OPPORTUNITIES FOR STRENGTHENING SEDIMENT MONITORING IN LARGE WATERCOURSES IN NEPAL

Preliminary Report by NVE
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Preface

This report is developed by the initiative of The International Centre for Integrated Mountain Development (ICIMOD) and the Norwegian Water Resources and Energy Directorate (NVE). The report aims at demonstrating opportunities for better coordination of sediment monitoring in large water courses in Nepal for the benefit of the nation of Nepal

The report focuses on the major users of the catchments, in particular the hydropower sector.

There is increasing interest in developing seasonal reservoirs in new hydropower projects in Nepal due to the general lack of dry season energy (which coincides with colder weather and higher energy demand) provided by existing hydropower projects. This requires a better understanding of all sediment transport processes in each river, including identifying differences from river to river and from decade to decade as we now observe that sediment transport is increasing due to changing land use and climate. In order to understand these trends, there is a need for a monitoring program to give long term measurements.

The basic network of such monitoring programs is often accepted as a government responsibility since hydropower developers are seldom willing to commit to such long-term activity.

The findings in the report are based mainly on desktop studies. Two experts from NVE embarked on a fact-finding mission of a week's time in 2019 and this was combined with a stakeholder workshop, facilitated by ICIMOD.

This report investigates opportunities for better coordination of the knowledge and data collection in Nepal. Realization of opportunities requires ownership in Nepal and necessary funding

The research for the report was done between 2019 and 2021, and editing finalized in 2022.

It is ICIMOD's and NVE's wish that the report may be useful for stakeholders as a tool to further develop the important work on sediment monitoring in Nepal.

1 Executive Summary

Purpose of the work

The purpose of this report is to provide an overview and status of sediment transport monitoring in the large rivers of Nepal and intends to demonstrate the value of strengthening Nepal's sediment monitoring system.

Methods used and limitations of the work

The information presented in this report is the result of engagement with stakeholders from Nepal, including a workshop held in Kathmandu on 22nd May 2019, follow-up interviews and expert consultations. Relevant experience from other countries and international best practices have also been reviewed and incorporated were useful. The report is not an extensive examination of sediment transport monitoring with respect to all sectors of activity in Nepal rivers, although they are mentioned, but focuses on the major users of the catchments, in particular the hydropower sector.

Acknowledgements

Funding was kindly provided by the Government of Norway under the project 'Snow accumulation and melt processes in a Himalayan catchment', better known as 'SnowAMP' (Phase 2). The report has been jointly developed by the International Centre for Integrated Mountain Development (ICIMOD) and the Norwegian Water Resources and Energy Directorate (NVE).

Thanks to Multiconsult for their contributions to incepting, drafting, editing and reviewing this report.

Major findings

The erosion rate in Nepal is very high compared to many other regions in the world, as indicated by the sediment loads of regional rivers. Sediment dynamics influence the landscape and infrastructure in Nepal. The country is vulnerable to mass wasting (i.e. landslides), glacial lake outburst floods and heavy monsoon rain which, combined with steep hillsides and gullies, mean that erosion dominates the landscape.

Fundamentally, regular sediment monitoring has not been a priority in Nepal, despite many sectors, such as hydropower and disaster risk reduction, relying on such data to determine sediment generation, transport, deposition and overall budgeting. Thus, there is an urgent need to better understand the reasons behind this situation and to seek opportunities for how sediment monitoring can be strengthened.

The major users of sediment data in Nepal are currently hydropower developers, particularly projects of medium and large scale. They need to prepare realistic forecasts of the sediment load passing the intake sites, the grain size distribution and the minerology of the finer fractions which are expected to pass through the turbines and cause damage. They will start by analysing historic data on the same river, but in most cases find that they need to start their own sampling and analysis program to be able to make such forecasts reliably. The time constraints of such projects means that there is often only 1-2 years of data collected by the developer by the time they have to present their project and report its environmental impact to the licensing authorities and financiers. Such short programs may miss the major sediment movement events and will often underestimate sediment yield and forecast turbine erosion rates. It is therefore important that monitoring stations with some years of good record of sediment transport are prioritised and continue to deliver uninterrupted data of high reliability. These are the only stations which can document the variability over many decades and demonstrate any long-term trends in sediment yield and will provide vital data for the analysis of sustainability of recent and future hydropower projects.

The Department of Hydrology and Meteorology, DHM, has a mandate from the Government of Nepal to monitor all the hydrological and meteorological activities in Nepal. Their scope of work includes the monitoring of river hydrology, water quality, sediment, limnology, snow hydrology, glaciology, weather, climate, agro-meteorology, air quality and solar energy. The public sediment monitoring network in Nepal is limited in its extent and no other entity is entitled to carry out such activities without a proper liaison with DHM, notwithstanding for private use. DHM oversee a sediment monitoring network comprising 28 stations, of which 12 stations are currently reported as operational (as of May 2019). Some private companies also collect sediment data locally to meet their production needs. Additional site-specific stations are operated by private entities, such as hydropower companies, but the data is not standardised or systematically collated and published in a common database. Analysis of sediments are mainly conducted by the DHM, Kathmandu University (KU), Tribhuvan University (TU) and private laboratories such as HydroLab. Hydropower companies occasionally make their data and analyses available, but the information is generally held as proprietary. DHM has established a sediment laboratory, but it is understood that this is presently not in full operation and that sediment analysis capabilities are limited.

There seems to be a lack of a consistent long-term strategy for how government intends to monitor sediment transport in the future, which generates uncertainty and the need for the private sector to each set up their own local sediment transport monitoring programs.

Opportunities for further Work

The role of the Nepali government in sediment transport monitoring and reporting could be better defined to make it clearer to the users and participants. One way to do this would be to work out an overall strategy document describing how the government can work together with data users, universities, and relevant stakeholders in the long-term.

The report identifies gaps and room for improvements in network completeness and quality and presents opportunities for improvements to this situation.

Currently, the limited quality and availability of sediment data is impacting Nepal's hydropower development projects. Ensuring that data is collected and made available could greatly benefit the design, reliability and maintenance of hydropower infrastructure. The collected data can support the needs of various sectors, including environmental and social considerations, be useful to both upstream and downstream areas in catchments, benefit river training, flood control, etc. Beyond the hydropower sector, the Departments of Road, Water Resources and Irrigation, of Mines and Geology as well as the Nepal Electricity Authority could benefit from improved continuity, completeness and quality of sediment data being reported by DHM.

The report highlights a number of opportunities for addressing this situation including:

- Strengthening capacity in DHM

- Refurbishing the DHM laboratory for sediment sample analysis
- Ensuring standardised methods for sediment data collection
- Focus on education and supply of new professionals in sediment-related fields
- Creating and updating a database with adequate quality control
- Development of sediment information products
- Data sharing and coordination between government agencies
- Enhancing public-private partnerships
- Increased basin-scale management & co-ordination
- Consider need for legal framework

2 Global experience with sediment monitoring and recent literature

2.1 Sediment transport measurement and monitoring

Within the field of hydrology one of the most difficult parameters to measure and monitor continually is sediment transport in rivers and streams. One reason for this is the extreme variability of sediment transport mechanisms both in space and in time. Another reason is that it requires time, equipment and skilled human resources which makes it an expensive exercise. It is costly in terms of cableways and transport for measurement teams, in terms of laboratory analysis and in some cases mineralogical analysis. It is not surprising to register that sediment monitoring programs tend to have insufficient sampling frequency and spatial coverage in most developing countries, and Nepal is no exception.

When planning a nationwide program of sediment monitoring it becomes important to start with the demand for such data and understanding the main drivers of this demand. When the data being gathered is relevant for the main users, there is a good chance that the monitoring program will remain relevant and sustainable in the long term. In Nepal we find that the main drivers of existing sediment measurement programs are hydropower developers, and this also applies across the border for Indian hydropower developers with much of their catchment areas within Nepal.

2.2 Sustainability of hydropower and the need for reliable sediment data

Hydropower development worldwide has a long history, and many projects reach an age of 100 years or more before the end of their useful life. We therefore have plentiful evidence that hydropower is implicitly a resource which is both renewable and sustainable in the long term.

Dams can be maintained (and strengthened if necessary), and hydropower machinery can be replaced and upgraded, so there are few reasons for calling a hydropower investment as “not sustainable”. However, one of these few reasons is the ability of the project to manage increasing sediment load filling the reservoirs and wearing out the machinery. Poorly managed sediment load can lead to the blocking of intakes or the erosion of turbine runners and jets and is often cited as an example of hydropower not being sustainable in the long term. In order to convince investors, financiers and decision-makers of the sustainability of hydropower, an agreed strategy for managing sediment risks should be developed as part of project preparation, which in turn requires good historic data and expert knowledge of sediment transport at the site of the dam or power intake. This is the main reason why adequate sediment monitoring has great value to potential hydropower developers in Nepal.

2.3 Selected recent literature and relevant resources[1]

In recent years, some relevant publications and software has become easily available online to aid the project developers in collecting and structuring sediment sampling data, and eventually choosing an appropriate sediment management strategy. One of the most used reference resources is the Reservoir Conservation Model RESCON 2 Beta tool. The software tool presents the most advanced economic and engineering evaluation of alternative sediment management strategies. It builds on the Reservoir Conservation Model (RESCON) Approach published in 2003 which helps hydropower developers to carry out a preliminary screening analysis of viable sediment management alternatives.

[1] State of the art in 2021

The upgrade to the RESCON 2 beta tool takes into consideration sustainability factors and hydrological uncertainties associated with climate change. (Ref. 1).

The International Hydropower Association (IHA), together with the World Bank hosted the South Asia Water Initiative (SAWI), which has launched the Hydropower Sediment Management Knowledge Hub (Ref.2), available online to promote strategies and case studies for effective sediment management. The objective of this knowledge-building project is to help hydropower developers and researchers to implement and refine sediment management strategies based on real-life industry experiences and practices and the website includes a number of useful case histories with contributions from several Nepali institutions and actors.

A useful book "*Extending the Life of Reservoirs: Sustainable Sediment Management for Dams and Run-of-River Hydropower*" available via the World Bank library (Ref.3) provides guidance on adopting sediment management practices for hydropower and dam projects. It stresses the importance of incorporating sediment management into projects in order to safeguard the many important services of these projects, including water supply, irrigation, and renewable electricity. In particular, the book stresses the importance of integrating sediment management into the early planning phases of projects. It also discusses sedimentation monitoring procedures, bathymetric mapping of sediment, and estimation of sediment bulk density.

The World Meteorological Organization (WMO) Manual on Sediment Management and Measurement produced in 2003 has a complete and thorough description of commonly used methods of sampling and analysis techniques, and is recommended as the primary literature source for determining which methods should be applied as standard in Nepal. As an example, one table which summarises the overall approach to sediment measurement methods is copied below as Table 2-1. The reader is referred to this manual for detailed descriptions and can be freely downloaded from the WMO library (Ref.4).

Programme of data acquisition according to the International Hydrological Programme (IHP)

Purpose of study	*Items of measurement*		
	Surveying	*Sediment transport*	*Relevant items*
Annual sediment discharge		Total sediment discharge or concentration at hydrometric stations	Water discharge, etc.
Erosion and deposition in river reach or reservoir; depletion of reservoir capacity	Sedimentation survey by ranges in a river reach or reservoir	Total sediment discharge at inflow and outflow gauging stations	Size distribution and/or unit weight of deposits
Fluvial processes in river reaches or in backwater reaches of a reservoir	Repetitive survey over entire reach or in localities of interest: aerial photographs if possible	Bed material discharge at inflow stations	Relevant hydraulic and sediment parameters such as water surface slope, bed material composition, velocity, depth and width, water temperature, size distribution of sediment

Source: UNESCO, 1982.

Table 2-1 Overview of type of sediment monitoring dependent on purpose. (Reproduced from WMO ref 4)

2.4 Examples from other ICIMOD countries and relevance to Nepal

India undergoes significant research and analysis into sediment monitoring techniques and their value to hydropower developers. This also includes research carried out in Nepali catchments such as in the

Kali Gandaki case study (Ref 5). Typically, we find that much sediment originates from high mountain regions where it is impractical to set up and maintain continuous sediment transport monitoring stations. We quote from the Kali Gandaki case study (our highlighting in bold):

"This study used the Soil and Water Assessment Tool (SWAT) to estimate the sedimentation yields in the Kali gandaki basin of Nepal, which is an important tributary that drains into the Ganges. Multi-source data from Beld observations, remote sensing platforms, surveys and government records were used to set up and run the SWAT model for the Kali gandaki basin from 2000 to 2009. Results for the 10-year model run indicate that ***73% of the total sediment load is estimated to come from the upstream regions (also known as High Himalayan region),*** *while only 27% is contributed from the Middle and High Mountain regions (where land-management based interventions were deemed most feasible for future scenarios). The average sediment concentration was 1986 mg/kg (ppm), with values of 8432 and 12 mg/kg (ppm) for maximum and minimum, respectively. Such high sedimentation rates can impact river ecosystems (due to siltation), ecosystem services and hydropower generation.* ***In addition, model results indicate the need for better high frequency observation data."***

Ref. 6 includes some good data obtained from catchments in India which have similar conditions to catchments in Nepal. The difficulties of using the sediment rating curve method to estimate total sediment yield when concentrations do not correlate well with simultaneous discharge measurements are also demonstrated in this. The figure is reproduced here as Figure 2-2.

