labor inputs and a common daily wage rate (US $3 per day;)[5] and all costs were adjusted to a common year (2018). Specific activities were grouped into the categories given in Table 3.1 above, and the average cost was calculated (Table 3.2). For the costs of landslide mitigation, the reported cases where similar interventions were implemented with the stated purpose of reducing or mitigating landslide impacts were used as the basis for the costs. We assume that those studies that reported a combination of grey and green engineering approaches – and correspondingly higher costs – were most applicable to landslide class 3.

As with the impact of interventions, the cost of implementation will likely vary based on specific site conditions. But assuming that, in some areas, costs are understated and in others they are overstated, the aggregate

[4] Such landslides are not considered a suitable target for nature-based mitigation measures, but modeling their location is nonetheless useful for hazard mapping and disaster awareness. These results are an important by-product of the analysis reported here.

[5] This wage rate was estimated as a representative value from roughly a dozen studies used in the generation of cost figures for Table 3.2. All studies save (Das and Bauer 2012) are summarized in the WOCAT (World Overview of Conservation Approaches and Technologies) database of sustainable land management practices (https://qcat.wocat.net/en/wocat/). Wage rates varied considerably over both the time (studies reported data from years between 2003 and 2014, a period over which both per capita income adjusted for inflation and consumer prices roughly doubled) and location of the studies. As labor expenses constituted a large share of costs, it should be appreciated that such cost figures are imprecise; see "Limitations" below.

Table - 3.1: Interventions modeled in this study, examples of practices normally included in such programs, and rules for where on the landscape each activity was modeled

Intervention modeled	Types of practices included	Implementation guiding principles	Sediment process affected
Hill terrace improvement[1]	Slope correction on existing terracing, planting nitrogen-fixing hedgerow species along the terrace margins in single or multiple rows, agroforestry	Croplands > 5% slope. We assume that there are some existing terraces that are in moderately poor condition.	Sheet erosion
Soil & water conservation practices[1]	Hedgerows, hedgerow inter-cropping, crop residues, mulches, cover crops, no tillage, reduced tillage, minimum tillage, windbreaks/shelterbelts, buffer strips/greenbelts, conservation trenching, agroforestry	Croplands <= 5% slope. We assume there are some existing soil conservation practices in place but not currently very effective.	Sheet erosion
Landslide mitigation (class I)	Revegetating denuded slopes and/or bioengineering for slope stabilization	Areas with high risk of landslide failure at a depth of <1.5m and in the topsoil only.	Landslide-mobilized sediment
Landslide mitigation (class II)	Revegetating denuded slopes, bioengineering for slope stabilization, slope correction and/or excavation of sub-soil drains	Areas with high risk of landslide failure at a depth >1.5m, but deeper than topsoil and with failure plane in the range of deep rooting trees.	Landslide-mobilized sediment
Landslide mitigation (class III)	Bioengineering for slope stabilization, revegetating denuded slopes, sub-soil drainage and/or retaining walls	Areas with high risk of landslide failure in the bedrock (i.e. below rooting depth), but with a failure plane <3m deep.	Landslide-mobilized sediment
Reclamation/ rehabilitation of degraded land (forest[2])	Planting fuel and fodder tree species, conservation trenching, eyebrow pits, revegetation, hedgerow planting across the slope to regenerate degraded areas	Degraded forest lands (defined using data from (Hansen et al. 2013).	Sheet erosion
Reclamation/ rehabilitation of degraded land (grasslands[2])	Greenbelts, buffer strips, rotational grazing, fodder planting, silvopasture improvement	Grasslands	Sheet erosion

[1] The DoFSC also invests in civil structures (such as check dams, gully dams in combination with other interventions) to prevent erosion, regulate velocities and trap sediment along a streamlets and tributaries. These structures are often included along with other types of landscape treatments reported in the studies from which we draw model parameters and costs (such as those derived from the observed change in sediment loads post-treatment). Therefore, they are implicitly a part of these activities in that the modeled impacts would reflect their contribution to the change in sediment; however, engineering-only solutions such as check dams in isolation of other vegetative treatments are not considered in the modeling approach of this study.

[2] Note that the DoFSC does not distinguish in their reclamation of degraded land between these different types, but we separate them because modeling the impacts of these activities will differ depending on the land cover class.

Table - 3.2: Cost summary for interventions modeled

Intervention modeled	Cost (USD/ha)		
	Average	Min.	Max.
Soil & water conservation	$ 1,100	$ 140	$ 2,200
Hill terrace improvement	$ 2,230	$ 50	$ 8,750
Degraded forest rehabilitation	$ 1,690	$ 1,080	$ 2,310
Grazing land rehabilitation	$ 880	$ 730	$ 1,030
Landslide mitigation I1	$ 3,850	$ 1,260	$ 8,030
Landslide mitigation I2	$ 3,850	$ 1,260	$ 8,030
Landslide mitigation I3	$ 39,480	$ 19,450	$ 59,520

cost of a portfolio of activities will be estimated reasonably accurately as the sum of an average cost per hectare. Many of the costs indicated here may seem relatively high, but it should be noted that we report gross costs, while studies of similar interventions often discount the labor or other costs borne by landholders (thereby reporting only net costs). Our analysis shows that this cost-share is on average 84% of the gross costs – explained in detail in Section 3.3.6 – and when this is taken into account, the net figures are more in line with costs reported for similar World Bank projects.

3.3.2. Impacts on hillslope erosion

To represent the impact of each type of watershed management activity, parameters in the sediment delivery ratio model (SDR) are altered to reflect changes in the biophysical condition of the landscape caused by the intervention.

The interventions "hill terrace improvement", "soil and water conservation", "rehabilitating degraded forest", and "rehabilitation of grazing lands" were assumed to impact hillslope erosion. For these practices, model parameters relating to the vegetation cover (USLE C) and management practice factor (USLE P) were changed.

In the baseline sheet erosion (SDR) model, we assume that all croplands have some form of soil management in place, and that these are operating at average effectiveness. Field studies from the Himalayan region that reported a change in erosion and/or sediment export from implementation of similar types of activities were collected (see Appendix 5 for details). The management practice factor (USLE P) was given a value in the mid-range of literature-reported values to represent the baseline condition (meaning that the current practices employed are operating at average efficiency), and a value at the low end of reported values were assigned to the intervention scenario (indicating that improved practices would be operating at maximum efficiency).

The SDR model results are used to evaluate the total sediment loading to streams under the baseline and the intervention scenarios. The output of the SDR model is the loading to streams, which was further scaled by the fluvial transport ratio (95%; as explained in Section 3.2.5) to arrive at the amount of sediment avoided going into KGA.

3.3.3. Impacts on landslide-related risks

3.3.3.1. Physical impacts

It is challenging to quantify the impact of the selected landslide treatment strategies on the parameters of the landslide risk model, and therefore the values presented in this analysis are a first, expert-based attempt at the parameter estimation. Model parameters for all treated landslides are changed according to Table 3.3 below (e.g., for all landslides of type 1, we apply the appropriate mitigation measure), which then results in an increase in the factor of safety and a reduction in failure probability. Specifically, the reduction

Table - 3.3: Landslide classes, mitigation approach assumed and parameters impacted

Landslide class	Mitigation approach	Impacted parameters
1: Shallow top soil	Plantation of grass and coir netting on the entire landslide surface. Reforestation.	• Soil cohesion: Increase soil cohesion by 15 KPa (Vanacker et al. 2003)
2: Deep top soil	Reforestation. Slope correction and/or excavation of sub-soil drains.	• Soil cohesion: Increase by 10 KPa (Vanacker et al. 2003) • Saturation: decrease m by 20%[6]
3: Shallow bed rock	Excavation of deep drains	• Saturation: decrease m by 20%

in slope failure probability is either because of increased soil cohesion or increased drainage resulting in reduced soil saturation. See Appendix 2 for more details.

This change in probability of slope failure implies a reduction in the sediment load to rivers as well as the risk to lives, structures and property associated with those landslides. Therefore, the resulting change in LSO failure probability is evaluated by comparing the pre- and post-intervention model results to obtain the change in mobilized sediment. Avoided sediment produced as a result of landslide mitigation is reduced by 5% to account for deposition in the river channels and the resulting change in sediment is valued as a benefit for KGA (see Section 3.3.5). The 5% reduction is to account for the effect that not all sediment that has been mobilized from a landslide and reached the river channels will be transported through the river network (here we assume that a 5% fraction is deposited in the river channels based on our analysis of sediment transport in Section 3.2.5).

Finally, the modeled change in probability of LSO failure as a result of mitigation measures is applied to the values of lives and assets at risk, as described in the following section.

3.3.3.2. Economic impacts

Between 1971 and 2013 – a period that did not include the 2015 earthquake and the landslides it triggered – landslides in Nepal destroyed nearly 19,000 homes, damaged 132 schools and eight hospitals, destroyed 20,000 hectares of crops, covered nearly 400 kilometers of roads, and killed almost 5,000 people (UNISDR 2015).

It has not proved feasible to place an economic value on reduced landslide risks to all these end points. In this study, values associated with three of the most important benefits are estimated: lives lost, structures destroyed, and roads damaged.[7] A slightly different approach is taken to the valuation of each endpoint, and each of the three is treated in turn below. In each case we calculate the expected net present value in perpetuity, that is, the expected value of the loss/damage discounted over all future periods, and assumed to be terminated when a slide occurs, on the assumption there is no further risk at the same site.

Lives saved

A reduction in the probability of landslides occurring translates into an expectation of lives saved. Economists bring reductions in expected mortality risks into cost-benefit

[6] The reduction in soil saturation will depend on many local factors, such as soil type, slope, quality of the drainage works, etc., so we assume the 0.2 value. However, the effectiveness of drainage for landslide prevention and its modeling on watershed scales would merit more detailed studies and is left for future work. (Ortigao and Sayao 2004,p. 178) report changes in the factor of safety as a response to drain installation of horizontal drains. They report an increase in the factor of safety in the range of 10 to 40% as a result of reduced soil moisture in the same range. The assumed value of 20% is, hence, rather conservative. See also (Hutchinson 1977) for a detailed discussion of drain designs for slope stabilization.

[7] Damage to crops is not estimated, as the detailed data required were not available. Agricultural damages might be separated into components. First, there is the loss of the current year's crop. Second, there may be costs of restoring land on which a slide has occurred to bring it back into productive use. Such costs should also include loss of infrastructure, e.g., for irrigation, or destruction of terraces. Third, there may be a permanent loss of some land that could be used for growing crops. The value of the first component would depend on the stage of the growing season at which landslide damage occurred. Since a crop would only be destroyed in the field if it had not yet been harvested, at least the costs of harvesting would need to be subtracted from the gross value of the crop in calculating damages; if the crop were destroyed still earlier, costs of cultivation would also need to be subtracted. Quite extensive damage might result in the permanent loss of entire fields (Thapa and Paudel 2002), in which case land value would be an appropriate measure of the value at risk. Regrettably, data on agricultural land prices in Nepal are sparse and so location-specific as to make transferring them highly speculative.

analysis by estimating the "value of a statistical life" (VSL). The term is something of a misnomer; it might be better stated as the value individuals assign to a small change in the mortality risk they face (Cameron 2010). The VSL has been estimated by various researchers using a number of methods, including compensating wage differentials required to accept riskier jobs, "stated preference" surveys that ask respondents directly what they would pay to reduce the risk of death (or what payment they would accept to tolerate a higher risk of death), and studies of housing price differentials between more and less risky areas.

As the VSL may be interpreted as the "price of risk," valuing a reduction in risk is a relatively straightforward exercise once the more difficult tasks of determining how an intervention will reduce risk and assigning a VSL have been completed. It is then only a matter of multiplying the change in risk by the VSL. If the risk is calculated as a probability of dying in a landslide in any given year, the value of lives saved from such a risk reduction should be discounted to derive the net present value of the risk reduction over the entire period it is realized.[8]

We apply the value of a statistical life in Nepal that was estimated by a recent World Bank study relating to the costs of air pollution, arriving at a figure of US $34,565 (Sall, private communication; see also (Narain and Sall 2016) for a review of VSL estimation procedures). This estimate is conservative compared to some other research, (M. Shrestha 2016), and so the resulting values could be even higher under alternative assumptions.

It is also necessary to have an estimate of the number of lives at risk. There are no surveys that document the number of people living in areas susceptible to landslides. This study, however, maps the locations of structures at risk (see, e. g., Figure 3.2). There is also historical data recording both the numbers of structures destroyed and lives lost from landslides in Nepal over more than forty years (UNISDR 2015). The ratio of lives lost to structures destroyed in that data is very nearly one-to-four. The average area of a structure in the areas identified at risk from landslides is about 45 meters; hence it is supposed that one life will be at risk for every 180 ($= 4 \cdot 45$) square meters of structures at risk.

Structures

The analysis assumes that a structure hit by a landslide is damaged beyond repair, and the site on which it was located is lost to further use. The value of an asset is determined by the yearly return it provides – in the case of a structure, its rental value – divided by the required rate of return. The rate of return an owner requires to hold an asset at risk of destruction will sum the compensation required for waiting a year – the discount rate – and the probability of the asset's destruction during the year. This calculation is detailed in Box 3.8.

As noted above, the average structure at risk from destruction from a landslide occupies an area of about 45 square meters. The Nepal Central Bureau of Statistics' *Annual Household Survey* (CBS 2018) asks respondents to report either their actual rental payments or estimate the rental value of the home they occupy. In rural areas, the household expenditures on rent average 27,180 NPR (US $243). It is assumed that most of the houses at risk from landslides in our study area would be in rural areas, so this figure is taken as a representative rent for a structure at risk in the mostly rural Kali Gandaki watershed. It is not possible to distinguish types of structures from the data, except for the footprint of structures at risk, so the rental value of homes is applied to all. To account for homes of different sizes, average rent is divided by the average footprint of structures at risk in the data, 45 square meters, to arrive at an estimated rental value of 604 NPR (US $ 5.39) per square meter. It should be noted that this method will underestimate the value for structures with multiple stories and hence a larger area than what can be inferred from the footprint. While this is a very rough figure, it corresponds to a value of about 225,000 NPR (about US $ 2,000) for a house at a two percent annual landslide risk. This is broadly consistent with Nepal's *Post Disaster Recovery Framework* (Government of Nepal 2016) following the 2015 earthquake, which offered stipends of 200,000 NPR (US $ 1,786) "per eligible homeowner to assist with housing reconstruction or pay for construction of a small core house."

Roads

Roads in Nepal are often cleared and opened for use again after landslides occur. One study found that maintenance crews remove, on average, between 400 and 700 cubic

8. More complicated formulations might be proposed if the value a person assigned to her life varied with the probability with which she expected to be killed in a future landslide. Such complications are not considered here, as they would likely have little effect in practice.

9. Very large landslides might fully damage a road beyond repair, requiring either its abandonment or reconstruction elsewhere. However, such large landslides likely cannot be mitigated with the watershed management techniques proposed in this report, and their recovery is an engineering problem outside the scope of this study.

Box 3.8: Methods used for calculating the value of a structure at risk from destruction in a landslide

Methods & Tools 3.8: The value of a structure at risk from destruction in a landslide

The value of a structure at risk from destruction by a landslide is the earnings that could be realized from owning it this year – its rental value – plus its expected present value next year. Expected present value is calculated by discounting the future value of an asset and multiplying it by the probability that it survives until the next year. Suppose V_s is the value of a structure, *R* the rent it would command, collected at the end of the year, *d* the discount rate, and *P* the risk of its destruction by a landslide. Suppose all these parameters remain constant as long as the structure survives. Then the value of a structure at risk, designated V_S, will be

$$V_S = \frac{R}{1+d} + \frac{1-P}{1+d} V_S$$

or

$$V_S = \frac{R}{P+d}$$

The risk of destruction is like an increase in the discount rate, in terms of its effect on the value of the structure.

meters of landfall detritus annually from mountain roads (UNEP 2012). It may be more appropriate, then, to model the economic value of a reduced risk of landslides as a reduction in expected costs of repair, rather than as a loss of asset value, *per se*.[9] The expected cost of road repair in every year is the probability of a landslide occurring times the cost of repairing the section of road damaged. The expected net present value of repair costs can be derived by dividing this expected cost of road repair by the sum of the discount rate and the probability of a landslide (see Box 3.9).

The costs of repairing a segment of road that has been damaged by a landslide depends on a number of factors, including the topography of the area affected, the extent of the damage, and the quality to which the segment is to be restored. The cost of new road construction may be a reasonable proxy for the costs of repair, although they may vary considerably between different types of roads and different places. Expenses for several relatively high quality roads in Nepal have been estimated at between 600 thousand and eight million Nepali Rupees (US $5,357 – 71,430) per kilometer of road completed (Starkey, Tumbahangfe, and

Box 3.9: Methods used for calculating the value of a structure at risk from destruction in a landslide

Methods & Tools 3.9: Expected costs of road repairs from landslide

Suppose the cost of repairing a segment of road damaged by a landslide is C and the probability of such a landslide occurring is P. The discount rate is δ. Suppose also that, once a landslide has occurred on a segment of road, there is no further risk to that segment. The expected present value of landslide repair costs is, then, the probability that a landslide occurs this year, times the cost of repair, assumed to be paid at the end of the year, plus the discounted expected present value of landslide repair costs next year, weighted by the probability that the landslide has not yet occurred. If K denotes the expected present value of landslide repair costs, then

$$K = \frac{P}{1+\delta} C + \frac{1-P}{1+\delta} K,$$

or

$$K = \frac{PC}{P+\delta}$$

Sharma 2013; Devkota et al. 2014; Suresh Sharma and Maskay 1999).

The figures presented by (Starkey, Tumbahangfe, and Sharma 2013) was employed here, as they provide specifications that can be used to extrapolate to roads in other areas. They report costs of 3.9, 4.6, and 5.9 million NPR per kilometer to construct 4.5-meter-wide earthen roads in three different locations, each capable of supporting vehicle traffic at average speeds of between 70 and 80 kilometers per hour. Other roads may be more or less expensive depending on their specifications, of course, but these estimates provide a benchmark against which to calibrate other costs. Taking the average of the three cost estimates and adjusting them for inflation between 2013 and 2018, the cost becomes 6.35 million NPR (US $56,670) per kilometer of road damaged by landslide.

These figures are adjusted for the width of the road and topographical factors that will determine the volume of material that would need to be removed in the event of a landslide, as summarized in section 3.2.4 above and detailed in Appendix 3. The costs of repair are assumed to vary proportionally with the volume of material that must be removed to build or restore the road.

3.3.4. Impacts on carbon storage

Land management and rehabilitation practices such as those modeled in this study have been shown to increase aboveground carbon storage (by increasing woody vegetation, as through adoption of agroforestry practices; Cardinael et al. 2018), and improve soil organic carbon (SOC) stocks through enhancing soil organic matter and improving soil health (Dahal and Bajracharya 2013; Paudel et al. 2017). Furthermore, carbon stocks can also be preserved by rehabilitation activities that reduce the risk of landslides. In addition to the harm they cause to people and structures, landslides are also associated with carbon emissions because they expose carbon sequestered in soil to various atmospheric and hydrological processes that may allow that carbon to form greenhouse gases. Therefore, we evaluate the baseline carbon storage in the watershed, and estimate the impacts of watershed management activities on both (1) additional carbon stored through vegetation and soil management, and (2) avoided loss of carbon through mitigating landslide risk.

