SEDIMENT ABRASIVE EROSION ON HYDROPOWER PLANTS IN NEPAL

A DISSERTATION

Submitted in partial fulfillment of the

requirements for the award of the degree

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MASTER OF TECHNOLOGY

in

ALTERNATE HYDRO ENERGY SYSTEMS

By

GUNA RAJ KHANAL

DEPARTMENT OF HYDRO AND RENEWABLE ENERGY

INDIAN INSTITUTE OF TECHNOLOGY ROORKEE

ROORKEE-247667, INDIA

June, 2019

CANDIDATE'S DECLARATION

I hereby declare that the work which is presented in this dissertation report, entitled, **"SEDIMENT ABRASIVE EROSION ON HYDROPOWER PLANTS IN NEPAL"** submitted in partial fulfillment of the requirement for the award of the degree of **Master of Technology** in **Alternate Hydro Energy Systems** in **Department of Hydro and Renewable Energy, DHRE** (formerly Alternate Hydro Energy Centre), **Indian Institute of Technology, Roorkee,** is an authentic record of my own work carried out during the period from June 2018 to June 2019 under the supervision and guidance of **Dr. Arun Kumar, Professor**, **Department of Hydro and Renewable Energy, Indian Institute of Technology, Roorkee, Uttarakhand, India.**

I also declare that I have not submitted the matter embodied in this report for award of any degree.

Date: June, 2019

Place: HRED, Roorkee **(GUNA RAJ KHANAL)**

(Enrollment. No- 17512006)

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

(Dr. Arun Kumar)
Professor,
Department of Hydro and Renewable Energy,
Indian Institute of Technology,
Roorkee – 247667 Date: June, 2019

ABSTRACT

Hydro energy is the most economically feasible renewable energy for Nepal due to favorable topographic and climatic conditions. Although there is high potential of hydropower in Nepal, presently only two percent of 43,000 MW as economically feasible hydropower has been developed. High sediment erosional transport cause problem in operation and maintenance of Hydropower Plant and at the same time the hydraulic efficiency of the system also reduces. Sediment abrasive erosion is one of the most challenging circumstances for hydro energy development in Nepal.

In this research work, sediment data collected from the hydro plant out of 13 hydro plants visited. Sediment samples were taken from different Hydropower Plants (HPP) owned by Nepal Electricity Authority (NEA) in different locations and capacity. The five hydropower plant stations situated at different locations in Nepal having sediment problems comprising three river basins are a) Trishuli hydropower plant, b) Kaligandaki A hydropower plant, c) Marsyangdi hydropower plant, d) Middle Marsyangdi hydropower plant, and e) Upper Marsyangdi A hydropower plant. Sediment particle concentration, and mineral analysis were carried out to find the mineral content and particle shape of the sediment. Under the study not only analysis has been carried out for the sediment abrasive erosion potential of the turbine due to the shape and the hardness of particle, but also the sediment abrasion in various components of HPP and corresponding reduction in efficiency due to abrasive erosion have been predicted. Revenue loss due to the reduction in energy generation has been also taken in account for financial analysis in addition the cost involved for repair and maintenance and or replacement of components at those plants.

All relevant data required for dissertation has been taken from feasibility report, initial environmental examination report and project financial analysis report provided by Department of Electricity Development (DoED), and Nepal Electricity Authority, Nepal.

All sediment samples were measured in sediment monitoring and erosion R&D lab at IITR for calculating relevant factors associated with them. The mineral particles found to be contained with large extent of Quartz as a hard minerals ranges from 44.6% in Upper Marsyangdi HPP to 68.32% in Kaligandaki HPP. According to IEC-62364 (2013), the shape of sediment particles in HPP found to be sub angular as their aspect ratio (b/l ratio) lies in between 1 to 2 whereas, the factor K_{Shape} for Upper Marsyangdi HPP has been taken as unity. The subangular shaped sediment particles are prone to more abrasive erosion. The Erosion in runner inlet and runner outlet and other turbine components is not uniform in all five cases.

Based on this study, out of 5 hydro plants investigated minimum erosion found at Upper Marsyangdi HPP where the least rate of turbine erosion is 0.61mm/yr with corresponding lower reduction in efficiency 0.069% per year resulting only 3.8 M INR total losses due to abrasive erosion. At Trishuli HPP, has the highest erosion rate of turbine 3.42 mm/yr with higher reduction in efficiency 1.265% per year causing about 16.5M INR losses due to abrasive erosion.

In addition while the revenue loss is concerned the Middle Marsyangdi HPP has the highest value of loss in revenue with 11.97 M INR associated with energy generation among the five hydropower projects while the least value of total loss in revenue only 0.08M INR is found in Upper Marsyangdi HPP.

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CHAPTER – 1

INTRODUCTION

1.1 BACKGROUND

Nepal is rich in water resources with 6000 large and small rivers flowing from higher Himalayas to plain Terai region. The topographical condition and runoff have made Nepal with hydropower potential of 83000 MW. Although Nepal has huge hydropower potential, only 2% that is just about 1047 MW has been harnessed by 2018. [NEA, 2018].

Most of the catchment of river basin suffers from inherent natural land erosion problem. Such phenomenon occurs mostly in Himalayan river basin which are young and fragile in geology with slope landscape [Galay et al., 2000] [Thapa, 2003]. The inherent continuous and random pattern of rainfall causes extreme sediment concentration in such zones. Therefore, only the Run of Rivers (RoR) hydropower projects are practical alternatives in most of the stretches of the Himalayan Rivers due to massive sediment load accumulation in storage dam and topographical limitations [Stole, 1993].

Erosion of hydro-mechanical components due to large quantities of sediment with hard abrasive mineral/rock fragments in Himalayan Rivers is one of the serious challenge in developing hydropower projects as it causes difficulty in operation and maintenance of the plants. [Thapa et.al, 2003]. Huge amounts of sediment in rivers are due to presence of weak rocks and extreme relief and therefore, sediment management has become prime. Even with sediment trapping systems, complete removal of fine sediment from water is impossible and uneconomic, hence most of the turbine components in Himalayan Rivers are exposed to sand laden water and subject to erosion, causing reduction in efficiency and life of the turbine [Pandit et al., 2008].

The hydropower components have been eroded due to excessive concentration of sediment having hard mineralogical contents. Development and operation of the hydropower plants in fragile young mountainous regions severely come across the problem of hydro-abrasive erosion of turbine parts and other hydraulic structures due to high sediment loads. [Rai et al., 2015].

There is a huge potential for hydropower development in Himalayan region. However, it encounters the technical challenges for hydropower development due to erosion and sedimentation problem.

1.2 SEDIMENT AND IMPACTS OF EROSION

Sediments has been defined generally as solid particles which are moved or might have been moved by flow in channel. Formation of sediments are due to the continuous disintegration and decomposition of rocks. Material becomes separate and is transported to a deposition site where it may be treasurable by solution, consolidation, cementation, and other biological action in the form of clay, gravel, boulder, sand and silt in rivers and streams. These sediments are carried with the water in irrigation canal and hydropower canal and even to face the turbine in reduced quantity after extraction and exclusion.

It’s a well-known fact that even with the well-designed sediment removal structure and flushing system, certain fraction of sediment passes through it causing severe erosion to civil and hydro mechanical component. In the power channel, sediment may also get deposited which results in reducing its capacity. Not only the power channel along with capacity of the reservoir gets reduced, the cost is also allied to remove it. With long duration of high sediment concentration; power channel, penstocks, turbine and accessories gets eroded.

In this research work, sediment data collected during site visit was used. Sediment samples were taken from different locations of Nepal Electricity Authority (NEA) owned Hydropower Plants (HPP). Sediment particle concentration, and mineral analysis were carried out to find the mineral content and particle shape of the sediment of visited HPP locations. Study not only analyse the sediment abrasive erosion potential of the turbine due to the shape and the hardness of particle, but also predicts the sediment abrasion in various components of HPP, and corresponding reduction in efficiency due to abrasive erosion. Revenue loss due to energy loss has been taken in account for financial analysis for the cost involved for repair and maintenance and or replacement of those plants.

1.3 ABRASIVE AND EROSIVE WEAR

The defined wear of hydraulic machinery is due to the sediment erosion. Sediment erosion is caused by the dynamic action of sediment flowing along with water impacting against a solid surface. Consequently, any hydropower components such as hydraulic turbine operating in sediment-laden water are subjected to abrasive and erosive wear. This wear reduces both the efficiency and the life of the turbine as well as causes severe problems in operation and maintenance, which eventually leads to economic losses.

Abrasive wear is the loss of material by the passage of hard particles over a surface. This wear occurs whenever a solid object is loaded against particles of a material that have equal or greater hardness. The abrasive wear encompasses processes such as micro cutting, grain detachment, brittle fracture, and fatigue.

Erosive wear is caused by the impact of solid and liquid particles on a surface. Erosive wear can be similar to abrasive wear when hard solid particles of microscopically visible size are eroding agent, the angle of impingement is low and the angle of impingement speed is of the order of 100 m/s.

1.3.1 Mechanism of Abrasive and Erosive Wear

The particles or grits may remove material by micro fracture, micro cutting, accelerated fatigue or pull-out of individual grains by repeated deformations as shown in below Figure 1.1.

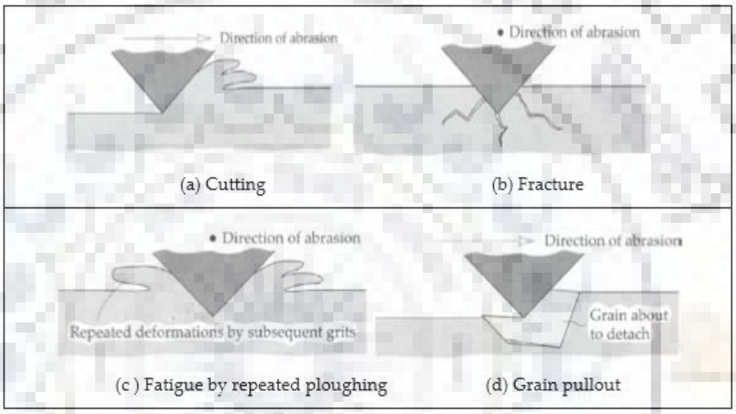

Figure 1.1 Abrasive wear mechanism [Stachowiak, et al., 1993]

Erosive wear experiences several wear mechanisms, which are controlled by particle size, particle material, impact velocity, and the angle of impingement. If the solid particle is hard then there is possibility of occurrence of a process of abrasive wear. The mechanisms of erosive wear are as shown in Figure 1.2.

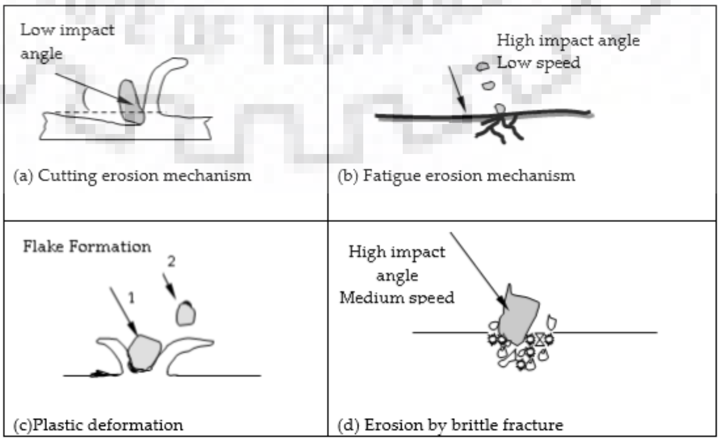

Figure 1.2 Erosive wear mechanism [Stachowiak et al., 1993]

1.4 FACTORS ASSOCIATING WITH ERODING PARTICLES

The rate and mechanism of erosion can alter depending on characteristics of the particles. The particle characteristics may remain same as in origin or it can change depending upon operating condition. Hence particle characteristics is very essential for estimation, reduction and prevention of erosion.

The hydro-abrasive erosion of turbine parts is correlated to following factors.

1.4.1 Size and Shape of Particles

Particle size can be characterized mainly in two basic dimensions mass and length. Round particles causes less abrasive erosion comparing to sharp and angular particles. The rate of abrasive erosion for a given velocity, kinetic energy of particle is directly proportional to mass and mass of spherical particle is proportional to $(\text{diameter})^3$. Hence in theory

$$\text{Erosion rate} \propto \text{diameter}^3$$

The fine particle is dangerous for turbine is operating under high heads. (Sharma, 2006)

The size of a spherical particle is clearly defined by its diameter *d*. For the size of non-spherical particles, the volume-equivalent sphere diameter functions as a simple and comparable parameter.

The particle shapes are defined qualitatively such as round, angular and semi-round based on visual observation. The shape of the particle is a good indicator of erosion process, for example; irregular shape with sharp edge increases erosion rate whereas blunt particles with round edges slowdown that in general.

The shape of the particles is one of the important factors which control erosion rate, but there are only limited studies on relation between erosion rate and particle shape. Beside erosion rate, the shapes of eroding particles are of interest because of its influence in shear strength, density, permeability, compressibility and capacity of sediment transport (Drolon, 2000).

1.4.2 Hardness of Particles

Quartz which has 7 Mohr's scale against 10 of diamond is considered harmful to turbine. Mineral constituent of sediment particle with Mohr's hardness greater than 5 are considered harmful to the turbine runner. The abrasive erosion is also directly proportional to hardness of particles irrespective of size [Sharma, 2006]. Hence, the ratio of hardness of sediment particle and substrate is very pretending in the erosion rate.

Quartz is found as main constituent of the sediment in Nepalese rivers. On average, Thapa, (2004) indicates nearly 70% of the constituent of the sediment are hard mineral content with hardness more than 5 Mohr's scale. The erosion capacity of particle was decreasing when they travelled long distance. The erosion rate has linear and slightly increasing trend with respect to percentage of hard particles.

1.4.3 Concentration of Sediment

Sediment concentration is most dominating factor influencing abrasive erosion of turbine. Increased concentration of sediment causes more damages irrespective of size. Increased concentration of sediment with larger size is more harmful. It is generally expressed in parts per million and kg/m^3.

1.4.4 Resistance of Runner Material

Generally coated runner has higher resistance than the non-coated runner. Martensitic stainless steel with 13 % Cr and 4 % Ni is more resistive than carbon steel runner [Sharma, 2006].

1.4.5 Net Head

Higher heads will imparts more kinetic energy to the sediment impinging to the turbine runner resulting in more abrasive erosion. Even very fine particle can cause severe damages in high head plants.

1.5 LOSS DUE TO ABRASIVE EROSION

Together with particle properties, particle transport mechanisms also have a role in erosion models. The movement of such particles basically depends on particle characteristics (density, shape, size) and fluid characteristics (velocity, turbulence, viscosity).

Runner, guide vanes, facing plates and labyrinth seals are most affected components of Francis turbine. Likewise, Nozzle, needle and buckets, are most affected components of Pelton turbine. Even low head Kaplan turbine and propeller turbines are also found eroded in rivers with high sediment contents.

Only limited model of erosion have been validated for their reliability, although various empirical and theoretical model have been formulated from experiment and field observation [Athar, 2012].

1.5.1 Pelton Turbine

Normalized mass loss of the Pelton turbine can be estimated using the relation developed by Padhy in her Doctor of Philosophy. [Padhy et al., 2008].

The relationship proposed by Padhy for normalized mass loss of Pelton turbine (gm/gm/m³/sec) is

$$W = 7.91 * 10^{-13} * t^{0.99} * S^{0.13} * C^{1.23} * V^{3.79} \tag{1.1}$$

Where, V, S, C, t are jet velocity in m/s, silt size in micron, silt concentration in ppm and time of operation in hours.