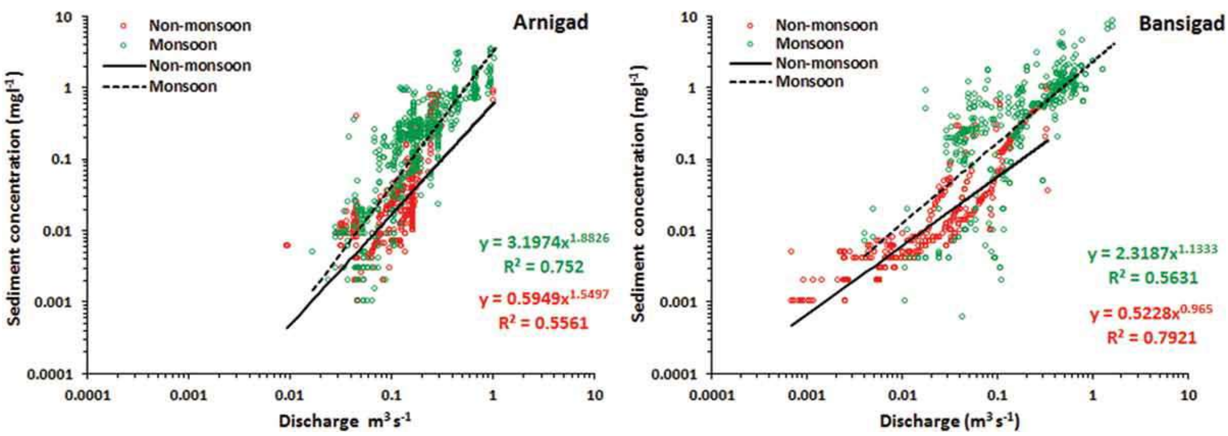

Figure 2-2 Rating curves between instantaneous daily discharge and suspended sediment concentration for Arnigad and Bansigad ***(Spatio-temporal dynamics of sediment transport in lesser Himalayan catchments, India - Ref 6.)***

Ref. 7 gives a similar comparison from the Koshi River in Nepal/India. Fig. 2-3 shows the rating curves for monthly sediment load and discharge for different points in the Koshi River. Both of these figures demonstrate a very broad scatter of points for which it is difficult to construct a sediment transport rating curve, and such curves demonstrate a poor correlation between suspended sediment concentration and flow discharge. This is a reflection of how variable sediment concentration is in Nepal, both in time and space. It takes a lot of reliable measurements of sediment concentration at a broad range of flows, including very high flows, before an understanding of sediment flux variations have been in the past. Furthermore, the prediction of sediment flux in the future must be based on reliably accurate measurement of past concentrations as well as good analysis of trends applicable to the river in question, both climatic and land use trends.

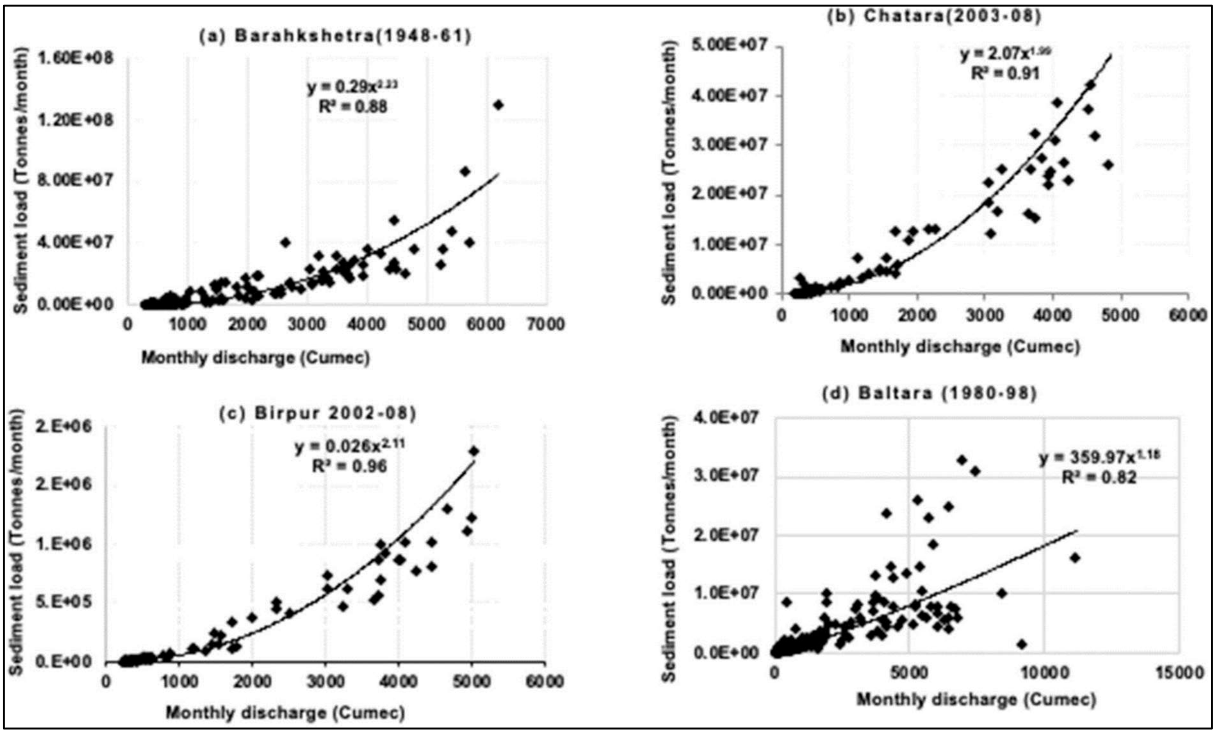

Figure 2-3 Rating curves for monthly sediment load and discharge for (a) Barahkshetra (b) Chatara, (c) Birpur, and (d) Baltara in the Koshi River (Ref. 7)

Bhutan has also a limited activity in sediment monitoring as explained in the following excerpt from the publication by Sonam Choden of University of Lund (Ref. 8):

"Reliable and consistent sediment rating equation is not found for the Himalayan Rivers. *The change in the flow rate and suspended sediment concentration is very rapid and unpredictable. In Bhutan, there are no published records on sediment transport studies. There are four sediment sampling stations in the whole country. …..In this report, the sediment concentration and river flow data from one gauging station along Punatsangchu River is presented to increase the understanding of sediment transport pattern in this river. Sediment transport in the Himalayan Rivers with regard to factors affecting sediment transport is addressed and some comparison is made with the Punatsangchu River. The factors affecting sediment transport are hydrology and climate, geology, land use and topography. The correlation between sediment concentration and river discharge for the year 2007 for Punatsangchhu River was found to be very good with an R2 value of 0.8. The correlation of average discharge and concentration over the record period of 1993 and 1996 to 2008 was found to be 0.53. For some years the correlation was very poor with an R2 value of 0.13. This shows that river discharge is not a reliable variable to predict the sediment concentration in Punatsangchu River.* ***Most of the sediments are transported during the monsoon months which account for about 90% of the total load transported in a year."***

All of these cases demonstrate the problems associated with relying on sediment rating curves to predict sediment flux in Himalayan rivers. Sediment transport in these rivers is very site specific and variable over time.

2.5 The hydropower owner's view on sediment management and monitoring

In Nepal, as in many countries, sediment transport in rivers can have impacts on and is important to monitor in different sectors. In Nepal, the hydropower sector is particularly interested in sediment transport in rivers and hydropower owners or project developers therefore have a focused and practical approach to obtaining sediment data which is of most value in assessing the project risks related to sediment transport. This usually can be divided into two alternative types of sediment monitoring plan, designed primarily for either one of the following cases:

- The long-term design life assessment and pattern of sediment accumulation in large reservoirs
- The properties and quantities of sediment for eroding turbine parts in run of the river projects and projects with only small reservoirs.

These two types require differentiated programs for sediment monitoring and measurement and should generally be treated separately depending on the size and characteristics of reservoir being planned. Basic sampling of sediment load in large rivers together with flow measurement at the same site is necessary for both purposes, but the extent of laboratory analysis differs. The more extensive analysis of particle shape and minerology is only needed for the second purpose. If a seasonal regulating reservoir is being planned, the focus will be on the quantities of sediment being transported into the reservoir and the typical grain size distribution, while the risk of turbine erosion will be less because most sand and coarse silt fractions will be deposited and not pass through the turbines.

The characteristics of erosion and sediment transport in Nepal described in the next chapter indicate a very high and sporadic transport of all sediment fractions from boulders down to fine glacial silt. Much of this transport is transported as bed load in the steep mountain rivers, while the suspended load will dominate the total sediment load in the lower plains. The developer of a particular project site wants to determine which of the two problems will dominate at their specific site. We find that run-of-the-river projects in the mountain rivers are much more interested in the turbine erosion problem and will quickly accept that their small reservoir will have to pass bedload and other sediments continually during floods. The total volumes of sediment arriving at the dam site have little relevance, but the functioning and dimensioning of desilting facilities will be in focus. Further downstream and across the border in India, the focus changes to determining the quantities of sediments entering a reservoir site, both for existing reservoirs and new ones being planned.

Another difference in the two types is the duration and frequency of sampling required. Determining accurately the long-term transport of all sediments requires several years of continuous and consistent monitoring of sediment transport, including many measurements during flood events and throughout many monsoon seasons. In contrast, the turbine erosion problem can be well illuminated by relatively short programs of sampling typical sediment fractions expected to pass through the turbines. This leads to a differentiation of the best type of monitoring program for each purpose.

In larger rivers the suspended load is measured and monitored continuously at reliable flow gauging sites, and such sites have greatest value if the record is long and continuous, say over 20 years or more, preferably including recent years. There is usually no attempt to measure bed load and an appropriate percentage addition is made to the measured suspended load, depending on the sediment grading and concentration as indicated in Table 4.1.

In smaller mountain rivers it may be impractical to develop such a long series at many different sites, while the need is generally to understand the grain size distribution of typical sand and silt fractions, particle shape and mineral content for predicting turbine erosion. In rare cases it may be relevant to measure or indirectly estimate bed load transport. Measurement and analysis of sediment in upper mountain regions is an activity which is natural to leave for each hydropower developer to design and finance entirely privately according to their specific needs.

There is increasing interest in developing seasonal reservoirs in new hydropower projects in Nepal due to the general lack of dry season energy (which coincides with colder weather and higher energy demand) provided by existing hydropower projects. This requires a better understanding of all sediment transport processes in each river, including identifying differences from river to river and from decade to decade as we now observe that sediment transport is increasing due to changing land use and climate. In order to understand these trends, we must design the monitoring program to give long term records at reliable gauging sites on each major river of interest. The basic network of such monitoring stations is often accepted as a government responsibility since hydropower developers are seldom willing to commit to such long-term activity.

This is a great opportunity to **d**evelop an appropriate long-term monitoring program of suspended load in the major rivers of Nepal.

Hydropower developers usually require sediment data during both planning and operation:

- Data to determine reservoir lifetime and measures to prolong the lifetime (suspended and bed load transport, reservoir sedimentation monitoring)
- Data to support measures to maintain the reservoir capacity and to mitigate downstream environmental impacts (reservoir flushing, channel aggradation or degradation and sediment pollution)
- Turbine wear (high sediment load and large potential for high pressure hydropower projects)
- Measures to reduce sediment flow (turbine wear and reservoir sedimentation) may require measurements of critical values of sediment concentration and grain size (mineralogy, shape)
- Identification of sediment sources in the catchment area to improve prediction of sediment flow and erosion intensity.

Sizing and estimation of reservoir parameters and their lifetime capacity are crucial in all hydropower planning, project economy and energy planning. Where sediment is an issue, mitigation and management methods need to be adopted, to maximise reservoir lifetime and production. Improved hydrological and sediment data should be collected, collated and made available to stakeholders before planning with the aim of optimizing the new hydropower plant design.