3.3.4.1. Carbon added via land management

We calculate total current carbon stock in soils, above- and below-ground biomass using the InVEST carbon (C) model (Sharp et al. 2014). The amount of C stored in each of these pools depends primarily on land use/land cover (LULC - e.g., forest, grassland, cultivation) but is also affected by land management practices (e.g., the existence of terracing or current tillage practices). We assign values of aboveground carbon stocks by LULC class (in Mg/ha) based on data provided in Ruesch and Gibbs (2008); for non-forest classes) and the Ministry of Forests and Soil Conservation National Forest Reference Level study (MoFSC 2016; for forest classes). Soil carbon stocks are taken from Dahal and Bajracharya (2012). The average of reported values for areas without sustainable soil management practices were assigned to croplands, grasslands, and orchards, while the average reported for forests was assigned to all forest classes. Baseline carbon stock values are given in Appendix 5. Our model assumed that carbon storage is a spatially-independent ecological process, that is, carbon dynamics are not affected by land cover and management practices in neighboring areas.

To calculate the carbon sequestration from watershed management interventions, we assume changes in above- and below-ground and soil organic carbon pools based on the type of land use land cover at the intervention site and the type of intervention. For soil and water conservation, hill terrace improvement, degraded forest rehabilitation, and degraded grazing land rehabilitation, we use data from Cardinael et al. (2018), which give a mean response ratio reflecting the ratio of soil organic carbon (SOC) before and after implementation of a variety of agroforestry practices (e.g. hedgerows, tree species intercropped with annual crops). These activities generally involve the planting of tree species, thereby increasing above- and below-ground carbon pools as well as SOC. SOC is by far the largest carbon pool in any of the relevant land classes, so the response ratios from Cardinael et al. (2018) were multiplied by the total baseline carbon pool to give the post-intervention carbon storage.

The benefits associated with watershed management actions will in reality take some time to reach full effectiveness, generally on the order of 10 – 20 years, depending on the intervention (Vogl et al. 2017). The post-intervention carbon storage was therefore adjusted to account for the fact that the benefit stream is not constant, but rather follows a trajectory that reaches 100% of the modeled benefit after a certain number of years. For simplicity and in the absence of more refined agronomic and soil data, we assume a linear trajectory from zero to full benefits after 20 years. We therefore scale the post-intervention carbon storage values by 0.43.

3.3.4.2. Avoided carbon losses in landslides

We assume that over any given time period, reducing the risk of landslides will reduce the present value of emissions due to those landslides, through a combination of lowering overall risk and from the effect of discounting as the reduced risk shifts the expected time to failure farther out into the future. This section explains these dynamics in more detail.

First, as elsewhere, we assume that:

1) A potential landslide object (LSO) has an average annual probability of sliding in the absence of treatment.
2) Landslide mitigation activities reduce this baseline average annual probability by some amount.
3) The occurrence of a landslide is an "attracting state" -- that is, once it is reached, the average annual probabilities of a slide no longer apply.
4) Landslide mitigation benefits take immediate effect from the time of treatment.

Together, these assumptions imply the probability of a landslide occurring in any specific year is the average annual probability, scaled down by the probability that no slide has occurred prior to that year.

We also need to make assumptions regarding the fate of the carbon conditional on a slide occurring. In reality, the fate of carbon in a landslide is highly uncertain and dependent on the site-specific conditions. One extreme would be that all carbon becomes oxidized immediately in that year. The opposite (also unlikely) possibility is that all carbon remains effectively sequestered due to immediate regrowth and protection from dense vegetation. As an intermediate assumption, we model the carbon as exponentially decaying from the landslides – that is, a certain fraction of the remaining carbon becomes carbon dioxide each year, once the landslide has occurred.

More precisely, each year is associated with an exponential decay emissions trajectory $E(t \mid t_L)$, which gives the emissions in year t conditional on the landslide occurring in year t_L:

$$E(t \mid t_L) = r\,[C_0 (1 - r)^{(t - t_L - 1)}]$$

Where the term in brackets is the carbon remaining at the start of year t, with C_0 being the initial carbon stock in the landslide object. (Implicitly, all emissions prior to the landslide occurring are zero.)

The climate damages D conditional on a landslide occurring in year t_L are simply found by multiplying the emissions trajectory by the social cost of carbon (SCC) and discounting:

$$D(t_L) = \sum_{t = t_L}^{T} SCC_t\, E(t \mid t_L)(1 + \delta)^{-t}$$

This value above is not dependent on the watershed management scenario. Rather, the impact of a watershed management scenario is manifested in the probabilities of a slide, which are used to create the total expected damages within a particular scenario:

$$D_{SCEN} = \sum_{t=0}^{T} \rho_{SCEN}(t_L = t)\, D(t_L)$$

That is, the damages are the present value of the damages in a particular year, multiplied by the scenario-specific probability of a landslide in that year, and summed over all future years.

The present value of the climate benefit associated with a management scenario is the difference in climate damages with no treatment and those with treatment:

$$PV_{CLIM} = D_{BASE} - D_{CAT}$$

Because the above framework is linear in both the initial carbon stock and the social cost of carbon, we estimated a multiplier for how carbon contained in landslide objects within the watershed should be translated to monetized benefits from avoided carbon emissions. We use a background average failure probability of 0.05, taken from the baseline model output, and a decay rate of carbon following a landslide of 0.2, resulting in a final benefits scalar of between 0.0024 and 0.011 (depending on the scenario and the modeled change in landslide risk), which was applied to the avoided carbon loss from landslide mitigation activities.

Therefore, assuming a constant social cost of carbon, the climate benefits of landslide risk mitigation are then calculated as:

$$PV_{CLIM} = \text{benefits scalar} \cdot SCC \cdot C_0$$

This approach assume that all carbon contained in the landslide object, including (previously) live biomass as well as soil carbon, decays to the atmosphere at a rate of 20% per year once a landslide has occurred, due to the exposure of previously sequestered soil carbon and the burial of existing vegetation. There are many complex dynamics associated with carbon fluxes that were not feasible to model, so these numbers should be treated as notional values that enable a rough estimate of the potential magnitude of this benefit stream.

3.3.4.3. Economic value of carbon

The above methods result in estimates of carbon either stored additionally or as loss avoided from each watershed intervention scenario. We calculate the value of this carbon benefit by using estimates of the social cost of carbon from the 2017 report of the High-Level Commission on Carbon Prices (Stiglitz et al. 2017). While carbon pricing is unavoidably imprecise (see, e. g, EPA 2017, which presents estimates of value spanning an order of magnitude) and controversial (see, e. g., (Editors, Journal of Economic Perspectives 2015; Tol 2009, 2014), it is useful to have some monetary estimate of climate-related benefits. The High-Level Commission's results were endorsed in a November 2017 World Bank guidance note on "Shadow Price of Carbon in Economic Analysis" (World Bank 2017). The Commission report recommended using prices ranging between US$40 and 80 per ton of CO_{2e} in 2020, rising to $50 – 100 per ton in 2030. The Bank's guidance note also recommended continuing to extrapolate results from 2030 to 2050 at the 2.25% annual rate of growth projected in the Commission report for 2020 – 2030. This would result in a range of values between US $78 and $156 per ton in 2050. In this analysis, we follow the guidance of the High-Level Commission on Carbon Prices and use a mid-range estimate of US $60 with $40 taken as a lower bound, and $80 as an upper bound.

3.3.5. Hydropower benefits

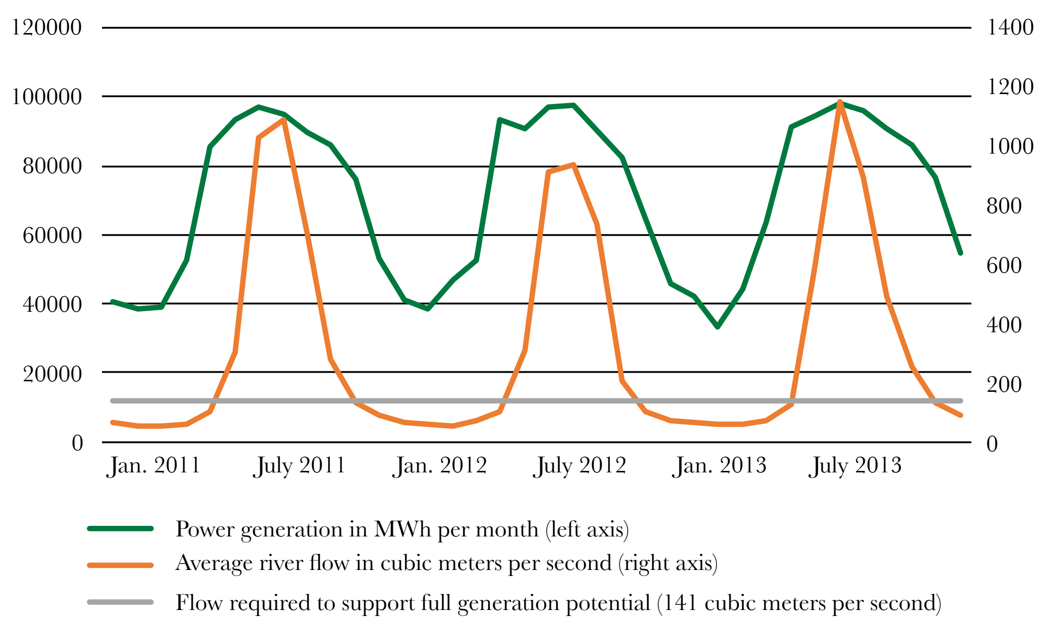
The effects of sediment on hydropower operations at KGA differ by season. Hydropower operations are greatly affected by the rate of water flow in the river. The capacity of the plant is 144 MW, which is designed to be achieved at a maximum flow rate of 141 m^3/s. For roughly half the year, in the months during and following the monsoon, this flow is available. During the winter and early spring months, however, the flow declines, and it is not possible to sustain generation at full power. Figure 3.4 depicts this pattern over a three-year period.

From the late spring through the fall, water is plentiful. This means sediment transport is also high. The concentration of sand in water increases dramatically with the velocity of flow in the river (Morris 2014). This is illustrated in Figure 3.5.[10] Comparing Figure 3.4 and Figure 3.5, peak water flow occurs in the mid-summer months, when sand concentration also peaks.

Water-borne sand has two related effects. First, it abrades the turbines and other equipment at the plant, reducing operating efficiency and necessitating their repair. Second, it increases the costs of operating the desanding basins[11] that were designed to intercept and retain much of the sand that would otherwise pass through the generating equipment.

During the winter and early spring months, flow in the river is below the level required to achieve the plant's maximum generation potential of 144 MW. At these times, the plant makes use of its limited storage capacity. By filling the reservoir at times of day when the demand for power is

Figure - 3.4: Power generation and river flow at KGA

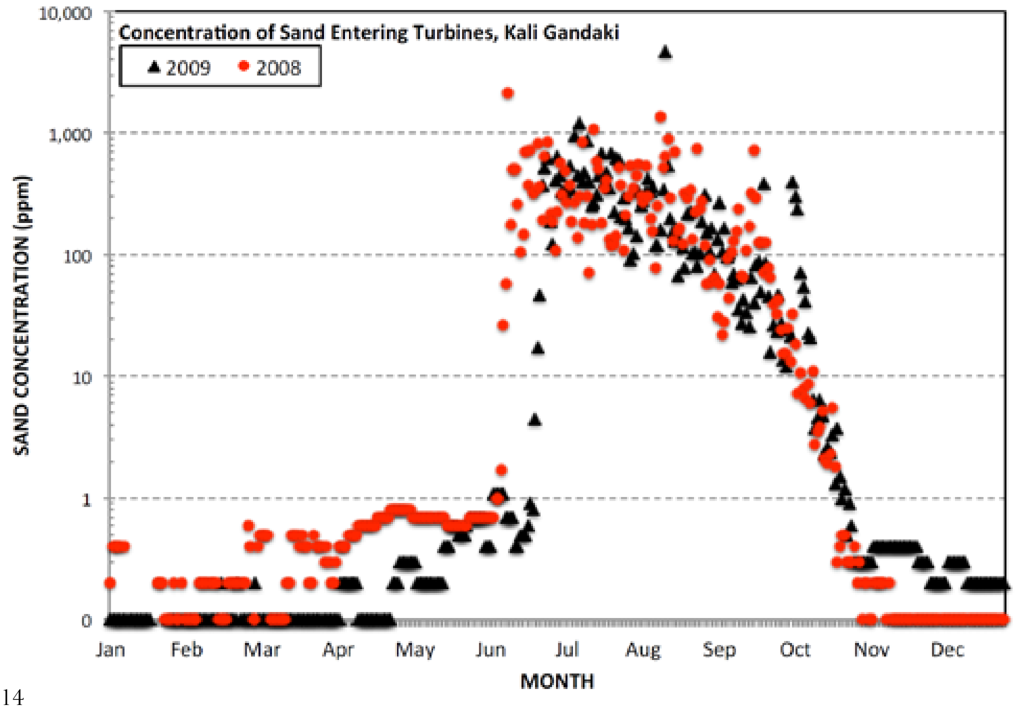


Source: Adapted from Chhetry and Rana (2015)

10. Note that the vertical scale in Figure 3.5 is logarithmic: each horizontal line marks an order of magnitude increase.

11. While different terms have been used for these structures, such as "silt traps" or "settling basins", we chose "desanding basins", as it seemed to be the term most commonly employed.

Figure - 3.5: Sand concentration entering turbines by month



Source: Morris 2014

relatively low, the operator may make use of the storage to time the discharge of water for power generation during the hours when it is more valuable. Accumulation of sediment in the reservoir reduces storage and thereby restricts the operator's ability to generate power when its value is greatest.

The remainder of this section will give an overview of the methods used for estimating these different seasonal benefits of sediment reduction.

3.3.5.1. Avoided costs and damages

Reducing the amount of sediment in the water that is diverted from KGA for power generation will result in two economic benefits. First, there will be *avoided damages.* Less hard, coarse sediment passing through the generating equipment means less abrasion. This, in turn, means that the turbines will generate more electricity per cubic meter of water flow through them, they will be less likely to break down, and they may require less frequent maintenance.

The challenges presented in operating a hydroelectric plant on a river with high sediment loads have been recognized since the design phase of KGA. The plant was equipped with two large desanding basins intended to trap and remove particles that could otherwise damage its generating equipment. It is costly to operate these desanding basins, however. The second benefit of reducing sediment concentration in the water diverted for generation is the avoided cost of operating the desanding basins.

Ideally, avoided damages and avoided costs associated with reduced sediment concentration would each be estimated with straightforward procedures. Damage would be measured by the reduction in operating efficiency resulting from abrasion, and abrasion would be related to sediment concentration.[12] This approach would require data relating sand concentration in the river to abrasion of turbine parts, as well as data relating abrasion of turbine parts to reduction in efficiency. However, these data sets were not available to

12. Reduced abrasion might also reduce maintenance costs if equipment that had suffered less damage needed to be repaired less frequently. Because of the seasonal variation in river flow and, hence, the possibilities for power generation, however, reductions in sediment delivery are unlikely to affect the maintenance schedule. Each of the three generating units at KGA is generally overhauled on a once-every-third-year rotation, with the work planned to occur during the dry season of the year, when water flow is not sufficient to use all three units at full capacity. Because the opportunity cost of having a turbine out of service for overhaul for several weeks when flows are high are substantial, large reductions in sediment would likely be required to motivate a delay in maintenance from one year's dry season until the next.

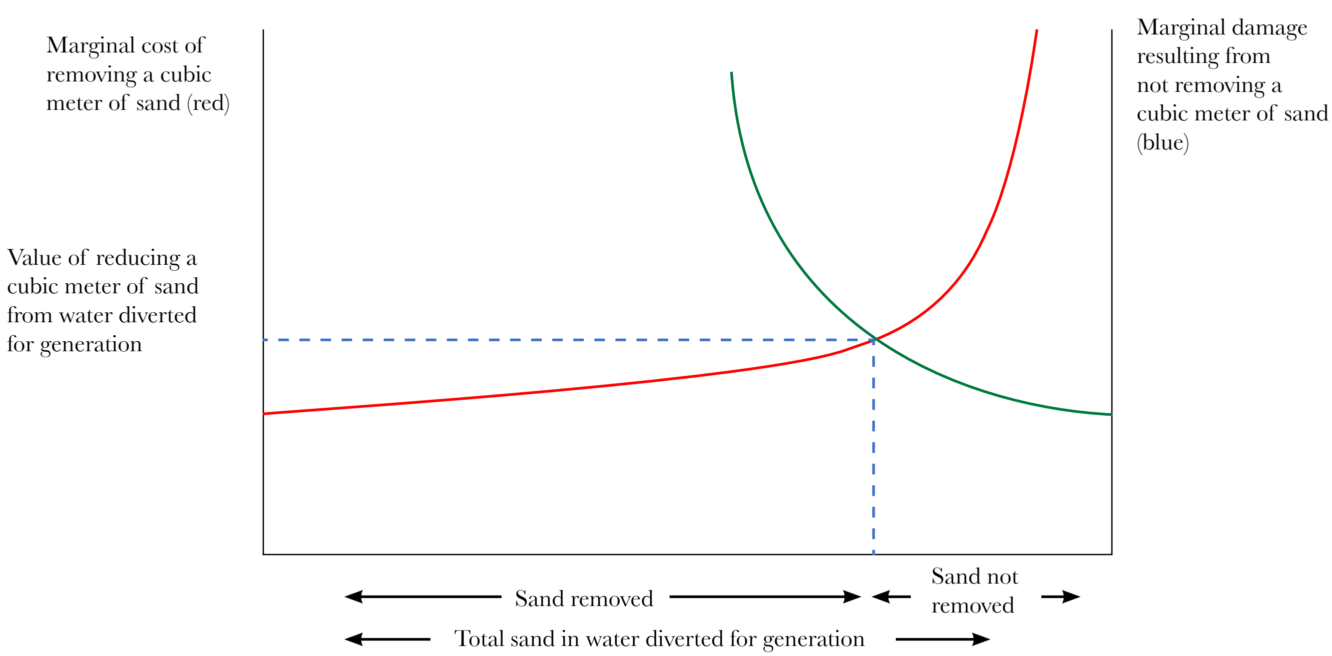
estimate avoided damages. An indirect procedure has, then, been adopted.[13]

This indirect procedure exploits the relationship between avoided damages and avoided costs. A detailed explanation of this procedure is given in Appendix 4, but the intuition underlying it may be explained using some simple economic ideas. Avoided costs and avoided damages are linked, in that the dam operator strikes a tradeoff between the two. It would be prohibitively expensive to prevent any sediment from reaching the generating equipment. Conversely, if no expense were incurred, little if any sediment would be prevented from causing damage. Both the cost and effectiveness of the desanding basins depend on the amount of sand that accumulates in them between flushes. They become less effective as more sediment accumulates in them. The operator could remove more sand by flushing the basins more frequently, and hence spare the turbines some damage. This would mean, however, that customers would be provided with less power while the basins are flushed. Conversely, the operator could generate a steadier supply of power if the desanding basins were flushed less frequently, but this would mean that less sand would be removed before it passed through the generating equipment, and the resultant increase in abrasion would reduce operating efficiency more rapidly.

The operator would, then, flush the desanding basins following a rule under which the marginal avoided damage from an additional cubic meter of sediment passing through the generating equipment would just balance the marginal avoided cost of removing that cubic meter of sediment via the desanding basins. This outcome is depicted in Figure 3.6.