1.5.2 Francis Turbine

IEC-62364 model has to be adopted to predict erosion in Francis runner outlet, runner inlet, guide vanes, facing plates, and labyrinth seal.

According to IEC-62364 model particle abrasion rate in turbine IEC-62364 (2013):

dS/dt = f (particle concentration, particle physical properties, particle velocity, turbine material properties, flow pattern, other factors)

Final, time integrated formula becomes

$$S = W^{3.4} * \mathrm{PL} * \mathrm{K_m} * \mathrm{K_f}/\mathrm{RS^p} \tag{1.2}$$

Various parameter associated with the estimation of abrasive erosion in IEC-62364 model are presented in below. IEC-62364 model has been adopted to estimate erosion in Francis runner outlet, runner inlet, guide vanes, labyrinth seal and facing plates illustrated in Table 1.1.

Table 1.1 Parameters associated with IEC-62364 model

Parameter	Definition	Unit	Governing Equation
W	Characteristic velocity for different components should be provided by the turbine manufacturer. When not provided, can be estimated approximately from equation.	m/s	$W_{runner} = (0.25 + 0.003 * n_s) * \sqrt{2gH}$ $W_{gv} = 0.55 * \sqrt{2gH}$
C	Particle concentration is the mass of all solid particles per m^3 of water solution.	$\mathrm{kg/m^3}$	
$K_{hardness}$	Function of how hard the particles are in relation to		$K_{hardness}$ = fraction of particle harder than turbine material

	the material at the surface.		
K_{size}	Particle size characterizes how abrasion is related to size of sediment particle.	mm	K_{size}= median diameter of particle
K_{shape}	Particle shape is particle angularity.		K_{shape} = 1 to 2 from round to sharp particle
K_m	Factor for material property of base material		K_m= = 1 for martensitic stainless steel, 2 for carbon steel
PL	Particle load is particle concentration integrated over the time, T, which is under consideration.	$\mathrm{kg} * \mathrm{h/m}$	$P = \int_0^T C(t).K_{size}(t).K_{shape}\,.(t).K_{hardness}($
K_f	Flow coefficient that characterizes how abrasion is related to water flow around each component.	$\frac{mm * s^{3.4}}{kg * hr * m^{-3}}$	K_f is different for different component and is calculated with reference to the observed erosion.
S	Depth of metal removed from a component due to particle abrasion	mm	$S = w^{3.4} * PL * K_m * K_f / RS^p$
RS	Reference diameter for Francis turbine.	m	For Francis turbines this is the blade low pressure section diameter i.e. band diameter.
p	Exponent which describe size dependent effects of erosion in evaluating RS.		p is different for different component and is based on observed erosion.

Flow coefficient and exponent which characterizes how the abrasion relates to water flow around each component for IEC model. These factor K_f and exponent p is calculated to get best for each component to get less error between the calculated and observed amount of erosion illustrated in Table 1.2.

Table 1.2 IEC-62364 factor K_f and exponent p for Francis Turbine

Component	**K_f**	**Exponent p for RS**	**Number of Observations**	**Standard Deviation %**
Francis guide vanes	$1.06*10^{-6}$	0.25	7	42
Francis facing plates	$0.86 *10^{-6}$	0.25	7	38
Francis labyrinth seals	$0.38**10^{-6}$	0.75	7	30
Francis runner inlet	$0.9 * *10^{-6}$	0.25	6	26
Francis runner outlet	$0.54 *10^{-6}$	0.75	6	41

1.5.3 Percentage Loss in Efficiency of Turbine due to Abrasive Erosion

Percentage efficiency loss of Pelton turbine due to abrasive erosion can be estimated using the relation developed by R. Thakur et.al [Thakur, 2017].

The relationship proposed by R. Thakur et.al. for percentage loss in efficiency by turbine abrasive erosion is

$$\eta = 1.752 * 10^{-9} * S^{0.166} * C^{1.1223} * V^{2.413} * t^{0.699} \tag{1.3}$$

Where, V, S, C, t are jet velocity in m/s, silt size in micron, silt concentration in ppm and operating time in hours.

According to Bajracharya [Bajracharya et al., 2008] expression for loss in efficiency of Francis runner related to erosion rate is as follows

$$\eta_t \propto \mathrm{a}\, \boldsymbol{E_r}^{b} \tag{1.4}$$

Where, a= 0.1522 and b=1.6946. E_r is abrasive erosion rate and η_t is loss in efficiency due to abrasive erosion alone.

Leakage loss should also considered due to abrasive erosion in seal (labyrinth) of Francis runner. So total loss is sum of leakage loss and loss due to runner abrasive erosion.

Thapa and Brekke, (2004), have drawn some conclusions based upon different hydropower plants erosion patterns observations: (i) If the particles are fine (silts), then there will be erosion on the needle but not much erosion in the buckets, (ii) If the particles are coarse (sand), then there will be erosion in the buckets and less erosion on the needles. And (iii) within the medium size particles, both needle and bucket will be eroded. [Thapa, et al., 2004]

The decrease of relative velocity at runner outlet is one of the alternate solutions to prevent sediment erosion in Francis turbines [Thapa, et al., 2012]. Likewise, Guide vane profile plays a significant effect for better performance of turbines operated in sediment laden water. Appropriate hydraulic design of guide vane with simple possible acceleration, reduction of clearance gaps between facing plates and guide vanes, careful choice of stay vane outlet angle, and new material are the key factors for their better performance in sediment laden water [Brekke, 2002].

1.5.4 Energy Loss due to Reduction of Turbine Efficiency

Energy loss due to reduction of turbine efficiency should be calculated considering the marketable dry energy and marketable wet energy with corresponding percentage loss in efficiency.

1.5.5 Revenue Loss due to Energy Loss

The loss in revenue is caused due to reduced generation on account of reduced efficiency, erosion of plant machinery, down time for repair and maintenance as well as additional expenditure on restoring the machinery and efficiency.

The cost involved of abrasive erosion on frequency of maintenance, repair and replacement cost, major breakdowns- downtime and closure of plant, corrective measures and remedial steps taken are financially analysed for respective sites and compared.

1.6 ABRASIVE EROSION MODEL STUDIES

Several researcher has developed the model of erosion. All these model, empirical equations and numerical simulation needs validation based on practical data from hydropower plants and corresponding calibration. Reduction in erosion can only be achieved with mutual collaboration between engineers, scientists and consultant working in the design and manufacturing of hydro mechanical equipment, operators of hydropower plant, and researcher of academic institutes [Felix et al., 2016].

Generally, three different methods are adopted for erosion studies, namely case study, experimental study and CFD study. In the case study method, the erosion and its adverse effects like material loss, efficiency reduction etc. are studied in actual prototype plant. The case study signifies actual degree of erosion in the most accurate way but do not include parameter variations. Moreover, the time involved to observe the erosion is high and erosion measurement is difficult. Though IEC 62364 (2013) proposed a theoretical model for estimating sediment erosion in prototype plants recently, few terms used in the standard, like the flow coefficient (K_f) and exponent of RS (p), are not provided for Pelton turbine erosion and other terms like K_m for coating, K_{Shape} etc. are qualitative.

According to IEC-62364 model particle abrasion rate in turbine predicted as per equation (1.2). Predicting and numerical modelling of hydro-abrasive erosion are challenging because of many parameters involved and their complex relationship. Guideline for investigating erosion in Francis, Kaplan and Pelton turbines has been developed by The International Electrotechnical Commission (IEC). [IEC-62364 (2013)].

The experimental study tries to replicate the erosion phenomenon in controlled laboratory set-up. The parameters can be varied according to requirement and time involved is less. The erosion occurrence is highly dependent on type of erosion set-up. So care must be taken to design the set-up as close as possible with actual erosion environment [IEC 62364, 2013].

In CFD study, an erosion model is applied in numerical approach to predict the erosion. Finnie model and Tabakoff model are the two models that has been widely used to simulate erosion in CFD software. Though flow in Pelton turbine is studied extensively using CFD [Perrig et al., 2007; Rygg, 2013], Different design and parameters variation can be integrated in CFD studies but validation is required along with high computational computers and software.

Naidu (2002) proposed an erosion model with erosion as function of sediment, flow and base material properties as follows:

$$W = S_1.S_2.S_3.S_4.M_r.V^n \qquad (1.5)$$

Where, W is the material loss in mm/year; S_1, S_2, S_3 and S_4 are coefficients of silt concentration, hardness, particle size and shape respectively; M_r is the coefficient of wear resistance of the base material; and V^n is the relative flow velocity.

Tsuguo (1999) studied eight years of erosion data for eighteen HPPs and has determined the repair cycle of turbine due to abrasion caused by suspended sand erosion. The relationship is as follows:

$$W = \beta.C^x\, a^y.k_1.k_2.k_3.V^n \qquad (1.6)$$

Where, W is the material loss in mm/year; β is turbine coefficient at eroded part; C is solid concentration; V is relative flow velocity; a is an average grain size coefficient on the basis of unit value for grain size 0.05mm; k_1 and k_2 =are the shape and hardness coefficients of sand particles; k_3 is the abrasion resistant coefficient of material; and x and y are the exponents value of concentration and particle size respectively. The proposed minimum value of n for Pelton bucket is 1.5 and for Francis turbine runner, can be maximum as 3.

Bajracharya et al. (2008) studied erosion on Pelton turbine due to suspended sediment from the site survey of 22 MW Chilime hydropower plant in Nepal with 80% quartz. The study found relationships between the erosion rate and the particle size at different quartz content levels and consequently, the rate of erosion and the corresponding reduction in efficiency as follows:

$$\text{Erosion rate, Er (mm/year)} \propto a\,(\text{size})^b \qquad (1.7)$$

For quartz content: 38% (a = 351.35, b = 1.4976), 60% (a = 1199.8, b = 1.8025) and 80% (a = 1482.1, b = 1.8125) for too many digits gave only 3 digits.

The relation between the erosion rate and the reduction efficiency was given by:

$$\text{Efficiency reduction, } \eta_r \text{ (per year)} \propto 0.1522(\text{Erosion rate})^{1.6946} \qquad (1.8)$$

The found major erosion parameters were hard minerals especially quartz and feldspar content and increased sediment load in the months of rainy season. The study discovered that the partial opening of needle caused in more erosive wear. [Bajracharya et al. 2008].

In another case study, Boes (2009) studied the sediment erosion problems in Pelton turbine of Dorferbach hydropower project by quantifying sediment parameters (SSC, PSD, sediment load, shape, mineral composition and hardness) with an optical back scatter turbidimeter and a laser diffractometer along with manual pumped sampling. Regular turbine erosion rate measurement was performed for quantifying turbine erosion with frequency once in a week or once biweekly. A relation was developed for erosion quantification at the Dorferbach HPP as follows:

$$W\,[\mu m/h] = 7.56 * 10^{-8} * u^{3} * SSC \qquad \text{for } SSC \leq 45 \text{ mg/l} \qquad (1.9)$$

$$W\,[\mu m/h] = 1.82 * 10^{-8} * u^{3} * SSC^{1.375} \qquad \text{for } SSC > 45 \text{ mg/l} \qquad (1.10)$$

Where u is the relative jet velocity and SSC is the suspended sediment concentration and W is the rate of erosion (µm/h).

Padhy et al., (2009, 2011, 2012) studied the effect of silt particle size (S), silt concentration (C), water jet velocity (V) and operating hours (t) on wear rate of small scale Pelton turbine made of brass along with impact on efficiency. Mechanisms of erosion were also discussed. The obtained relations for normalized erosive wear rate (loss of weight/original weight, mg/kg) (W) and percentage efficiency loss of rated efficiency (η%) are as follows:

$$W = 4.02 * 10^{-12} * S^{0.0567} * C^{1.2267} * V^{3.79} * t \text{ (Error within } \pm 6.7\%) \qquad (1.11)$$

$$\eta\% = 2.43 * 10^{-10} * S^{0.099} * C^{0.93} * V^{3.40} * t^{0.75} \text{ (Error within } \pm 10\%) \qquad (1.12)$$

Liu et al. (2012) designed a rotating and jet experiment system with high flow velocity to study the anti-erosion performance of materials of three Pelton turbine components: nozzle tip, needle shaft and runner bucket. 8 different resultant velocities (V) in range 61.12 – 106.47 m/s were selected with sediment concentrations (C) varying between 720 - 12,590 ppm. The sediment size parameters used were d50 = 33.111 µm, d_{mean}= 44.56 µm and range = 2.599 – 101.46 µm. The hydro-abrasive erosion (E) in Pelton turbine components found in (g/h) were as follows:

$$\text{Nozzle tip (ZG230-450): } E\,(g/h) = 5.45 * 10^{-9} * V^{3.16} * C^{0.98} \qquad (1.13)$$

$$\text{Needle shaft (42CrMo): } E\,(g/h) = 1.47 * 10^{-9} * V^{3.41} * C^{1.02} \qquad (1.14)$$

$$\text{Runner bucket (X3CrNiMo13-4): } E\,(g/h) = 8.82 * 10^{-10} * V^{3.51} * C^{1.01} \qquad (1.15)$$

Thapa, et al., (in 2012) presented an erosion model which is kept as improved model of (IEC:62364, 2013; Bajracharya, 2008) to estimate erosion rate and loss in runner efficiency of Francis turbine. It has been tested for JHC, Nepal, estimated drop in efficiency of the runner alone to be 1% per year, which is consistent to the results of field measurements. [In Sangal et al., 2018]. The erosion rate Er (mm/year) and loss in efficiency η_r in %/year were as follows:

$$Er = C.K_{hardness}\, K_{shape}\, K_{m}\, K_{f}\, .a\, (size)^{b} \qquad (1.16)$$

$$\eta_r = a\, (Er)^{b} \qquad \text{From equation (1.4)}$$

1.7 MITIGATION MEASURES TO IMPACT OF SEDIMENT EROSION

In order to maintain hydraulic machines in good condition, frequent maintenance and repair works as well as replacements of eroded parts are required. This results in increased costs as well as in losses in electricity generation and revenues due to reduced efficiency and downtimes during works. The causes and consequences of hydro-abrasive erosion are schematically summarized:

In the design, operation and maintenance of HPPs, various types of measures can be taken to reduce hydro-abrasive erosion and its negative consequences. Naidu, (1999) proposed some measures in his study as (i) use of materials and coatings with high resistance to erosion; (ii) optimizations of turbine design and maintenance schedule; (iii) construction and operation of facilities for partial sediment exclusion (storage reservoirs, gravel and sand traps, etc.); (iv) temporary closing of intakes and pausing of turbine operation (HPP shutdowns) in periods with exceptionally high erosion potential. [Naidu, 1999]

The first measure increases the resistance to erosion, whereas the last two reduce the sediment “loading” on the machine parts. Despite considerable advances in material sciences, hydro-abrasive erosion cannot be fully prevented at medium- and high-head HPPs with high sediment loads. [Felix, 2017] Moreover, fine sediments cannot be fully excluded from the turbine water. Thus, a combination of measures is generally adopted, involving the design, operation and maintenance of civil structures and electro-mechanical equipment.

For an overall optimization of a HPP with respect to fine sediment and its consequences, information on the costs and benefits as well as the energetic losses and gains of the measures are required. Currently, only a part of the information required to solve the optimization problem is available. Firstly, there is a lack of practically proven measurement techniques and reliable measurement data on suspended sediment load, turbine erosion and efficiency changes.

Secondly, generally applicable quantitative relations between these three elements are rare in literature.