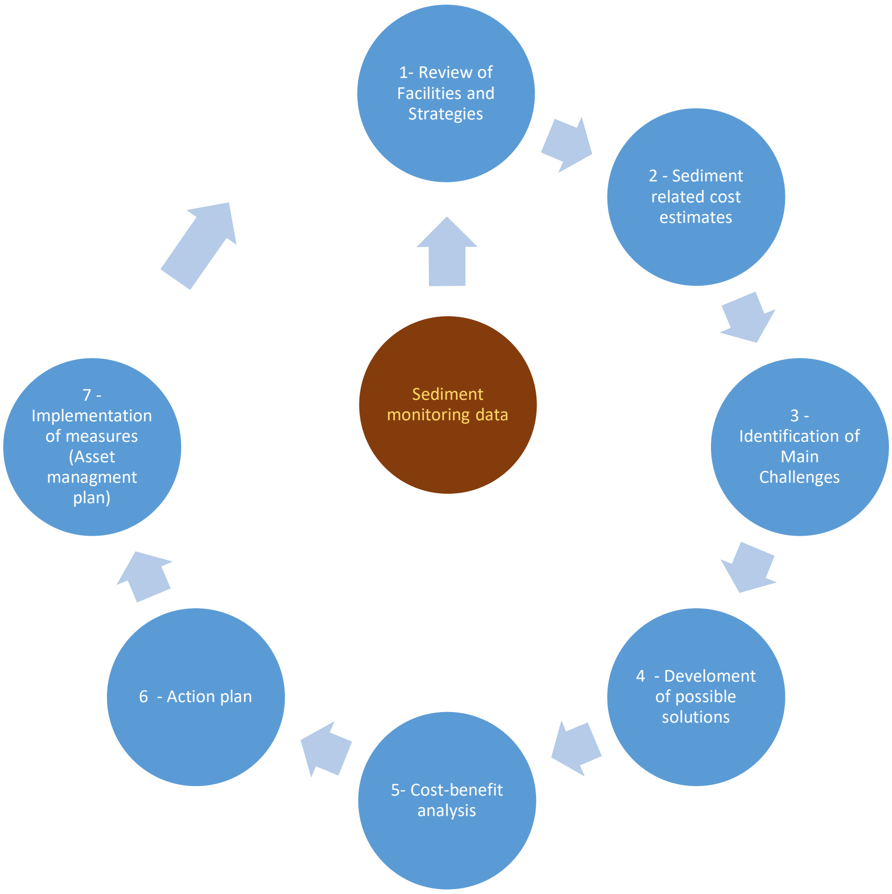

Figure 2-4 Guideline on Sediment Handling

3 Characteristics of Nepal relevant to sediment transport

3.1 Geography and climate of Nepal

The Federal Democratic Republic of Nepal spans several climatic zones and physiographic regions with diverse topography, vegetation and geography. The landscape and hydrology reflect this diversity including other associated processes such as erosion due to the direct impact on the fluvial processes of the rivers flowing from upstream to downstream. This diversity and complexity in physical and climatic conditions over short distances are challenging to fully quantify but remain important parameters for understanding the status of sediment dynamics in Nepal (Mishra and Coulibaly, 2009, Ref. 9).

Due to its location in the Himalayas, Nepal has a tremendous geographic range within a limited area of 147,181 km^2. The lowest point in the country is just 70 metres above sea level (Kechana Kalan), while in the high Himalaya there are some 90 peaks exceeding 7,000 m.a.s.l., including Mount Everest (8,849 m.a.s.l.).

The country has eight climatic zones – from tropical to perennial snow. The tropical zone below 1,000 m.a.s.l. comprises 36% of the land area, the subtropical zone (1,000 – 2,000 m.a.s.l.) 22%, the temperate zone (2,000 – 3,000 m.a.s.l.) 12%, the subalpine zone (3,000 – 4,000 m.a.s.l.) 9% and the alpine zone (4,000 – 5,000 m.a.s.l.) 8%. Above 5,000 m.a.s.l. the climate is nival (no human habitats or even seasonal use are established here).

There is a general trend of wetter conditions in the east (Taplejung at 1,768 m.a.s.l. receives an annual average of 2,204 mm) and drier in the west (Baitadi at 1,635 m.a.s.l. receives 1,037 mm) (Miehe and Pendry 2017). The average rainfall in Nepal is about 1,600 mm, with about 80% falling in the monsson season between June and September (above 5,500 m.a.s.l. this falls as snow). The southern slopes of the Himalayas receive the highest rainfall (3,477 mm in Pokhara at 850 m.a.s.l.; 5,500 mm in Lumle at 1,642 m.a.s.l.), whilst the trans-Himalaya lands north of the main Himalayan range are in the rain shadow with a desert-line barren tundra, barely getting 250 mm of annual rainfall (Jomsom at 2,650 m.a.s.l. receives 255-295 mm).

There are three large river systems with perennial discharge in Nepal. The map below shows the river systems from East to West:

- Koshi (Sapta Koshi) with seven Himalayan tributaries in the eastern Nepal: Indrawati, Sun Koshi, Tama Koshi, Dudh Koshi, Likhu, Arun and Tamor
- Gandaki/Narayani with seven Himalayan tributaries in the centre of Nepal: Araudi, Seti Gandaki, Madi, Kali, Marsyandi, Budhi and Trishuli (Sapta Gandaki)
- Karnali with two major tributaries in western Nepal: Beri and Setis

Figure 3-1 Major River systems in Nepal

(by Kelisi at the English language Wikipedia, CC BY-SA 3.0, (Ref.10)

Another group of rivers, with somewhat different hydrological features, flow in the Middle Hills and Mahabharat Range, from east to west: Mechi, Kankai, Kamala (south of the Koshi), Bagmati (drain Katmandu Valley between Koshi and Gandaki systems), West Rapti and Babai (between Gandaki and Karnali systems) – these rivers are without glaciers and their annual flow regimes depend on precipitation, with limited flow during the dry season. There also exist a few seasonal rivers in the outermost Siwalik foothills (Agrawala *et al*., 2003; Bajracharya and Mool, 2009; Basnyat and Watkiss, 2017; Sangroula, 2009; Sharma and Awal, 2013; Shreshta and Aryal, 2011).

3.2 Erosion and sources of sediment transport in Nepal

The rapid uplift of the Himalayas causes the high mountains to be formed which are then exposed to erosion from the elements, causing high erosion rates and consequently high sediment loads in the river basins. Annually, regional rivers transport millions of tons of sediments downstream as bed load and suspended sediments. High erosion rates and fluvial sediment transport results in heavy sedimentation and shifting rivers (Sinha *et al*., 2019) where the gradient decreases and substantial sedimentation occurs in lakes, reservoirs and plains (Abderrezzak and Findikakis, 2019, 2018b, 2018a; Koirala *et al*., 2016). Flash floods, erosion and landslides along steep tributaries are frequent and support highly variable amounts of sediments to the river systems.

The erosion rate in Nepal is very high compared to many other regions in the world, as indicated by the sediment loads of regional rivers. The suspended sediment load of the Koshi river at Chatara (where the river leaves mountains and enters the Indo-Gangetic Plains), for example, is about 100 million tons per year (Sinha *et al*. 2019). Sediment dynamics influence the landscape and infrastructure in Nepal. The country is vulnerable to mass wasting (i.e. landslides), glacial lake outburst floods, heavy monsoon rain which, combined with steep hillsides and gullies, mean that erosion dominates the landscape.

Climate change has caused temperatures across the Himalaya to rise due to Elevation Dependent Warming. This has accelerated the melting of glaciers. These changes impact sediment sources, erosion and deposition rates as well as sediment transport in general in the downstream rivers. Increases in magnitude and frequency of floods also directly affect the erosion and transport processes along the river systems.

Morin et al (Ref. 11) analysed erosion in the Narayani River basin to assess the relative contributions of erosion processes to the annual sediment export. An erosion rate was found similar to the average value of 1.6 mm/year estimated from 15 years of records and long-term denudation rates of 1.7 mm/year derived from cosmogenic nuclides. The Naranyani River at the monitoring station Naranyghadhi is a large river combining subcatchments at various altitudes and is considered to be representative for most rivers in Central Nepal.

The stability of erosion is attributed to efficient buffering behaviour and spatial integration in the drainage system. Strong relations between rainfall events and the sediment export suggest that the system is mainly supply limited. They estimate that glacial and soil erosion do not contribute more than a small percentage of the total sediment yield budget and are only detectable during pre-monsoon and early monsoon periods. During the monsoon, erosion by landslides and mass wasting events overwhelms the sediment yield budget, confirming the dominant role of these erosional processes in active mountain chains such as we find In Nepal.

4 Sediment monitoring and measurement methods and products

4.1 Monitoring of total sediment load in large rivers

Inorganic particulate load in rivers is commonly separated into bed load and suspended load. Current techniques can give accurate information of suspended load, but bed load sampling is more challenging, and is therefore less frequently undertaken. Therefore, a percentage addition to suspended load is usually used to allow for bed load when estimating total sediment load. Indicative percentage additions for bed load compared to measured suspended load are given in Table 4-1 below.

Estimation of ratio of bed load to suspended load

Suspended sediment concentration (ppm)	*Bed composition*	*Suspended load composition*	*Ratio (r)*
< 1 000	Sand Gravel, consolidated clay	Similar to bed Small amount of sand	0.25–1.50 0.05–0.12
1 000–7 500	Sand Gravel, consolidated clay	Similar to bed 25% sand or less	0.10–0.35 0.05–0.12
> 7 500	Sand Gravel, consolidated clay	Similar to bed 25% sand or less	0.05–0.15 0.02–0.08

Table 4-1 Estimates of bed load as function of suspended load (from WMO Ref 4)

Monitoring total sediment load for all rivers in any country is a complex and time-consuming task. It comprises a number of separate activities: the collection of representative samples at selected sites in the river network and the laboratory analysis of these samples and subsequent quality control and publishing of the results. The monitoring system to be applied must suit the resources available to remain sustainable and provide a consistent set of continuous data over many decades. It should be designed in terms of the representativity, frequency, timing, location, and volume of sampling which is affordable and can be handled by competent staff. Furthermore, containers and transport resources are needed to ensure safe and intact transport of the samples for a systematic and regulated analyses of sediment data (Ancey, 2020a). Monitoring sediment transport is closely associated with flow measurement and is often carried out by the same crews who perform flow measurement at important gauging stations.

The normal method of measuring suspended sediment load is by taking a series of water samples across the entire measurement river cross-section and analysing the sediment content in each sample. The lab analysis techniques vary according to the concentration and grading of the sediment content. If the main objective is to measure total suspended load, then high concentration samples can be analysed by the displacement method which compares the weight of the sample with an equivalent volume of clean water. However, in most cases more information is required on particle size distribution, portion of organic sediments etc.

	Range of application (diameter in mm)	*Concentration (g/l)*	*Required sample weight (g)*
Fine sediment--------Settling in clear water (two-layer system)			
Siltmeter	0.062–0.5; may be more if longer tube is used		0.3–5.0
Visual accumulation tube	0.062–2.0		0.05–15.0
Fine sediment------- Settling in dispersed medium system			
Pipette	0.002–0.062	3.0–20.0	3.0–20.0 in 1 000 ml
	0.002–0.062	2.0–5.0	1.0–5.0
Photo-sedimentation	0.005–0.062; may be used for 0.005–0.1	<1.0	<1.0
Hydrometer	0.005–0.062; may be used for 0.002–0.05	15.0–30.0	15.0–30.0 in 1 000 ml
Coarse sediment			
Sieve	0.062–20.0 or more 0.062–32.0		100–200 if done independently More than 20 for coarse particles; min. 0.05
Direct measurement			Sufficient quantity

Table 4-2 Different lab techniques for analysing sediment content in water samples, (from WMO Ref 4)

Most water samples include both dissolved organic and inorganic matter, organic particles, and dissolved gasses. These may also be analysed in sediment laboratories but have relevance only in special cases where the chemical and organic content is of particular interest. This chapter therefore concentrates on the methodology of measuring inorganic suspended sediment.

4.2 Measuring suspended sediment load

Since suspended load is the largest component of total sediment load, the monitoring system must be designed around the practicalities of obtaining frequent samples of suspended load at many sites in the river network. Sampling of suspended sediment requires turbulent conditions at the river sampling site where the sediment particles are fairly evenly distributed over the river wet section (vertical and horizontal). Monitoring of suspended sediment transport usually comprises taking dozens of instantaneous “point samples” of water-sediment suspension, and subsequent analysis in laboratories of the sediment weight and content. Common sampling methods are either direct (manual sampling) or indirect (automatic recording of surrogate parameters such as turbidity) in their approaches. All indirect methods must be calibrated against direct measurements taken at each measurement site. Automatic recorders should therefore only be considered as additional methods which can supplement the direct sampling methods once a reliable corelation is achieved between the parameter being measured and the directly measured suspended sediment concentration.

A single measurement of suspended sediment load at one site involves taking dozens of samples across the entire river section and may take several hours of skilled work by an experienced team. During these hours the sediment concentration may vary over time, as will the flow discharge, so attempts have been made to speed up the sampling procedure by using a depth integrating sampler which takes one continuous single sample during a lowering and raising of the sample bottle at a fixed rate. This introduces other potential sources of error and the depth integrating technique requires even greater skill and experience of the sampling team. It must be recognised that accurate and consistent monitoring of sediment load requires trained skilled staff, preferably working over several years at the same sites using the same equipment. Changing the equipment, methodology applied or the team itself can often lead to inconsistencies in the methods used which itself can cause inconsistencies in the data series of sediment load.