There are two axes in Figure 3.6. The left axis indicates the marginal cost of removing a cubic meter of sand from water diverted for generation by more frequent flushing of the desanding basins. The red curve, which rises from left to right, represents the marginal cost of sand removal. The right axis in Figure 3.6 indicates the marginal damage from not removing a cubic meter of sand, i.e., from allowing that cubic meter to pass through the turbines. The blue curve, which rises from right to left, represents marginal damage. The sum of costs and damages will be minimized when the

Figure - 3.6: Conceptual representation of operating the desanding basins to minimize the sum of costs and damages



[13] Two different indirect approaches were, in fact, developed. In addition to the procedure reported below, avoided damages were also inferred from a procedure that asked "how much damage must be occurring every year in order to make the observed every-third-year maintenance schedule optimal?" However, data limitations and other considerations made the results of this exercise less reliable than those of the alternative approach reported here.

marginal value of each is the same, as represented by the point where the red and blue curves cross. The volume of sand removed in this efficient outcome is measured from left to right on the horizontal axis, and the volume of sand not removed and, consequently, passed through the generating equipment is measured from right to left. The volume of sand removed plus the volume of sand not removed must, of course, be equal to the total volume of sand present in water diverted for generation, as represented by the distance between the two vertical axes.

The procedure adopted for estimating the avoided costs and avoided damage from a reduction in sediment involves characterizing the conditions under which the marginal cost of sand removal and the marginal damage from sand that is not removed are equal; that is, characterizing the conditions under which the red and blue curves in Figure 3.6 cross. Such conditions can be represented as a function of three variables:

1. The cost of flushing the desanding basins,[14] as calculated from the value of power generation forgone during the time required for flushing;
2. The volume of sand allowed to accumulate before flushing, as reported in dam operating practices;
3. The fraction of sand captured and removed, and, by implication, the fraction that is not removed, as recorded in studies of dam operations.

Flushing is only necessary during the high-flow periods when sediment concentrations are high. It can, however, be timed to occur in off-peak periods when the opportunity cost of forgone power is relatively low. A value of 6 NPR (US $ 0.054) per kWh is assigned for the value of generation forgone during flushing (see Annex 4 for details). The basins are flushed sequentially, so power can be produced at half of full capacity using flow through one basin while the other is being flushed. During the nine hours the basins are flushed, then, about $\frac{1}{2} \cdot 9$ hours $\cdot$ 144 MW = 648 MWh of power generation is forgone, at an opportunity cost of $648{,}000 \cdot 6$ = 3.89 million NPR (US $ 34,730) per flush. Labor or other costs of flushing are not estimated for lack of data. These are felt to be small compared to the opportunity costs of forgone generation, however.

The parallel desanding basins at KGA are each 187 meters long and 40 meters wide (Bishwakarma 2012). They are flushed when the depth of sediment accumulated in them reaches three meters. Thus, a volume of $187 \cdot 40 \cdot 3 \cdot 2 =$ 44,880 m^3 of material is removed with each flush.[15]

Finally the fraction of sediment removed is taken as 0.733, in accordance with estimates of removal efficiency from an International Hydropower Association study of KGA (IHA, n.d.). This estimate is also broadly consistent with the figures on the volume of material removed per flush, information provided by NEA on the frequency of flushing, and estimates of the volume of sand transported in the river (Morris 2014).[16]

Details of the calculations applied are given in Appendix 4, and results of these calculations are reported in Section 4.2.2.

3.3.5.2. Retention of peaking capacity

While it is often described as a run-of-the-river plant, KGA was designed to have more than three million cubic meters of live storage. This is sometimes described as "six hour peaking capacity" (Morris 2014). The three million cubic meters would be sufficient to operate the plant at full generating capacity (corresponding to 141 m^3/s, or a little over half a million cubic meters per hour) for about six hours.

The storage capacity of the reservoir has declined over time. As documented in the previous sections, approximately 35 million tons of sediment flow down the Kali Gandaki. This flow was enough to fill the reservoir's dead storage (the volume below its hydroelectric intakes) before the plant began commercial operation (Morris, 2014). The annual flow of sediment would be enough to fill live storage several times over if it were all retained in the reservoir. Because flows are rapid when sediment concentrations are greatest, however, most sediment remains suspended, and is transported out of the reservoir, either by releases over the spillway or, as discussed in 3.3.5.1, by being flushed from the desanding basins or passed through the generating equipment.

While only a small fraction of the annual sediment load is retained in the reservoir (IHA, n.d.),[17] NEA personnel report

[14] The cost of flushing the desanding basins is not identical with the cost of removing sand, as the latter reflects changes in the efficiency of removal resulting from difference in the frequency of flushing.

[15] As flushing occurs when river flow is high, and all flushed sediments would eventually have made their way downriver, there are few if any downriver costs associated with flushing.

[16] While finer and lighter sediments may not be removed as efficiently in the desanding basins, they are of less concern, as they tend to be less abrasive.

[17] At 1.5 tons per cubic meter, some 22 million cubic meters of sediment are transported through the Kali Gandaki Dam yearly. If as much as one percent of this load had settled in the reservoir during the dam's seventeen years of operation, the reservoir would now be completely filled.

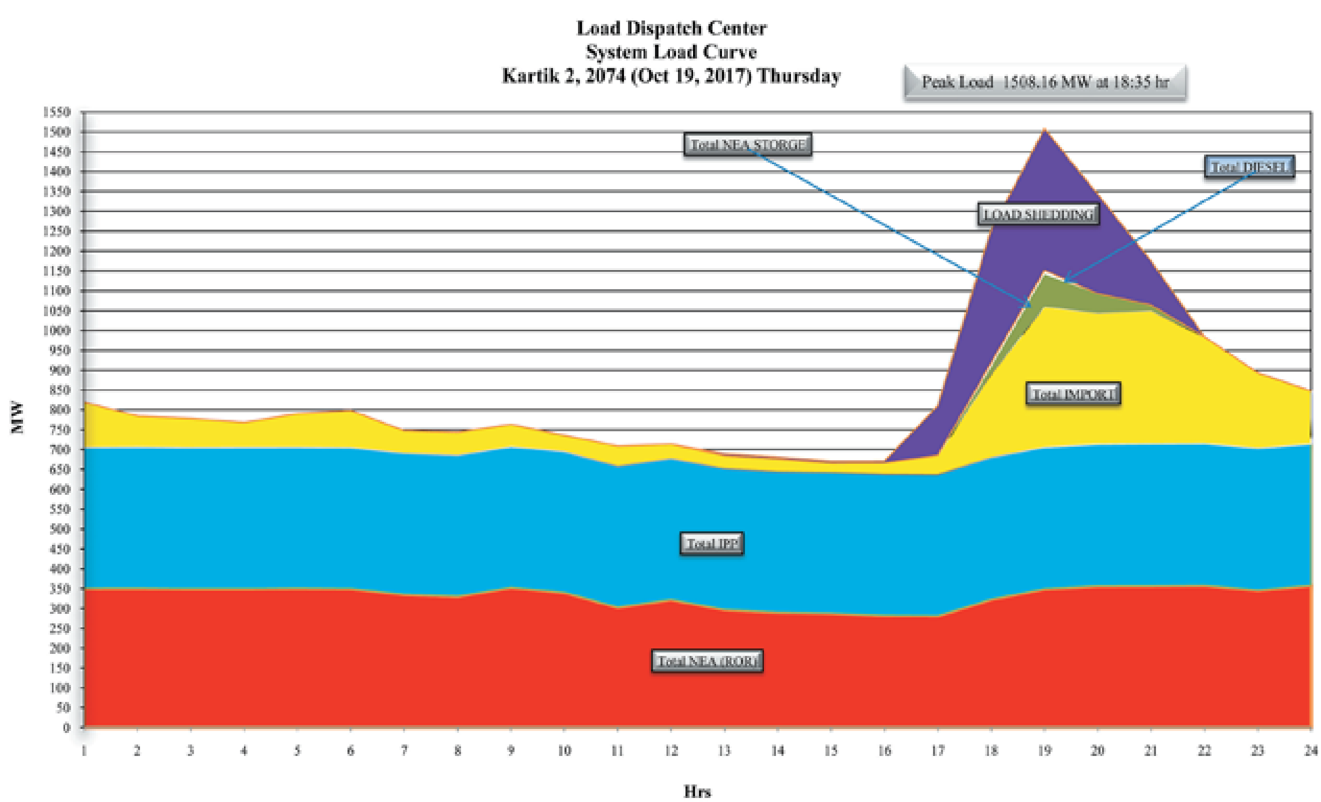
that this has, over time, reduced live storage, an observation confirmed by bathymetric measurements (Morris, 2014). It has also motivated management efforts to prevent further accumulation (Morris, 2014). Retention of reservoir capacity may provide benefits, then, both in terms of the availability of storage to meet peak demand and avoided costs of preventing further losses.

Appendix 4 presents a detailed analysis of the value of reduced sediment load as it relates to retention of reservoir storage capacity. That analysis may be summarized as follows. Reservoir capacity is only needed during the dry season, when flow in the Kali Gandaki River is insufficient to support power generation at the designed maximum flow rate of 141 cubic meters per second. During and after the annual monsoon, flow may be several times this rate (see Figure 3.4 above). When flow is below the rate required to support maximum generation, the total amount of power that can be generated over the course of a day depends on the total volume of flow in the river over the day. The limited storage capacity of the reservoir does not determine *how much* power can be produced. Rather, storage capacity allows the plant operator to determine *when* during the day the fixed amount of power production the water flow in the river will allow is generated.

Power demand in Nepal shows marked variation over the course of a day. Figure 3.7 shows a daily load curve for Nepal. Demand peaks in the evening hours between about 5:00 and 11:00 pm. When it is possible, the dam operator would prefer to store water during the lower demand periods of the mid-day and have it available to generate power when consumers demand more.

Reservoir capacity allows such intertemporal switching from low- to high-demand periods. During lower-demand periods less water can be discharged than flows in and, consequently, less electricity will be generated. By refilling the reservoir, however, the water that is flowing in at the time may be discharged later in the day, generating more power when it is more valuable. This underscores the basic principle of valuing reservoir capacity. The value of an extra cubic meter of reservoir capacity is the difference between the value of power at peak and off-peak periods.[18] It is the difference between the value consumers get from a little electricity provided when they value it more and the value they forgo

Figure - 3.7: Daily electricity demand (NEA 2018)



18. It might also be possible to derive this value from the monetary or opportunity costs the dam operator would incur to restore a marginal cubic meter of capacity. If the dam is operated optimally, however, this procedure should give the same result; see Appendix 4.

by having a little less electricity generated when water is kept in storage rather than used for off-peak generation.

Figure 3.7 also suggests a reason for which the estimation of this difference in values may be challenging. The purple-shaded peak in the figure is labeled "load shedding". At many times the quantity of power demanded in Nepal has exceeded system supply. At such times the rates paid by consumers for the power they purchase may not reflect how much they would be willing to pay to purchase more power, if it were available[19]. This presents challenges for the estimation of the value of power during periods of shortage. These challenges are addressed in more detail in Appendix 4. In short, a figure of 12 NPR (US $0.108) per kWh is adopted for the value of peak power, based on NEA tariffs and some additional considerations as detailed in Appendix 4. The resulting difference between peak and off-peak values is 6 NPR (US $ 0.054) per kWh.

This figure must be multiplied by the number of days in a year (assumed to be 180) during which reservoir capacity constrains operations, and a conversion factor giving the amount of electricity produced per cubic meter of flow through the turbines (0.284 kWh/m^3). Finally, as in all the analyses conducted for this report, a discount rate of 10% is applied to arrive at a net present value.

3.3.6. Local (on-site) benefits

Section 1 discusses the various benefits that might arise from management interventions implemented on crop, pasture, and forest lands. The costs of watershed management are typically borne by the owners and users of the land on which the soil conservation and related practices are implemented. The benefits of such practices might accrue both to the people implementing them and to downstream beneficiaries. The previous sections have largely considered downstream benefits: sedimentation of reservoirs, damage to power generating equipment, and risks to lives and property from landslides. However, landowners may also realize substantial benefits from erosion control measures they adopt.

A number of studies have been undertaken to estimate economic benefits associated with sustainable land management programs. The World Bank has appraised many proposed watershed management projects that consider many of the same activities contemplated for Nepal, including appraisals of proposed projects in Ethiopia (World Bank 2008), Nigeria (World Bank 2018a), the countries of the Eastern Nile Basin (World Bank 2009a), China (World Bank 2009b), and several states in India (World Bank 2012, 2005, 2014). They include implementation or enhancements of terraces; hedgerows, trenches, eyebrow pits and bunds; planting of grasses, trees, and other vegetation; and reform of grazing management. These programs were generally motivated by an appreciation not just of the benefits that might arise from physically implementing them, but also of the need for institutional reforms to achieve benefits landowners had not realized on their own. That is, there may be many reasons why landholders are not adopting such practices voluntarily, but policies are needed to better align incentives and overcome barriers to adoption (a broader discussion of this topic is given in Section 5). Moreover, each of the project appraisals note substantial on-site benefits of better land management. Several predict substantial improvements in agricultural productivity as a result of program implementation. All of the appraisals project benefits in excess of costs. In fact, some of the World Bank Project Appraisal Documents relied *only* on the agricultural benefits of land management practices in their cost-benefit analyses (e. g., World Bank 2009a, 2008).

It would not be surprising, then, to find that substantial on-site benefits would be associated with sustainable land management practices in Nepal, since such benefits have been identified for other countries at a similar income level that have adopted similar sets of measures. However, we have identified few detailed cost-benefit analyses of sustainable land management measures adopted for Nepal (an exception is Das and Bauer (2012), which finds that hedgerow planting and minimum tillage practices have a positive benefit-cost ratio at a discount rate of 10%).

Another set of data does afford some insight into the magnitude of benefits likely to be realized by land users when terracing, hedgerows, reforestation, improved grazing management, and other sustainable land management strategies are adopted, however. The World Overview of Conservation Approaches and Technologies (WOCAT) Sustainable Land Management database contains data on the costs of establishing and maintaining a number of different land management practices. It lists information drawn from almost 2,000 examples from over 130 countries, including several dozen from Nepal.

19. This may be true at other times, as well, since unlike in a competitive market, what consumers are willing to pay for power may not reflect the full societal cost of providing that power. This issue is discussed in more detail in Appendix 4.

In Table 3.4, cost data on the types of land management practices that could be used to control erosion in the Kali Gandaki watershed have been assembled from eleven WOCAT studies (nine in Nepal, and another two in neighboring India). The column headed "Total NPV of gross cost" gives the net present value (NPV) of establishing and maintaining the indicated practice. The WOCAT data generally break down costs by labor, materials, and other expenses, and report them for both the one-off costs of establishing a practice and the ongoing costs of its maintenance. The latter were discounted at 10% per annum (Table 3.4).

These eleven studies are particularly useful for present purposes because they also contain information on the share of costs borne by local landholders. The second-to-last column in Table 3.4 is labeled as "benefits implied by land users' cost share". As participation in the programs is voluntary, the benefits the users perceive they will gain must be at least as great as the costs they would bear from establishing and/or maintaining the indicated practices. Local users' cost shares are also broken out by establishment and maintenance costs in the data. On average, local users bear about 84 percent of the costs of these practices.

The costs reported in Table 3.4 are, then, multiplied by the factor of 0.84 identified above, on the assumption that cost-bearing share is representative of the broader set of cost data available. We then use these impute on-site benefits of the interventions modeled in the benefit-cost calculations reported below.

Table - 3.4: Costs to implement various watershed management activities and benefits to landholders implied based on reported cost sharing

Practice	Location	Total NPV of gross cost (US$ per ha)	Benefits implied by land users' cost share	B/C ratio implied by users' benefits alone
Terrace	Nepal	$ 8,746	$ 7,581	0.87
Ditches, bunds, tree and grass planting	Nepal	$ 5,598	$ 4,301	0.77
Hedgerows	Nepal	$ 1,361	$ 1,361	1.00
Contour bunding	Nepal	$ 52	$ 52	1.00
Contour trench/bund	India	$ 1,075	$ 323	0.30
Gully plugging with check dams and bamboo planting	Nepal	$ 725	$ 725	1.00
Controlled gullying by building retaining walls and plantings	Nepal	$ 69	$ 69	1.00
Riverbank protection by check dams and grass and bamboo planting	Nepal	$ 5,391	$ 4,053	0.75
Hedgerows, eyebrow pits and trenches, planting trees and grasses	Nepal	$ 1,029	$ 1,029	1.00
Fodder cultivation on terraces, abandoned agricultural land	Nepal	$ 2,203	$ 2,203	1.00
Contour trenches, tree and grass planting	India	$ 2,308	$ 1,330	0.58

3.4. WHERE TO INTERVENE? PRIORITIZING WATERSHED MANAGEMENT ACTIVITIES AND LOCATIONS

The first step in prioritizing where different activities should be implemented is to understand where in the watershed each activity can be most effective to achieve a set of objectives, and then use a multi-dimensional optimization approach to identify a set of optimal portfolios of interventions that maximize objectives at minimal cost. The objectives used in the optimization are listed in Table 3.5.

We divide the study area into 821 hydrologically-defined sub-watersheds, with an average size of approximately 900 ha. Based on stakeholder consultations with DoFSC, this is roughly the size of the individual micro-watersheds that DoFSC typically addresses through their current watershed management programs. Each of these sub-watersheds becomes a "decision unit" – spatial regions representing the smallest area on which an activity (or group of activities) will be implemented. While it is technically possible to optimize activities at a pixel scale, that level of precision does not align well with the underlying model assumptions, nor is it a feasible unit to implement activities under a community-based watershed management program.

To evaluate each activity's effectiveness in different locations, a series of hypothetical "full implementation" scenarios are created one activity at a time, to represent the landscape as if the activity were implemented everywhere it is possible. We also generated scenarios to represent combinations of activities (for example, hill terrace improvement, soil and water conservation, and forest rehabilitation are simultaneously implemented wherever they are possible). Each scenario is then run through the relevant model (SDR or landslide) and the total change is estimated for each of the objectives in each of the 821 sub-watersheds.

An optimization approach was deemed to be appropriate for this study, because it allows for development of investment portfolios that meet multiple objectives, and explicitly reports on trade-offs that exist when prioritizing one kind of benefit over another. Another approach would be to simply rank the sub-watersheds and activities in terms of the highest benefit per unit cost, and to select the areas with the highest benefit sequentially until a given budget is exhausted. However, this method requires that the metric to maximize is selected a *priori* and does not allow for explicit examination of trade-offs inherent in making that decision.

For this analysis, the Natural Capital Project's ROOT tool is applied to perform the optimization (Beatty et al. 2018; Gourevitch et al. 2016). ROOT first summarizes the

Table - 3.5: Objectives used to prioritize watershed management activities and locations

Objective	Unit	Beneficiary	Valuation approach
On-farm benefits of soil retention	Tons of sediment/yr	Local landholders	Revealed preference based on reported cost-share from similar programs
Avoided sediment reaching Kaligandaki reservoir	Tons of sediment/yr	KGA hydropower plant	Avoided damage Avoided costs of desanding Peaking capacity maintained
Avoided lives lost from landslides	USD	People at risk from landslides	Value of statistical life
Avoided damages to structures	USD	Structures and associated communities at risk from landslides	Rental rate
Avoided repairs to roads	USD	Dept of Roads, VDCs and communities at risk from landslides	Avoided repair costs
Added carbon storage	Metric tons	National (e.g. REDD+ program), Global	Social cost of carbon in 2020

marginal value of each activity within each sub-watershed into a table. For each of the potential management options, the table contains the value to each objective for each sub-watershed (calculated as the sum of pixel-level marginal values within each sub-watershed).