1.7.1 Mitigation Measures in Practice

Some mitigation measures that has been practiced in hydropower projects under National Hydroelectric Power Corporation (NHPC) for reducing the impacts of hydro abrasive erosion are as follows:

1.7.1.1 Sediment Management

Providing drawdown flushing during monsoon season (Flushing), either maintaining reservoir level near MDDL during the Monsoon (Drawdown sluicing) or provision of desilting chambers: wherever necessary for removal of coarser sediment particles to avoid the entry of sediment into the turbines.

1.7.1.2 Operation Optimization

Operating the units in accordance to the manufacturers' guidelines. Units are run in accordance with the operating zone defined in prototype hill chart of the specific machines. Plant has to be shut down in case the silt content reached beyond the prescribed limit; Avoiding the operation beyond operating zone as much as possible. Closing of inlet valve at shutdown is must.

1.7.1.3 Maintenance Measures

The assessment of turbine before and after annual capital maintenance in hydropower plant. NHPC, India ensures the assessment of gaps between rotating and stationary parts, guide vanes and facing plates, checking of areas affected by erosion, and cavitation, and areas of damage for coated parts and keeps the records data related machine performance for quality maintenance and reserves of spare parts for monsoon season emergencies.

1.7.1.4 Surface Coatings of Underwater Parts

Various surface treatments and e.g. chrome coatings were developed and tested over decades, but erosion was not much reduced in cases with harder particles [Felix, 2017].

Thermal spray coating or HVOF coating of underwater parts like runner, guide vanes, cheek plate process to extend equipment life by significantly increasing erosion, wear resistance, as well as corrosion protection. In NHPC, HVOF coating on runner has increased the capital maintenance period to 3 years leading to improved machine availability.

1.7.1.5 Design Aspects

IEC-62364 (2013) guidelines explain some recommended methods to minimize particle abrasion and the effects thereof, by modifications to design for clean water. While it is possible to design a unit to be more resistant against particle abrasion, this may adversely, affect other aspects of the turbine. The optimum combination of abrasion resistant design features must be considered and selected for each site based on its specific conditions.

Generally, for the design, the area exposed to the abrasive wear should be as small as possible. As well, discontinuities and sharp transitions or direction change of the flow should be avoided. The thickness of the runner blade in the area prone to erosion should be increased.

CHAPTER – 2

LITERATURE REVIEW

Several studies have been carried out to understand the abrasive erosion. Under this section, some of the published research articles related to sediment abrasion, are reviewed.

Erosion potential is described by the two characteristics factor of the sediment i.e. sediment particle size and mineral content. Hydro abrasive erosion is challenging problem for ROR hydropower development in sediment-laden rivers of Himalayas. Gradual removal of base material causes loss of turbine efficiency as well as cost associated with maintenance. [Thapa et al, 2003].

If hydraulic turbines and pumps are operated in sediment-laden water, their components and other parts along waterways may be subject to hydro-abrasive erosion. Factors for severe erosion are: High relative velocities between the flow and the exposed surface, and high concentrations of relatively coarse, hard and angular suspended sediment particles. High flow velocities prevail in medium- and high-head hydro-electric power plants (HPPs), where Francis and Pelton turbines are employed. High-head Pelton turbines are particularly prone to hydro-abrasive erosion. [Felix, 2017]

The sediment erosion of turbine runners is a complex occurrence, which depend upon different parameters such as concentration, silt size, hardness, base material properties and similarly velocity of water. The efficiency of the turbine decreases with the increase in the sediment wear and ultimately results breakdown of the hydro turbines. Researchers have followed investigates to study the impact of these parameters on sediment wear, but most of these investigates are on small size samples in varied types of test rigs to simulate the flow conditions in the turbine. However, the phenomenon of sediment wear and actual flow conditions are too challenging to simulate. [Padhy et al., 2008].

2.1 HYDRO ABRASIVE EROSION

Sediment erosion rate depends on sediment types and characteristics, hydraulic design and operating conditions of turbine and base material used for the components of hydropower project [Neopane et.al, 2010]. In hydropower plants, the mitigation of hydro-abrasive erosion and reservoir siltation require recurrent and high quality suspended sediment data related to their parameters like particle size distribution (PSD), suspended sediment concentration (SSC), mineral composition, and shape of particles. [Bishwakarma et.al, 2008] [Boes et. al, 2009].

In high head hydropower plants, the hydro-abrasive erosion becomes more distinguished with increase in head. Because of economic reasons, higher operating velocities are allowed in penstocks and turbines of these plants. In case of run-of-river (R-o-R) hydropower plants, the erosive effect is prominent as there is no or very less storage available to allow the settling of suspended sediment. High head Francis and Pelton turbines are most affected by hydro-abrasive erosion. Sometimes, the damage of turbine is extensive even after running one monsoon season. [Rai et al., 2015].

Mann (2000) based on their vulnerability to hydro-abrasive erosion and number of monsoon seasons required between repairs, has classified the hydropower plants in India in three categories A, B, and C.

The hydro-abrasive erosion is a complex process depending on many factors. The hydro abrasive erosion of the surfaces due to sediment laden water depends on many factors such as i) sediment characteristics (size, concentration, mineral contents, shape); ii) flow characteristics (flow velocity, angle of impingement, time of operation, effect of media, temperature etc.) last but not least iii) properties of substrate materials (properties of the coating, hardness, surface morphology) [Thapa, 2004].

Though the significant parameters for hydro-abrasive erosion have been identified (Gummer, 2009; Winkler et al., 2011), but it is still not fully understood to which extent these parameters contribute to the hydro-abrasive erosion. IEC 62364 (2013) recommends selecting an abrasive test with test conditions similar to actual hydropower conditions.

Sheldon and Finnie (in 1966) observed the change of ductile mode of erosion to the brittle mode when particle size is changed from small to larger (in Stachowiak and Batchelor, 1993). Small size particles have a more cutting effect while bigger particles deform material by elastic deformation and fatigue. Along with the erosion rate ranking depends on hardness in case of erosion due to small particles, whereas in the case of large particles, it is dependent on the toughness of a material.

Silt and clay particles are cohesive and may form flocs which are larger than the primary particles. For turbine erosion, the size of the primary particles is significant because flocs are disaggregated before and during the turbine passage. [Felix, 2017]

The aspect ratios, b/a and c/b; where a being in the direction of the longest extension of the particle, b the intermediate and c the shortest dimension; indicate the basic particle shapes, which can be cubic (equant), platy (discoid, flaky), blade- or rod-like or flat. Mineral particles with isotropic strength (e.g. quartz) generally have the first type of shape with no preferred dimension. [Felix, 2017]

Most of the erosion models have integrated the effect of shape; hence quantification of the shape parameter is necessary for the estimation of erosion by solid particles. Together with the some of the methods suggested by Bahadur and Badruddin (1990), roundness factor (Perimenter^2 / 4 π Area) and other statistical parameters are also defining the particle shape.

Chen and Li (2003) carried out simulation on erosion using computer model (Micro-scale dynamic model, MSDM) and examined the difference in erosion rate by three basic shapes: circle, square, and triangle and found the highest erosion loss in single particle impact is by triangular particle followed by circular and square. When the square particle is rotated at 45° and contact become smallest, the erosion loss changes. Because of plastic deformation after succeeding strikes are in a larger area in this case, erosion caused by the square shape particle is bigger than the circular. In general, the erosion rate due to triangular or square particles may be 1.5 times higher than that of circular particles. [Chen and Li, 2003]. Considering the shape of the sediment; round particles causes less abrasive erosion comparing to sharp and angular particles. [Sharma, 2006].

Neopane et al, (2009) designed a test rig to insert different shapes and sizes (1 to 10 mm) of particles. The flow in the guide vane cascade was simulated to be able to discover the drag force of a particle in swirl flow. Different shapes and sizes of the particles were tested with the same operating conditions and found that triangularly- shaped particles were more likely to hit the suction side of the guide vane cascade. It is revealed that erosion on a turbine blade is strongly dependent on the shape of the particle. The reduction of expected erosion rate density is also related to the reduction of particle velocity obtained from experiments. [Neopane et al, 2009].

IEC 62364 (2013) mentions to take the sediment shape factor for hydro-abrasive model between 1 to 2 depending on shape of sediment particles using scanning electron microscope (SEM) images for round to angular particles respectively. However, this is a qualitative method. Sediment parameters such as aspect ratio and roundness can be quantified as of sediment shape at a site. [Li et al., 2016].

The shape and hardness of particle accompaniment each other, even hard but relatively blunt particle may not cause severe erosion. Hard particles tend to have a sharp profile; compared to edges of soft particle round off even with slight impact. Severe erosion occurs if the particles are harder than the substrate; in contrast, if particles are softer, erosion occurs only if the substrate has low fracture toughness. [Thapa, 2004].

Stole (1993) suggests to exclude most particles larger than 150-300 micron to minimize cost related to abrasive erosion and generation losses. However, as the severity increases with the increase of head, the removal of particles should be done accordingly. Mosonyi (2009) therefore suggests removal of quartz particles larger than 250 micron in medium head plants (15 m < H< 50 m), 100-200 micron at high head plants (50 < H< 250m) and 10-50 micron at plants operating under very high heads of several hundred meters. As the quartz particles cause enormous damage to the hydro-mechanical equipment and accessories and are chiefly available in most of the rivers, the physical properties of quartz particles are therefore normally used as a reference for designing sediment exclusion devices. [Mosonyi 2009].

Sediment concentration is made of the disintegration of rock due to natural, chemical and mechanical weathering. Principally, it is a sand fraction of the sediment which causes turbine erosion. The sand fraction can be further classified into fine (0.06 to 0.2 mm), medium (0.2 to 0.6 mm) and the coarse (0.6 to 2 mm). The increase in sediment concentration increases the erosion of actual hydropower turbine. [Thapa et al, 2003]

2.2 EROSION IN HYDRAULIC TURBINES

A comprehensive study on sediment erosion in hydraulic turbines has conducted by Brekke, (2002). High head Pelton and Francis turbines are most affected by sand erosion. Low head reaction turbines will be eroded only in case of extremely high sediment concentration. He characterised erosion of hydraulic machinery into: (i) micro erosion due to fine particles (<60μm) at high velocity, (ii) secondary flow vortex erosion caused by secondary flow or obstacles, (iii) acceleration of large particles (>0.5mm). It has been suggested the basic design criteria for Pelton runners operating in sand laden water as buckets with largest possible curvature and size, lowest number of jet and largest hydraulic radius. Further, for Francis turbines, smooth acceleration in guide vane, stay vane outlet angle to retain guide vane at a neutral position in normal operation condition are essential to design criteria. Finally, to minimize effect of sand erosion, it was also suggested that, in overlapping zone of turbine selection diagram, Pelton turbines should be chosen to Francis with lower number of units should be selected taking lowest possible speed. [Brekke, 2002].

A methodical study of sediment erosion in hydro turbines and its components has been done in PhD studies by Thapa [Thapa, 2004]. In this study, sediment samples from major basins in Nepal were collected and processed. Investigation was done to identify PSD and type and amount of hard particle distribution in samples. To quantify erosion rates of different sediment samples on different turbine materials and coatings, set laboratory tests were conducted in high velocity test rig. After field observation and measurements, he concluded that due to leakage of the water, incorrect direction of flow and secondary flow or friction loss, the turbine efficiency drops. The efficiency of eroded turbine decreases and turbine becomes structurally weak and revealed because of sand erosion. Francis turbine has largest drop in efficiency at part load and Pelton turbine has largest loss at best efficiency point (BEP). [Thapa, 2004].

Bajracharya, et al., (2008) has studied different parameters viz: sediment characteristics as PSD, SSC, mineral content and shape; erosion as wear depth and surface texture; and analysis of sediment laden water through surface of needle; sediment load calculation, sediment deposition volume in the reservoir estimated, and developed profile of erosion surface of spur needle for both units and established relation of erosion in mm/year and respective efficiency loss for the Chilime Hydroelectric power plant and concluded that the manual sediment sample collection lead to incorrect sediment load in case frequency of water sample collection is not high, erosion measurement technique is bulky and time consuming, no erosion measurement of splitter and turbine bucket. [Bajracharya, et al., 2008]

Boes, (2009) has established the relation between mean sediment diameter and SSC, and derived an erosion relation for Dorferbach HPP. An experimental setup was developed for continuous monitoring of SSC and PSD with optical backscatter and laser diffraction sensor along with regular conventional pumped sample along with runner bucket geometry and splitter, 17 erosion measurements of bucket was performed using Ultrasonic flow meter and pressure measurement data for flow and head. The total sediment load was derived and erosion velocity computed via net head. Sediment parameters like SSC and PSD are useful for better quantification of their effects Splitter width is stablished as controlling measure for erosion, continuous monitoring of sediment parameters like SSC and PAD are useful for better quantification of their effects. [Boes, 2009]

Padhy, (2008) has carried out review of sediment erosion in hydro turbines as well as major theoretical examinations, experimental studies and case studies and concluded that sediment erosion in hydro turbines cannot be avoided completely, but can be reduced to an economically tolerable level. Even though design changes in the turbine components and providing different materials and coatings to the turbine blades, the improvement in most cases is not quite significant. [Padhy, 2008].

According to Padhy et al., (2009, 2011, and 2012) the weight loss of bucket is correlated to parameter variation such as suspended sediment concentration (SSC), sediment size and velocity for the duration of experiments. The efficiency loss of the turbine model is also related with parameter variations; where sediment is recirculated; the material of bucket was taken brass whereas in actual case it is steel in prototype plants and mechanism of wear is predicted. In the study, a mixture is prepared as known amount of water is mixed with measured amount of sediment, other properties of sediment measured in laboratory before mixing and weighing the buckets before and after erosion; head and discharge measured via pressure transducer before nozzle, and v – notch respectively. [Padhy, et al., 2009, 2011, and 2012]

Liu, et al., (2012) carried out in their study as weight loss of three different materials are calculated per hour and related with concentration of sediment and velocity of erosion. The measured amount of sediment is mixed with known amount of water and projected; velocity and operating time are calculated during tests. Recirculation of sediment during experiments may have changed the sediment shape, and mechanism of wear is predicted through the weight loss. [Liu, et al., 2012]

Felix et al., (2012), and Abgottspon et al., (2013) conducted experiments with five different possibilities of geometric changes due to erosion like reduction of splitter height, increase of splitter width, volume difference etc. are presented along with efficiency decrease, sediment load and operating time. In their experimental set up, the different possibilities with use of optical scanner for erosion measurement is presented along with suggestion that splitter width practically, can provide easy way to relate erosion with other parameters. For this five different types of turbidimeters, acoustic method and a laser diffractometer to measure sediment properties. Optical scanning camera (3D digitization of two Pelton buckets) are employed for the measurement of wear depth and a thickness gauge for coating surface erosion. Finally, efficiency of turbine is achieved by index efficiency measurement. [Felix et al., 2012 and Abgottspon et al., 2013]

Rajkarnikar, et al., (2015) has developed a more accurate method and setup to compare effects of sediment erosion in alternate designs of Francis runner blades. Two alternative designs of the runner blades which were developed from other discrete studies were tested in their experiment, where Francis runner blades are casted specimens of the scaled model and bolted in a rotating disc at the angle representing actual inlet flow conditions. The disc is inserted in a closed housing with water and sediment mixture and driven by means of the motor up to the speed of 1400 rpm, then erosion patterns on the blades are observed by removal due to sediment erosion is estimated by the measurement of weight loss from blades after successive time intervals. [Rajkarnikar, et al., 2015]

2.2.1 Impact on Turbine Runner

Predicting and numerical modelling of hydro-abrasive erosion are challenging because of many parameters involved and their complex relationship [Felix et al., 2016].