The most useful data on sediment content is obtained during flood flows when sediment transport is at its greatest and sampling by wading or by boat is usually too dangerous. In medium and large rivers sampling of the entire river cross-section would require a cableway and depth sampling equipment with a heavy weight known as a submersible bomb. For this reason, sediment sampling is usually combined with flow gauging at the same site, where a cableway and bomb exists for taking samples during high flows, as well as using a current meter for flow measurement.

The relative volumes (of water and sediments), sediment grain size distribution, weight, mineral composition, particle shapes etc. can be measured in a laboratory, usually involving transport of the samples back to the laboratory, although some methods exist for estimating concentrations and grain size distribution on site.

4.3 Quality control, data storage and publication

In most countries the basic data series of sediment data derived by government units is made publicly available for wide use at nominal cost or even free of charge.

If the monitoring system is to be partly funded by income from sales of data, then the data must be proven consistent, accurate and reliable. Quality control before publication becomes the responsibility of the organization supplying the data, which in turn requires experience and skills in sediment transport processes, sampling and analysis techniques.

The sediment data available at present seems to be held by many entities and there is a clear potential for improving both quality and usefulness of data by centralising and standardising a common database for all sediment data, independent of source or ownership.

4.4 Applications of Sediment Data

Currently hydropower development is the biggest user of sediment transport data. In addition, strategically relevant areas exist where sediment management plays an important role, such as road construction and maintenance, agricultural activity, forestry, mining and so forth. These anthropogenic activities can cause severe soil erosion and even trigger landslides. Steep slopes, unconsolidated rock and soils in Nepal's varied landscapes are usually very susceptible to erosion. Earthquakes constitute an additional and dangerous trigger of unpredictable landslides. Thus, the sources of sediment to rivers vary greatly geographically and also at any one site over time.

Understanding sediment dynamics, the characteristics of transport in river systems is fundamentally important for any river engineering project in the planning, construction and maintenance phases. As explained above, such complex information is challenging to estimate or model without the supporting information from in site measurements. The information is based on sediment samples from a monitoring network and their analysis in a laboratory. The scope of sampling and analysis are therefore tailored to the selected application areas. These are called hereafter "sediment data products".

4.4.1 Sediment data products for Hydropower development

Hydropower development and good water resources management rely on quantitative knowledge and data to optimize the power production value, to reduce the negative impacts of the project and improve protection of life, infrastructure and land use (Agrawala *et al.*, 2003; Bajracharya and Mool, 2009; Basnyat and Watkiss, 2017). Therefore, it is imperative that reliable, high quality hydrological data is gathered, including suspended sediment load. Such data are crucial to hydropower planning and plant operation in Nepal.

4.4.2 Other applications of sediment data products

Sediment transport data can be used to estimate or confirm the rates of catchment soil erosion, but seldom is the only method applied for this purpose because of incomplete monitoring of the total load, and the spatial variability due to local landslides.

The agricultural sector may be interested in some sediment data if trying to estimate fluxes of nutrients to agricultural flood plains, and the need for artificial fertilisers, but they often require more detailed and costly analysis of sediment particles.

The geomorphology of large rivers can be of interest to planners of roads and bridges, and flood control works, and the sediment transport of the river is a big feature in predicting meandering, bank erosion and other geomorphological processes.

However, in Nepal the hydropower sector seems to remain the dominant user of sediment data products.

4.5 Methods of sediment monitoring

4.5.1 Methods of analysing suspended sediment content

Imhoff cones are conical glasses of 1 litre capacity in which the water sample containing sediment is poured and the measured height of settled material after 1 hour (and sometimes 24 hours) is used as a fast and simple comparative measure of the sediment content in each water sample. It is widely used in wastewater monitoring but has the limitation that it records only total sediment volume in the particular water sample and is less accurate for low sediment concentrations. It can be calibrated against more exact measurement by lab analysis in order to show time variations in sediment concentration, provided frequent samples are taken consistently at the exact same site by the same sampling method. For example, Imhoff cones can prove useful in monitoring variations in high sediment concentrations below dams during flushing operations.

There are some new techniques that are non-invasive and surrogate methods which are becoming more popular. These approaches are aimed at shortening or simplifying the monitoring chain by observing alternative parameters and assuming functional relation to those resulting from classical sediment monitoring (Dingman, 2009). Most new techniques require expensive investment in equipment, however, and are therefore not always an option unless private investment is available. These techniques are mentioned at the end of this chapter.

There are several Nepali laboratories offering services in analysing and reporting results from sediment sampling. The simplest analysis requires only a sieving and filtration process followed by drying and weighing the samples, which will deliver good results of the suspended load at the sampling site and the grading of sediments passing at the time of sampling. More sophisticated equipment is needed if the minerology and shape of the sediments is to be studied, which gives important information on the likely rate of wear on turbine parts. This is of great interest to project developers and of less interest to the Nepal authorities and public in general. It is therefore natural that the mineralogical analysis is offered by private laboratories to clients able to pay for such analyses.

4.5.2 Indirect methods of sediment monitoring

Optical and acoustical sampling methods enable the continuous and contactless measurement of sediment concentrations. This gives unmanned continuous readings which is an advantage compared to the mechanical sampling methods. Although based on different physical phenomena, optical and acoustical sampling methods are very similar in the principles of scattering by suspended particles of ultrasonic, light or infrared waves. The needed equipment is often expensive and requires a skilled process of calibrating the instrument readings against the sampling method of obtaining total sediment load at the same site and the same time. There can be problems getting good readings during very high concentration events which are important in determining the sedimentation rate of reservoirs.

Various acoustic point sensors (ASTM, UHCM, ADV) (Ref.12) are commercially available. Delft Hydraulics has developed acoustic point sensors (ASTM or USTM; Acoustic or Ultrasonic Sand Transport Meter; in Dutch: Acoustische Zand Transport Meter) for measuring the velocity and sand concentration in a point. The USTM or ASTM is an acoustic instrument for measuring the flow velocity in one or two horizontal dimensions and the sand concentration.

Optical Laser diffraction point sensors (Laser In-Situ Scattering and Transmissiometry (LISST).

Various Optical Laser diffraction instruments (LISST) (Ref.10) are commercially available to measure the particle size and concentration of suspended sediments.

5 Capacity for sediment sampling, analysis and quality assurance in Nepal

5.1 Department of Hydrology and Meteorology (DHM)

The Department of Hydrology and Meteorology, DHM (Ref. 13) has a mandate from the Government of Nepal to monitor all the hydrological and meteorological activities in Nepal. Their scope of work includes the monitoring of river hydrology, water quality, sediment, limnology, snow hydrology, glaciology, weather, climate, agro-meteorology, air quality and solar energy. The department delivers the periodical Climate Bulletin to the public through its website and generates Agrometeorological Notices for the Agriculture Management and Information System (AMIS). Furthermore, the Department provides a 24/7-day service of Flood Forecasting and Early Warning to the public during the period of the Monsoon Season.

As a member of the World Meteorological Organisation (WMO), DHM contributes to the global exchange of meteorological data on a regular basis. DHM actively participates in the programs of relevant international organisations, such as UNESCO's International Hydrological Program (IHP) and WMO's Operational Hydrology Program (OHP). In the past, DHM has hosted several regional and international workshops, symposia, seminars and meetings on different aspects of meteorology, hydrology, sediment, water quality and snow hydrology. The department is also a focal point for the meteorological activities of the South Asian Association for Regional Co-operation (SAARC).

The Principal Activities of DHM are:

- Collect and disseminate hydrological and meteorological data and information for water resources, agriculture, energy, and other development activities.
- Issue hydrological and meteorological forecasts for public, mountaineering expedition, civil aviation, and for the mitigation of natural disasters.
- Mitigate weather, flood and drought induced disaster by providing early warning services to the concerned communities.
- Conduct special studies required for the policy makers and for the development of hydrological and meteorological sciences in the region.
- Promote relationship with national and international organisations in the field of hydrology and meteorology.

5.2 Nepal's Public Hydrological Monitoring Network

The DHM monitoring network of flow measurement stations is listed in the Appendices in Chapter 9.1 including a map of the location on rivers. These data are updated in 2021 and may not be accurate.

DHM maintains nationwide networks of 337 precipitation stations, 154 hydrometric stations, 20 sediment stations, 68 climatic stations, 22 agrometeorological stations, 9 synoptic stations and 6 Aero-synoptic stations. From the list published in Appendix there are 94 stations with river flow measurements of which only 15 are categorised as having data of good quality. The remaining 79 stations will have difficulties in developing sediment rating curves if the flow measurements are of poor quality, so it is assumed that sediment monitoring will remain confined to a selection of the 15 stations with good flow data. Furthermore, it is not clear how many of these stations are maintained as actively collecting data in 2021. Other indications point to considerably fewer stations in active use.

Data are made available to users through published reports, bulletins, and computer media outputs such as hard copies or electronically. DHM publishes data on an annual basis. The hydrological data generated by DHM data is made available on request for a fee but is not regularly published on their website (Ref 13). There is also a requirement to prevent further distribution, which limits the access of the public to such data.

The public sediment monitoring network in Nepal is limited in its extent and no other entity is entitled to carry out such activities without a proper liaison with DHM, notwithstanding for private use as outlined below. DHM oversee a sediment monitoring network comprising 28 stations, of which 12 stations are currently reported as operational (as of May 2019).

Some private companies also collect sediment data locally to meet their production needs. Additional site-specific stations are operated by private entities, such as hydropower companies, but the data are not standardised or systematically collated and published in a common database.

5.3 Current sediment monitoring network and measurement practice

As mentioned above, the 12 stations where sediment concentration is measured by DHM are the main parameter. In some cases, grain size distribution is also being calculated. Suspended sediment concentration is assumed to be the main parameter being reported, and it is unknown if sediment rating curves exist and are regularly updated. It is also unknown if adjustments are being made to add bed load and if so by whom.

The standard method of sediment sampling consists of using the Depth Integrated sampling technique to monitor the sediment transport by a river. In this method, lowering and then lifting a sampler at uniform speed collect one sediment sample from each vertical section of a river. Thus, few numbers of samples from several vertical sections are taken to obtain a mean sectional sediment concentration. The samples are analysed by filtration method at the site; and the dried samples are sent to the sediment laboratory in DHM in Kathmandu.

5.4 Sediment Analysis in Nepal

Analysis of sediments is conducted mainly by DHM, KU, TU and private laboratories like HydroLab. Hydropower companies occasionally make their data and analyses available, but the information is generally held as proprietary. DHM has established a sediment laboratory, but it is understood that this is presently not in full operation and that sediment analysis capabilities are reduced.

5.5 Facilities in Nepal’s Universities and private laboratories

Table 5-1 provides a list of the relevant institutions with respect to sediment monitoring in Nepal.

Table 5-2 provides a limited overview on present sediment monitoring and analytical capacity in Nepal. It is based on information provided at the consultation workshop on 22 May 2019 and an additional questionnaire from DHM. In the following sections we provide some details of the activities of some of these bodies.

5.5.1 HydroLab

HydroLab conducts research on sediment dynamics in Himalayan rivers, specifically in the context of hydropower development in Nepal. Hydro Lab operates sediment analysis laboratory with modern measuring equipment and specialist staff. It conducts sediment measurement and analyses, measurement campaigns, constructs gauging stations and runs training sessions. To complement its field-based work, they also have large scale physical modelling facilities with measurement devices, allowing them to develop physical and numerical simulation of sediment transport.

Development of real time sediment concentration and flow monitoring system for hydropower plants is also a part of research on optimum sediment handling. Considerable work has been done in this direction by Hydro Lab in co-operation with Norwegian University of Science and Technology (NTNU), Norway. The equipment has been tested and data collected in controlled lab set up as well as natural sediment laden flow in power plants. The results are so far promising. It is expected that a reliable system for real time sediment concentration monitoring will come out in near future. Hopefully this will help in establishing early sediment concentration warning system for efficient plant operations.