ROOT implements the optimization using binary integer programming. Formally, the problem is to find the optimal $\vec{x}_{ij}$, where the value of each x_{ij} is 1 if management option j is chosen for sub-watershed i and 0 if it is not. If all the x_{ij}'s are zero for a given sub-watershed, then the choice is to maintain current (baseline) land use.

The optimization problem is

$$\min_{\vec{x}_{ij}} C(\vec{x}_{ij})$$

such that

$$V_s(\vec{x}_{ij}) > T_s$$

where

$$C(\vec{x}_{ij})$$

is the total cost of the selected management options.

$$V_s(\vec{x}_{ij})$$

is the value to objective s of the management choice. The value is given in terms of avoided sediment, avoided damages, etc. (column 2 in Table 3.5 above).

T_s is the target value for each objective *s*. Here we use the target to constrain the cost, representing different levels of investment in a watershed management program. We ran the optimization at a budget constraint ranging from US $500,000 US $50M. At each of these budget scenarios, a portfolio of interventions was generated with the objective of maximizing the monetized benefits of sediment retention, avoided loss of structures, avoided road repairs, and avoided loss of life. After portfolios were generated, on-farm benefits and the value carbon sequestration were calculated.

The results show the optimal portfolio of interventions for a given budget, by identifying which sub-watersheds should be selected for which intervention to maximize benefits and minimize costs. We also identify intervention portfolios using different weights on the objectives, to demonstrate how the targeting of watershed management activities might change depending on whether the program prioritizes sediment reduction, landslide risk mitigation, or reducing on-site erosion, for example. The model also outputs an agreement map, showing how often each spatial decision unit (SDU) is chosen for a particular activity, regardless of the weight given to different objectives.

3.5. SUMMARY OF DATA REQUIREMENTS

Table - 3.6: Sources and descriptions of data used in this study

Data type	Description	Format/resolution	Source
General landscape characteristics			
Elevation	ASTER Digital elevation model	GeoTIFF, 30m resolution	METI/NASA: https://asterweb.jpl.nasa.gov/gdem.asp
Land use and land cover	Nepal national land use/land cover, year 2000	GeoTIFF, 30m resolution	Nepal Department of Survey
Cropping patterns	District data on land use and crops grown in the district	Table of values by district	Nepal Department of Irrigation
Degraded forest lands	Forest loss/disturbance/change occurring between years 2000-2018	GeoTIFF, 30m resolution	Hansen/UMD/Google/USGS/NASA Global Forest Change 2000–2018, version 1.6. https://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.6.html
Hillslope erosion			
Rainfall erosivity	A measure of the intensity of rainfall, estimated from annual precipitation data	GeoTIFF, 1km resolution	Rainfall data: WorldClim Version 2 current; Erosivity calculation from FAO Soils Bulletin 70, Roose (1996)
Soil erodibility	Soil property based on texture, indicating how easily the soil detaches to become erosion	GeoTIFF, 1km resolution	ISRIC Soil Grids - https://www.isric.org/explore/soilgrids
USLE C factor	Erosion potential factor based on vegetation type	Unitless, mapped to land use/land cover	A variety of published literature sources - See Appendix 5
USLE P factor	Support practice factor based on management practice type	Unitless, mapped to land use/land cover	A variety of published literature sources - See Appendix 5
Glacial erosion			
Precipitation	10-year time series of daily rainfall from national weather stations	Point data	Nepal Department of Hydrology and Meteorology (DHM)

Data type	Description	Format/resolution	Source
Location of glaciers	Location and extent of glaciers in 2010	Polygon shapefile	ICIMOD, dowloaded from: http://data.thethirdpole.net/layers/65
Landslides			
Elevation	ASTER Digital elevation model	GeoTIFF, 30m resolution	METI/NASA: https://asterweb.jpl.nasa.gov/gdem.asp
Soil Depth	Soil depth to bedrock	GeoTIFF, 1km resolution	ISRIC Soil Grids: https://www.isric.org/explore/soilgrids
Precipitation	Daily precipitation data at 35 stations from 1995 - 2014	Point locations of stations	Nepal Department of Hydrology and Meteorology (DHM)
Hydrologic soil type	Required to divide precipitation into runoff and infiltration components	GeoTIFF, 1km resolution	ISRIC Soil Grids: https://www.isric.org/explore/soilgrids
Infrastructure at risk	Locations of structures and roads	Line and polygon shapefiles	Open Street Map: https://www.openstreetmap.org
Land use and land cover	Nepal national land use/land cover, year 2000, used to determine root cohesion	GeoTIFF, 30m resolution	Nepal Department of Survey
Road-induced erosion			
Elevation	ASTER Digital elevation model	GeoTIFF, 30m resolution	METI/NASA: https://asterweb.jpl.nasa.gov/gdem.asp
Road locations	Locations of structures and roads	Line and polygon shapefiles	Open Street Map: https://www.openstreetmap.org
Road width and surface material	Estimated from reported road types	Assigned by road type, width in meters	Open Street Map: https://www.openstreetmap.org
Fluvial sediment connectivity			
Elevation	ASTER Digital elevation model	GeoTIFF, 30m resolution	METI/NASA: https://asterweb.jpl.nasa.gov/gdem.asp

Data type	Description	Format/resolution	Source
Discharge	Observed discharge at DHM gauging stations, approx. 5 years of daily records	Point locations of gauges	Nepal Department of Hydrology and Meteorology (DHM)
Channel width	Manually sampled from Google Earth	Numeric value assigned to each channel	Variety of satellite image sources as provided by Google Earth
Carbon			
Carbon pools	Aboveground, belowground and soil carbon pools by land cover & management type	Tonnes/hectare, mapped to land use/land cover	Most values from Reusch & Gibbs New IPCC Tier-1 Global Biomass Carbon Map for the Year 2000; Forest values from the National Forest Reference Level of Nepal (2000-2010)
Land use and land cover	Nepal national land use/land cover, year 2000	GeoTIFF, 30m resolution	Nepal Department of Survey
Carbon values	US$ 40 - 80 per ton CO_2e sequestered	Value per ton CO_2e	Stiglitz, et al., 2017.
Activities and implementation costs			
Costs of sustainable land management (SLM) practices	Online databases and peer-reviewed literature on costs of implementing SLM, reported as or converted to 2018 US $ per hectare	Cost per hectare	WOCAT SLM database: https://qcat.wocat.net/en/wocat/; Dahal, Hasegawa, Bhandary, & Yatabe, 2010; Das & Bauer, 2012; Devkota et al., 2014; Sharma 2003
Economic valuation			
Value of power generated	Tariff rates, costs of imports and purchases from independent power producers, Nepalese rupees (NPR) per kWh by conditions of purchase and time of day, converted to 2018 US$.	2018 US$ per KwH	Nepal Electricity Authority Annual Reports, 2009 – 18.
	Estimates of shadow price of unserved demand during periods of load shedding	Nepalese rupees (NPR) or US$ per kWh	J. P. Shrestha & Shrestha, 2016; R. S. Shrestha, 2011; Timilsina & Toman, 2016; Karki, Mishra, & Shrestha, 2010

Data type	Description	Format/resolution	Source
Maintenance	Scheduling, duration, and costs of overhauls, flushes, and other procedures	NPR converted to 2018 US$	Nepal Electricity Authority Annual Reports, 2009 – 18; data obtained from NEA; interviews with NEA personnel; Morris, 2014, and Bishwakarma, 2012, for physical dimensions.
Reservoir capacity	Initial reservoir capacity and subsequent changes	Millions of cubic meters	Morris, 2014; interviews with NEA personnel
Value of homes at risk from landslide damage	Rental value of rural homes, pro-rated per meter of area	NPR per annum, converted to 2018 US$	Nepal Central Bureau of Statistics Annual Household Survey 2016/17. Area from data on structures at risk.
Cost of road repairs from landslide damage	Costs of road construction, corrected for road width	NPR per km converted to 2018 US$	Road construction costs taken from (Starkey, Tumbahangfe, & Sharma, 2013); corrections for with from OSM data.

4. RESULTS

4.1. BASELINE CONDITIONS

4.1.1. Sediment budget

The sediment budget for the 5 major sub-watersheds of the Kali Gandaki was determined from sediment measurements performed by Kathmandu University. These measurements help to determine the contributions of the Mustang Plateau, the Upper Kaligandaki, the middle and lower Kali Gandaki, the Modi Khola and Myagdi Khola tributaries (see also Figure 2.6). A key finding is the great diversity in sediment load and yield, which is not aligned with the spatial distribution of rainfall in the sense that the tributary watersheds receiving most of the watershed's precipitation do not contribute the most to the its sediment budget. This suggests that improved data on geologic factors such as lithology, uplift rates, and fracturing of rocks along fault lines are critical for improving understanding of where and how sediment is generated in the watershed.

A comparison of observed sediment load to our multi-model approach with separate models for hillslope erosion (SDR), landslides, roads, and glaciers shows that the models generally perform well in terms of total modeled sediment loads, although the models tended to over-predict sediment load from some tributaries and under-predict load from the Mustang and the Upper Kaligandaki.

Because landslides make up the largest part of the sediment budget of each sub-watershed, we focus calibration on the landslide model, which is in line with the understanding that landslides and other mass movements are the most important factors in the sediment budget of this region (Struck et al. 2015). Specifically, we modify the soil cohesion in each sub-watershed (see Appendix 1 for details). This assumes that each sub-watershed is a homogeneous unit with regard to the geomorphic processes impacting landslides. While this is a simplification, it should be noted that these units are indeed distinct with regard to their topography, climate and geology (lithology, uplift, fracturing), key factors that influence the occurrence of landslides.

Model calibration greatly improved the model's fit to observations (Figure 4.1). Hillslope erosion (red) makes up only for a small part of the observed sediment load of the various sub-watersheds (black squares). According to other observations, we assumed that the majority of sediment in the watershed is generated by landslides (yellow) and so model calibration focused on the landslide model as described above. Results show that landslides make up for a majority of each sub-watershed's sediment load, and especially in the upper Kali Gandaki (draining to Nayapul) and the middle Kali Gandaki (draining to Modi Beni). The high diversity in sediment load between sub-watersheds points to the need for ongoing monitoring at multiple locations to build a longer record of sediment dynamics, and ideally to also collect more evidence on what processes produce sediment in different locations.

To identify which processes generate most sediment in different parts of the watershed, we use the previously defined 821 sub-watersheds as unit of analysis (Figure 4.2, left panel). Notably, landslides produce most of the sediment in the upper and middle watershed, while hillslope erosion dominates in the south, center-west and around the rim of the Mustang Plateau (Figure 4.2, right panel). The sediment load of very few, high elevation sub-watersheds is dominated by glaciers. Roads are not dominant in any major sub-watershed. Figure 4.3 shows the sediment generation by process and sub-watershed, and Table 4.1 gives the modeled sediment yield for the most dominant processes – hillslope erosion and landslides – by land use type. These maps are a first step in understanding which activities may be implemented to manage sediment, as interventions will be most effective when they are targeted to the dominant sources of sediment in the relevant areas.

Figure - 4.1: Comparison of modeled and observed load from the multi-model suite, including the calibrated mass-movement/landslide model (yellow) Observed load is the same as Figure 2.7, error bars indicate ± 1 standard deviation in observed loads

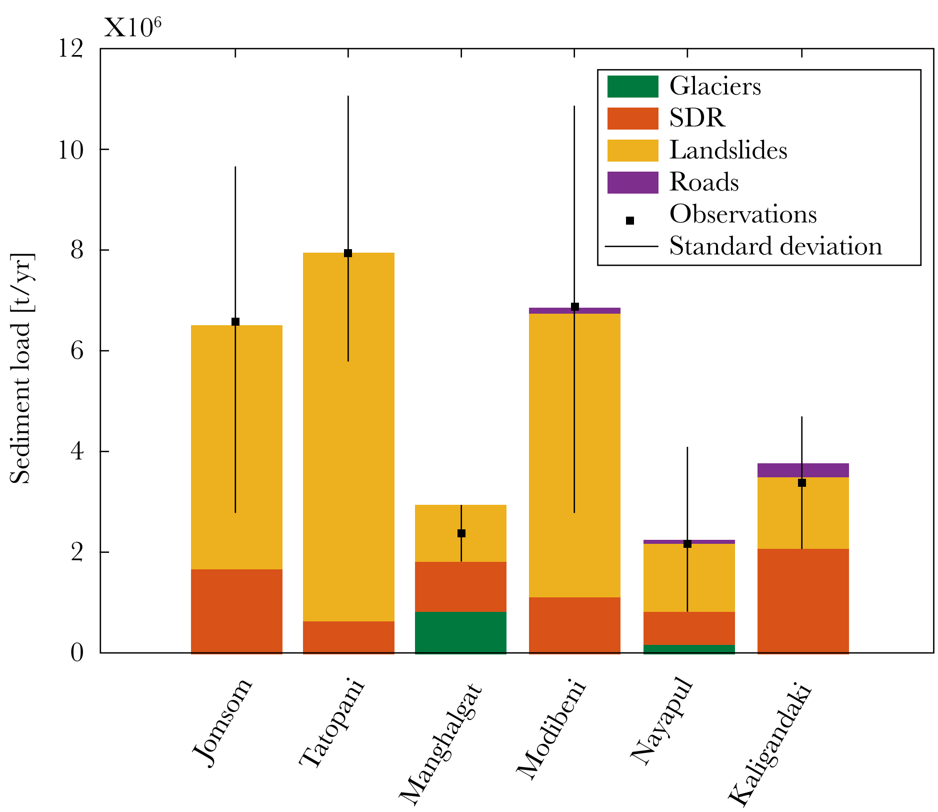


Figure - 4.2: Sediment load from each sub-watershed to the streams (left) and the processes dominating sediment load in each sub-watershed (right)

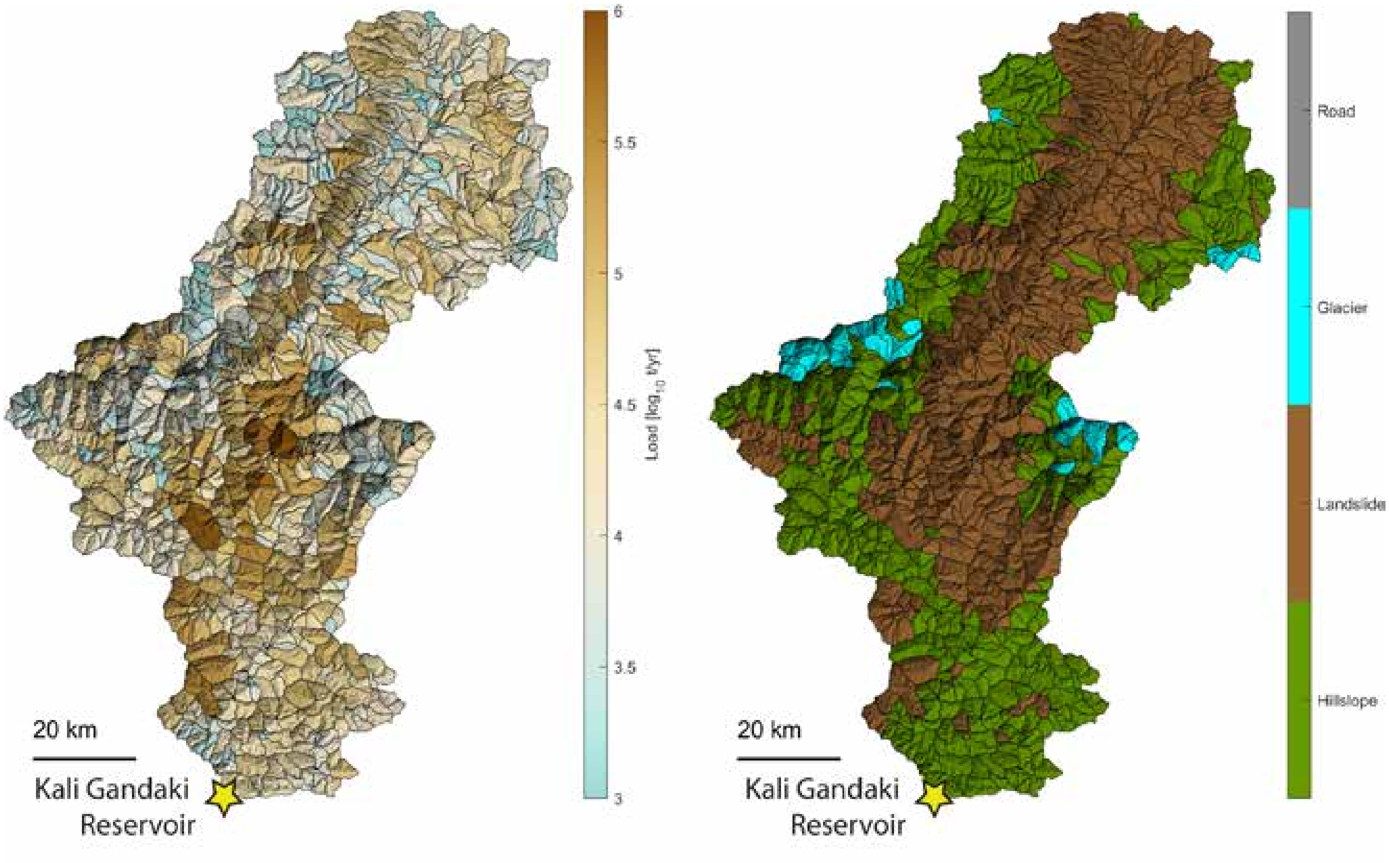
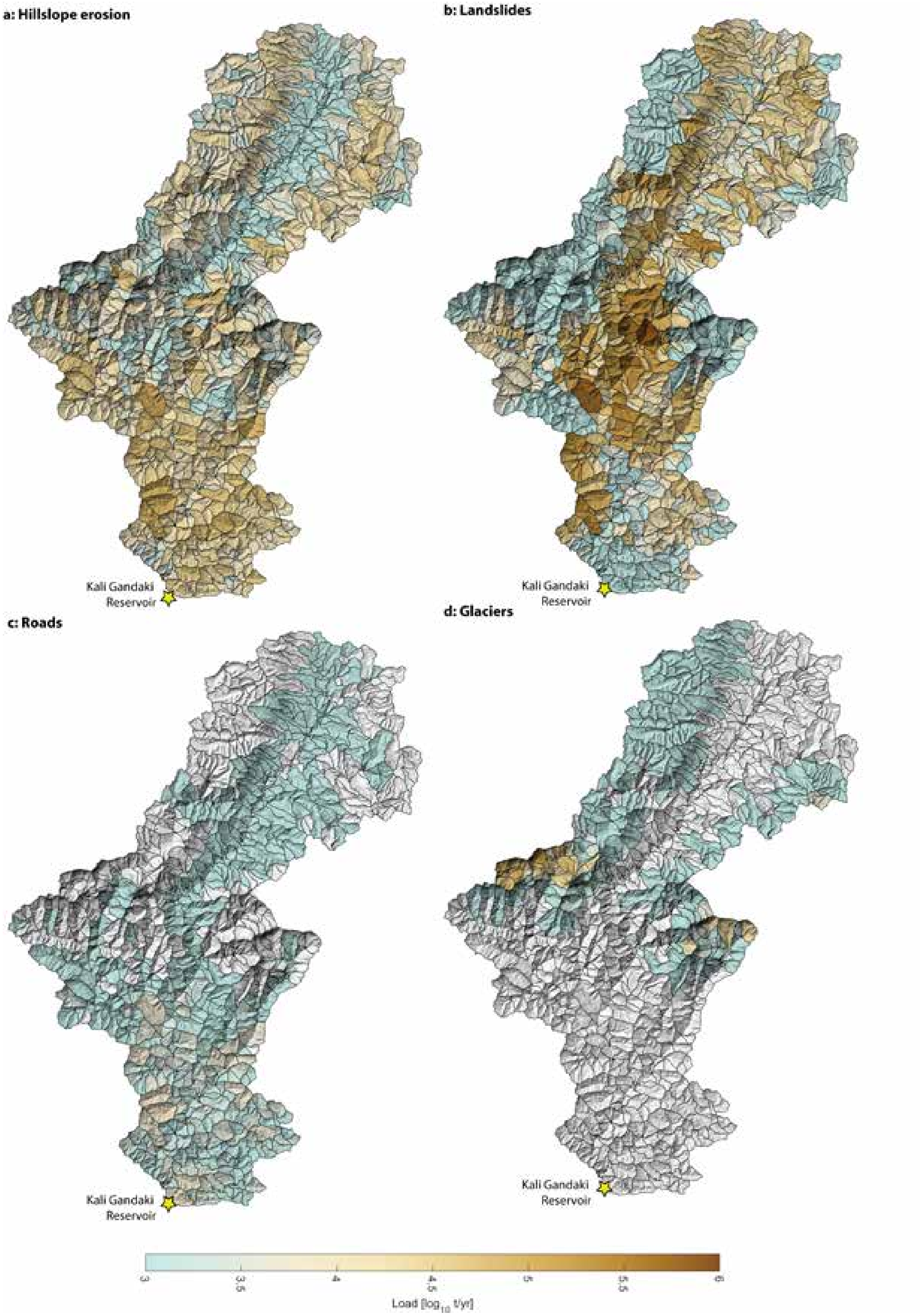


Table - 4.1: Total mean sediment load and sediment yield (per unit area) for major land uses in the study area. Note that glaciers are not included, because their contribution to sediment loads are calculated separately and do not include hillslope erosion nor landslides.