Only limited model of erosion have been validated for their reliability, although various empirical and theoretical model have been formulated from experiment and field observation [Athar et al., 2012].

Guideline for investigating erosion in Francis, Kaplan and Pelton turbines has been developed by The International Electrotechnical Commission (IEC). According to IEC: 62364 (2013) model particle abrasion rate in turbine is a function of particle concentration, particle physical properties, particle velocity, turbine material properties, flow pattern and other factors [IEC: 62364, 2013].

Reduction in erosion can only be achieved with mutual collaboration between engineers, scientists and consultant working in the design and manufacturing of hydro mechanical equipment, operators of hydropower plant, and researcher of academic institutes [Felix et.al, 2016].

Normalized mass loss of the Pelton turbine can be estimated using the relation developed by Padhy in her Doctor of Philosophy. [Padhy, 2008].

Percentage efficiency loss of Pelton turbine can be estimated using the relation developed by R.Thakur [Thakur et al., 2017]. Loss in efficiency of Francis runner can be estimated using the relation developed by Bajracharya. [Bajracharya et al., 2008].

2.3 ABRASIVE EROSION EXPERIENCES IN NEPAL

Himalayan river basin which are young and fragile in geology with slope landscape suffers from inherent natural land erosion problem. The inherent unceasing and random pattern of rainfall causes extreme sediment concentration in Himalayan river basin [Galay et. al, 2000] [Thapa et al, 2003].

The climatic and physical conditions are highly favourable for erosion and sedimentation. High sediment in the Himalayan River is due to the presence of weak rocks, heavy monsoon rain, and extreme relief. Some studies for sediment erosion in hydropower projects were carried out in Nepal are as follows:

The power plants (>2MW) operation in Nepal, almost all have sand erosion problem. [Thapa, 2004] stated the 1.83 million tons/year average sediment load is damaging Francis turbine components of 3X23 MW Marsyangdi hydropower project (MHP). More than 80% of particles in the suspended sediment passing through turbine are smaller than 0.05 mm and about 90% of this is quartz and feldspar [Kayastha, 1999]. The repair cycle for each unit is three years.

Thapa, (2004) observed the 3X4MW Francis turbine components of Jhimruk hydropower project (JHP) is severely damaged by about 9300 tons of sediment through one unit within one monsoon season. Around 83% particles are smaller than 0.09 mm consisting 85% quartz. The repair cycle of this turbine is only 1 year.

The Khimti hydropower project (KHP) with 5X12 MW Pelton turbine is also eroded due to fine sediments. The maintenance cost is less than 10% of replacement cost at JHP and 15% at MHP. Hence maintenance is preferred in power plants in Nepal even if efficiency of system is degrading. [Thapa, 2004]

The thermodynamic efficiency measurement at JHP revealed 4% loss at BEP and 8% loss at 25% load for operating time from Sept-Nov, with only 9600 tons of sediment. The leakage loss is 50% of total efficiency loss. The provision to prevent sand laden water through labyrinth can reduce this loss. One of such provision could be inserting clean water through these seals. Relative efficiency measurement was not successful because of blocking of pressure tap by sediment. [Thapa, 2004].

Kali Gandaki “A” Hydroelectric Plant with 3X48 MW Francis turbine is eroded severely in its components by about 2.8 million tons /year suspended sediment load passing through the turbines on 17 July, 2003. After every flood operation of the machine a significant damage and weight loss were observed in the turbine components such as runner, wearing ring, guide vanes, and facing plates due to injurious effect of sediment load. The abrasion rate of the runner vane outlet was roughly estimated 5.37 mm/3 rainy seasons. [Chhetry et al., 2015]

Multidimensional approaches, such as management of catchments area to avoid sediment production, settling basin management to screen large particles and enhancing erosion resistance of underwater components are needed to tackle with the sediment problems.

2.4 GAPS IDENTIFIED

Based on literature review, the following gaps has been identified:

i. Many studies on sediment erosion are available, considering sediment parameters as particle size and concentration. The effect due to other parameters viz: mineral contents and shape on erosion potential to the turbine has been less studied.

ii. Silt erosion enhances the performance drop of the turbines. Similarly, other components of hydropower plant like nozzles, guide vanes, penstock, gate and valves, seat rings, cooling systems are also subject to the sediment abrasion problems.

iii. Lack of financial analysis done based on sediment abrasive erosion for the hydropower plants to check the economic viability of frequency of repair and maintenance due to abrasion.

2.5 OBJECTIVES

The following are the objectives of this research study:

i. To analyse the abrasive erosion potential of the turbine due to the hardness of sediment particle (a) quartz content and (b) shape of sediment in various hydro project sites in Nepal.

ii. To assess sediment abrasion in various turbine components especially Francis turbine such as runner, guide vanes, seat ring, facing plates, gate and valves, labyrinth seals in hydropower plants.

iii. To work out the financial aspects of hydro abrasive erosion on the cost of repair and replacement, major breakdowns and closure of plant, corrective measures and remedial steps taken.

CHAPTER -3

METHODOLOGY

3.1 METHODOLOGY ADOPTED

The methodology followed for study is shown as per Flowchart in Figure 3.1.

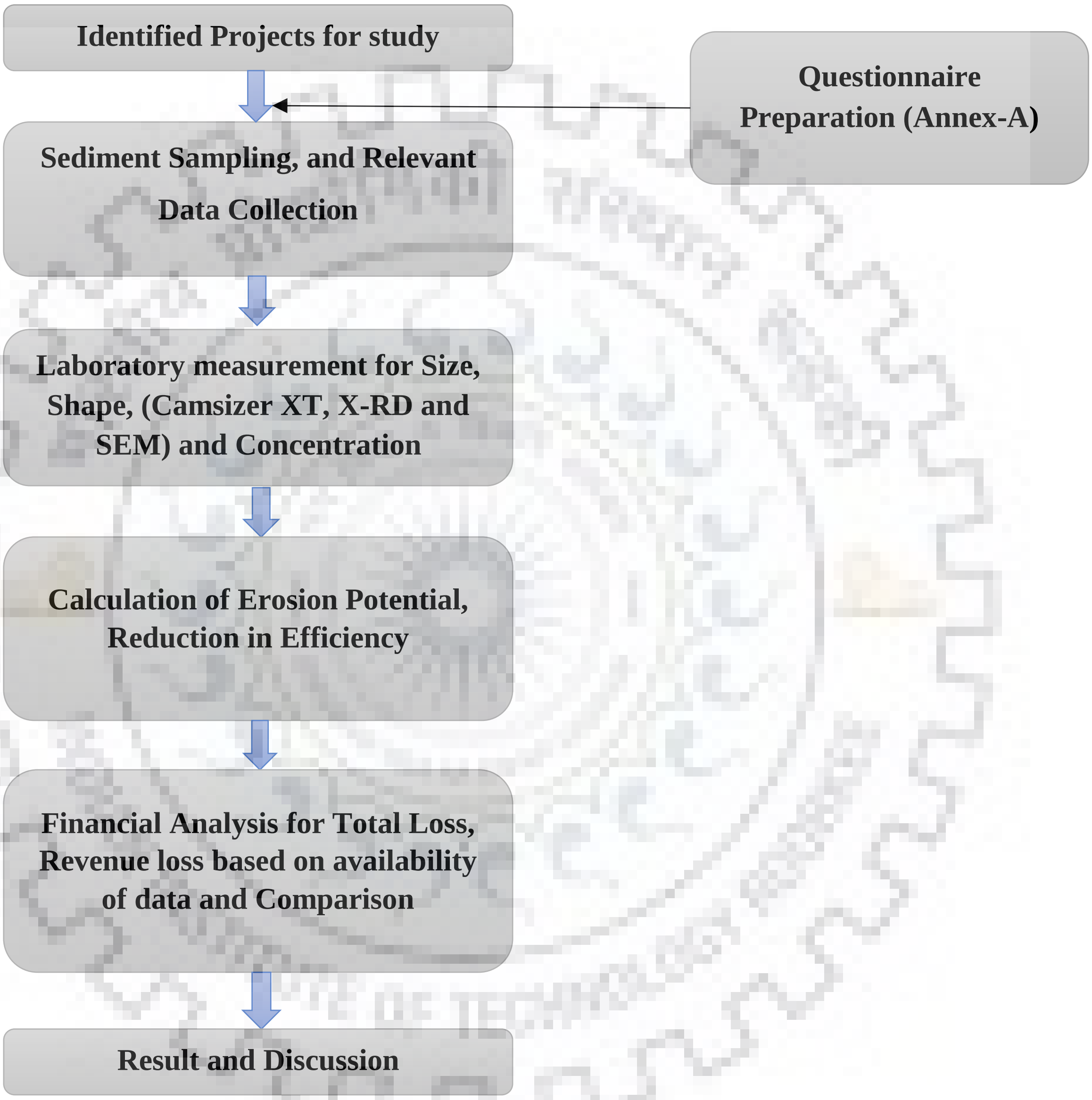

Figure 3.1 Methodology Flow diagram for dissertation work

3.1 IDENTIFIED HYDRO PROJECTS FOR STUDY

Based on the literature survey, identified research gaps in the area of hydro-abrasive erosion in hydropower plants, all together thirteen hydropower plants under Nepal electricity Authority (NEA) owned were identified as study area to overcome the set objectives. Among which five number of hydropower plants from three river basins have selected and finalized for the study as visualized in the Figure 3.2., and detailed shown in Table 3.1.

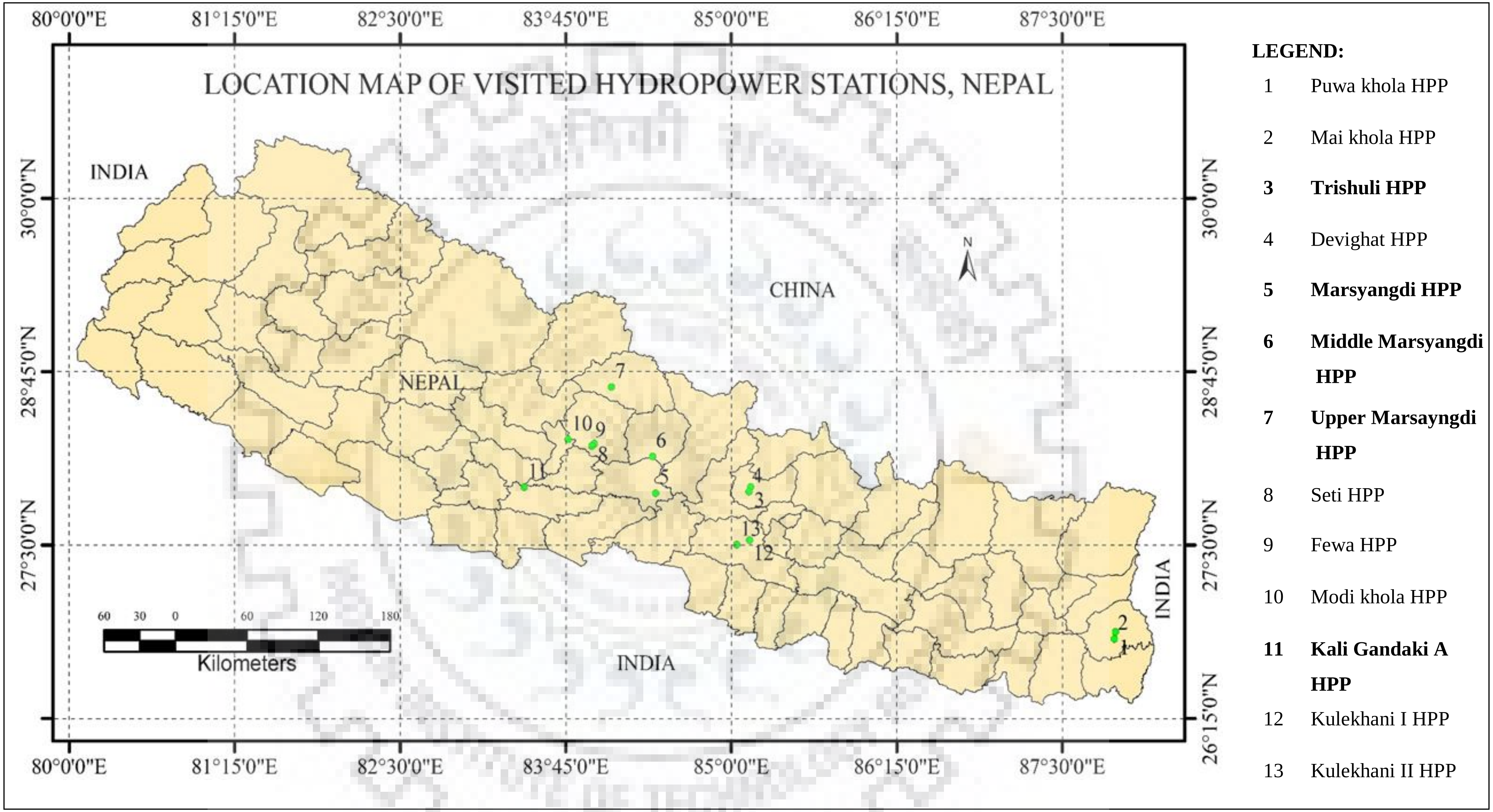

Figure 3.2 Study Area Map showing the locations of visited Hydropower stations

Table 3.1 Details of Hydropower plants visited for research work in Nepal [NEA, 2018]

S. N	**HPP Names**	**Capacity (MW)**	**River/ Tributary**	**Location**		**VDC/ District**	**Date of Commission**	**Type of Turbine No. of Units**
				Latitude	**Longitude**			
1	Puwa khola	6.2	Puwa	26°52' 28''	87°54' 04''	Ilam	04-04-2004	Pelton, 2*3.1 MW
2	Mai khola	4.5	Mai	26.82277	87.891944	Ilam	2011	Francis, 3 *1.5 MW
3	Trishuli	24	Trishuli	27°55' 09''	85°08' 45''	Nuwakot	14-04-1967	Francis, 7 Units (6*3.5 MW & 1*3 MW)
4	Devighat	15.0	Trishuli	27°53' 07”	85°07' 55''	Nuwakot	01-12-1984	Francis, 3*5MW
5	Marsyangdi	69	Marsyangdi	27°52' 25''	84°25' 40''	Tanahu	05-11-1989	Francis, 3*23 MW
6	Middle Marsyangdi	70	Marsyangdi	28°08' 20''	84°24' 18''	Lamjung	1-11-2008	Francis, 2*35 MW
7	Upper Marsyangdi 'A'*	50	Marsyangdi	28°38' 20''	84°05' 45''	Lamjung	26-09-2016	Francis, 2*25 MW
8	Seti	1.5	Seti	28°13' 50''	83°57' 54''	Kaski	01-11-1985	Francis, 3*0.5MW
9	Fewa	1.0	Fewa	28.214167	83.947222	Kaski	12-06-1969	Francis, 4*0.25MW
10	Modi Khola	14.8	Modi	28°15' 42''	83°43' 47''	Parbat	01-12-2000	Francis, 2*7.4MW
11	Kali Gandaki 'A'	144	Kali Gandaki	27°55' 00''	83°26' 12''	Syangja	16-08-2002	Francis, 3*48 MW
12	Kulekhani-I (Reservoir Type)	60	Kulekhani	27°32' 06”	85°08' 21”	Makawanpur	01-05-1982	Pelton, 2*31 MW
13	Kulekhani-II (Reservoir Type)	32	Kulekhani	27°30' 06''	85°02' 32''	Makawanpur	01-11-1986	Francis, 2*16.5MW

** Upper Marsyangdi 'A' HPP is promoted by IPP: Synhohydro Nepal -Sagarmatha Power Company Ltd.*

Nepal Electricity Authority (NEA) is the regularity body for electricity generation, distribution and management in Nepal; has developed number of hydropower plants in Nepal. Under which twelve HPP were promoted by NEA and one by IPP situated at different locations in Nepal, The eleven plants among them are R-O-R type and remaining two are reservoir type.