5.5.2 Kathmandu University (KU) Turbine Testing Lab

Although the Turbine Testing Lab of Kathmandu University does conduct research and practical testing related to sediment abrasion on turbines and conduct analysis on mineralogy, particle characteristics and distribution, they do not provide any sediment monitoring or analysis. Discussions with Kathmandu University highlighted the following:

> ***"Fran Sed project****. Major objective to design turbine that mitigate erosion due to sediment. Hence a small portion of it has analysis related to sediment."*
>
> ***"Sediment analysis***
> *Scope: supporting the activity above. Involves riverbed core analysis of samples taken upstream HP intakes and suspended sediment analysis at HP outlets. Quartz content, size and composition, shape and similar are analysed. Results and sediment samples are archived from previous projects."*
>
> *"**PhD** (Suman Shrestha) on landslide and sediment Kavre district site."*
>
> ***"SEDIPACS** Objective: Research and Sediment measurements. Partners; NTNU, Hydro Lab, PhD/masters (2015-2019)"*

5.5.3 Tribhuvan University

In a meeting with Tribhuvan University the following issues and ideas were noted:

Discussions with Tribhuvan University highlighted the following:

> *"Pressing issues:*
>
> - *The sediment presence and consequences are underrated in the industry, Awareness should be increased.*
> - *Available sediment data and sampling are limited and of low quality, no national archive, legal support for that and willingness among potential sponsors are present.*

- *Especially, data quality should be improved, which would require changes in methods, equipment and follow-up of projects.*

Proposed ideas:

- *Require HP Companies to support long-term sediment management in their catchments (where they have licenses)*
- *Encourage cooperation with other projects/licensees on the same catchment: sediment management can only be tackled on catchment basis – obvious connectivity issue is not reflected in licensing policy*
- *Improve awareness on available technical options, which seem to be neglected or not considered typically in HPPs. The idea of "sediment management option" a s opposed to "maximum production" and "capacity loss due to siltation" should be strongly promoted. Sustainability is seemingly not considered much in river and sediment management, the long-term impact may therefore be catastrophic*
- *Ideas for means to tackle these issues*
- *Development of National sediment monitoring network (observations and analysis capacity) to be able to develop better-founded plans. Present data are limited in amount, and those available are uncertain and unreliable.*
- *Standardising and recollecting existing historic data to a national sediment database*
- *Developing legal solutions in licensing, especially on required obligations to provide data, and applying sustainable solutions harmonised among all users within single catchments"*

5.5.4 Community Based Flood and Glacial Lake Outburst Risk Reduction Project

Nepal is ranked as the fourth most vulnerable country in the world due to the impacts of Climate Change. A total of 3,808 glaciers and 1466 glacial lakes have been identified in Nepal. These lakes include 21 potentially dangerous lakes in the sense that they are growing rapidly in size and pose a potential and increasing threat with respect to the risk of glacial lake outburst floods. Six of these lakes are under very high risk in this respect of which Thso Rolpa and Imja Lakes are among them (Ref. 14 and Ref. 15).

The status of these glacial lakes is being monitored with a view to trying to give advance warning of a GLOF event. Although such events will undoubtedly transport large sediments such as gravel and boulders over long distances, it is not part of the continuous sediment transport because, although GLOF events are relatively frequent in Nepal as opposed to some other countries, they are usually relatively short in duration as compared with other flood events. Therefore, it is not considered a priority in design of a national sediment monitoring system, but there may be advantages to coordinating sediment monitoring with the local activity in certain districts such as the Imja Dudh Koshi River corridor in Solukhumbu.

The Building Resilience to Climate-Related Hazards (Ref. 16) program aims to transition Nepal's hydro-meteorological services into a modern service-oriented system that will build resilience today as well as adaptive capacity for the future. It intends to enhance government capacity to mitigate climate related hazards by improving the accuracy and timeliness of weather and flood forecasts for disaster preparedness by the general population and warnings for climate-vulnerable communities. The project will also support agricultural management information system services to help farmers mitigate climate-related hazards.

5.5.5 Some Hydropower Projects with relevant data:

- The Arun-III hydroelectric power plant is a 900 MW run-of-the-river hydropower project under construction in Nepal. Scheduled for commissioning by 2024, it will be the biggest hydroelectric facility in the country. It comprises a 466 m-long and 70 m-high concrete gravity dam with four underground desilting chambers, a headrace tunnel, a surge shaft, an underground powerhouse equipped with four 225 MW Francis turbine units, and a tailrace tunnel. The 466 m-long, 11 m-diameter diversion tunnel for the project will have a discharge capacity of 1300 m^3/s, while the storage capacity of the dam will be approximately 14 Mm^3, which is very small relative to the sediment transport volumes at the site.
- The Marsyangdi Hydropower Station is a run-of-river hydro-electric plant located in Aanbukhaireni, Tanahu District of Nepal. The flow from the Marshyangdi River is used to generate 69 MW of electricity and 462.5 GWh of annual energy. The rated net head is 90.5 m, and the rated flow is 30.5 m^3/s. The plant is owned and operated by Nepal Electricity Authority. The plant started generating electricity in 1989. There are some 8-9 years discharge and sediment data available from the project.

Table 5-1 List of relevant institutions related to sediment monitoring in Nepal

Institutions	Major objective	Programs & projects	Budget source
Department of Hydrology and Meteorology (DHM)	• Operation and maintenance of hydro-meteorological network • Flood forecasting • Weather forecasting • Sediment load measurements	• Discharge measurement • Sediment measurement • Landslide-EVO (together with Tribuvan University) Projects: • Map landslide areas • Satellite mapping • Rainfall intensity identification • Early warning system for landslide	Government & other funds UK government: Department for International Development (DFID) & Natural Environmental Research Council (NERC).
Nepal Electricity Authority (NEA) + Private Developers	• Sediment removal from the dam	• Improving Modikhola Hydropower Station • Rehabilitation Study of Trishuli Hydropower Station • Dudkoshi storage hydroelectric project • Tanahu (previously Upper & Lower Seti) HPP • Maintenance of Middle Marsyangdi HPP • Upper Arun Hydroelectric project • Etc.	Government, & other donors & private sector
Department of Forests, Soil and Conservation (DoFSC)	• Catchment restoration • Sediment retention • Integrated Watershed Management	• Soil and water conservation activities & landslide management • Water source protection & irrigation, canal improvements etc. • Wetland Management	Government & other donor agencies
Water and Energy Commission Secretariat (WECS)	• River Basin Plan (water availability & catchment management) • Sediment plan (hydropower and agriculture) • Sectorial Plan (hydropower & agriculture) • Conservation (water & soil)	• Sediment management guideline (not publicly available, but linked to hydropower projects)	Government & hydropower companies

Institutions	Major objective	Programs & projects	Budget source
	• Mitigation and flooding & river training • Sediment management & bed-load		
Kathmandu University (KU)	Research related to • Sediment measurements & analysis • Environmental issues • Turbine design, etc	• Various programmes with Hydro Lab • Turbine design material to mitigate erosion caused by sediment. Turbine design, efficiency measurement • Fran Sed Project: Turbine design to mitigate erosion from sedimentation • SediPass Project: sediment measurement, environmental issues, turbine, physical modelling	Many different projects, NTNU & other Norway (Fran Sed, SediPass projects) Butwal Power Company (BPC) Hydro Lab
Independent Power Producers Association Nepal (IPPAN) – Butwal Power Company Limited (BPC) including Hydro Consult Engineering Ltd (HCEL)	• Online Sediment Monitoring System at headworks of Jhimruk • Study on sediment Management in Run-of-River Hydropower Projects of Nepal • Map landslide areas/satellite • Rainfall intensity	Marsyangdi: 8-9 years flow & sediment data (monsoon period: 2/d; lean season: 1/d or 1/w), Jhimruk, Khimti ongoing project), Kabeli (licencing).	Own sources, joint ventures
ICIMOD	•	Sediment dynamics (Koshi River Basin) – sediment transport processes, budget and dynamics	

Table 5-2 limited overview of present sediment monitoring and analytical capacity in Nepal

Organisation - entity	Details on Discharge monitoring	Suspended sediment load	Bed load	Laboratory	Comments
DHM	51 stations	12 (28) Suspended	Yes, but less frequent, very few stations	Yes, but limited operation; Regional and Central Offices,	National mandate to monitor, collect and store discharge and sediment transport data (minerals and organic sediments). New: "Sediment and Reservoir Monitoring Section", which has potential to be strengthened.
Kathmandu University	Ad-hoc, project-based stations			Particle size and shape, mineralogy, physical modelling	Focus on turbine design and turbine erosion studies. More than 50% quartz in sediment which are impacting turbine lifespan.
Tribhuvan University	Ad-hoc, project-based stations			(CDES-TU) Sediment studies in Koshi Basin	Low quality and limited availability of sediment data – no national archive
Hydro power companies	Ad-hoc, project-based stations	Site specific monitoring, modelling – Project planning?	Site specific monitoring, modelling – Project planning?	Hydro Lab DHM – lab KU Turbine lab Private – (power) company lab)	Hydrological analyses (discharge, sediment transport, particle analyses) for project planning and design (intake, turbine, reservoir-lifetime)
IPPAN	Stations operated by member organisations				Sustainable HPD depends on reliable sediment data; Risk reduction, optimizes investments and revenues, reduces maintenance costs. Reservoir sedimentation and lifetime capacity
Hydro Lab	Project-based stations, assistance to others in station building, operation	Analyses: Suspended (organic, inorganic) Grain size distribution		Fully equipped and modern sediment analyses laboratory Large scale physical modelling Coming: Extended CFD/numerical modelling	Cooperation: NTNU, Trinity, Nanjing, Deltares; Tribuwan U., KU, + Owners like Butwal HPCo, etc. Financing: Research funds, HPP contracts (new and existing), other projects (sediment expertise),

					Limited extent: governmental or PPP funds/action programs. Assignments: Physical modelling HP design solutions, sediment measurement and analyses, construction of gauging stations and related training, Power generation efficiency testing (turbines in field)
Other International cooperation	Project-based stations				Hydropower development; Education – universities. Climate Change Programme/projects

6 Challenges in Sediment Monitoring in Nepal

6.1 Sediment data users and their challenges

Sediment monitoring in Nepal has remained underdeveloped, impeding the sustainability of the main user of sediment data, namely hydropower development in the country. There are many complicating factors ranging from geographical constraints to limited funding and expertise, as will be discussed in this chapter.

6.1.1 Hydropower and dam owners

The major users of sediment data in Nepal are currently hydropower developers, particularly projects of medium and large scale. They need to prepare realistic forecasts of the sediment load passing the intake sites, the grain size distribution and the minerology of the finer fractions which are expected to pass through the turbines and cause damage. They will start by analysing historic data on the same river, but in most cases find that they need to start their own sampling and analysis program to be able to make such forecasts reliably. The time constraints of such projects means that there is often only 1-2 years of data collected by the developer by the time they have to present their project and report its environmental impact to the licensing authorities and financiers.

Such short programs may miss the major sediment movement events and will often underestimate sediment yield and forecast turbine erosion rates. It is therefore important that monitoring stations with some years of good record of sediment transport are prioritised and continue to deliver uninterrupted data of high reliability. These are the only stations which can document the variability over many decades and demonstrate any long-term trends in sediment yield and will provide vital data for the analysis of sustainability of recent and future hydropower projects.

Recently, several plans for Nepali reservoir projects have been submitted for licensing and construction, and for these projects the sediment yield is an even more important feature of the planning process. Reservoir sedimentation is unavoidable, but can be mitigated by good sediment management strategies, which in turn requires good knowledge of the types and quantities of sediment entering the reservoir. The rate of reservoir sedimentation is often the major uncertainty in the lifetime of such projects and is the parameter most often discussed in debates on project long-term sustainability. Reservoirs also lead to sediment transport reduction downstream which in turn may impact downstream water users and communities, both positively and negatively. Both of these features underline the great importance of good sediment data and analysis for the future success of reservoir projects in Nepal.

6.1.2 Other users and infrastructure developers

In addition to the hydropower sector which has already been highlighted, there are a number of other sectors where a better understanding of sediment and sediment transport in rivers can be useful. This includes agriculture, river navigation, flood alleviation, road and bridge constructions, land use, and water quality. Sand and gravel mining is an important activity along rivers in Nepal. However, the quantification related to this activity is very uncertain. There is increasing demand for sand for building materials in Nepal, much of which has been supplied from terrace and riverbed extraction. Although riverbed excavation is prohibited, the majority of the sand comes from such local sources. Mining laws and policing do not succeed in preventing illegal mining. Local sands around Kathmandu are hazardous in terms of mica content that approaches 10 to 32%, which is above the acceptable limit of 8% (See report on status of sand mining and quality in Northern Kathmandu – Ref 17). Most rivers in Nepal still have uninterrupted transport of sand and gravel due to the current absence of large reservoirs. However, the monitoring of sediment transport should take account of sites downstream of future large reservoirs where sand and gravel extraction is a substantial resource, since the resource is likely to diminish after the reservoir impoundment.

6.2 Limited spatial and temporal coverage and data gaps

At present, the national network for sediment transport comprises a limited number of active sediment monitoring stations distributed throughout the country. Bed load measurements are less frequent and only undertaken at a few sites (Gabet *et al*., 2008; Ghimire *et al*., 2013). The location of flow gauging stations and sediment monitoring sites on major rivers is shown in Appendix 9.1. It can be seen that many major rivers have currently no sediment monitoring and that those that have only one station, located quite far downstream. Since there is a high probability of very great variations in sediment sources leading to great variation in sediment yield from tributary to tributary, the monitoring of sediment load at one station is not revealing these upstream variations.

Another issue is the lack of continuity in the collection of sediment load measurements. Indeed, sediment data has been gathered and made available for a limited number of stations, operating at variable capacities and over different time periods. An example is given below from Morin et al, 2017 (Ref 18) where a change is sampling methodology has caused an apparent change in sediment flux which makes interpretation of long data series rather difficult or can lead to wrong conclusions.