Land use	Sediment load (t/yr)	Sediment yield, total (t/ha/yr)	Sediment yield, hillslope erosion (t/ha/yr)	Sediment yield, landslides (t/ha/yr)
Cliff	241,600	167.5	65.7	101.8
Cultivation	5,008,400	47.2	30.1	17.1
Forest	5,934,800	38.2	1.7	36.5
Grass	7,118,100	45.4	3.8	41.6
Barren Land	4,806,300	17.9	8.2	9.7
Bush	3,969,200	108.1	12.3	95.8
Pond or Lake	182,600	65.5	34.3	31.2
Sand	314,400	31.9	19.4	12.5
Waterbody	42,200	28.5	17.1	11.4
Built Up	2,100	6.8	2.7	4.1
Nursery	800	3.9	2.3	1.6
Airport	1,000	4.2	1.8	2.4
Scattered Tree	3,900	13.7	3.0	10.6
Orchard	500	0.5	0.1	0.4

Figure - 4.3: Sediment load from each process in the sediment budget and each sub-watershed to the streams. Processes considered are: Hillslope erosion (a), landslides (b), roads (c) and glaciers (d).



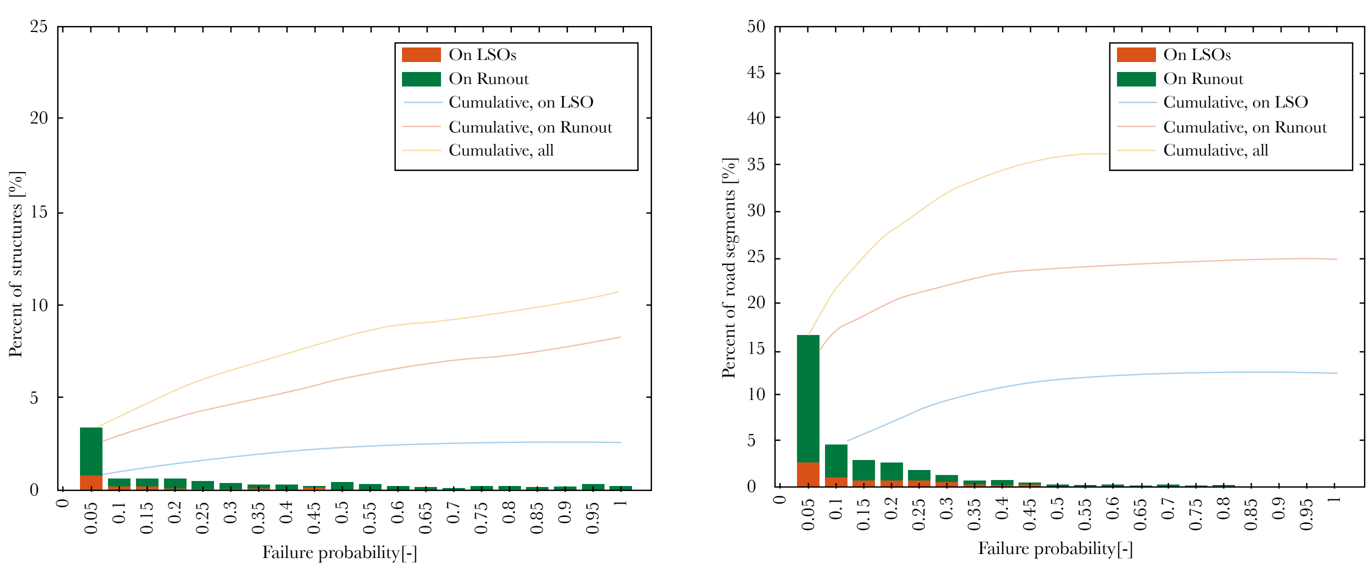
If all possible watershed management activities that we model here were to be implemented in the Kali Gandaki watershed (covering about 39% of the total land area, as barren lands, glaciers, cliffs, built up areas, etc. were excluded from consideration), the total avoided sediment is approximately 6.5M tons/year, or 20.5% of the estimated fine sediment load of 31.7 Mt/yr. A previous study (World Bank 2018b) estimated a possible 8% reduction in sediment from land management activities in the lower watershed only; however, that study did not include landslide mitigation measures and only considered activities in the Middle and High Mountain physiographic regions. These findings make sense in light of the fact that Himalayan geology is known to be unstable and background sediment production very high. Understanding the scope for watershed management to control sediment problems can help to set realistic expectations for what such programs can achieve. In reality, a combination of green and grey engineering solutions will likely be needed to fully minimize the negative impacts of sedimentation in this area.

4.1.2. Landslide risk

Landslide hazards are unique in that they not only produce sediment, they also threaten lives and infrastructure. The results of our landslide hazard mapping assess the landslide hazard of different structures and roads in the watershed (Figure 4.4). The x-axis shows groups of buildings (left panel) and roads (right panel), grouped by the failure probability of their associated landslide and runout hazards, and the y-axis reports the percentage of the total buildings/in each failure class. Less than 10% of all buildings are on landslides or on downstream runout pathways (Figure 4.4, yellow line in left panel). This finding is logical, because it is unlikely that a high percentage of buildings will be constructed in places that are obviously at risk of landslides. Of all buildings at risk, most fall in a low risk category (<10 %) and even in this category, many more structures are at risk because they are located on a potential runout pathway, rather than directly on a landslide object (LSO). These results are then the basis for the economic analysis, which considers monetary losses because of destroyed structures and lost lives. Population centers that are located within the runout path of landslides are places where a high risk of sliding corresponds to a high density of values at risk.

The percentages at risk are much higher when it comes to roads. In total, more than 40% of roads are at risk (Figure 4.4, yellow line in right panel). Again, most of the segments at risk (around 17% of all segments) are in the lowest (< 5% failure probability). However, compared to houses, a much greater percentage falls into higher risk classes (10 – 50% pa). Similar to houses, there are much more roads at risk because they are on a runout path, rather than because they are directly located on an LSO. Figure 3.2 shows a comparison of the modeled high-risk areas for both landslides and their runout potential, overlaid with data on homes and roads. To the extent that these data sets could be improved in future versions of this work, a more complete picture of assets at risk could be developed.

Figure - 4.4: Buildings (left) and roads (right) at risk, binned by the failure probability of the landslide/runout they are located on. Lines show cumulative values.



4.2. ECONOMIC VALUES OF WATERSHED MANAGEMENT

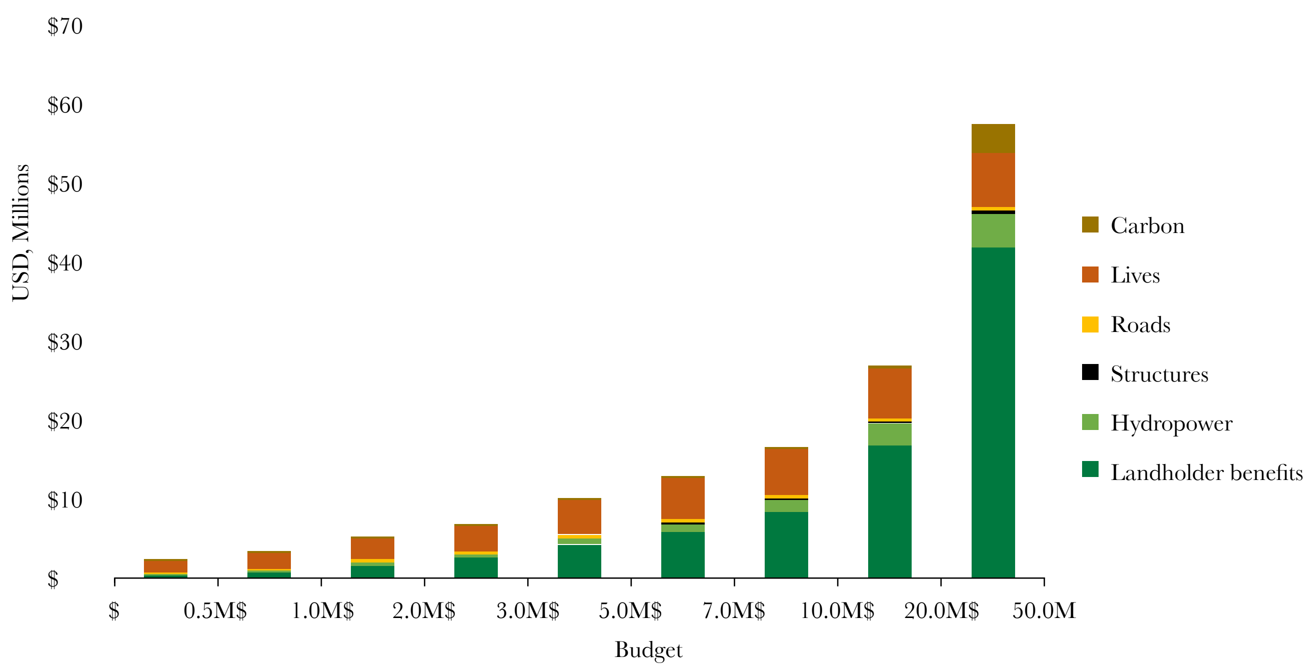
In this study, we derived a net present value (NPV) of five benefit streams that result from implementation of the watershed management activities described in Section 3.3.1: 1) reduction of sediment to benefit the KGA hydropower facility, 2) avoided damages to structures and roads due to landslide mitigation, 3) avoided lives lost due to landslide mitigation, 4) changes in carbon stocks, and 5) on-site benefits to landholders. We use a discount rate of 10%, a value consistent with practice among development agencies (Bonzanigo and Kalra 2014) and deemed appropriate by some commentators for Nepal (Das and Bauer 2012). Additional, non-monetized benefits from the program of interventions could include improvement in water quality and water flow in streams for drinking water and irrigation, improved water infiltration and regulation for local springs, water flows for downstream fisheries, and biodiversity. We focus here on the five monetized benefits and examine how benefits scale as a function of implementation budget and the program's primary objective(s).

4.2.1. The value of an optimal portfolio

Results for watershed management portfolios ranging in cost from US $500,000 to $50M show that such programs can have a significant, positive impact across many sectors (Table 4.2). The benefits are driven largely by local benefits and the value of avoided lives lost in landslides, with the next highest beneficiary being downstream hydropower (Figure 4.5).

At a US $500,000 budget, each $1 invested yields $4.38 in benefits, but this ratio drops as budgets are increased. However, even with an investment of US $50M, the program still has a positive benefit: cost ratio, even without considering the carbon sequestration benefit. There is a large increase in carbon benefits between US $20M and $50M, this is due to the fact that costs were allocated in these portfolios without consideration for carbon benefits. The interventions with the greatest non-carbon benefits are for mitigating landslides, which accrue relatively lower carbon benefits. Once all sites for cost-effective landslide mitigation are treated, and budget is still available, the focus of the intervention portfolios shifts toward reclamation of degraded forest and grazing land, which carries with it higher carbon sequestration benefits.

Figure - 4.5: The multiple values of watershed management. The benefits are driven largely by local benefits and the value of avoided lives lost in landslides, with the next highest beneficiary being downstream hydropower (KGA). Note that X-axis location only represents distinct budget scenarios; it is not proportional to the cost of each portfolio



In the following sections, detailed results for each benefit stream are given and discussed in the context of a single illustrative portfolio: that of a US $1M investment, which has an overall benefit: cost ratio of 3.2.

Figure 4.6 shows the benefit: cost ratio of the modeled portfolios of interventions, including high and low bounds on the estimated total benefits. These bounds are based on potential values for each benefit stream using a range of parameter estimates in the economic valuation models (see Sections 4.2.2 through 4.2.5 below for information on how these ranges were developed). These ranges illustrate that the positive economic benefit of watershed management interventions is relatively robust to model assumptions but should not be interpreted as confidence intervals.

4.2.2. Value of sediment reduction to Kali Gandaki A

In this section, monetary estimates of avoided damages and avoided costs are first presented following the process outlined in Section 3.3.5, followed by estimates of the value of retained reservoir capacity. More details on the methods used are given in Appendix 4.

Avoided costs and damages

Section 3.3.5 argued that the marginal cost of reducing a cubic meter of sediment from water withdrawn for generation should be set equal to the marginal damage of not reducing a cubic meter of such sediment. This marginal cost is calculated from three factors: the cost of flushing the desanding basins, the volume of sediment disposed with each flush, and the fraction of all sediment in water diverted for generation that is removed and flushed from the desanding basins.

Combining this information and using the formula derived in Annex 4, the net present value of a one cubic meter reduction every year in perpetuity is computed to be 1998 NPR (US $17.84) at a discount rate of 10%.

There are a great many factors that affect the calculation of this number. It would take considerable effort and study to quantify the uncertainty of the estimate. As an illustration, it has been assumed that off-peak power is priced at $0.054 per kWh. This assumes that markets clear at this price and that the price reflects the full societal cost of power. If some demand went unmet during periods of desanding basin flushing, however, a higher price might be inferred; this might be especially true if alternative generators with local air quality or global climate implications were used in such periods. If it were supposed that the value of off-peak power were $0.08 per kWh, the value of a cubic foot reduction would increase to $26.43. Conversely, expansion in system capacity might lead to a reduction in the price of off-peak

Figure - 4.6: Benefit/cost ratio of modeled portfolios (blue points), showing high and low boundaries on estimates (lines). High and low bounds are based on calculations of ranges of potential values for each benefit based on parameter ranges given in the text. These ranges should be considered illustrative and not to be interpreted as confidence intervals

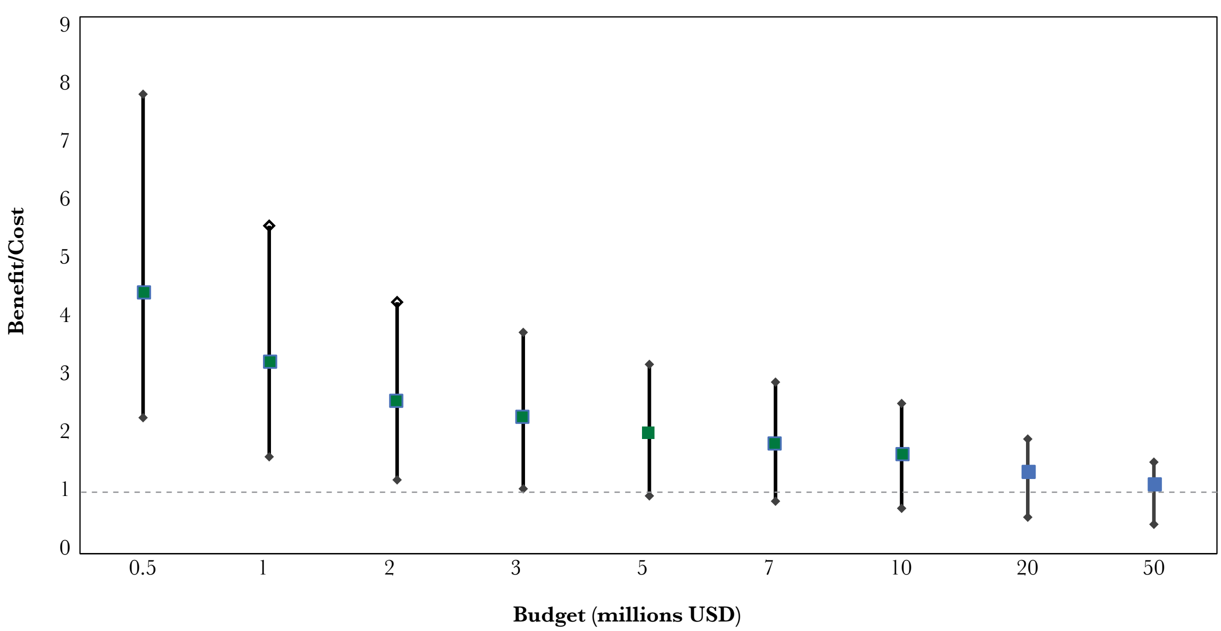


Table - 4.2: Breakdown of values of investment in watershed management and benefit/cost analysis, for budgets ranging from US $500,000 to $50M

Budget (USD)	Values to hydropower from sediment reduction to KGA	Values of landslide reduction						On-site benefits based on % cost-share	Carbon value based on social cost of carbon	TOTAL VALUE	
		Avoided costs of replacement & repair				Avoided lives lost, mean per year	Value of avoided lives lost (VSL)			USD	Benefit/ Cost
		Avoided structures at risk (n)	Avoided loss of structures value	Avoided roads at risk (km)	Avoided costs of road repairs						
$ 0.5 M	$ 76,000	17	$ 42,000	3.3	$ 189,000	4.20	$ 1,451,000	$ 420,000	$ 12,000	$ 2,190,000	4.38
$ 1.0 M	$ 121,000	23	$ 69,000	3.6	$ 206,000	5.67	$ 1,959,000	$ 840,000	$ 24,000	$ 3,219,000	3.22
$ 2.0 M	$ 256,000	32	$ 95,000	5.0	$ 286,000	7.93	$ 2,740,000	$ 1,680,000	$ 35,000	$ 5,092,000	2.55
$ 3.0 M	$ 415,000	40	$ 126,000	5.2	$ 296,000	9.88	$ 3,413,000	$ 2,520,000	$ 75,000	$ 6,845,000	2.28
$ 5.0 M	$ 760,000	52	$ 179,000	5.3	$ 302,000	12.95	$ 4,477,000	$ 4,200,000	$ 140,000	$ 10,058,000	2.01
$ 7.0 M	$ 1,056,000	61	$ 215,000	5.6	$ 320,000	15.15	$ 5,238,000	$ 5,880,000	$ 196,000	$ 12,904,000	1.84
$10.0 M	$ 1,592,000	66	$ 242,000	6.8	$ 385,000	16.54	$ 5,717,000	$ 8,400,000	$ 289,000	$ 16,626,000	1.66
$20.0 M	$ 2,865,000	71	$ 261,000	8.2	$ 462,000	17.71	$ 6,123,000	$ 16,800,000	$ 560,000	$ 27,071,000	1.35
$50.0 M	$ 4,370,000	78	$ 290,000	9.4	$ 530,000	19.51	$ 6,745,000	$ 42,000,000	$ 3,764,000	$ 57,699,000	1.15

power. Increased in electricity imports from India, as well as increases in domestic capacity resulting from the opening of the new Upper Tamakoshi Plant, for example, might make power more plentiful, and hence cheaper. If off-peak power prices declined by one quarter, to $0.041 per kWh, the cubic foot of sediment load reduction would only be worth $13.38.