3.2 HYDROPOWER PLANTS VISITED

During the dissertation work, following five hydropower plant stations having sediment problems comprising three river basins visited were Trishuli hydropower plant, Kaligandaki A hydropower plant, Marsyangdi hydropower plant, Middle Marsyangdi hydropower plant, and Upper Marsyangdi A hydropower plant respectively.

3.2.1 Trishuli Hydropower Station

Trishuli hydropower plant 24 MW installed capacity is stationed at Nuwakot district, owned and operated by NEA is constructed in Trishuli river basin. This station was visited from 19/12/2018 to 20/12/2018. Mailung khola, Chilime HPP are also lies in this river basin shown in Figure 3.3.

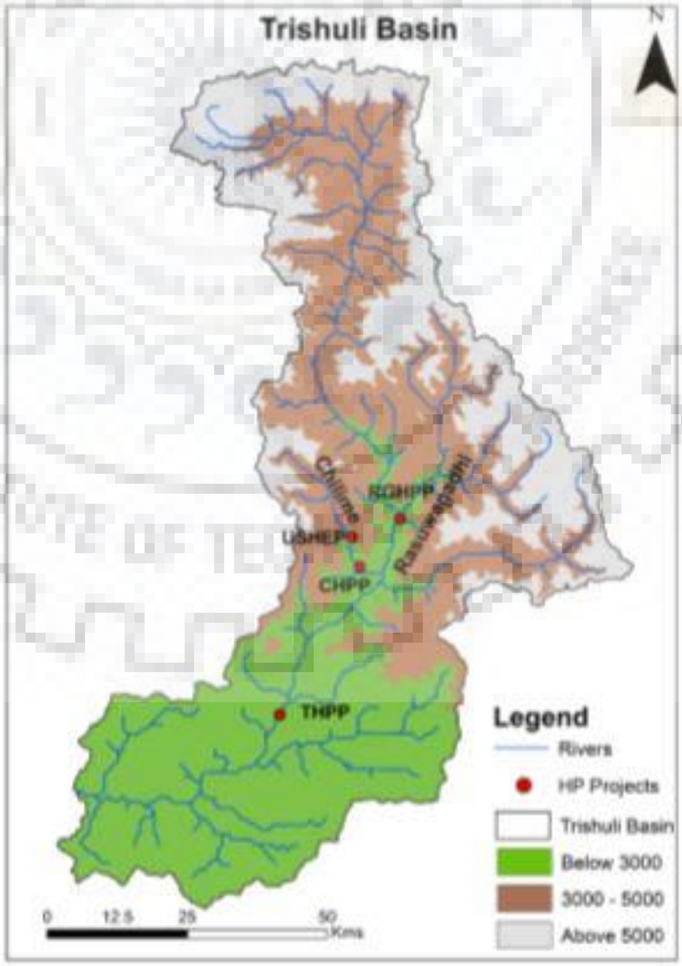

Figure 3.3 Location of Trishuli HPP at Trishuli River Basin [DoED, 2018]

Seven Francis turbines with rated speed of 500 rpm are furnished in the powerhouse. The HPP has been facing severe sediment problems and due to high sediment load early erosion of runners were observed. In general, shut down of plant is not done for monitoring of damages in the turbine and its parts. But it was noticed that, in any events, if an unpleasant grinding noise was observed, the plant was shut down immediately for the inspection. In the view of operation staff of the plant, generally the runners were not changed until the turbine reached in critical stage.

3.2.2 Kaligandaki 'A' Hydropower Station

Kaligandaki 'A' Hydropower plant lies in Kaligandaki river basin has 144 MW installed capacity is the largest HPP so far constructed and in operation in Nepal. The NEA owned plant annually generates electric energy about 842 GWh, was visited from 28/12/2018 to 29/12/2018. KGA powerhouse is equipped with 3* 48MW Francis turbines, and overhauling of each turbine unit is done in every three years of operation alternatively saying one individual unit every year. The runner and guide vanes are not only excessively eroded due to the sediment but other components exposed to water also have been wore out.

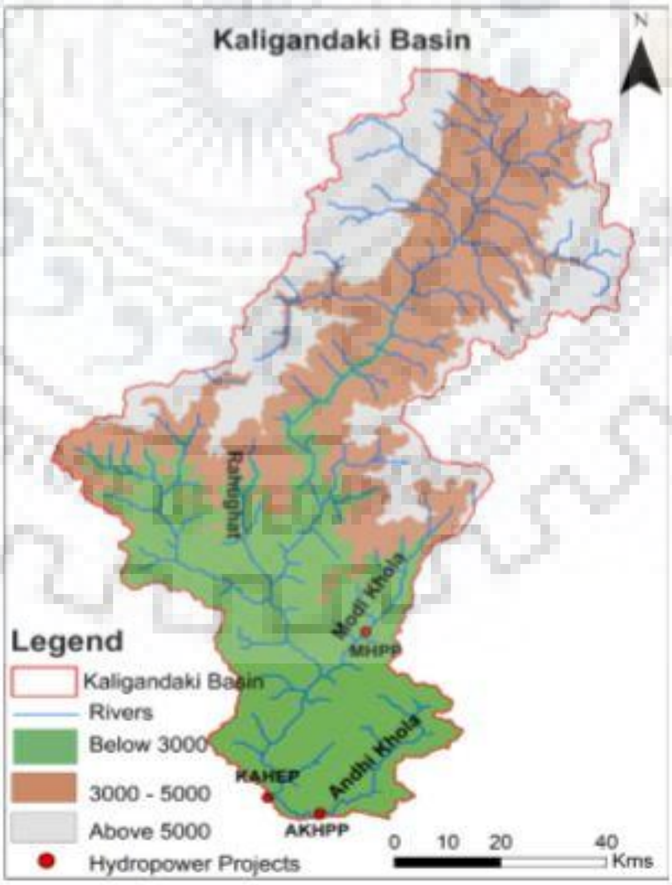

Figure 3.4 Location of Kaligandaki A HPP in Kaligandaki River Basin [DoED, 2018]

3.2.3 Marsyangdi Hydropower Station

Marsyangdi hydropower plant of 69MW installed capacity is located at Aanbu Khaireni VDC, Tanahu district Nepal lies in Marsyangdi river basin was visited from 22/12/2018 to 23/12/2018. It is a peaking R-O-R power station with design generation 462.5 GWh annually. According to station manager, turbine erosion has been inspected and in every 3 years of interval, it is completely overhauled for maintenance for each unit. Turbines have fairly eroded due to the sediment but not found severe as in other power projects.

Marsyangdi HPP, Middle Marsyangdi HPP, Khudi HPP and Upper Marsyangdi A HPP are major hydropower projects constructed in the Marsyangdi basin as presented in below Figure 3.5.

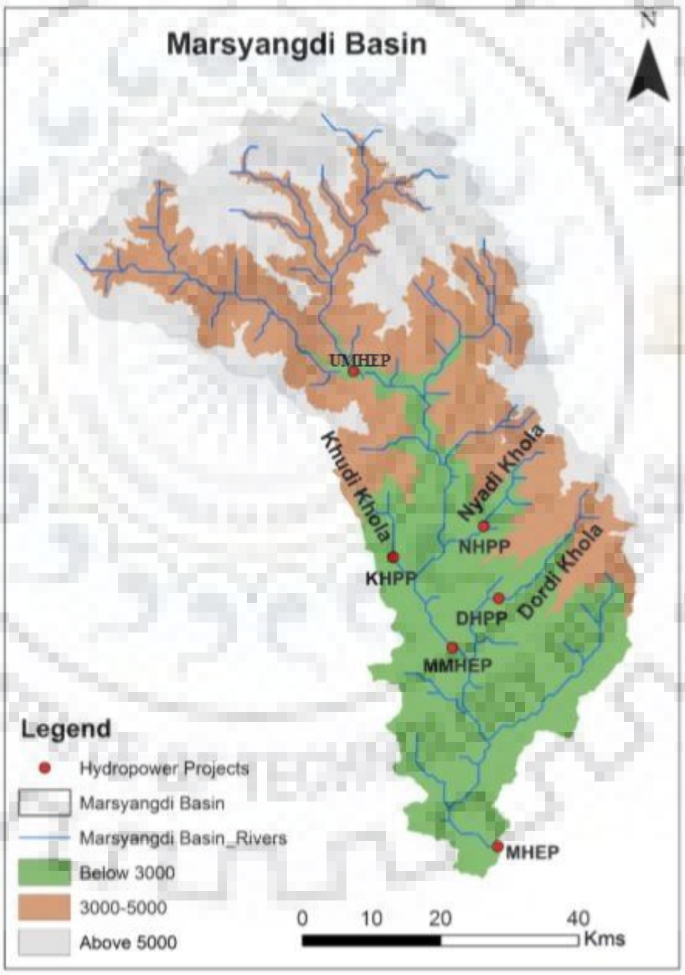

Figure 3.5 Location of Marsyangdi HPP, Middle Marsyangdi HPP and Upper Marsyangdi A HPP in Marsyangdi River Basin [DoED, 2018]

3.2.4 Middle Marsyangdi Hydropower Station

Middle Marsyangdi Hydropower plant consists of two 35MW vertical axis Francis turbines is the biggest HPP among the Marsyangdi river basin is located at Siudibar, Lamjung, Nepal. The station was visited from 24/12/2018 to 25/12/2018.

As per personnel interview, it was noted that during overhaul of turbine heavy erosion is found. Inspection of runner and other components is not only done annually but complete overhauling of individual unit is also executed each year. Welding and grinding are the major maintenance practices done to repair the runner as well as the other turbine parts like wicket gates, draft tube.

3.2.5 Upper Marsyangdi A Hydropower Station

To investigate data for the erosion potential, Upper Marsyangdi ‘A’ Hydropower Station located at Bhulbhule, Lamjung, Nepal was visited from 26/12/2018 to 27/12/2018. For power generation, this plant consists of 2*25 MW Francis turbines executing energy about 317.2 GWh per annum. Complete overhauling of one turbine unit and its components is carried out each year, which resembles two years of interval for each single unit. As reported, during overhauling no heavy erosion is found in the turbine.

3.3 SEDIMENT SAMPLING, AND RELEVANT DATA COLLECTION

Direct technique of taking representative sediment samples were used by selecting appropriate sampling devices, and transported them to the R&D laboratory for further sediment measurements analyses.

At least three sediment samples were taken from location of intake, downstream of desilting tank and tailrace respectively from respective sites. There was radially available sediment data; among the visited sites, only five hydropower plants comprising three different river basins have relatively available data and gathered accordingly. A questionnaire was developed before going to field visit to ensure all relevant data required for the research work and were taken from feasibility report, personnel interview, initial environmental examination report and project financial analysis report provided by Department of Electricity Development, Nepal.

3.4 LABORATORY ANALYSIS

The mineralogical composition of sediment particle is quantified in the laboratory using Rietveld X-ray diffraction (XRD) analysis. The hardness of the particles is assigned based on the mineralogy using tables from petrographic literature.

Particle count method is followed for mineral analysis which indicated quartz is the predominant mineral in those river sediment.

The Laser diffraction particle size analyser (LISST) apparatus, and the Camsizer XT measurement tool was used for size, concentration and shape measurements related to sediment characteristics from collected samples and were measured at R&D laboratory of Department of Hydro and Renewable Energy (formerly Alternate Hydro and Energy Centre), and X-RD measurement and Scanning Electron Microscope (SEM) image were taken out at Institute Instrumentation Centre (IIC) of Indian Institute of Technology, Roorkee.

3.5 CALCULATION OF EROSION POTENTIAL, LOSS IN EFFICIENCY

The measured characteristic values of sediment samples are used as a factor to predict the erosion potential to the turbine and it’s components. With available erosion models and relevant data, the gradual loss of efficiency of the turbine caused by hydro-abrasive erosion is also calculated for five different HPP of three basins. The following erosion models are used for the calculation purpose. Generally, IEC-62364 model being adopted to predict erosion rate in Pelton, Francis and Kaplan turbines. According to IEC-62364 model from equation (1.2), time integrated formula: IEC-62364, (2013)

$$\mathrm{S} = W^{3.4} * \mathrm{PL} * \mathrm{K_m} * \mathrm{K_f}/\mathrm{RS^p} \qquad \text{From equation (1.2)}$$

Various parameter associated with the estimation of erosion in IEC-62364 model are presented in Table 1.1. This Model can estimate both absolute erosion rate (mm/year) as well as corresponding reduction in efficiency (% per year) of Francis runners due to suspended particles. This erosion model comprises constant factors recommended by IEC model and proportionality constants for erosion model recommended by Bajracharya in his research.

$$\mathrm{Er} = \mathrm{C.K}_{\mathrm{hardness}}\, \mathrm{K}_{\mathrm{shape}}\, \mathrm{K}_{\mathrm{m}}\, \mathrm{K_f}\, .\mathrm{a}\,(\mathrm{size})^{\mathrm{b}} \text{ from equation (1.16)}$$

And according to Bajracharya, loss in efficiency of all three turbine runner related to erosion rate will be predicted using equation no. (1.4) [Bajracharya et al., (2008)]

$$\eta_t \propto a\mathrm{E}_r{}^b \qquad \text{From equation (1.4)}$$

Where, a= 0.1522 and b=1.6946. E_r is abrasive erosion rate in mm/yr and η_t is loss in efficiency in percentage due to abrasive erosion alone.

In case of Francis turbine, leakage loss should also be considered due to abrasive erosion in labyrinth seal, so total loss is sum of leakage loss and loss due to runner abrasive erosion.

3.6 FINANCIAL ANALYSIS

Financial analysis is done to compare ability of each case to repay the investment. As per the data availability the financial analysis is carried out, in which costs involved in repair and maintenance, preventive measures such as coating included to find out an optimum strategy regarding hydro-abrasive erosion.

For financial analysis steps according to Rai et al., (2018), as per data available; is followed. The calculated values of measurements of suspended sediment, hydro-abrasive erosion potential and efficiency reduction for specific plants, downtime loss, repair cost, non-compliance loss are considered for the calculation of losses in financial analysis.

3.7 RESULT AND CONCLUSION

Finally all the five hydropower sites are analysed in terms of hydro abrasive erosion potential to the turbine due to hardness and quantifying the shape factor and hence compared the reduction in efficiency and the total cost of loss as per data availability.

CHAPTER -4

ANALYSIS AND DISCUSSION

4.1 ABRASIVE EROSION POTENTIAL PREDICTION

Among five hydropower plants visited, the calculation of abrasive erosion potential to the turbine and its components, all individual HPP are introduced for the prediction as follows.

4.1.1 Prediction for Marsyangdi HPP

I. General Features:

General features of Marsyangdi hydropower plant is shown in table 4.1.

Table 4.1 General features of Marsyangdi HPP

1	Name of hydropower	Marsyangdi HPP
2	Installed capacity	3*26 MW
3	Type of turbine	Francis turbine
4	Net head	90.5 m
5	Rated turbine speed	300 rpm
6	Rated turbine discharge	30.5 m^3/s
7	Designed annual generation	462.5 GWh

II. Particle Size Distribution:

The representative sample are taken each day before settling basin and at tail race each by the hydropower. Sample is processed in the R&D lab at hydropower. Annual average sediment load passing through turbine is 1.83 million tons [Chaudhary, C.S., 1999]. The sample PSD at tailrace is shown in Figure 4.1.