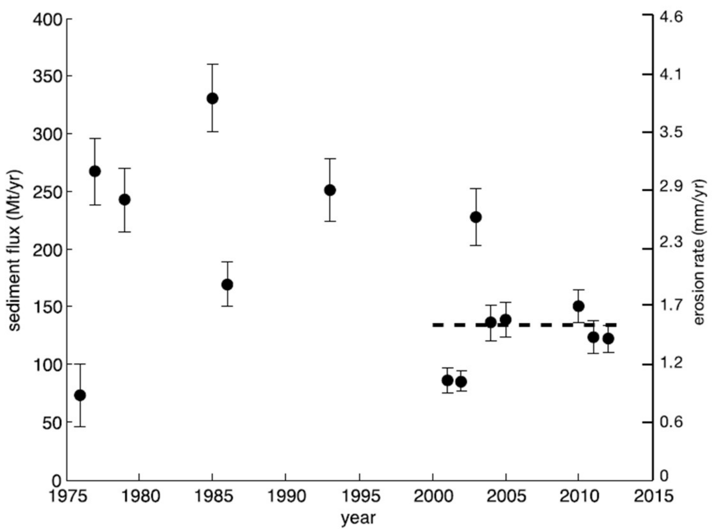

Figure 6-1 Annual sediment flux and equivalent erosion rate derived from DHM daily suspended load data over 14 non-contiguous years. The average flux of 135 Mt/year (dashed line) was calculated only for records after the year 2000.

(From Morin et al, 2017 (Ref 18)

This causes the value of historic data to be reduced since it is difficult to document trends and in some cases the data may lead to the wrong conclusions. For example, if an interruption of data collection is due to damage to the station during a major flood event, then the major sediment transport event of the decade may have been omitted from the record while the other years with little sediment movement appear to represent the average value.

In conclusion the present lack of long series of continuous sediment transport data coupled with a poor geographic coverage of the sampling network presents significant challenges to the users of the historic data. This feature needs to be addressed in the design of a long-term monitoring network throughout Nepal.

6.3 Institutional and regulatory challenges

The relevant acts, policies and plans relevant to the water sector are listed below. Some of these are in the process of revision (quoted from WB 2015). It is reported that none of these documents have specific rules or strategies for the monitoring of sediment transport.

- Water Resource Act, 1992
- Water Resource Regulation, 1993
- National Environmental Impact Assessment Guidelines, 1993
- Water Resource Strategy, 2002
- National Water Plan, 2001
- The Hydropower Development Policy 2001

DHM have been operating continuously since 1988 under the Ministry of Agriculture, but were recently placed under the Ministry of Energy, Water Resources and Irrigation. This is a positive development for giving sediment transport monitoring a higher priority than previously under the Ministry of Agriculture.

Nevertheless, there is a need for a consistent long-term strategy for how government intends to monitor sediment transport in the future, which generates uncertainty and the need for the private sector to each set up their own local sediment transport monitoring programs.

6.4 Financial and operational constraints

The main objective of DHM is to collect hydrological and meteorological data throughout Nepal, process the data, publish it, and disseminate the data to all types of users. The fundamental goal of DHM is to support the overall development of the water resources of the country and is mandated to generate information on extreme hydrological and meteorological events and to deliver such information publicly in a timely manner to save the lives and property of the people.

DHM has headquarters in Kathmandu, and four regional offices in Dharan, Pokhara, Bhairahawa and Kohalpur. The regional office in Pokhara has a field office called Narayani Basin Field Office, Narayanghat which investigates the hydrometric network of the Trishuli and East Rapti River system. Similarly, the regional office in Kohalpur has a field office called Mahakali Basin Field Office, Dhangadi which investigates the hydrometric network of the Mahakali River and Mohana River system respectively.

DHM has a total staff of nearly 200 including headquarters and district offices. However, the skills required for consistent and reliable measurement of both suspended sediment and bed load are very specialised, but there may be a shortage of resources within the DHM organisation to uphold this specialised capacity. This severely affects DHM's capacity to provide continuous sediment monitoring data on a nationwide scale.

The DHM has highlighted challenges related to having adequate human resources. There is a need for an adequate number of staff with training and experience to maintain and utilise the sediment monitoring network.

DHM website lists 51 hydrological stations of which only 6 are located above 1000 m in altitude. Only one (Banga on the West Set River) is listed as having sediment monitoring and the type and frequency of monitoring is not stated. This site may not have been updated in recent years, but it suggests that there is also a lack of equipment and laboratory capacity for sediment monitoring within DHM.

Investment allocated in the public sector for expanding the sediment monitoring network appears to be very limited, and sediment monitoring is understandably not among the highest priorities for allocation of government funds. According to DHM, the sediment-monitoring activities are hindered due to several reasons including organisations, economic, and practical reasons.

Nevertheless, initiatives such as the DHM's Pilot Programme for Climate Resilience (PPCR, a World Bank project) to install more stations to get real time data, are vital to enhancing understanding of sediment dynamics in Nepal, (Ref. 16). Typically, hydropower projects conduct Cumulative Impact Assessments which only review historical hydrological data, forest cover, land-use and geo-morphological dynamics (changes in hydrology, precipitation and temperature for specific locations) to determine the proposed management measures for operating hydro plants. Under a climate change scenario, the review of historical data is insufficient, and projects may require further studies and potential modifications during the implementation phase, which can be costly and even jeopardize the project's long-term viability. With the support of the PPCR funds, the project will be able to incorporate analysis of climate change related future hydrological and geo-morphological dynamics in the project design.

6.5 Non-standard methods and proprietary data

There is no nationally standardized protocol for measuring sediment. The DHM follows the United States Geological Survey (USGS) protocol, whereas Hydro Lab and Kathmandu University follow a Swedish protocol. Similarly, private sectors such as the hydropower companies are likely to be following different methods. This is unfortunate, as the sampling undertaken by private hydropower companies is more frequent (up to 3-5 samples per day) and site-specific.

In addition to high frequency data gathering, the approaches adopted by private entities, like Hydro Lab and the KU Turbine Lab, have expanded the scopes of their analysis to covering quartz content, particle size and shape. Such data can assist efforts to reduce the frequency of repair and maintenance of hydraulic equipment, particularly turbines. With these datasets continually being developed by the private sector, there are opportunities for better quality control and for standardisation of data collection and processing protocols within Nepal.

6.6 Few large reservoirs for sedimentation monitoring

Regular reservoir sedimentation surveys by bathymetric mapping are one of the useful means to monitor reservoir sedimentation rate. Reservoir sedimentation surveys in large seasonal reservoirs are often being used to determine the total capacity of the reservoir, the sediment deposition rate, the capacity-elevation curves, and the sediment yield from the watershed. However, in daily peaking reservoirs designed to regulate only for the peak hours of a day, the variability in the flushing process makes this method impossible to interpret. Most reservoirs in Nepal are of the daily peaking type and therefore unsuited to use for monitoring sediment flux or deposition rates.

At present, Kulekhani, Kaligandaki A and Middle Marsyangdi hydropower reservoirs are the only sizable reservoirs in Nepal, and the sustainability of these reservoirs is a key issue. In this respect, bathymetric surveys were conducted in December 2010 in order to prepare base line maps of the reservoir and to monitor the sedimentation process in these reservoirs. The Kaligandaki A and the Middle Marsyangdi reservoirs have lost 51% and 65% of their total volume, respectively.

Reservoir sedimentation surveys in the Kulekhani reservoir were also carried out using Differential Global Positioning Systems (DGPS) method in 2009 and 2010. The Kulekhani reservoir has lost 20.4 mill. m3 in total and 14 mill. m3 in its live storage capacity during last 27 years of operation, representing average annual loss of 0.56 % of the total reservoir capacity.

6.7 Flood risk and climate change impacts

DHM maintain several stations with real time monitoring of river levels to monitor and warn of coming flood events via the DHM website http://www.hydrology.gov.np/#/river_watch?_k=4xrrjo under the River Watch banner. These cover 10 of the largest river basins in Nepal with several water level recorders on each. These stations almost certainly include many stations with cableways and discharge rating curves suitable for expanding to provide long term continuous monitoring of sediment load and providing the backbone of a future sediment monitoring network.

As most of the rivers in the HKH region are transboundary, flowing through two or more countries, effective flood management calls for meaningful co-operation of the riparian countries for exchanging real time hydrometeorological data to improve flood forecasts. In this connection, the International Centre for Integrated Mountain Development (ICIMOD) in collaboration with the World Meteorological Organisation (WMO) and six partner countries Bangladesh, Bhutan, China, India, Nepal and Pakistan have initiated a project on establishment of a regional flood information system. A summary of the HYCOS collaboration and additional reports can be found in Ref 19.

7 Opportunities

As described in the previous chapter there are several challenges with the present situation of sediment monitoring in Nepal which need to be addressed. The following recommendations are proposed to address these challenges and improve long-term sediment management in Nepal.

As in many countries access to data in Nepal is not always straightforward and can be challenging. The data generated by DHM is available for purchase by the public. Hydropower companies occasionally make their data and analyses available, but the information is generally held as proprietary and can therefore be difficult to obtain. Much data is therefore being retained by the commissioning entity as proprietary. This is understandable, as private resources are invested in the generation and collation of said data, and private operators are not presently incentivised or mandated to make their data publicly available.

On the other hand, this is an inefficient practice which leads to extra socio-economic cost and delay in developing new resources and managing sediment transport issues. Whilst there are exceptions, with data being shared for specific research projects, sharing data is not the norm.

7.1 Need for a government strategy for sediment monitoring

If the role of the Nepali government in sediment transport monitoring and reporting was better defined, this would improve the clarity for users. One way to do this would be to work out an overall strategy document describing how the government can work together with data users, universities and relevant stakeholders in the long-term. Some potential contributions to be described in such a strategy document could be:

- Distinction between long-term and short-term goals of the strategy, with short-term goals adhering to reality with respect to available resources and long-term goals more in line with a preferred situation.
- Government plans for long-term monitoring of suspended sediment transport in major rivers. A selection of few stations with cableways could be prioritised as government stations with rigorous sampling and analysis such that continuous data becomes reliable and consistent from these few stations.
- Standardisation and improvement of government sampling and analysis equipment and methods. Current sampling procedures do not seem to meet the standards required to provide a consistent and accurate measure of total sediment transport.
- The number of sediment transport monitoring stations the government will maintain and continue sampling from, could be reduced to fit the skilled resources and budget available to DHM for this purpose. The strategy could suggest how long-term funding can be ensured to maintain an uninterrupted continuous record at these few stations. Income from sales of DHM data could be viewed as additional to annual budget allocations.
- Recruitment and training of skilled hydrometeorologists in sediment sampling, analysis and data quality control is needed to improve the accuracy and relevance of the data being reported by DHM.
- A strategy for the publication of quality-controlled data could be discussed, including whether the current procedure for sale of data which has not been quality controlled should continue.

- The strategy could describe the possible role of the private sector in sediment measurements and analysis and any intended obligations for them to share data with government.
- The establishment of a database of historic sediment data and reports.

A general understanding of which stations the government can realistically provide data for in the near future based on capacity constraints would be very helpful to hydropower utility and dam owners and developers and could encourage them to make their own data available to the government. It is recommended that DHM focus on stations where flow gauging's are frequently carried out, especially during floods, and where cableways are available to provide the full range of samples across the full river cross-section.

7.2 Strengthening the Network Completeness and Quality

7.2.1 Quality control and modernising key gauging stations

Although the current sediment monitoring network is limited in extent and does not provide adequate coverage of many of Nepal's rivers, the resources of DHM skilled staff for sampling seem to be undermanned. Current sampling procedures do not meet the standards required to provide a consistent and accurate measure of total sediment transport. It seems that only one half-litre sample is delivered from a particular site on a particular day. With such limited number of samples, the average total sediment load being reported are underestimated. The sampling procedure should follow the recommended methodology stated in ref 1. Realistic estimates of sediment transport need to be based on around 10-30 samples taken across the river, either by depth integrating samplers correctly used or by point sampling at 2-3 different depths and about 10 different locations across the river.

Furthermore, the calculations which integrate the sample concentrations into total suspended load should be presented for independent quality control by a skilled hydrometeorologist. The variation of flow during the sampling period should also be reported and compared with hydrograph records for that same day to make adjustment for expected variations in sediment transport with time over the 24-hour period. Finally, an additional factor to allow for bed load (which has not been captured by the sampling) should also be made based on the characteristics of each river and each station site (based on flow velocity, grain size, river gradient etc).