US $17.84 is the estimate value of a cubic meter of sediment in water diverted for power generation. It is estimated, however, that only about 15% of all sediment transported in the river is carried in water that is diverted for generation. Thus, when crediting watershed management interventions for the avoided costs and damages they achieve, a value of 0.15 · $17.84 = $2.68 per cubic meter of loading reduced is used (leading to a low-end estimate of $2.01 and a high-end estimate of $3.96).

The fraction 0.15 is given in an International Hydropower Association study of sediment damage and management at the Kali Gandaki Plant (IHA, n.d.). A figure of this magnitude is plausible. In a detailed study of the Kali Gandaki, Morris (2014) finds that the concentration of sand suspended in water varies as the fourth power of the rate of flow. This implies that water flowing at 1,000 cubic meters per second would carry 16 times as much sediment as would water flowing at 500 cubic meters per second. From Figure 3.4 and Figure 3.5 above, it can be seen that the vast majority of sediment is delivered during the few months of the year when average flow is on the order of 1,000 cubic meters per second. As 141 cubic meters per second – 14.1% of 1,000 cubic meters per second – are diverted for power generation, a figure of 15% does not seem unreasonable. In any event, the value of watershed management varies proportionally with the assumed fraction of sediment borne in water diverted for generation. If the fraction were assumed to be 10, rather than 15%, value would be reduced by a third; if 25, rather than 15%, value would be increased by two-thirds.

Retention of peaking capacity

Based on the calculations and assumptions presented in Section 3.3.5, we arrive at a net present value of US $273.60 per cubic meter of reservoir storage space retained. Again, some sense of how this number might vary with assumptions can be developed by considering alternative scenarios for electricity pricing. It is the difference between peak and off-peak prices that determines the value of capacity. If, instead of a peak price of $0.108 per kWh and an off-peak price of $0.054 per kWh, it were assumed that the off-peak price were $0.08 per kWh, the value of a cubic meter of storage would decline to $184.70. Conversely, if peaking capacity is slow to be augmented, the value of storage might increase. If, instead of a difference of $0.054 per kWh between peak and off-peak prices, a difference of $0.08 per kWh were assumed, the value of storage would increase to $405.30 per cubic meter. Such a difference might also reflect environmental externalities associated with alternative peaking generation. As with other comparisons of valuation outcomes, it should be appreciated that there are many, many other sources of variation in both economic and physical calculations that would affect values; thus, these calculations illustrate how estimate values might vary with some such variations.

Taking the mid-range estimate of US $273.60 per cubic meter, an additional adjustment must be made to this figure – which provides the value of a cubic meter of sediment occupying space in the reservoir – to arrive at the value of a reduction in sediment loading to the river by one cubic meter (which is the output of the sediment model). It is assumed that one quarter of one percent of sediment carried in the river settles in the reservoir.

Before explaining how this fraction is estimated, it may be useful first to consider an upper bound on it. The live storage capacity of the reservoir is about 3 million cubic meters. Annual sediment transport is about 22 million cubic meters.[20] The plant has been in operation since 2002. If, for example, 3 million m^3/(17 years · 22 million m^3/yr) = 0.8 percent of the sediment transported in the river had settled in the reservoir, it would already be completely filled. The fraction must be less than 0.8 percent then.

The International Hydropower Association study cited above estimates that less than one-tenth of one percent of sediment in the river settles in the reservoir. This is consistent with Morris's (Morris 2014) estimate that approximately seven percent of live storage in the reservoir was lost in the first decade of plant operation: seven percent of 3 million cubic meters would be about 210,000 cubic meters over ten years, or around 21,000 cubic meters per year, or a little less than one tenth of one percent of the 22 million cubic meters annual sediment load. NEA personnel have reported more severe capacity loss, however, with perhaps as much as a million cubic meters having been filled by sediment. This higher estimate of capacity loss over the life of the reservoir

[20]. Annual sediment transport is about 35 million tons, so at a density of 1.5 tons per cubic meter, a little less than 22 million cubic meters would be conveyed.

yields the figure of one-quarter of one percent, which was then used in this study for deriving the value of loading reductions in the watershed.

The benefits of capacity reduction ascribed to watershed management interventions will be proportional to the fraction of sediment transported that is assumed to settle in the reservoir. If the fraction were assumed to be one tenth, rather than one quarter, of 1% the estimate of value would be 60% lower. Conversely, if the fraction were assumed to be four tenths, rather than one quarter, of 1%, the estimate of value would be 60% higher. Again, however, much higher estimates may become implausible, as they would imply that the reservoir would soon be completely filled.

To take the example of a US $1M portfolio of watershed management interventions, it is estimated that about $120,000 in hydroelectric-related benefits would arise for KGA. Roughly $96,000 of such benefits would come from avoided damages and costs, and the remaining $24,000 from retention of reservoir capacity.

4.2.3. Value of reduction in landslide risk

We derive three values for reducing landslide risk through land management measures: avoided lives lost, avoided replacement cost of structures, and avoided road repairs. Considering the case of a US $1M budget for watershed management, approximately six lives would be expected to be saved per year. At a VSL of $34,565 per life saved, this would translate into a benefit of US $196,000 per year or, at a discount rate of 10%, a net present value of US $1.96M. Under this same scenario, the net present value of reduced risk of destruction of homes and other structures is estimated at about US $69,000 , and the net present value of expected cost savings on road repair would be about US $113,000. It should be noted that the values derived for avoided damages to assets are in reality the long-term increases in asset values associated with the modeled reductions in expected losses (not an estimate of actual damages averaged over a finite time period).

The expected value of mortality risk reduction could vary with a great many factors, including differences in the value assigned to a statistical life and the number of people assumed to be at risk from landslides. More generally, the probability of a landslide occurring, and the change in that probability as a result of interventions to stabilize slopes, divert runoff, of other measures also depends on a number of uncertain factors. A complete uncertainty/sensitivity analysis was infeasible due to time and resource constraints. However, to give some sense of how results might vary under alternative assumptions, recall that the VSL is assumed to be US $ 34,565. A number of different empirical procedures have been adopted for estimating the VSL, as well as a number of different procedures for transferring VSL estimates from one country to another based on per capital income or other factors (Narain and Sall 2016). Some recent work has inferred a considerably higher VSL for Nepal, based on workers' compensation to migrate in pursuit of better paying, albeit more dangerous work (M. Shrestha 2016). For the purposes of illustration, then a VSL of twice $34,565: $69,130 (which is still considerably lower than Shrestha's (2016) central estimate) is considered as a high-end estimate. Conversely, while a much lower figure for the VSL itself might be unlikely, it has been assumed that the number of lives at risk is proportional to the number of structures at risk. While the constant of proportionality (one life at risk per four structures) is based on reported fatalities and damages from over forty years of records (UNISDR 2015), the correlation between the series is not perfect. One might, then ask, how our figures would differ if only half as many lives were at risk, and this is then taken as a low-end estimate for calculating the value of avoided lives lost.

In terms of the values of damages to structures, a range of figures for our estimate of rental costs could also be considered. For example, *gross* rental payments might reflect payments both for the benefit of occupying a structure and the annual cost of maintaining it from routine wear and tear. If maintenance costs were assumed to be half of gross rental payments, the net rental value of structures at risk would be $2.70, rather than $5.39, per square meter. On the other hand, our approach assumes that the value of structures at risk is proportional to their footprint alone. Whereas if there are many structures built with multiple stories, then our estimate might be underestimating the rental value per unit footprint. Therefore, we take $7.19 as an upper estimate of the per-square-meter rental value, reflecting the case where reported values were 75% of actual values.

Considering the costs of road repairs, again there are many different factors that could affect the cost of road repair, and it would not be possible to characterize the sensitivity of results to all, or even a substantial number of them, without extensive study. Inasmuch as the estimates reported come from the midrange of three estimates, however, it might simply be noted that the lower end of the range would have yielded an $51,600 per kilometer of road damaged, the upper end, $78,100.

Summing the three categories of benefits quantified (using our mid-range estimates of value), US $1M spent on watershed management is estimated to provide an expected net present value of benefits in excess of US $2.2M from reductions in expected losses from landslides alone. While a number of assumptions have gone into the derivation of this estimate, it should be noted that 1) the value of expected lives saved generates most of the monetized value estimated, and the figure used for value of a statistical life, US $34,565, is lower than some estimates in the literature; 2) the road damage estimates have been confined to costs of repair only, and do not reflect either lost benefits during times when a damaged road may be impassable or the possibility that a road cannot be rebuilt, and would need instead to be relocated to what would likely be a more circuitous route; and 3) due to data limitations, this study does not estimate potential damages to agricultural production from landslides, which might also be significant in some areas.

4.2.4. Value of carbon storage

Carbon sequestration has the largest potential value from rehabilitation of degraded lands, followed by terrace improvement and soil and water conservation. Landslide mitigation has a much lower carbon benefit, due to the fact that benefits are not immediately and fully accrued, rather they are scaled by the change in probability that the treated landslide will occur.

The US $1M portfolio shows a total carbon benefit of only $13,200 (using the social cost of carbon at $60 per CO2e, with a range of between $8,800 and $17,600). This value is so low because up to budgets of around US $5M, the prioritization of activities is driven by the high values of lives and avoided infrastructure damage that come with landslide mitigation. In scenarios where carbon values are prioritized, the values can be much higher.

4.2.5. Local (on-site) benefits

Assuming that 84% of the cost of the watershed management program is shared by landholders, the on-site benefits of a US $1M investment would total $840,000. If the low- (30%) and high-end (100%) reported cost-shares are applied instead, we would expect on-site benefits to range from US $300,000 to $1M in this example. It is worth noting that even if this rough calculation of local benefits is not included in the total, the benefit: cost ratio still remains greater than one for portfolios up to US $5M.

Our estimate of on-site benefits based on the average reported cost-sharing by landholders is, of course, an imprecise estimate of the true benefits of implementing these practices. Over and above the fact that cost-sharing estimates may not be exactly applicable to any particular context, there are reasons they might give either over- or underestimates. The figure overestimates the share of on-site benefits to the extent that costs of program administration add to the establishment and maintenance costs recorded. On the other hand, some of the market imperfections noted in Section 3.3.6 might drive a wedge between the actual value of practices to land users and the cost they would bear to implement them; a land user might not be able to borrow the funds required for an initial investment in terracing, for example. Moreover, an actual watershed management project would likely adopt practices for which land users were willing to bear a greater fraction of the cost, other things being equal. Interventions that are not attractive to local land users would be less likely to be proposed.

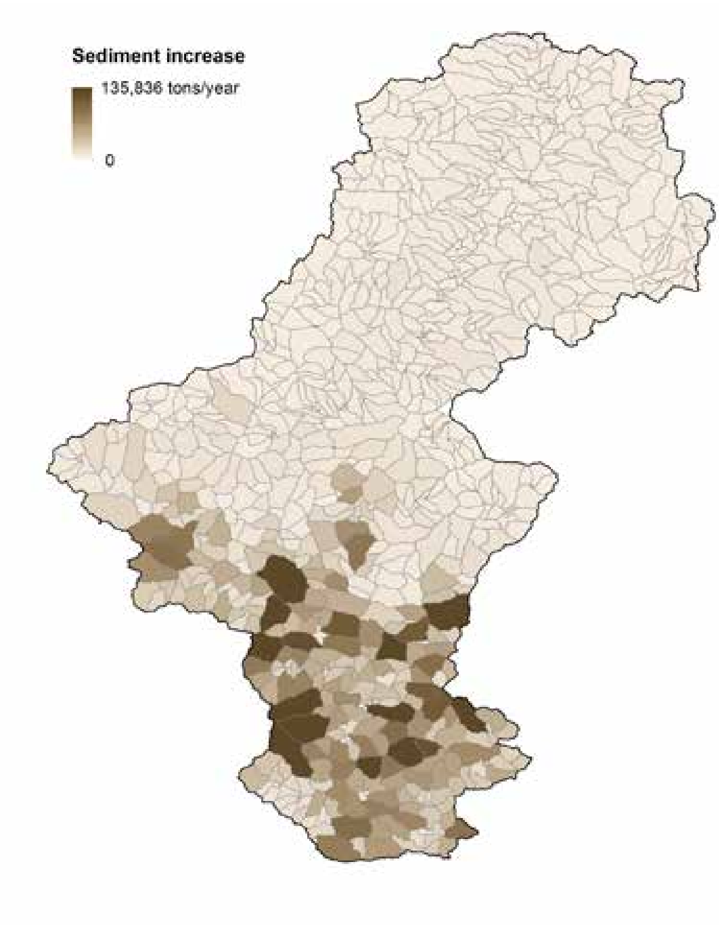
4.2.6. The costs of degradation

Another way to consider the benefits of watershed management is to look at the contrary case, where terraces are abandoned as the population shifts from rural to urban areas and the land is allowed to degrade. Results indicate that the potential increase in sediment load to the Kali Gandaki River under this scenario reaches 6.3M tons/year. This 20% increase over the current rate is concentrated in the lower portions of the watershed, and could have huge implications for sedimentation at KGA, as well as existing and planned facilities planned upstream (Figure 4.7). For example, the sediment load reaching the Modi Khola hydropower facility increases 0.42M tons/year (+34%) in this scenario, and the load to the Lower Modi 1 facility increases by 0.85M tons/year (+44%). The increased sediment load implies an additional net present cost to operations and maintenance at KGA of nearly US $13.5M. While we do not have sufficient data to calculate the net present cost of impacts on the upstream hydropower facilities, the large percentage increase suggests that funding watershed management to at least maintain terraces and soils in good condition could be a smart investment. The impacts on instability of slopes and corresponding landslide impacts could be even greater, although quantifying this impact through a mechanistic landslide model is outside the scope of the current study.

4.3. PRIORITIZING WATERSHED MANAGEMENT ACTIVITIES

We have shown that watershed management can provide significant benefits to downstream hydropower and to local communities, and that the benefits are not evenly distributed among different sectors. It is imperative, therefore, to understand where in the Kali Gandaki watershed these

Figure - 4.7: Additional sediment export that could result from abandonment of watershed management activities and existing soil conservation structures (e.g. terraces) in cultivated areas in the lower watershed. The total increase in sediment reaches 6.3M tons/year in this scenario, an increase of 20%



activities should be prioritized, in order to deliver the greatest possible benefits for any given budget level. In the following sections, we further narrow our focus to a range of budgets more likely feasible for implementation in the near future.

4.3.1. Evaluating individual activities

The following figures show the impacts of each individual watershed management activity on reducing sediment. These figures highlight the sub-watersheds where each type of activity has the highest potential to reduce sediment load to the Kali Gandaki River, regardless of its performance on other objectives (such as reducing local erosion or storing carbon), and regardless of the cost of implementation. Investing in watershed management in the darkest areas, therefore, will result in the greatest benefits in terms of downstream water quality and hydropower impacts at KGA.

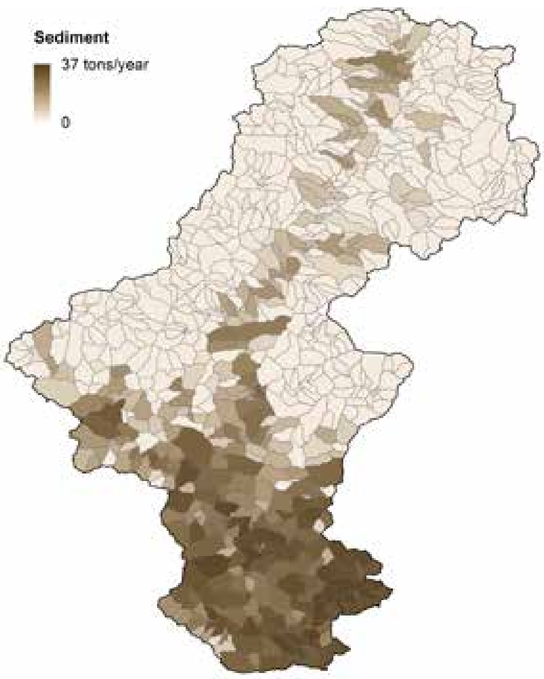
4.3.2. Intervention Portfolios

Watershed management activities can be prioritized based on different objectives, which will impact where investments should be focused. In the case of the Kali Gandaki watershed, there are multiple entities involved in promoting and implementing various types of best management practices, with different goals: the DoFSC invests in activities to control sediment and promote healthy functioning watersheds broadly, the Ministry of Agriculture and Livestock Development promotes best management practices to support productive and sustainable farming and grazing practices, and the NEA has a program to invest in sediment management in areas surrounding the KGA reservoir.

The results described above are based on a set of optimal activity portfolios made to maximize the total monetized values, across budget levels ranging from US $500,000 to $50M (Table 4.2 and Figure 4.5). Using the ROOT tool, activity portfolios can also be developed to maximize multiple objectives. A set of 1000 scenarios was developed using the ROOT optimizer, setting an objective function to minimize sediment exported to the Kali Gandaki river, minimize local erosion, maximize avoided lives at risk from landslides, maximize the value of landslide risk mitigated for structures and roads, maximize carbon value, and to minimize cost.

As noted above, local landholders often agree to assume a portion of the costs of implementation, with the expectation of local benefits in terms of maintaining soil health and productivity. However, if a program were to expect local landholders to bear part of the burden of the cost of watershed management, then it is necessary to ensure that local objectives (such as maintaining or enhancing agricultural productivity) are being given equal weight with downstream objectives (such as reducing sediment for hydropower operations). Figure 4.9 and Figure 4.10 illustrate the potential trade-off between prioritizing activities for local versus downstream benefits. The portfolio maps in Figure 4.9 show that when downstream sediment is the primary focus, reducing sediment through mitigating mass movement in landslides along the main stem and tributary channels are frequently the preferred options. However, when local erosion is the main concern, the focus shifts more toward terrace improvement, grazing land and forest rehabilitation in the middle hills area.