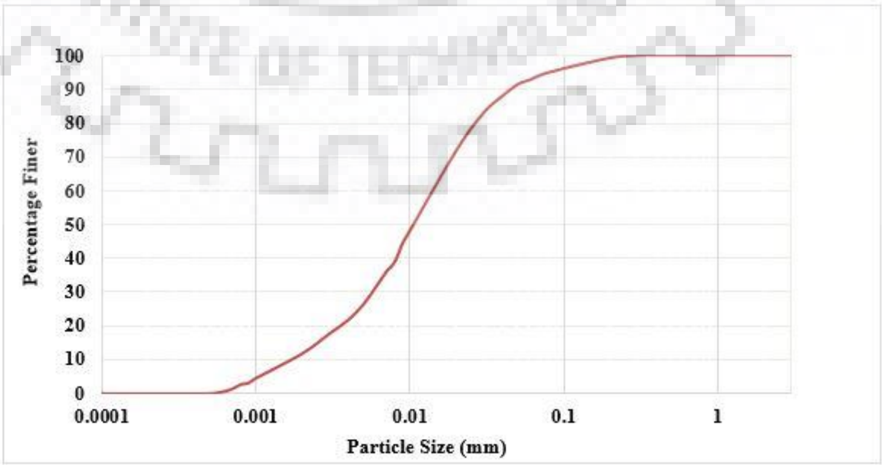

Figure 4.1 PSD at Tailrace of Marsyangdi HPP [NEA, 2018]

Medium diameter of particle size passing through turbine is 0.0108mm. 89.58 % of sediment load passing through turbine falls in the range of 0.001 mm to 0.07 mm.

III. Shape:

The shape of the sediment particle is measured in relation to b/l ratio. Figure 4.2 (a) and (b) shows SEM image (2.5k magnification) and Camsizer XT measurements were employed for the shape factor calculation.

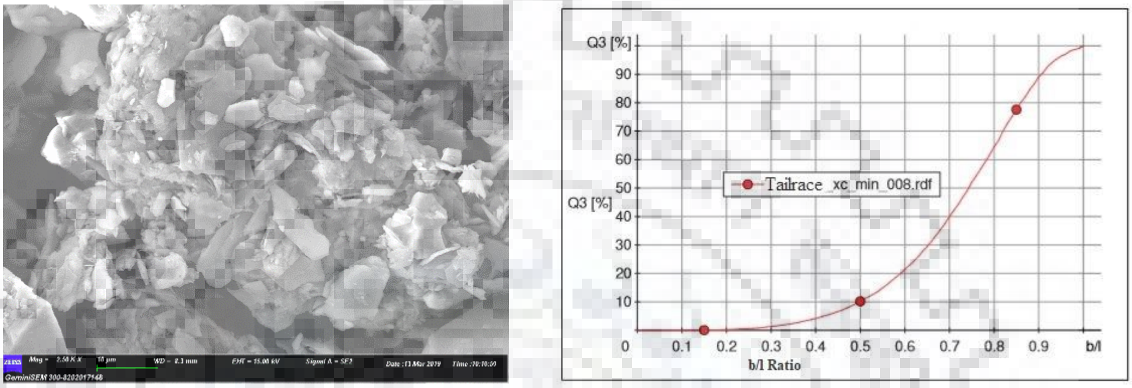

Figure 4.2(a) SEM Image for sediment and 4.2(b): CamsizerXT plot for b/l ratio Vs percentage finer.

The recommended value of shape factor (Kshape), as per IEC-62364 (2013) for round, sub-angular and angular particles for hydro-abrasive erosion to be 1, 1.5 or 2 respectively. In this case, the Kshape value will be (2.000 - 0.72) i.e., 1.28 as sub-angular by nature, is the precise estimate than just a qualitative prediction. [Rai et.al, 2017].

IV. Mineral type:

The X-Ray diffraction analysis provides the constituents of mineral particles of the sediment, for which an expert support has been taken. Figure 4.3 shows the riveted head from X-ray diffraction.

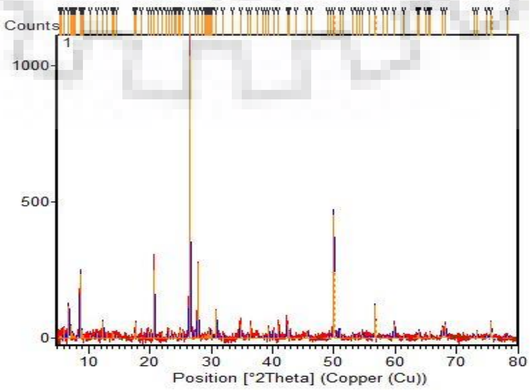

Figure 4.3 XRD plot of riveted head vs particle counts for Marsyangdi HPP

Mineral content is 56.29 % quartz, 10.4 % feldspar, 12.78 % muscovite 4.64 % biotite 5.83 % tourmaline 4.49 % garnet and 5.63 % other. [Bastola et.al, 2014]

V. Abrasive Erosion:

Relevant data of Marsyangdi hydropower station for erosion model IEC-62364 (2013) is shown in Table 4.2.

Table 4.2 Relevant data of Marsyangdi HPP

S.N	Parameters	Unit	Values
1	H	m	92.25
2	P	kW	26000
3	n	rpm	300
4	ns	rpm	169.200
5	C	kg/m3	0.6342
6	Ksize	mm	0.0108
7	Kshape		1.28
8	Khardness		0.77
9	Km		1

Annual average sediment load passing through turbine is 1.83 million tons. Average Sediment Concentration in monsoon (PPM) is: 58.02892 kg/sec = 0.634196 kg/m3 = 634.2 ppm. [Thapa, B., (2004)]

IEC-62364 model has been adopted to estimate erosion in runner inlet, runner outlet, guide vanes, facing plates, and labyrinth seal and the respective values are tabulated in Table 4.3.

Table 4.3 Erosion for different components as per IEC-62364, (2013)

S.N	Parameters	Unit	Runner		Guide vanes	Facing plates	Labyrinth seals
			Inlet	Outlet			
1	W	m/s	32.23	32.23	23.39	32.23	32.23
2	PL	kg*hr /m^3	59.14	59.14	59.14	59.14	59.14
3	Km		1	1	1	1	1
4	Kf	mm*s^3 /kg*hr	9.00E-07	5.40E-07	1.06E-06	8.60E-07	3.80E-07
5	RS	m	2.234	2.234	2.234	2.234	2.23
6	p		0.25	0.75	0.25	0.25	0.75
7	S	mm	**5.05**	**1.23**	**2.12**	**3.59**	**1.05**

Erosion depth in runner inlet is 5.05 mm and runner outlet is 1.23 mm at Marsyangdi HPP, for annual average sediment concentration passing through the turbine 0.634 kg/m3 with sub-angular shape of particle and hardness factor of 0.77 for median size of 0.0108 mm particle.

Corresponding erosion depth in guide vane, facing plates and labyrinth seals is 2.12, 3.59, and 1.05 mm respectively.

4.1.2 Prediction for Middle Marsyangdi HPP

I. General Features:

General features of Middle Marsyangdi hydropower Plant is shown in Table 4.4.

Table 4.4 General features of Middle Marsyangdi HPP

1	Name of hydropower	Middle Marsyangdi HPP
2	Installed capacity	70 MW (2*35MW)
3	Type of turbine	Francis turbine
4	Net head	98 m
5	Rated turbine speed	333.33 rpm
6	Rated turbine discharge	40 m^3/s
7	Designed annual generation	398 GWh

II. Particle Size Distribution:

The processed representative sample, taken from tail race by the hydropower. The sample PSD at tailrace is shown in Figure 4.4. Median size of particle passing through turbine is 0.019mm. 90 % of sediment load passing through turbine falls in the range of 0.0056 mm to 0.063 mm.

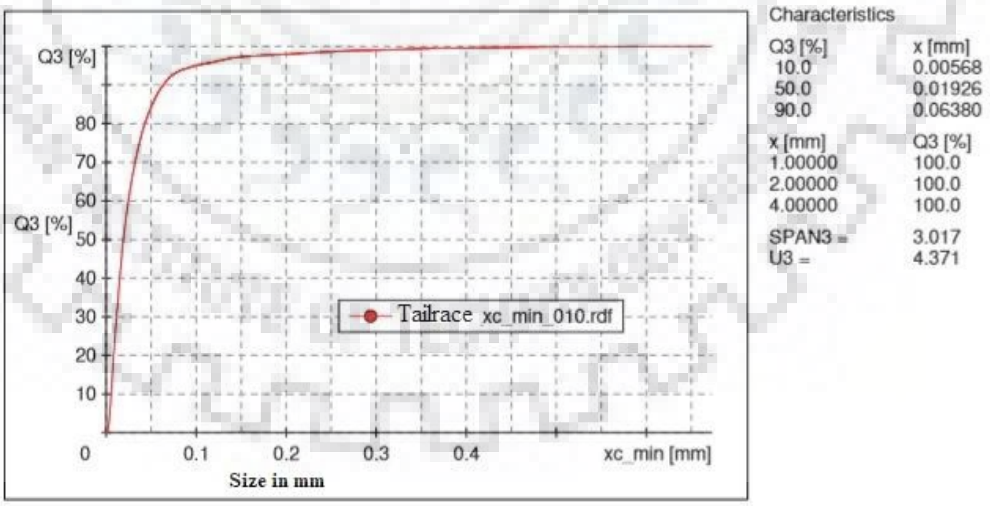

Figure 4.4 PSD at Tailrace of Middle Marsyangdi HPP

III. Shape:

The shape of the sediment particle is measured in relation to b/l ratio. Figure 4.5 (a) and (b) shows SEM image in 2.5k magnification and Camsizer XT measurements were employed for the shape factor calculation.

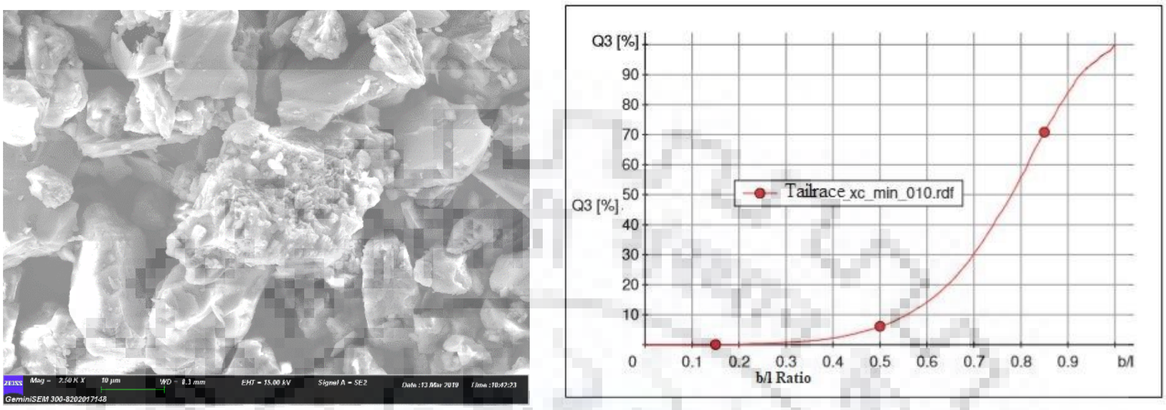

Figure 4.5 (a) SEM Image for sediment and 4.5 (b) CamsizerXT plot for b/l ratio Vs percentage finer.

The recommended value of shape factor (Kshape), as per IEC-62364 (2013) for round, sub-angular and angular particles for hydro-abrasive erosion to be 1, 1.5 or 2 respectively. In this case, the Kshape value will be (2.0 – 0.78) i.e., 1.22 as sub-angular by nature, is the precise estimate than just a qualitative prediction. [Rai et.al, 2017].

IV. Mineral type:

The X-ray diffraction analysis provides the constituents of mineral particles of the sediment. Mineral content for the sample taken at Middle Marsyangdi HPP is found to be 52 % quartz, 17 % feldspar, 19 % mica and 12 % others with their hardness scale based on Mohr's scale $K_{hardness}$ is 0.72 shown in Table 4.5. The riveted head graph from XRD is shown in Figure 4.6.

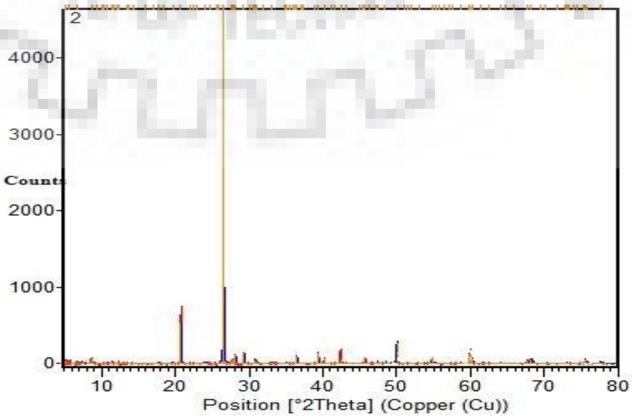

Figure 4.6 Middle Marsyangdi HPP XRD plot for riveted head Vs particle counts

Table 4.5 Mineral contents with hardness factor

Minerals		**Average (%)**	**Hardness (Mohr's scale)**
Quartz		**52**	**7**
Feldspar		**17**	**6**
Mica		19	2 to 6
Others	A	**3**	**≥5**
	B	9	<5

V. Abrasive Erosion:

Relevant data of Middle Marsyangdi HPP for erosion model IEC-62364 is shown in Table 4.6.

Table 4.6 Relevant data of Middle Marsyangdi Hydropower Station

S.N	**Parameters**	**Unit**	**Values**
1	H	m	98
2	P	kW	35900
3	n	rpm	333.33
4	ns	rpm	204.83
5	C	kg/m3	0.52343
6	Ksize	mm	0.019
7	Kshape		1.22
8	Khardness		0.72
9	Km		1

According to sediment measurement by hydropower plant (through LISST Infite), Average Annual Sediment Concentration from three consecutive years (2016 to 2018) is: 523.429 ppm = 0.52343 kg/m3.

IEC-62364, (2013) model has been adopted to estimate erosion in runner inlet and outlet, guide vanes, facing plates, and labyrinth seal and tabulated in Table 4.7. The erosion depth in different components found as: runner inlet is 5.26 mm and runner outlet is found 1.31 mm at Middle Marsyangdi hydropower plant, for annual average sediment concentration passing through the turbine 0.523 kg/m3 with sub-angular shape factor 1.22 of particle and hardness factor of 0.72 for median size of 0.019 mm particle. Corresponding erosion depth in guide vane, facing plates and labyrinth seals is 3.32, 3.70, and 1.25mm respectively.

Table 4.7 Erosion for different components of Middle Marsyangdi HPP as per IEC-62364 (2013)

S.N	Parameters	Unit	Runner		Guide vanes	Facing plates	labyrinth seals
			inlet	outlet			
1	W	m/s	37.91	37.91	24.12	37.91	37.91
2	PL	kg*hr /m3	76.53	76.53	76.53	76.53	76.53
3	Km		1	1	1	1	1
4	Kf	mm*s3 /kg*hr	9.00E-07	5.40E-07	1.06E-06	8.60E-07	3.80E-07
5	RS	m	2.24	2.24	2.24	2.24	2.24
6	p		0.25	0.75	0.25	0.25	0.75
7	S	mm	**5.26**	**1.31**	**3.32**	**3.70**	**1.25**

4.1.3 Prediction for Upper Marsyangdi A HPP

I. General Features:

General features of Upper Marsyangdi A HPP is shown in table 4.8.