7.2.2 Prioritising data quality and relevance

The current concentrations in the data sets seem to consistently underestimate the average concentration of the river over the day of sampling. This is confirmed by Morin et al., 2017 (Ref 11), section 5.1, quote here:

> *"Previous estimates of the Narayani suspended load flux are 100 ± 50 Mt/year (Andermann, Crave et al., 2012; Sinha & Friend, 1994). Our estimates of 150 ± 20 Mt/year for 2010 and 135 ± 15 Mt/year during the previous decade based on DHM data are in the higher range of previous estimates because they account for vertical variations of concentration with depth, whereas we obtain a flux around 100 Mt/year when this gradient is ignored (case DMC0, Table 2). Thus, even when the Narayani River is highly turbulent during monsoonal floods, vertical sorting must be integrated into the sediment flux; otherwise, the Narayani sediment flux can be underestimated by up to 50%. Our approach to integrating the concentration over depth is simplified and based on measurements operated during only a few days. To perform depth*

integration on a more physical basis, a complementary study would be necessary to document the concentration gradient during low to intermediate (<3,000 m3/s) and very high flows (>7,000 m3/s)."

Elsewhere in the same publication it is reported that previous sampling before about year 2000 was carried out using USGS depth integrating samplers, but current sampling is of the single bottle type, taken from the surface water. The lack of analysis and correction for the fact that sediment concentration increases with depth is the main reason why an unexplained reduction in average reported sediment flux after 2000. It is recommended to add bedload or account for bed load to get better data on sediment concentration and estimation of sediment flux.

There appears to be a disconnect between the need for user- relevant sediment data of reliable quality and the present system of monitoring and reporting sediment concentrations. One recommendation is that the Nepali strategy for future sediment monitoring should prioritise the quality of data and their relevance for data users rather than collecting frequent single-bottle samples over such a wide number of stations as seems to be the current practice.

The sediment (and discharge) gauging network of DHM could be improved considering various optimisation objectives. Below is a list of suggested actions.

- Consider synergy with other existing programs (consider ICIMOD-DHM-NVE project)
- Initiate a joint project DHM – Hydropower sector involving Hydro Lab
- Complement sediment data to snow-runoff-erosion-climate analysis in Trishuli basin

7.3 Capacity Strengthening

7.3.1 Strengthening capacity in DHM

Currently, the limited quality and availability of sediment data is affecting Nepal's development projects. Ensuring that data is collected and made available would greatly benefit the design, reliability and maintenance of hydropower infrastructure. The collected data should support the needs of various sectors, including environmental and social considerations, be useful to both upstream and downstream areas in catchments, benefit river training, flood control, etc.

Beyond the hydropower sector, the Departments of Road, Water Resources and Irrigation, of Mines and Geology as well as the Nepal Electricity Authority would benefit from improved continuity, completeness and quality of sediment data being reported by DHM.

To enhance the current capacity to collect and analyse the sediment data, capacity strengthening must be prioritised. The following training topics are recommended, with relevant audiences for the different topics:

- Development, management and use of sediment gauging networks and single stations (test station – in field training) as an exercise to improve capacity of DHM
- Conduction and use of sediment analyses in laboratories as exercise for DHM
- Quality control and data publishing
- Sediment budgeting including erosion, connectivity, transport and deposition
- Applications of sediment data: what can be used for which purpose?

7.3.2 Refurbishing the DHM lab for sediment sample analysis

Dependent on how many samples are to be expected from the prioritised stations described above, the DHM laboratory analysis capacity should be matched with the number and frequency of sample bottles arriving for analysis. A simple standard analysis method of obtaining consistent values for sample mean concentration and grading curve should be applied. Depending on the sampling methodology applied, there should be made adjustments to mean sample bottle concentrations before providing published data for average sediment flux on the day of the sample. This includes an addition for bedload at each site since bed load is not being sampled.

It is recommended that DHM remain in charge of the entire process of sampling, analysis (at DHM lab) and adjustment calculations before providing official data of daily mean total sediment flux. It does not seem suitable in the long term for DHM to contract out sample analysis to external laboratories, since it is more expensive and confuses the situation regarding data quality control.

7.3.3 Standardised methods

Sediment data collection needs to be conducted based on common, standardised methodologies, so that data can be used by various sectors, universities and private stakeholders. It is recommended to follow the standards established by WMO as far as they are relevant for Nepal (Ref 4).
Further, this data should be regularly collated and linked to a centralised data storage facility – a National Sediment Database. The database could also collect available historical data from different sources as described below.

7.3.4 Supply of new professionals in sediment-related fields

Local universities and certain international universities/technical colleges should be able to educate a stream of Nepali hydrometrics and sediment transport experts in coming years. An emphasis should be put on training hydrometrics and laboratory analysts on the basic principles of sampling of suspended load, adding bed load and making adjustments to bottle concentrations. These should cover both practical and analytical capacity.

At university level, both KU and TU run regular BSc and MSc programs for students partly related to hydropower development, management, physical geography, hydrology and environmental sciences, which necessarily include basic principles of sediment transport and monitoring methods. These programs conform with commonly accepted standards and are accredited internationally. Further specialised education programs are also available to build up Nepali expertise in specialist topics.

Outside of the country, there is a large Nepalese diaspora, with students completing their education partly or fully abroad. There are various cooperation programmes related to sediment or hydropower studies. One example is the Hydropower Development Master programme in NTNU in Norway, where a large number of Nepalese students reached MSc level in different topics related to hydropower

In addition to the hydropower sector, the Departments of Road, Water Resources and Irrigation, of Mines and Geology and the Nepal Electricity Authority could benefit from capacity building of Nepali sediment experts to take up positions in DHM and other technical departments within government information management.

7.3.5 Creating and updating a database with adequate quality control

The ultimate goal on sediment information management should be a comprehensive National Sediment Database which includes all sediment data collected by all entities, both state and private. In order to achieve this there must be considerable work to improve the quality control of data before they are published and the removal of administrative and commercial barriers to creating such a database. Once the database is created it is easy to update it continually with recent data, again with appropriate quality control before publishing.

7.3.6 Sediment information products

Analysis and research related to erosion and sedimentation in the river basins of Nepal is important for future applications. Useable knowledge products can support informed planning and decision making. The following information products could be generated.

- Datasets on the spatial and temporal variability of sediment flux (total load) in a few large Nepalese rivers;
- Information on grain size and, in very important rivers for hydropower development, the mineral composition;
- Better information on how to allow for bed load (based on sediment concentration, grain size and some characteristics of the river at the sampling site)

Such information can improve information regarding available technical options for sustainable sediment management. For example, in hydropower development use of the RESCON 2 strategy optimisation model (Ref. 1) could be promoted, giving due attention to the "capacity loss due to siltation".

7.3.7 Data sharing and coordination between government agencies

Although DHM is mandated to generate sediment monitoring data, it is not a clear mechanism on how the different agencies will be using such information. For example, how the Road Department, the Department of Energy or Department of Mines and Geology will use the sediment data while developing infrastructure plans and designs. The Water and Energy Commission Secretariat, is also preparing sediment management guideline but how this will be related to sediment monitoring is also not evident.

Improving coordination between government agencies such that there is a clear mechanism established for sediment data use by various government agencies is important. Coordination mechanism among governmental agencies for sharing and using data could also be developed.

Stakeholders including private and academic institutes do not currently have obligations and mechanism to share sediment data with the government or outside their network. Mechanisms to incentivize sharing of data and collaborative structures could be developed for sediment data generators within the catchment or more widely.

7.3.8 Enhancing public-private partnership

Internationally, cooperation between the public and private sectors on sediment monitoring is commonplace. Collaboration between public administration, universities and private sector companies has led to identification of and development across numerous areas of mutual interest and benefit. Building on these synergies may strengthen bilateral collaboration, professional quality and improve the results and benefits for all stakeholders. Governmental entities could, for example, initiate relevant joint activities to establish and operate sediment accumulation monitoring stations for reservoirs and evaluate the cooperation after a defined timespan.

An existing, underexploited nexus lies between the government and private sectors. Between the two, there is considerable experience, competence and the resources to markedly enhance understanding of sediment dynamics. There are certainly “win-win” opportunities, should public and private parties work together more closely. Issues like suspended sediment and bed load sampling, laboratory analyses, sediment transport and erosion modelling and training are areas of pre-existing synergy and overlapping interest and expertise. Ultimately, improved quality and capacity in data sampling will facilitate better analyses and quantification of the erosion processes in Nepal.

7.3.9 Basin-scale management & coordination

The private sector should be encouraged and incentivised to invest in long-term watershed intervention. At present, the private sector seems less interested as project ownership period is limited. Current laws require hydropower developers to hand over ownership to state after 30 years, which does not encourage the private sector to invest in or institute sustainable watershed management practices.

To redress this, hydropower companies could be obliged to support long term sediment management in their catchment (where they have licenses) and co-operate with other projects/licences in the same catchment. Sediment management can only be tackled on a catchment scale.

7.4 Conclusion

Monitoring sediment in Nepal is important to encourage hydro power development. There are several other sectors where a better understanding of sediment and sediment transport in rivers can be useful. This includes agriculture, river navigation, flood alleviation, road and bridge constructions, land use, and water quality.

Our hope is that this report can be of use for stakeholder in pursuit of opportunities for better coordination of the collection, analysis and distribution of knowledge and data.

A next step for the government of Nepal could be to establish a project to develop these ideas further and seek funding from international donors.

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9 Appendices

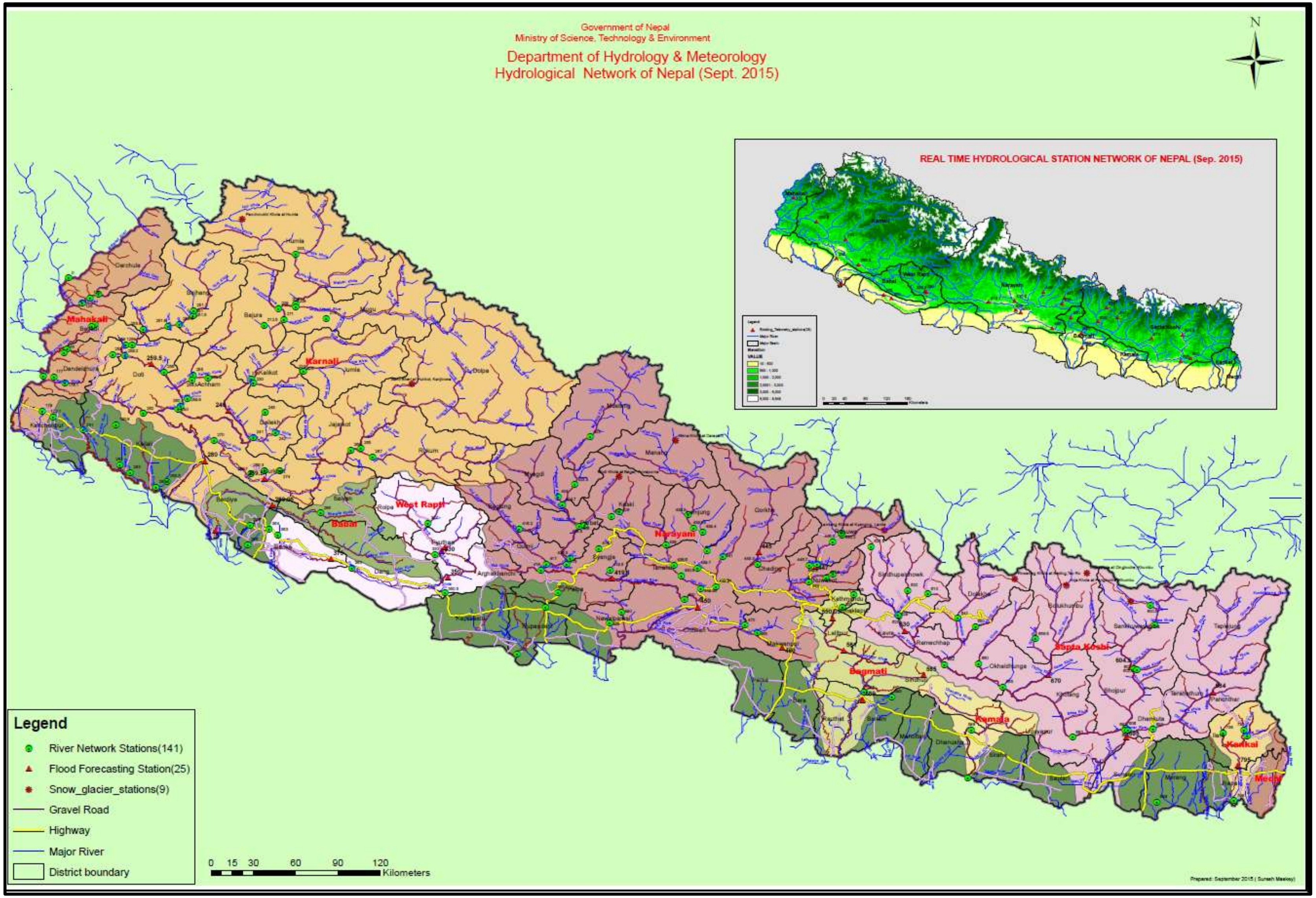
9.1 Hydrometric Network in Nepal

The list of stations and the network map here, available for download on the DHM webpage, give the locations of the hydrometric stations in the hydrometric network in Nepal.