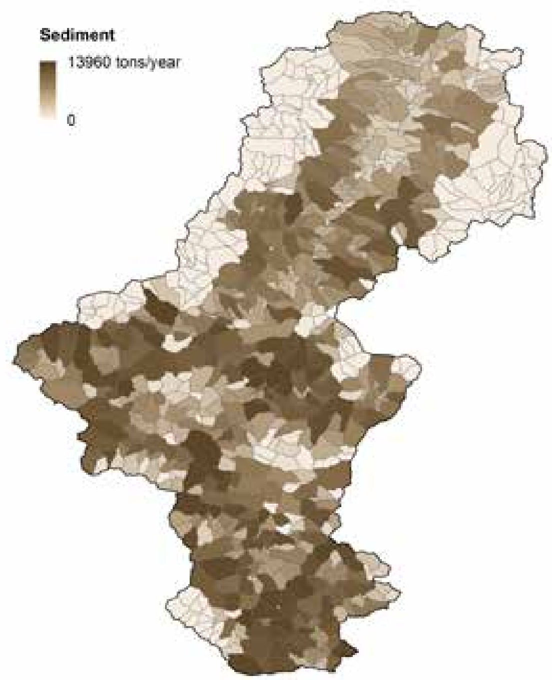
Figure - 4.8: Modeled sediment reduction by sub-watershed, with full implementation of different management practices. Note the different scales on each panel



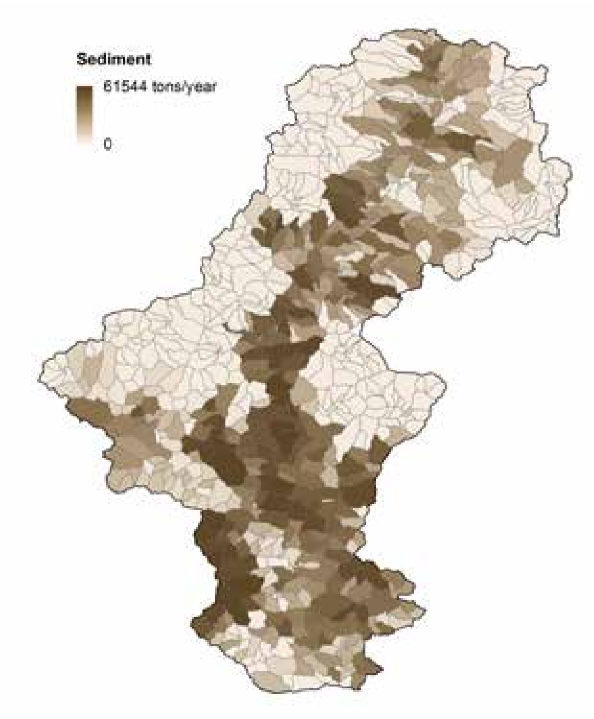
A) Modeled sediment reduction from soil & water conservation practices.

B) Modeled sediment reduction from hill terrace improvement practices.

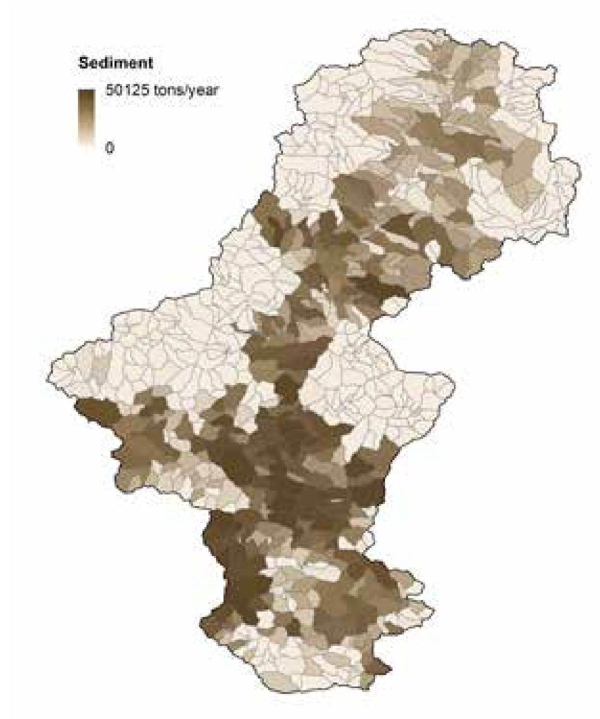
C) Modeled sediment reduction from degraded forest rehabilitation practices.



D) Modeled sediment reduction from degraded rangeland rehabilitation practices.

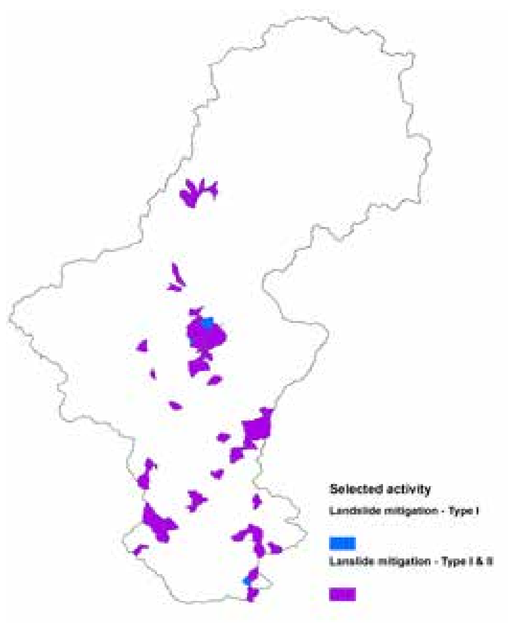


E) Modeled sediment reduction from landslide mitigation practices – Type I and II.

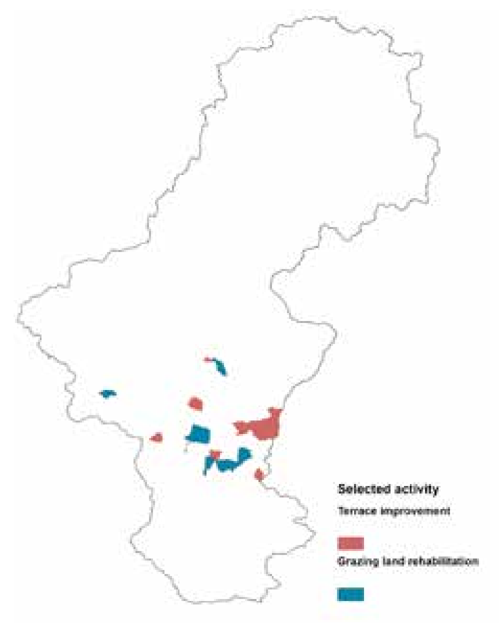


F) Modeled sediment reduction from landslide mitigation practices – Type III.

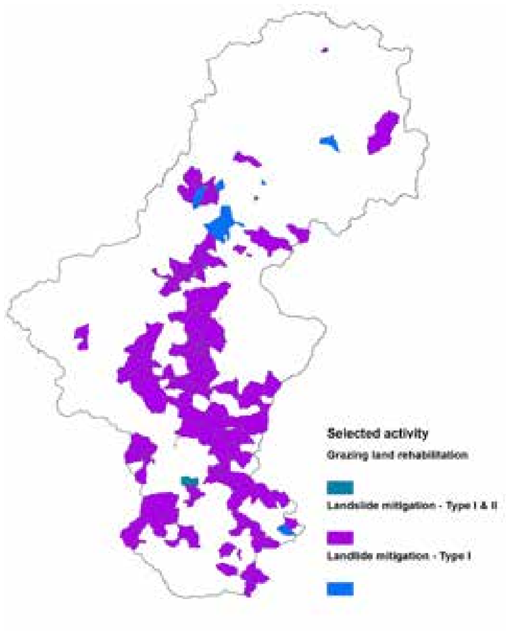
Figure - 4.9: Intervention portfolios optimized for two competing objectives (left column: downstream sediment for hydropower and right column: local erosion reduction) and two budget levels (US $5M and $20M), for comparison. Note that different activities and sub-watersheds are chosen for implementation to meet the different objectives



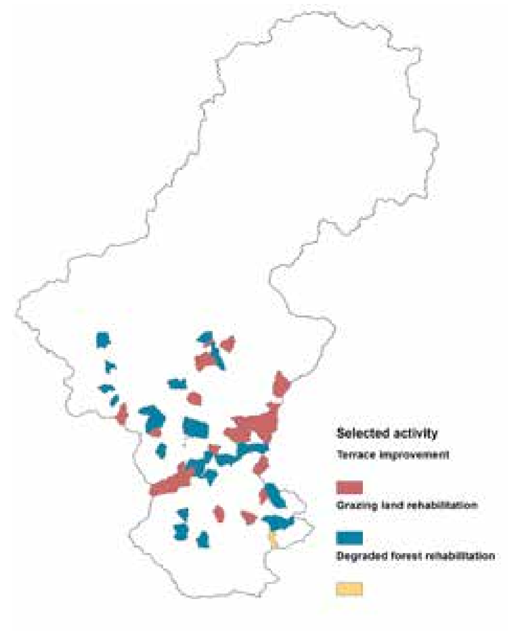
A) Downstream sediment-optimized portfolio, US $5M budget



B) Local erosion-optimized portfolio, US $5M budget



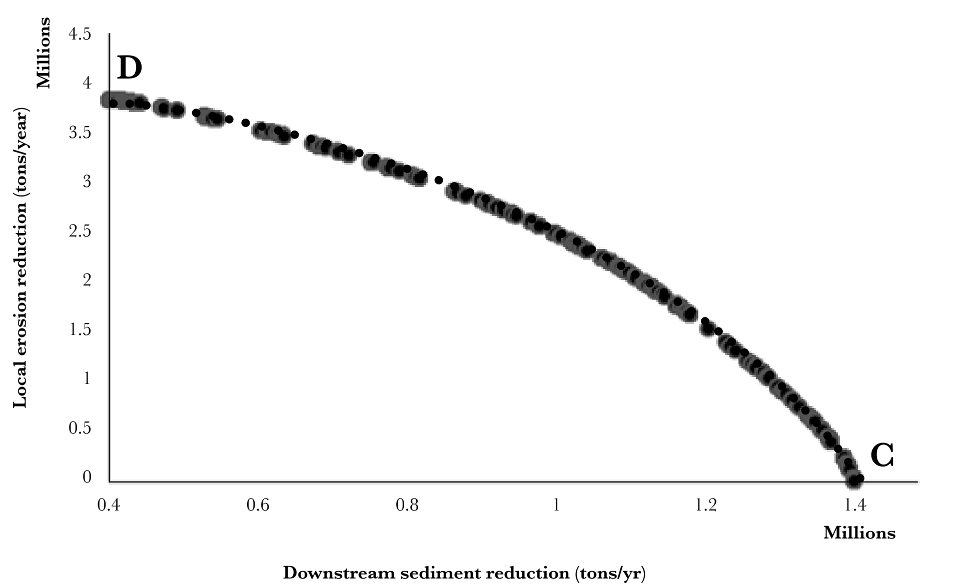
C) Downstream sediment-optimized portfolio, US $20M budget



D) Local erosion-optimized portfolio, US $20M budget

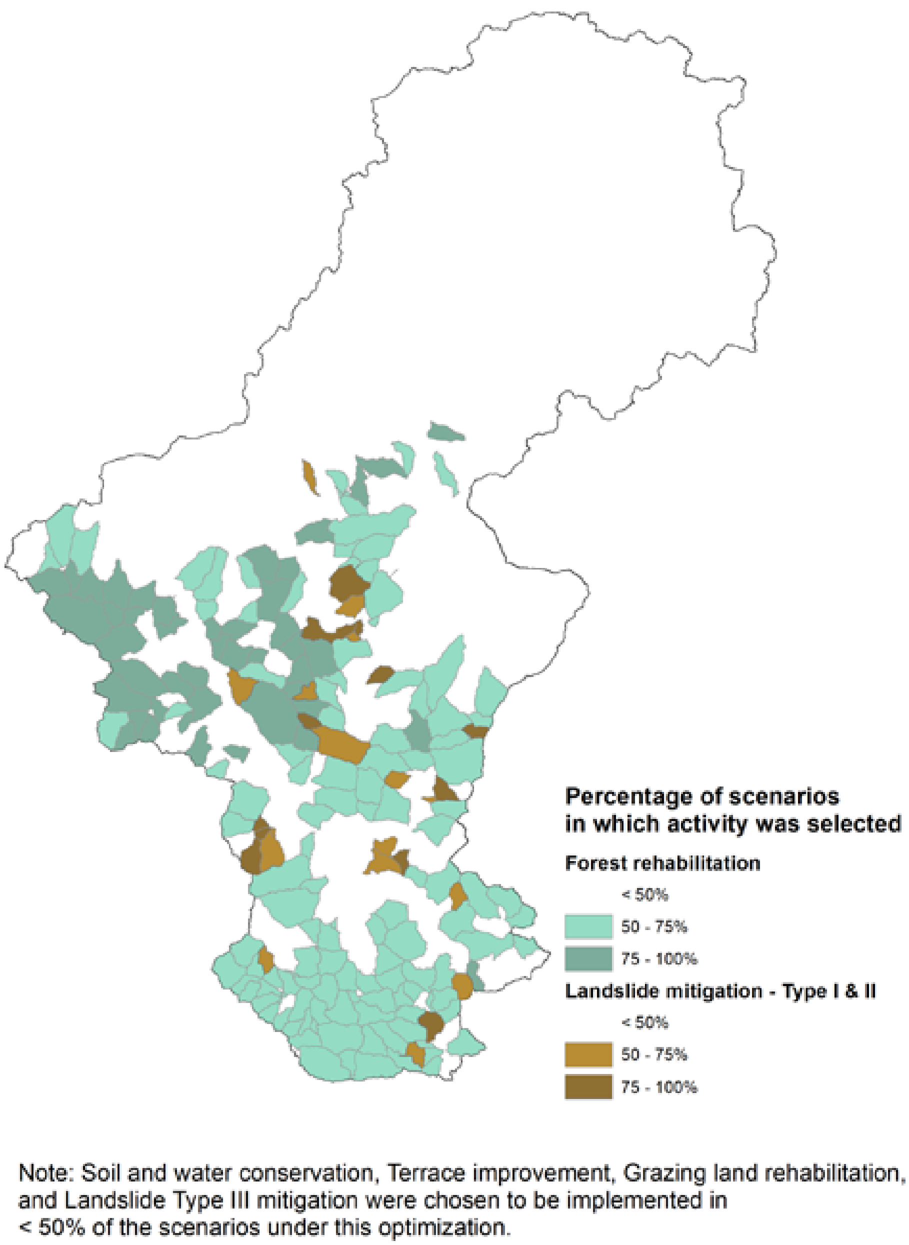
Figure 4.10 demonstrates this trade-off in another way, by showing the full set of 1000 optimal portfolios at the US $20M budget and the change in downstream sediment local erosion achieved in each portfolio. Points to the right on the curve prioritize downstream sediment reduction, while points to the left on the curve prioritize reducing local soil loss. Each point on the curve represents a scenario of interventions. For example, the portfolio shown in Figure 4.9.C is the point of maximum downstream sediment reduction on this curve, while the point of maximum reduction in local erosion corresponds to the map shown in Figure 4.9.D.

Figure - 4.10: Trade-off curve showing performance of 1000 optimal scenarios (US $20M budget) in terms of their reduction in downstream sediment and local erosion control. Points to the bottom and right on the curve prioritize downstream sediment at the expense of reducing local erosion, while points on the upper left of the curve prioritize local erosion control



Finally, prioritizing specific activities and locations can be difficult when faced with so many different options that can benefit different objectives. In this case, an agreement map is a useful tool to identify places and interventions that are repeatedly chosen in portfolios that optimize for different objectives. Figure 4.11 shows an agreement map for the US $5M portfolio. The colors represent two different activities that were consistently chosen in at least 750 of the 1000 iterations of this scenario in a given location. Higher agreement (>75%) indicates that the activity is very cost-effective in that sub-watershed, regardless of the relative importance given to specific objectives that might be considered by the watershed management program. In this scenario, soil and water conservation, hill terrace improvement, grazing land rehabilitation, and landscape type III mitigation were not consistently selected across the iterations.

Figure - 4.11: Agreement map for US $5M scenario. The colors show the fraction of all scenarios in which a given activity was selected. No color indicates the sub-watersheds where each activity was selected in less than half of all iterations. Higher agreement (>75%) indicates that the activity is highly cost-effective in that sub-watershed, regardless of the specific objectives sought with the watershed management program



4.4. CHANGING CONDITIONS, CHANGING VALUES

It is often more analytically tractable to suppose that the conditions that now determine benefits and costs will continue unchanged in the future. It is also sometimes reasonable to suppose that present conditions are the best predictors of those that will prevail in the future. For these reasons, most of the analysis presented above has assumed that future conditions will continue as in the past.[21] By the same token, however, conditions assuredly will change in the future, and so we discuss below how certain changes might affect the analysis.

Future changes can be relevant for many parts of our analysis, impacting processes of sediment generation, the valuation of hydropower and storage, and the link between watershed management and livelihoods. Some of these changes might also be competing, in the sense that they lead to an opposite effect on a given response variable. For example, sediment yield might increase in the future, but technical advances in hydropower technology (e.g., turbine coatings) might reduce the vulnerability, so that the final net-change in sediment-related damages to hydropower remains relatively stable. At the same time, many of the uncertain and non-stationary processes are highly non-linear, which means that a small change in, e.g., glacial melt, results in a major change in sediment generation.

A thorough quantitative analysis of all these deeply uncertain sources of future change was beyond the scope of this analysis, however, this section provides a short qualitative discussion of future scenarios for selected sectors and hydrologic processes.

Hydropower: Reservoir capacity is valuable only to the extent that flow in the river is insufficient at times to meet demand. If climate change makes river flow even more irregular than the monsoon cycle now implies, capacity might become more valuable, as would measures to preserve it by reducing sediment delivery. The marginal value of power depends on where supply and demand balance. Both are likely to change greatly over time. The value of capacity, however, depends on the *difference* between the value placed on power during periods of high and low demand, so the effects of potentially uneven supply and demand growth are unclear. One factor that would clearly make the peaking capacity at KGA and other plants more valuable would be increased reliance on renewable energy sources, such as solar and wind power on a national level. The intermittency of such sources puts a premium on the capacity to maintain generation when renewables are not available.

At the same time, increased dispatching of intermittent renewable, e.g., wind and solar, might go hand in hand with an increased regional linkage of power grids, which might reduce reliance on storage at any particular location and improve access to the major storage capacity in India and China. Similarly, Nepal has a major untapped hydropower potential and less than ten percent of the country's estimated technically feasible potential has been exploited. In addition to the two operational facilities on the Modi Khola tributary, there are three under construction (Lower Modi Khola, Middle Modi, and Lower Modi 2, with a combined capacity of 45.6 MW) and at least three more for which survey licenses have been issued (Department of Electricity Development, GoN). On the one hand, building more projects upstream of KGA would increase the number of beneficiaries of watershed management, as more plants would be impacted by changing sediment loads. This implies that the value of watershed management to the hydropower sector would increase as generation capacity expands, as many of these plants are run-of-river, which means that incoming sediments would be passed downstream through the turbines of several plants, potentially causing abrasive damage to each in turn, or would need to be flushed from the desanding basin of one plant after another, thereby compounding the benefits of reduced sediment loads. On the other hand, more plants will also increase redundancy, thereby reducing the value of storage and the overall costs of plant shutdowns for maintenance at any given facility, in terms of foregone energy generation during times of peak demand. Of course, if overall peak demand for electricity also increases, storage could become more valuable. The actual benefits of watershed management for the energy sector as a whole are thus difficult to determine, without more detailed study of the operations of all facilities, expansion plans, and projections of energy demand.