Table 4.8 General features of Upper Marsyangdi A HPP

1	Name of hydropower	Upper Marsyangdi A Hydropower Project
2	Installed capacity	2*25 MW
3	Type of turbine	Francis turbine
4	Net head	113 m
5	Rated turbine speed	375 rpm
6	Rated turbine discharge	24.4 m^3/s
7	Designed annual generation	317.2 GWh

II. Particle Size Distribution:

The representative sample are taken each day before settling basin and at tail race each by the hydropower. Representative sample and corresponding discharge for each week from June 2017 to October 2017. [Jha, B., 2017]. The sample PSD at tailrace is shown in Figure 4.7.

Form figure it is obtained that the medium diameter of particle size passing through turbine is 0.00884. 81.12 % of sediment load passing through turbine falls in the range of 0.002976 mm to 0.029907 mm.

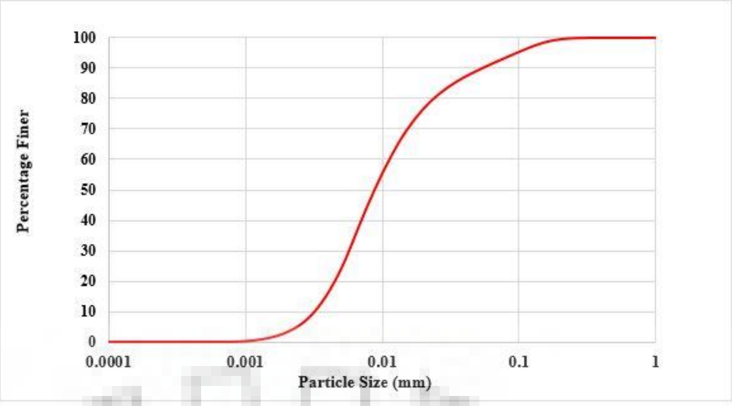

Figure 4.7 PSD at tailrace of Upper Marsyangdi A HPP [Jha, B., 2017].

III. Shape:

The shape of the sediment particle is assumed round and taken the unity value.

IV. Mineral type:

The X-ray diffraction analysis provides the constituents of mineral particles of the sediment. Mineral content for the sediment sample taken at Upper Marsyangdi HPP is found to be is 44.6 % quartz, 9.9 % feldspar, 17.3 % plagioclase, 16.6 % calcite, 2.9% dolomite and 8.7 % clay.

Likewise, previous study for Mineral content for this HPP sediment is 48.2 % quartz, 5.1 % feldspar, 16 % plagioclase, 19.2 % calcite, 3.8% dolomite and 7.7% clay. [Bastola et.al, 2014]

V. Abrasive Erosion:

Relevant data of Upper Marsyangdi A HPP for erosion model IEC-62364 is shown in table 4.9.

Table 4.9 Relevant data of Upper Marsyangdi HPP

S.N	Parameters	Unit	Values
1	H	m	113
2	P	kW	25000
3	n	rpm	375
4	ns	rpm	160.94
5	C	kg/m3	0.43142
6	Ksize	mm	0.0085
7	Kshape		1
8	Khardness		0.71
9	Km		1

According to sediment measurement by hydropower plant (LISST Infinite), Average Annual Sediment Concentration for Upper Marsyangdi HPP is as follows: Average annual flow is 194.16

m3/sec, Average sediment transport is 0.943 kg/m3 and Average Sediment passing to turbine is 0.43142 kg/m3. [Bastola. et.al, 2014].

IEC-62364 (2013) model has been adopted to estimate erosion in runner inlet, runner outlet, guide vanes, facing plates, and labyrinth seal and tabulated in Table 4.10.

Table 4.10 Erosion for different components of Upper Marsyangdi A HPP as per IEC-62364 (2013)

S.N	Parameter	Unit	Runner		Guide vanes	Facing plates	labyrinth seals
			Inlet	Outlet			
1	W	m/s	34.5	34.5	25.89	34.5	34.5
2	PL	kg*hr /m3	22.77	22.77	22.77	22.77	22.77
3	Km		1	1	1	1	1
4	K_f	mm*s3 /kg*hr	9.00E-07	5.40E-07	1.06E-06	8.60E-07	3.80E-07
5	RS	m	1.97	1.97	1.97	1.97	1.97
6	p		0.25	0.75	0.25	0.25	0.75
7	S	mm	**2.93**	**1.25**	**1.30**	**2.80**	**0.88**

Erosion depth in runner inlet is 2.93 mm and runner outlet is 1.25 mm at Upper Marsyangdi A HPP, for annual average sediment concentration passing through the turbine 0.431 kg/m3 with round shape of particle and hardness factor of 0.71 for median size of 0.0085 mm particle. Corresponding erosion depth in guide vane, facing plates and labyrinth seals is 1.3, 2.80 and 0.88 mm respectively.

4.1.4 Prediction for Kaligandaki A HPP

I. General Features:

General features of Kaligandaki A hydropower plant is shown in table 4.11.

Table 4.11 General features of Kaligandaki A HPP

1	Name of hydropower	Kali Gandaki A Hydropower Station
2	Installed capacity	144 MW (3*48MW)
3	Type of turbine	Francis turbine (Horizontal)
4	Net head	115 m
5	Rated turbine speed	300 rpm
6	Rated turbine discharge	44.86 m3/s
7	Designed annual generation	842 GWh

II. Particle Size Distribution:

The processed representative sample, taken from tail race by the hydropower. The PSD of sediment sample at tailrace as in Figure 4.8. The medium diameter of particle size passing through turbine is 0.0109 mm. 90 % of sediment load passing through turbine falls in the range of 0.0046 mm to 0.028 mm.

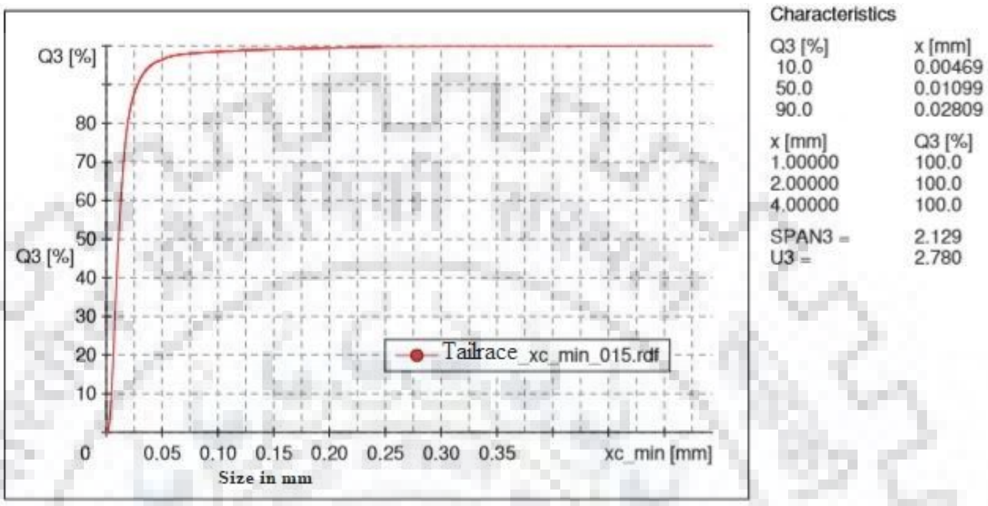

Figure 4.8 PSD at tailrace of Kaligandaki A HPP

III. Shape:

Shape of the sediment particle is measured in relation to b/l ratio. Figure 4.9 (a), and (b) shows the SEM image in 2.5k magnification and Camsizer XT measurements were employed for the shape factor calculation.

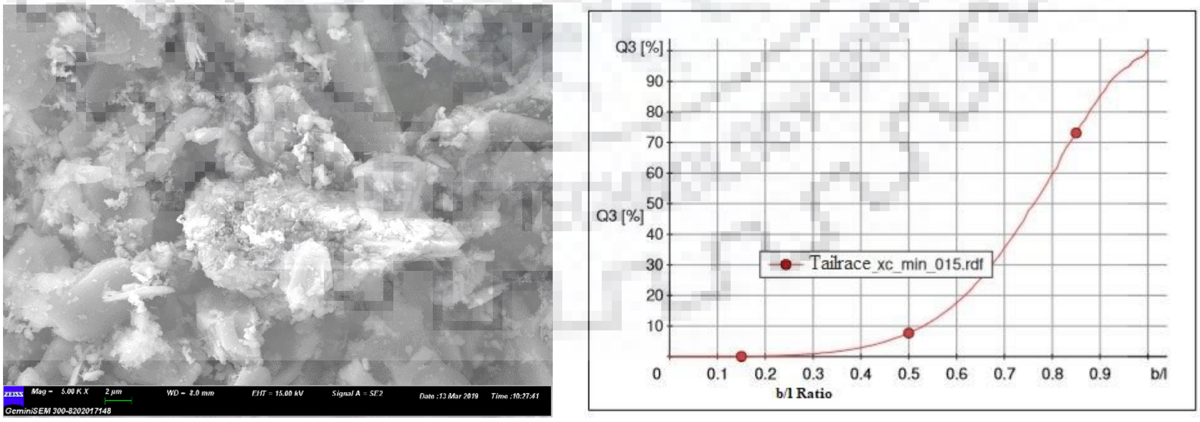

Figure 4.9 (a) SEM Image for sediment and (b) Camsizer XT plot for b/l ratio Vs percentage finer (Q3%)

The recommended value of shape factor (Kshape) as per IEC-62364 (2013) for round, sub-angular and angular particles for hydro-abrasive erosion to be 1, 1.5 or 2 respectively. In this case, the Kshape value will be (2.000 – 0.77) i.e., 1.23 as sub-angular by nature, is the precise estimate than just a qualitative prediction. [Rai et.al, 2017].

IV. Mineral type:

The XRD analysis provides the constituents of mineral particles of the sediment. Mineral content for the sample taken at Kaligandaki A HPP is found to be 75 % hard materials including 68.32 % quartz, 7.08% Horneblende, and 11.84% Garnet and other. [Chhetry, B. et.al, 2015] The riveted head graph from X-ray diffraction is shown in Figure 4.10.

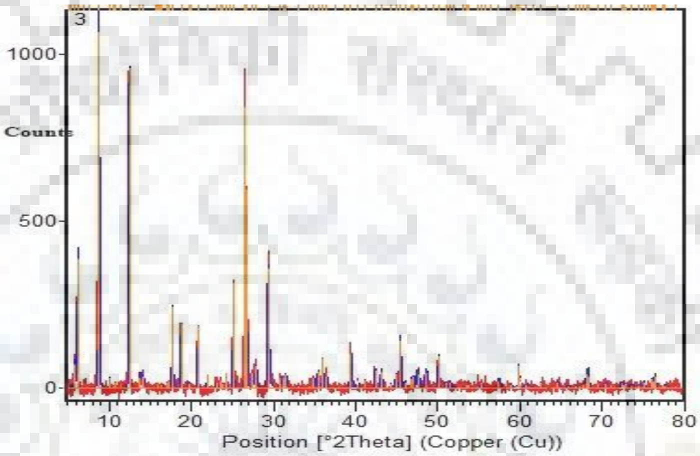

Figure 4.10 XRD plot for riveted head Vs particle counts for Kaligandaki A HPP

V. Abrasive Erosion:

The relevant data of Kaligandaki A hydropower plant for erosion model IEC-62364 (2013) is given in Table 4.12.

Table 4.12 Relevant data of Kaligandaki A Hydropower Station

S.N	Parameters	Unit	Values
1	H	m	115
2	P	kW	48000
3	n	rpm	300
4	ns	rpm	174.530
5	C	kg/m3	0.65974
6	Ksize	mm	0.011
7	Kshape		1.23
8	Khardness		0.75
9	Km		1

According to sediment measurement by hydropower plant (through LISST Infinite); the average annual sediment load is 2.8 MT/Yr. [Chhetry, B. et.al, 2015].

The sediment concentration is: 88.787kg/sec = 0.65974 kg/m3 = 659.74 ppm. IEC-62364 (2013) model has been adopted to estimate erosion in runner inlet, runner outlet, guide vanes, facing plates, and labyrinth seal and tabulated in table 4.13.

Table 4.13 Erosion for different components of Kaligandaki A HPP as per IEC-62364(2013)

S.N	Parameters	Unit	Runner		Guide vanes	Facing plates	Labyrinth seals
			inlet	outlet			
1	W	m/s	36.75	36.75	26.13	36.75	36.75
2	PL	kg*hr /m3	58.65	58.65	58.65	58.65	58.65
3	Km		1	1	1	1	1
4	Kf	mm*s3 /kg*hr	9.00E-07	5.40E-07	1.06E-06	8.60E-07	3.80E-07
5	RS	m	2.564	2.564	2.5 64	2.564	2.564
6	p		0.25	0.75	0.25	0.25	0.75
7	S	mm	**8.75**	**3.28**	**3.23**	**8.36**	**2.31**

Erosion depth in runner inlet is 8.75 mm and runner outlet is 3.28 mm at Kaligandaki A HPP, for annual average sediment concentration passing through the turbine 0.659 kg/m3 with sub-angular shape factor 1.23 of particle and hardness factor of 0.75 for median size of 0.011 mm particle. Corresponding erosion depth in guide vane, facing plates and labyrinth seals is 3.23, 8.36, and 2.31 mm respectively.

4.1.5 Prediction for Trishuli HPP

I. General Features:

General features of Trishuli Hydropower plant is shown in Table 4.14.

Table 4.14 General features of Trishuli HPP

1	Name of hydropower	Trishuli HPP
2	Installed capacity	24 MW (6*3.5MW+1*3MW)
3	Type of turbine	Francis turbine (Horizontal)
4	Net head	51.4 m
5	Rated turbine speed	500 rpm
6	Rated turbine discharge	7.8 m^3/s
7	Designed annual generation	163 GWh

II. Particle Size Distribution:

The representative sample taken from tailrace by the hydropower. The particle size distribution of sample at tailrace is shown in Figure 4.11. Medium diameter of particle size passing through turbine is 0.022 mm. 90 % of sediment load passing through turbine falls in the range of 0.0065 mm to 0.060 mm.

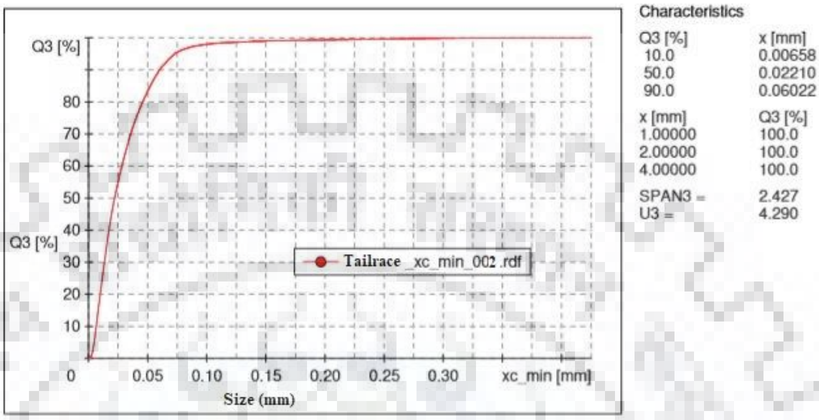

Figure 4.11 PSD at Tailrace of Trishuli HPP

III. Shape:

Shape of the sediment particle is measured in relation to b/l ratio SEM image and Camsizer XT measurements were employed for the shape factor calculation as shown in Figure 4.12 (a) and (b).