LIST OF PUBLISHED STATION

S.no.	St.No.	Name of river	Location	Latitude			Longitude			Elev.	Drainage Area	From	To	Quality
				DD	MM	SS	DD	MM	SS	(m)	(km2)			
1	115	Naugragad	Harsingbagar	29	42	7	80	36	26	784	203	2000	2014	Fair
2	120	Chamelia	Nayalbadi	29	40	20	80	33	30	685	1150	1965	2015	Fair
3	125	Jamadigad	Panjkonaya	29	38	18	80	30	50	580	228	2001	2011	Fair
4	170	Surnayagad	Patan	29	27	30	80	33	23	1110	188	1966	1987	Fair
5	215	Karnali	Lalighat	29	9	32	81	35	28	590	15200	1977	2006	Fair
6	220	Tilanadi	Nagma	29	6	26	81	40	49	1935	1870	1973	2015	Fair
7	225	Sinjhakhola	Diware	29	12	0	81	55	0	1943	824	1967	2015	Poor
8	240	Karnali	Asaraghat	28	57	10	81	26	30	629	19260	1962	2014	Good
9	250	Karnali	Benighat	28	57	40	81	7	10	320	21240	1963	2015	Fair
10	251.6	Langurkhola	Chhanna	29	29	52	81	7	55	1158	159	2001	2014	Fair
11	253.9	Kailashkhola	Mattada	29	9	49	81	19	8	751	196	2001	2006	Fair
12	256.5	Budhiganga	Chitra	29	9	47	81	12	59	506	1576	2000	2008	Fair
13	258	Dhungad	Bhasme	29	22	16	80	47	6	700	135	2000	2006	Poor
14	259.1	Sailigad	Gautada	29	22	0	80	50	0	770	179	2000	2006	Good
15	259.2	Seti	Gopaghat	29	18	0	80	46	30	750	4420	1986	2014	Fair
16	260	Seti	Bangga	28	58	40	81	8	40	328	7460	1963	2015	Fair
17	265	Thulo	Bheri	28	42	47	82	17	0	550	6720	1977	2015	Fair
18	269.5	Bheri	Samaijighat	28	31	2	81	39	25	500	12200	1992	2014	Fair
19	270	Bheri	Jamu	28	45	20	81	21	0	246	12290	1963	2010	Poor
20	280	Karnali	Chisapani	28	38	40	81	17	30	191	42890	1962	2015	Fair
21	283.3	Kandra	Pahalmanpur	28	30	41	80	56	24	143	479	2001	2006	Poor
22	286	Saradakhola	Daradhunga	28	17	58	82	1	30	579	816	1972	2015	Poor
23	289.95	Babai	Chepang	28	21	4	81	43	14	325	2557	1990	2013	Fair
24	290	Babai	Bargadha	28	25	20	81	22	10	192	3000	1967	1987	Fair
25	330	Marikhola	Nayagaon	28	4	20	82	48	0	536	1938	1965	2015	Poor
26	339.5	Jhimrukkhola	Chernata	28	3	0	82	49	40	762	683	1971	1995	Poor
27	340	Jhimruk	Kohla	28	2	10	82	53	0	692	696	1965	1970	Fair
28	350	Rapti	Bagasotigaon	27	51	12	82	47	34	381	3380	1976	2015	Fair
29	360	Rapti	Jalkundi	27	56	50	82	13	30	218	5150	1964	2006	Fair
30	363	Jhajharikhola	Dhakeri	28	9	22	81	45	13	159	78	2000	2011	Fair
31	364	Duduwakhola	Masurikhet	28	12	15	81	41	44	162	54	2000	2006	Fair
32	375	Rapti	Kusum	28	0	2	82	6	58	235	5200	2003	2015	Fair
33	387.4	Dumrekhola	Kalimati	27	47	40	83	32	3	595	90	2000	2014	Fair
34	390	Tinaukhola	Butwal	27	42	10	83	27	50	184	554	1964	1969	Fair
35	404.7	Mayagdi	Khola	28	21	10	83	31	16	914	1112	1976	2015	Fair
36	406.4	Modikhola	Bagar	28	31	0	83	57	0	3549	158.2	1999	2006	Poor
37	406.5	Modikhola	Nayapul	28	15	15	83	43	27	701	601	1976	2015	Poor
38	410	Kali	Gandaki	28	0	14	83	36	31	546	6630	1964	1995	Fair
39	415	Adhikhola	Andhimuhan	27	58	28	83	35	58	543	476	1964	1991	Fair
40	415.1	Adhikhola	Borlangpul	27	58	27	83	34	26	749	195	2000	2015	Fair
41	419.1	Kaligandaki	Ansing	27	53	5	83	47	42	351	10020	1996	2015	Good
42	420	Kali	Gandaki	27	45	0	84	20	50	198	11400	1964	2015	Fair
43	428	Mardikhola	Lahachowk	28	18	2	83	55	6	915	160	1974	2015	Fair
44	430	Seti	Phoolbari	28	14	0	84	0	0	830	582	1964	1984	Fair
45	430.5	Seti	Gandaki	27	57	12	84	15	54	290	1350	2000	2015	Good
46	438	Madi	Shisaghat	28	6	0	84	14	0	457	858	1975	2015	Fair

S.no.	St.No.	Name of river	Location	Latitude			Longitude			Elev. (m)	Drainage Area (km2)	From	To	Quality
				DD	MM	SS	DD	MM	SS					
47	439.3	Khudikhola	Khudibazar	28	17	12	84	21	27	990	151	1983	1995	Fair
48	439.35	Marshyandi	Bhakundebesi	28	12	13	84	24	11	610	2950	2000	2015	Good
49	439.7	Marshyandi	Bimalnagar	27	57	0	84	25	48	354	3774	1987	2015	Good
50	439.8	Marshyandi	Goplingghat	27	55	35	84	29	42	320	3850	1974	1986	Fair
51	440	Chepekhola	Gharmbesi	28	3	41	84	29	23	442	308	1964	2015	Fair
52	445	Burhi	Gandaki	28	2	37	84	48	59	485	4270	1964	2015	Fair
53	446.1	LangtangKhola	LangtangVillage	28	13	0	85	37	0	3640	360.6	1993	2012	poor
54	446.8	Phalankhukhola	Brtrawati	27	58	25	85	11	15	630	162	1971	1995	Poor
55	447	Trishuli	Betrawati	27	58	8	85	11	0	600	4110	1977	2015	Good
56	448	Tadi	Belkot	27	51	35	85	8	18	475	653	1969	2015	Good
57	449.91	Trishuli	Kalikhola	27	50	8	84	33	12	220	16760	1994	2015	Good
58	450	Narayani	Devghat	27	42	30	84	25	50	180	31100	1963	2015	Good
59	460	Rapti	Rajaiya	27	26	50	84	58	26	332	579	1963	2015	Fair
60	465	Manaharikhola	Manahari	27	32	37	84	49	3	305	427	1964	2010	Poor
61	470	Lotharkhola	Lothar	27	35	14	84	44	7	336	169	1964	2009	Poor
62	505	Bagmati	Sundarijal	27	46	49	85	25	36	1600	17	1963	2015	Fair
63	530	Bagmati	Gaurighat	27	42	35	85	21	10	1300	68	1991	2015	Fair
64	550	Bagmti	Chovar	27	39	40	85	17	50	1280	585	1963	1980	Good
65	550.05	Bagmati	Khokana	27	37	44	85	17	41	1250	658	1992	2012	Fair
66	565	Kulekhanikhola	Lamichaur	27	36	13	85	9	39	1515	122	1976	1978	Fair
67	570	Kulekhanikhola	Kulekhani	27	35	10	85	9	30	1480	126	1963	1977	Good
68	581	Bagmati	Bhorleni	27	21	43	85	28	10	250	1540	2000	2006	Poor
69	589	Bagmati	Padharadovan	27	9	6	85	29	30	180	2700	1979	2006	Fair
70	590	Bagmati	Karmaiya	27	8	22	85	29	22	177	2720	1965	1979	Fair
71	600.1	Arun	Uwagaun	27	35	21	87	20	22	1294	26750	1985	2010	Fair
72	602	Sabayakhola	Tumlingtar	27	18	36	87	12	45	305	375	1974	2015	Poor
73	602.5	Hinwakhola	Pipaltar	27	17	45	87	13	30	300	110	1974	2015	Poor
74	604.5	Arun	Turkighat	27	20	0	87	11	30	414	28200	1975	2006	Good
75	606	Arun	Simle	26	55	42	87	9	16	152	30380	1986	2015	Fair
76	610	Bhotekosi	Barbise	27	47	18	85	53	55	840	2410	1965	2012	Fair
77	620	Balephi	Jalbire	27	48	20	85	46	10	793	629	1964	2015	Fair
78	627.5	Melamchi	Helambhu	28	2	21	85	32	7	2134	84	1990	2006	Fair
79	629.1	Idrawati	Dolalghat	27	38	20	85	42	30	1225	1230	2006	2013	Fair
80	630	Sunkosi	Pachuwarghat	27	33	30	85	45	10	602	4920	1964	2015	Fair
81	640	Rosikhola	Panauti	27	34	50	85	30	50	1480	87	1964	1987	Fair
82	647	Tamakosi	Busti	27	38	5	86	5	12	849	2753	1971	2012	Fair
83	650	Khimtikhola	Rasnalu	27	34	30	86	11	50	1120	313	1964	2013	Fair
84	652	Sunkosi	Khurkot	27	20	11	86	0	1	455	10000	1968	2015	Fair
85	660	Likhu	Sangutar	27	20	10	86	13	10	543	823	1964	2006	Good
86	668.4	Taktorkhola	Beni	27	33	46	86	33	28	2400	73	1986	1991	Fair
87	670	Dudhakosi	Rabuwabazar	27	16	14	86	40	2	460	4100	1964	2006	Good
88	680	Sunkosi	Kampughat	26	52	28	86	49	10	200	17600	1966	1985	Good
89	681	Sunkosi	Hampchuwar	26	55	15	87	8	45	150	18700	1991	2006	Fair
90	684	Tamur	Majhitar	27	9	30	87	42	45	533	4050	1996	2012	Fair
91	690	Tamur	Mulghat	26	55	50	87	19	45	276	5640	1965	2013	Poor
92	695	Saptakosi	Chatara	26	52	0	87	9	30	140	54100	1977	2012	Fair
93	728	Maikhola	Rajdwali	26	52	45	87	55	45	609	377	1983	2008	Poor
94	795	Kankai	Mainachuli	26	41	12	87	52	44	125	1148	1972	2011	Fair



Hydrological Network of Nepal (DHM, 2015)

9.2 List of operational hydropower stations in Nepal

Hydropower plant	Capacity (MW)	Commissioned	Location	Owner
Kaligandaki A Hydroelectric Power Station	144	2002	Syangja	NEA
Middle Marsyangdi	70	2008	Lamjung	NEA
Marsyangdi	69	1989	Tanahun	NEA
Kulekhani I	60	1982	Makwanpur	NEA
Khimti I	60	2000	Dolkha	Himal Power Ltd.
Upper Marsyangdi A		2016	Lamjung Marsyangdi Rural Municipality	SSPC, Power China
Bhote Koshi Power Plant (*Upper Bhote Koshi*)	45	2001	Sindhupalchowk	Bhote Koshi Power Company Private Limited (BKPC)
Kulekhani II	32	1986	Makwanpur	NEA
Chameliya	30	2018	Darchula	NEA
Trishuli	24	1967 *(Initially 21 MW, 24 MW in 1995)*	Nuwakot	NEA
Chilime Hydropower Plant	22	2003	Rasuwa	Chilime Hydropower Company Ltd.
Gandak	15	1979	Nawalparasi	NEA
Modi Khola	14.8	2000	Parbat	NEA
Devighat	14.1	1984	Nuwakot	NEA
Madkyu Khola	13	2018	Kaski	Silkes Hydropower Pvt. Ltd.
Jhimruk Khola	12	1994	Pyuthan	Butwal Power Company Ltd.
Thapa Khola	11.2	2018	Mustang	Mount Kailash Energy Co. Pvt. Ltd.
Sunkoshi	10.05	1972	Sindhupalchowk	NEA
Lower Modi I	10	2012	Parbat	United Modi Hydropower Pvt. Ltd.
Andhi Khola	9.4	1991 *(Initially installed 5.1 MW,9.4 MW in 2016)*	Syangja	Butwal Power Company Ltd.
Indrawati III	7.5	2002	Sindhupalchowk	National Hydropower Co. Ltd.
Puwa Khola	6.2	1999	Ilam	NEA
Mailun Khola	6	2013	Rasuwa	Mailun Khola Hydropower Pvt. Ltd.
Chatara	3.2	1996	Sunsari	NEA
Panauti (Khopasi) Hydropower	2.4	1965	Kavre	NEA
Seti	1.5	1985	Pokhara	NEA
Fewa Hydropower	1	1969	Pokhara	NEAG