Costs and on-site benefits: Nepal has, as have other countries in South Asia, experienced urbanization and substantial migration from rural areas. If this movement

21. The exceptions are: i) the social cost of carbon estimates, as adapted from (Stiglitz et al. 2017), assume real values risking at a rate of 2.25% per year; ii) we suppose carbon storage values increase over time as plants grow; and iii) we distinguish between the establishment costs of interventions which are assumed to be borne immediately, and their maintenance costs, which we assume begin in the year following establishment.

of population is matched by reduced agricultural activity on steep and vulnerable terrain, then the opportunity cost of restoring native vegetation will likely decline as it will displace less croplands. At the same time, outmigration might make the work-force scarce and hence increase costs of implementation, and on-site benefits of increased agricultural productivity may be less significant if fewer farms and farmers avail themselves of them. Of course, food production would need to be made up elsewhere, either by expansion in the Terai region of Nepal, from exports, or by intensification of production in existing areas. It may well be, however, that the challenge in the future is not so much to make agricultural production sustainable on areas of land devoted to growing crops as managing the reversion from farmland to native forests and grass without excessive erosion.

Sediment yield from different processes: Future sediment yield from different processes is highly uncertain due to possibly compounding effects of future land use changes in the watershed and global climatic changes. Take, for example, the aforementioned uncertainty in future land use, which will have a major impact on sediment delivery. For example, Rodrigo-Comino et al. (2018) found that erosion from abandoned terraces in the Mediterranean can be very high, but that the increase of erosion depends strongly on the crop types and land management practices pre-abandonment. Similarly, many of the makeshift roads that are now being constructed to small villages might be abandoned in the future and might, if they are not decommissioned properly, continue to yield large amounts of sediment for decades. In turn, increasing affluence in remaining population centers might enable investing in paved roads and better road construction practices which might reduce erosion from the roads that remain in service.

In terms of natural processes, increasing rates of glacial melt that are expected in the Himalayas might exponentially increase the delivery of fine and abrasive sediment, which could not be mitigated with common watershed management strategies. Conversely, slightly wetter climate in the Mustang plateau, where soils are mostly bare and erodible, could lead to an increase in hillslope erosion that might be targeted by increasing vegetation cover through watershed management practices.

Landslide losses: Some of the most substantial benefits identified above arise from saving lives that might otherwise be lost in landslides. Landslides are only a risk in relatively steep terrain. These tend to be the areas from which Nepalis are now moving to cities or overseas. On the other hand, however, experience in other countries suggests that wealthy people may later be drawn to the more spectacular viewsheds of ravines and hillsides. Socio-economic growth in the watershed and remittances from emigrated family members might also lead to a growing value of remaining houses. Landslides are also associated with extreme events, particularly earthquakes and rainstorms. An increase in extreme precipitation could increase the value of interventions compared to our current analysis which is based on climate observations of the past two decades.

Conclusion

In general, it should be noted that changing conditions – both in terms of economic development and climate impacts – might greatly change the future value of sediment management both with regard to sediment generation but also with regard to the value of ecosystem services. For example, higher standards of living might greatly increase the value of structures of risk and hence the value of avoiding destruction of structures by landslides. At the same time, more wealth might also decrease the dependence of the population on ecosystem services, e.g., on-site fuel, fodder, and food production to ensure their livelihoods.

A thorough analysis of such future scenarios or the uncertainty and non-stationarity in natural processes and scenarios of socio-economic development was beyond the scope of this study. However, it should be noted that there are proven techniques for participatory development of relevant scenarios with local stakeholders, as well as numerical methods for analyzing coupled human-natural systems under deep uncertainty, which might be very beneficial to narrow down future value ranges for watershed management in the Himalayas.

5. CONCLUSIONS & RECOMMENDATIONS

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5.1. CONCLUSIONS

This study presents a novel attempt to generate a comprehensive valuation of the multiple benefits that can result from implementing a watershed management program to control erosion and sedimentation in the Kali Gandaki watershed. A physically-based modeling approach, in combination with micro-economic modeling of major benefit streams, was employed using watershed- and region-specific data to evaluate these benefits rigorously. In this way, our study goes beyond the often-used approach of simply transferring area-based estimates of the value of watershed benefits from one region to another and represents a proof-of-concept for how such approaches may be applied in other contexts.

Conservative assumptions were applied throughout the economic analysis, and even so the results show that the aggregated benefits of such a program can greatly outweigh the costs. The benefits to cost ratio is highest at the lower investment levels and decreases to 1.2 at $50M US investment. There is both a physical limit and a feasibility limit to how much can be achieved with watershed management alone – our results indicate a maximum of 20.5% reduction in fine sediment load using the types of practices evaluated in this study. But as part of a comprehensive sediment strategy that includes land management improvements, structural sediment mitigation approaches, reclamation of degraded lands, and best practices for road engineering, our results show that a data-driven and targeted program of watershed management can contribute greatly to a broader social benefit through real and significant economic gains to society.

The results in Table 4.2 highlight the importance of considering multiple benefit streams and sources of value to make the case that investments in watershed services are sound. With the exception of the benefits from landslide mitigation , no one sector receives enough benefits to justify 100% of the investment cost. The fact that values accrue to many different sectors also means there is flexibility for building coalitions of different actors and funding sources to underwrite such programs. Consider, for example, the case of a US $1M investment portfolio, where the value of avoided lives lost is the largest single contributor to the total benefits from the program (estimated at $2M). Even if those benefits are ignored, the benefit: cost ratio is still enough to justify making the investment (changing from 3.2 to 1.3). Further, this portfolio assumes a net benefit to landholders (from improved soil fertility, water capture, and agricultural productivity, for example) of US $840,000. Considering this scenario from a break-even perspective, the local benefits could be 30% lower (at only $580,000) and the overall benefit: cost ratio would still reach 1. On the other hand, if the values of landslide risk reduction are fully realized and funded through disaster risk reduction efforts, then local landholders could receive the benefit of watershed management practices without any cost-share required on their part. Strategic partnerships between sectors are therefore necessary to pool resources and achieve these widespread benefits.

However, in some cases, targeting investments to benefit one sector will reduce the benefits accrued to other sectors. For example, sediment generation affecting hydropower infrastructure may be a huge problem in an area with relatively few people, which would argue for an engineering approach to sediment management, such as building retaining walls or sediment-trapping structures rather than investing in vegetation-based interventions that bring fuelwood and fodder benefits. Conversely, investing in on-farm management practices in another area may deliver huge development gains, but may not address the most critical sources of sediment for the hydropower sector. Mapping and quantifying the sources of sediment and benefit pathways will help policymakers to design equitable programs that distribute the costs of sediment management across different actors who receive benefits, and that address conservation and development goals as well as the need for sustainable energy and rural development.

As with any study that relies on physically-based models and extrapolates landscape-scale effects from local data, there are uncertainties inherent in the analysis. Every attempt has been made to use the best available data, vetted through a stakeholder engagement process. Errors in the underlying data on topography, historical climate, streamflow and sediment concentrations, and uncertainties about the costs and characteristics of watershed management practices as implemented in specific and varying locations on the ground means that the results of this study should be taken as demonstrative, rather than definitive. However, this study overall is conservative in its assumptions and thus provides evidence that watershed management can have positive economic benefits that greatly exceed the costs of its implementation.

It is worth noting that the benefits accruing to landholders are a large fraction of the total benefits shown in the results of this analysis. The assertion that better land-management practices might provide such benefits to the landholders implementing them may beg the question of why they are not already adopting them. There are several reasons they may not be. The first may just be that the on-site benefits of adoption do not fully cover the private costs. Economists have modeled farmers' soil conservation choices as a problem in the management of a depletable resource (a seminal paper is (McConnell 1983). They describe farmers as balancing the benefits of enhanced soil fertility against the costs of measures to maintain or restore fertility. If a farmer has struck this balance between on-site benefits and costs, the benefits of doing a little more to prevent erosion and loss should roughly approximate the costs. Other choices farmers make may be more discrete: whether to establish terraces or hedgerows at all, for example. Inasmuch as many areas have features such as terraces and hedgerows in place already, however (Bhattarai 2018), it is reasonable to suppose that the costs of expanding their use in other areas would be offset by substantial benefits.

In addition, several market failures may explain why farmers do not adopt on their own practices that might confer net benefits. Farmers in developing countries often face credit constraints that prevent them from making profitable capital investments (Das and Bauer 2012; Blackman 2001). There

[22]. The total benefits from reducing landslide risks (value of avoided lives lost, avoided loss of structures and avoided road repairs) is greater than the cost of implementation only up to a budget of about US $5M.

may also be a lack of information. Many projects have been instituted to demonstrate to farmers the benefits of sustainable land management without necessarily susbsidizing their adoption. The fact that such projects often are adopted by many local land users without subsidies suggests that the land users did not have information regarding their effectiveness before the program was initiated (see Section 3.3.6 for several examples).

Finally, many successful interventions to encourage more sustainable land management practices have focused as much or more on the institutions for management as on technologies or practices instituted per se. Seminal contributions such as (Hardin 1968; Ostrom 1990) document how lack of an effective governance structure can result in the overexploitation of resources with consequent degradation of the asset base that provides them. Instances of such degradation have often been noted, along with descriptions of the societal attitudes that underlie them. Ahmad (2001), for example, writes of local people who were concerned that the lands they managed would be appropriated by the government if local actions improved their condition. Baig et al. (2013) write of grazing lands producing at less than a third of their potential because nomadic users frustrated local attempts to institute rotational grazing systems. Another study found that the productivity of grazing lands increased by a factor of ten when local people were organized to better manage grazing access (WOCAT 2012). While these studies were conducted in other countries, similar concerns have been cited in grazing land management in Nepal (Guedel, n.d.).

There are, then, many benefits that landowners might enjoy as a result of interventions to manage watershed to prevent erosion, as well as reasons to suppose that landowners may not always act on incentives to supply these benefits to themselves. Aligning the incentives for landholders with broader societal goals for improving the value of ecosystem services from watersheds is therefore a policy challenge, and one that can be informed by the types of information provided by this study: e.g., where watershed management practices provide greatest overall economic benefits and how these benefits accrue to different sectors. Such a systematic approach allows for further engagement with different sectors to align interests and leverage resources.

The **agriculture, forestry, and water sectors** can use this valuation methodology to make a case for why watershed management programs are good investments. Understanding and quantifying the benefits that accrue to different sectors enables the design of more efficient and robust payments for ecosystem services (PES) schemes and can leverage investment from multiple actors. Application of the sediment modeling and prioritization tools can inform the design of watershed management programs to reduce sediment and improve water quality, by targeting interventions to the best places to achieve particular outcomes and balancing trade-offs, thereby making such programs more cost effective and transparent.

The **transportation and disaster risk management sectors** can apply the landscape-scale hazard mapping developed in this study to estimate the exposure of assets such as roads, at a finer spatial resolution than is currently available from landscape-scale screening analyses. While cutting of hill slopes, slope stabilization, landslide risks, water impacts, and other parameters are currently considered in a typical impact assessment study, the relatively simple sediment model employed here could be applied to assess the potential for downstream impacts outside the project area. Further, the prioritization tools can be used to identify areas of particular risk that may require higher standard of impact assessment and/or consideration of cumulative (rather than project-specific) impacts on ecosystem services.

The **hydropower sector** can use the valuation and prioritization methodologies to design PES schemes that more effectively control sediment from watersheds. Where policy mechanisms exist that require revenue-sharing from hydropower plants, the sediment budget and prioritization tools can be used to identify priority areas for investment that promote rural development (satisfying the motivation for why such policies often exist), while simultaneously reducing sediment-induced impacts on operations and maintenance of facilities.

The tools also have relevance for **environmental and social safeguards,** by providing a data-driven and systematic way to incorporate ecosystem services impacts into environment management plans, ensuring that infrastructure projects are more resilient in the context of other forces and pressures on the landscape. Beyond identifying impacts of proposed projects, the prioritization tools can also help to identify mitigation opportunities to offset project impacts to ecosystem services.

Overall, the methods and data resulting from this study demonstrate why effective and efficient targeting is key to achieving the greatest benefits at the lowest costs. Across all of these sectors, the use of watershed-scale tools to evaluate and integrate the multiple benefits of watershed management into sectoral and cross-sectoral policy and planning can be used a strategic tool to build resilience as climate change impacts are increasingly felt. Further, the stakeholder-driven process employed here allows for more durable and sustainable solutions, and the science-based, landscape-level assessment uncovers the underlying drivers of problems instead of focusing only the individual, localized results of such problems.

5.2. CAPACITY, DATA, AND TECHNICAL NEEDS

This study, like many assessments of hydrologic ecosystem services, draws heavily on numerical watershed-scale models. This is because it is in general not possible to observe processes generating sediment or storing carbon on whole watershed scales. Numerical models also allow us to evaluate the effectiveness of different management scenarios applied at scale to achieve objectives of watershed management.

Data are crucial to calibrate these numerical models, as demonstrated in the previous sections of this report. To bring the results of studies based on numerical models to the field, local agencies will require the knowledge to critically evaluate model input data, run models, and compare model outputs to their experience and use the results for prioritizing their work in watershed management.

This section presents some brief evaluation of the greatest data gaps in the study region, and some measures to address data gaps and capacity improvements.

Priorities for data collection

- **Suspended sediment data:** River suspended sediment data collected by Kathmandu University were of high quality and the sampling frequency matched the needs of this study. Importantly, most of the relevant tributaries, except for the Aadhi river, were monitored. Sediment monitoring took place from the river banks and using multiple grab samples. Depth integrated sampling along an entire cross-section would likely yield more accurate results, but would also require expensive equipment such as a cable crane or a suspension bridge (wading is not feasible in most of the rivers). For the purpose of ongoing watershed assessment and management, it is advised to sample with a simple but replicable method at many locations and for at minimum 5 years. Given the usefulness of sediment data for watershed management, it should be explored what options are available for automated sediment sampling (e.g., using turbidity meters).

  The sampling campaign did not include bed-load measurements or detailed assessments of grainsize composition of the bed material. Bed load measurements would be very resource intensive and should not be prioritized. However, assessments of bed material composition throughout the watershed could yield very important information for modeling bed-load transport (Schmitt et al. 2018; Ferguson et al. 2015) with relatively small effort.
- **Sediment yield from glaciers:** Glaciers are often considered of great importance for sediment management of Himalayan hydropower plants. That is because glaciers are often perceived as an important contributor in terms of total sediment, and especially in terms of fine and abrasive particles that can pass through the desanders and directly damage turbines. Glacial sediment yield might also greatly increase in a warmer climate. Despite the relatively high rates of glaciation in the Myagdi and Modi Rivers, the relative contribution of these tributaries to the overall sediment budget is relatively small, however our estimates of how much of that fine sediment originates from glaciers is purely model based. Some measurements of sediment yield directly downstream of glaciers would be of great value to determine the contribution of glaciers and the mineral composition of the mobilized material (similar to Haritashya et al. 2006).
- **Sediment yield from roads**
  Sediment yield from roads is not monitored in the Kaligandaki area and indeed there are very few studies on that in Nepal. Establishing a network of sediment traps for measuring sediment load from roads could be of great importance for better management and planning of road sediment generation.
- **Sediment composition and provenance:** While initial results of KU indicate that glaciers do not supply sediment of greater hardness than other erosion processes, more distributed samples of mineral composition, geo-chemistry, and isotopes could be a very cost effective measure to confirm the origins of different minerals, and to provide an independent line of evidence for sediment provenance in the watershed (Garzanti et al. 2016).
- **Exposure data:** Data of exposed infrastructure and buildings is based on Open Street Map data, i.e., data mapped by interested citizens. Our visual quality control indicated that these data represent the location of most structures and roads well. However, there is no guarantee that these data are comprehensive. Incomplete exposure data can lead to underestimating the risk of natural hazards as well as to underestimating the value of measures reducing hazards. Given the rapid and

unplanned development in the watershed, satellite data and machine learning approaches could be used for infrastructure and building identification.

- **Landslides:** Data on landslides in a georeferenced format are absent. Such data would be of great value to better calibrate and validate the landslide model. Landslide data could be obtained either by trained citizen scientists (e.g. people who already work on mapping for open street maps) or from satellite data and machine learning approaches. Similarly, better understanding road and structure damages by landslides and the related repair costs could help to better value mitigation measures.
- **Hydromet data:** Hydrometeorological data were mostly of good quality and there is a dense network of precipitation stations in the study area. Discharge data from Jomsom gauging stations turned out to be invalid for most of the year because of changing river cross sections. If such inconsistencies are observed, mechanisms should be in place to correct cross section data as soon as possible, as data gaps can greatly reduce the data quality.
- **Data on activity implementation:** Models that predict impacts of watershed management activities rely on data to parameterize the models so that they reflect how effective the practices are at restoring vegetation and reducing sediment. More site-specific studies from the study region would help to reduce uncertainty in model estimates. Further, specifics on average costs of activities and the physical & economic conditions that affect costs would improve estimates of program efficiency. Finally, local information on the willingness to pay on the part of landholders to adopt practices, and the co-benefits that they expect to receive from them, would improve greatly our estimates of the total value of implementing such practices.

5.3. FUTURE WORK

Further work that could be undertaken to expand on this analysis could include:

i. extending the analysis of benefits to the hydropower sector by incorporating detailed economic analysis of sediment impacts on upstream hydropower plants, both those currently operational (Modi Khola and Lower Modi 1) and planned (Middle Modi, Lower Modi Khola, and Lower Modi 2, among others).
ii. improving the data basis for on-site benefits versus local and total program costs, through improved monitoring of site-level impacts and data sharing among programs;
iii. extending the landslide hazard analysis by considering co-seismic landslides and improving data on assets at risk;
iv. exploring partnerships with WOCAT, FAO and other experts in the field of sediment and watershed management, to bring in other perspectives and link to other knowledge bases on watershed management;
v. improving the understanding and technical approaches for considering episodic phenomena (e.g. landslides, floods);
vi. explore other modeling approaches for watershed hydrology and sedimentation (e.g. SWAT), to compare the results of different approaches and thereby develop ways to reduce computational complexity (e.g. using simple coefficients based on calibrated models to quickly evaluate particular interventions impacts both locally and downstream);
vii. extending the analysis to model and compare the impacts of civil works alone, vegetative interventions alone, and then a more integrated approach to improve understanding of the relative values and synergies of grey and green infrastructure approaches;
viii. building a global knowledge coalition (facilitated, for example, by The World Bank), to collect and make accessible a global database of watershed intervention costs;
ix. develop a capacity-building program including, for example, virtual trainings related to sediment modeling and management to build up interest and capacity, showcase local progress, and improve access to global good practice and expertise. This can include existing communities of practices and can slowly expand to other elements of watershed planning, monitoring, management, and instruments (e.g. PES) that can all be better designed on the bedrock of good watershed management data and analytics.

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