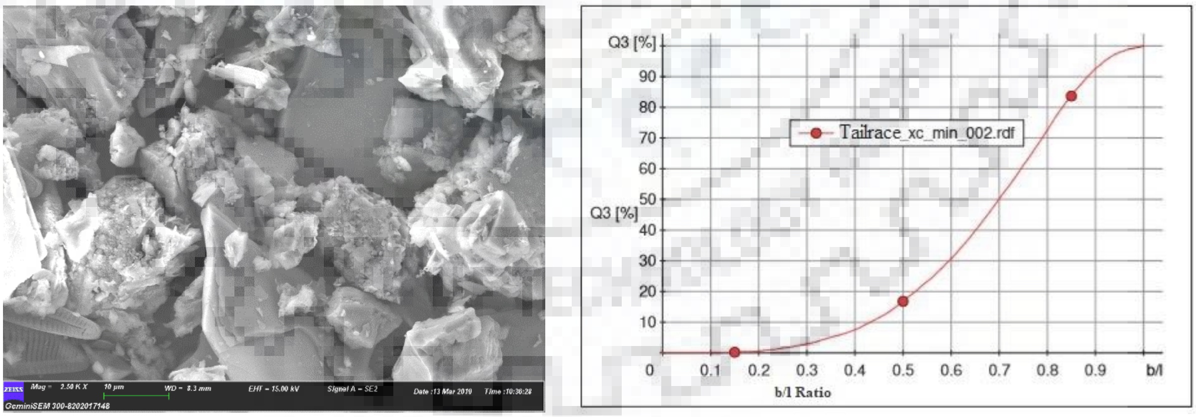

Figure 4.12 (a) SEM Image for sediment and (b) Camsizer XT plot for b/l ratio Vs percentage finer (Q3%)

According to IEC-62364 (2013) the recommended value of shape factor (Kshape) for round, sub-angular and angular particles for hydro-abrasive erosion to be 1, 1.5 or 2 respectively. In this case, the Kshape value will be (2.00 – 0.72) i.e., 1.28 as sub-angular by nature, is the precise estimate than just a qualitative prediction. [Rai et.al, 2017].

IV. Mineral type:

For the mineral constituents of the sediment, X-ray diffraction measurement is carried out. Mineral content for the sample taken at Trishuli HPP is found to be Quartz 67.5%, Feldspar 2.0%. Metamorphosed rock fragment 5.6%, Igneous rock fragment 0.5%, Mica 22.5% and few other constituents. [DoED, 2018] Figure 4.13 shows the riveted head graph from X-ray diffraction measurement.

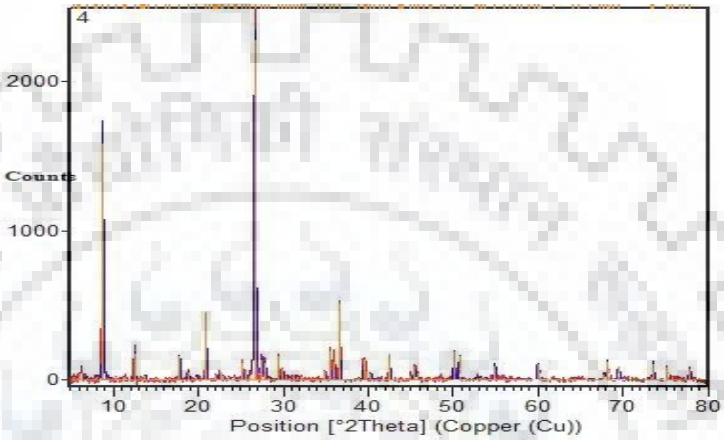

Figure 4.13 XRD plot for riveted head Vs particle counts for Trishuli HPP

V. Abrasive Erosion:

Table 4.15 illustrates the relevant data of Trishuli Hydropower plant for erosion model IEC-62364 (2013) as,

Table 4.15 Relevant data of Trishuli HPP

S.N	Parameters	Unit	Values
1	H	m	51.4
2	P	kW	3620
3	n	rpm	500
4	ns	rpm	218.59
5	C	kg/m3	0.39505
6	Ksize	mm	0.022
7	Kshape		1.28
8	Khardness		0.76
9	Km		1

According to sediment measurement by hydropower plant (NEA 2017), Average annual sediment concentration is: 21.57kg/sec = 0.3951 kg/m3 = 395.11 ppm.

IEC-62364 (2013) model has used to estimate erosion in different components runner inlet, runner outlet, guide vanes, facing plates, and labyrinth seal and tabulated in Table 4.16.

Table 4.16 Erosion for different components of Trishuli HPP as per IEC-62364 (2013)

S.N	Parameters	Unit	Runner		Guide vanes	Facing plates	Labyrinth seals
			inlet	outlet			
1	W	m/s	28.76	28.76	17.47	28.76	28.76
2	PL	kg*hr /m3	74.06	74.06	74.06	74.06	74.06
3	Km		1	1	1	1	1
4	Kf	mm*s3 /kg*hr	9.00E-07	5.40E-07	1.06E-06	8.60E-07	3.80E-07
5	RS	m	1.1	1.1	1.1	1.1	1.1
6	p		0.25	0.75	0.25	0.25	0.75
7	S	mm	**5.93**	**3.39**	**1.28**	**5.67**	**2.39**

Erosion depth in runner inlet is 5.93 mm and runner outlet is 3.39 mm at Trishuli HPP, for annual average sediment concentration passing through the turbine 0.395 kg/m3 with sub-angular shape factor 1.28 of particle and hardness factor of 0.76 for median size particle of 0.022 mm. Corresponding erosion depth in guide vane, facing plates and labyrinth seals is 1.28, 5.67, and 2.39 mm respectively.

4.2 REDUCTION IN EFFICIENCY AND TOTAL LOSS

The reduction in efficiency of all five hydropower plants is calculated through an improved erosion model proposed by Thapa B. S. et al (2004).

This Model can not only estimate the absolute erosion rate (mm/year) of Francis runners but also provides corresponding reduction in efficiency (% per year) due to suspended particles. This erosion model take account of constant factors recommended by IEC model and proportionality constants for erosion model recommended by Bajracharya (2008) in his research.

The factor Kf for the both inlet and outlet of runner are known, therefore the individual erosion rate is determined from IEC erosion model and average erosion of runner (mm/yr) calculated for further determination of the corresponding reduction in efficiency per year in that particular plant.

4.2.1 Efficiency Reduction and Total Loss in Marsyangdi HPP

4.2.1.1 Efficiency Reduction

The erosion rate and the loss in efficiency percentage determined from IEC-62364 (2013) erosion model is illustrated in Table 4.17.

Table 4.17 Determination of Erosion rate and loss in efficiency for Marsyangdi HPP

	Factors					Const		Const		Constant		Reduction in efficiency per year (n%)=a1* (Er)^b1
Runner	**C kg/ m3**	**K hardness**	**K shape**	**K m**	**Kf**	**a**	**Size (mm)**	**b**	**Er (mm /yr)**	**a1**	**b1**	
Inlet	0.63	0.77	1.28	1	9.0	1199.8	0.011	1.8025	**1.93**	0.1522	1.6946	**0.4619**
outlet	0.63	0.77	1.28	1	5.4	1199.8	0.011	1.8025	**1.16**	0.1522	1.6946	**0.1944**
Average									**1.54**			**0.328**

The reduction in efficiency per year for concentration of sediment particle 0.634 kg/m3 for Marsyangdi HPP corresponding the predicted erosion rate 1.54 mm/yr is 0.328 %. In case of Francis turbine, the leakage loss is considered as 50% of the erosion loss hence the total reduction in efficiency per year is 0.492%.

4.2.1.2 Total Loss

The total loss in cost is the sum of loss in energy per year due to erosion and leakage, loss in generation during maintenance and repair and maintenance or replacement cost calculated as in Table 4.18.

Table 4.18 Calculation of Total Loss for Marsyangdi HPP

Loss in amount due to reduction in efficiency and Leakage		
Reduction in efficiency due to erosion	%	0.3281
Leakage Loss (Approx. 50 % of loss due to erosion)	%	0.1641
Total Loss in Efficiency per year	%	0.4922
Annual design energy	GWh	462.5
Loss in energy per year due to erosion and leakage	GWh	2.276512
Tariff per kW	US Cent	7.1519
	US $	0.071519
Loss in amount	US $	162813.85
Loss in generation during maintenance		0

Maintenance is done during dry season so the discharge will be only sufficient to run single turbine, therefore maintenance can be done in alternate turbine.		
Loss in maintenance cost		
Cost for material	US $	40909.09
Incentives to worker and staff	US $	1770.46
Total loss in maintenance	US $	42679.55

Loss in amount due to reduction in efficiency and Leakage	US $	162813.85
Loss in generation during maintenance	US $	0
Loss in maintenance cost	US $	42679.55
Total Loss in Amount	US $	205493.40
	INR	**14,179,045**

(1 US $ = INR 69.00)

The total loss in amount is obtained 14.2 M INR per year for the Marsyangdi HPP for predicted erosion rate 1.54mm/yr with sediment concentration 0.634 kg/m3 corresponding reduction in efficiency 0.328%.

4.2.2 Efficiency Reduction and Total Loss in Middle Marsyangdi HPP

4.2.2.1 Efficiency Reduction

The erosion rate and the loss in efficiency percentage determined from IEC-62364 (2013) erosion model is shown in Table4.19.

Table 4.19 Determination of Erosion rate and loss in efficiency for Middle Marsyangdi HPP

	Factors					**Const**		**Const**		**Constant**		**Reduction in efficiency per year (n%)=a1* (Er)^b1**
Runner	**C kg/m3**	**K hardness**	**K shape**	**K m**	**Kf**	**a**	**Size (mm)**	**b**	**Er (mm /yr)**	**a1**	**b1**	
Inlet	0.52	0.72	1.22	1	9.0	1199.8	0.019	1.8025	**3.92**	0.1522	1.6946	**1.5414**
outlet	0.52	0.72	1.22	1	5.4	1199.8	0.019	1.8025	**2.35**	0.1522	1.6946	**0.6486**
Average									**3.14**			**1.095**

The reduction in efficiency per year for concentration of sediment particle 0.523 kg/m3 for Middle Marsyangdi hydropower plant corresponding the predicted erosion rate 3.14 mm/yr is 1.095 %. In case of Francis turbine, the leakage loss is considered as 50% of the erosion loss hence the total reduction in efficiency per year is 1.642%.

4.2.2.2 Total Loss

The total loss in cost is the sum of loss in energy per year due to erosion and leakage, loss in generation during maintenance and repair and maintenance or replacement cost calculated as in Table 4.20.

Table 4.20 Calculation of Total Loss for Middle Marsyangdi HPP

Loss in amount due to reduction in efficiency and Leakage		
Reduction in efficiency due to erosion	%	1.0950
Leakage Loss (Approx. 50 % of loss due to erosion)	%	0.5475
Total Loss in Efficiency per year	%	1.6425
Annual design energy	GWh	398
Loss in energy per year due to erosion and leakage	GWh	6.537118
Tariff per kW	US Cent	7.1519
	US $	0.071519
Loss in amount	US $	467528.17
Loss in generation during maintenance		**0**
Maintenance is done during dry season so the discharge will be only sufficient to run single turbine, therefore maintenance can be done in alternate turbine.		
Loss in maintenance cost		
Cost for material	US $	45045.45
Incentives to worker and staff	US $	1164.75
Total loss in maintenance	US $	46210.21

Loss in amount due to reduction in efficiency and Leakage	US $	467528.17
Loss in generation during maintenance	US $	0
Loss in maintenance cost	US $	46210.21
Total Loss in Amount	US $	**513738.37**
	INR	**35,447,948**

(1 US $ = INR 69.00)

The total loss in amount obtained is 35.44 M INR per year for the Middle Marsyangdi HPP for predicted erosion rate 3.14 mm/yr with sediment concentration 0.523 kg/m3 corresponding reduction in efficiency 1.095%.

4.2.3 Efficiency Reduction and Total Loss in Upper Marsyangdi HPP

4.2.3.1 Efficiency Reduction

The Table 4.21 shows erosion rate and the loss in efficiency percentage determined from IEC-62364 (2013) erosion model.

Table 4.21 Determination of Erosion rate and loss in efficiency for Upper Marsyangdi HPP

	Factors					**Const**		**Const**		**Constant**		
Runner	**C kg/m3**	**K hardness**	**K shape**	**K m**	**Kf**	**a**	**Size (mm)**	**b**	**Er (mm/yr)**	**a1**	**b1**	**Reduction in efficiency per year (n%)=a1*(Er)^b1**
Inlet	0.43	0.71	1	1	9.0	351.35	0.0085	1.4976	**0.77**	0.1522	1.6946	**0.1461**
outlet	0.43	0.71	1	1	5.4	351.35	0.0085	1.4976	**0.46**	0.1522	1.6946	**0.0615**
Average									**0.61**			**0.069**

The reduction in efficiency per year for concentration of sediment particle 0.431 kg/m3 for Upper Marsyangdi hydropower plant corresponding the predicted erosion rate 0.61 mm/yr is 0.069%. In case of Francis turbine, the leakage loss is considered as 50% of the erosion loss hence the total reduction in efficiency per year is 0.104%.

4.2.3.2 Total Loss

The total loss in cost is the sum of loss in energy per year due to erosion and leakage, loss in generation during maintenance and repair and maintenance or replacement cost calculated as in Table 4.22.

Table 4.22 Calculation of Total Loss for Upper Marsyangdi HPP

Loss in amount due to reduction in efficiency and Leakage		
Reduction in efficiency due to erosion	%	0.0692
Leakage Loss (Approx. 50 % of loss due to erosion)	%	0.0346
Total Loss in Efficiency per year	%	0.1038
Annual design energy	GWh	317.20
Loss in energy per year due to erosion and leakage	GWh	0.3291
Tariff per kW	US Cent	7.15190
	US $	0.071519
Loss in amount	US $	23538.47
Loss in generation during maintenance		**0**

Maintenance is done during dry season so the discharge will be only sufficient to run single turbine, therefore maintenance can be done in alternate turbine.		
Loss in maintenance cost		
Cost for material	US $	30227.27
Incentives to worker and staff	US $	1169.19
Total loss in maintenance	US $	31396.46

Loss in amount due to reduction in efficiency and Leakage	US $	23538.47
Loss in generation during maintenance	US $	0.00
Loss in maintenance cost	US $	31396.46
Total Loss in Amount	US $	**54934.94**
	INR	**3,790,511**

(1 US $ = INR 69.00)

The total loss in amount obtained is 3.79 M INR per year for the Upper Marsyangdi HPP for predicted erosion rate 0.61 mm/yr with sediment concentration 0.431 kg/m3 corresponding reduction in efficiency 0.069%.

4.2.4 Efficiency Reduction and Total Loss in Kaligandaki A HPP

4.2.4.1 Efficiency Reduction

The Table 4.23 shows erosion rate and the loss in efficiency percentage determined from IEC-62364 (2013) erosion model.

Table 4.23 Determination of Erosion rate and loss in efficiency for Kaligandaki A HPP

	Factors					Const		Const		Constant		
Runner	**C kg/m3**	**K hardness**	**K shape**	**K m**	**Kf**	**a**	**Size (mm)**	**b**	**Er (mm/yr)**	**a1**	**b1**	**Reduction in efficiency per year (n%)=a1* (Er)^b1**
Inlet	0.66	0.75	1.23	1	9.0	1199.8	0.011	1.8025	**1.94**	0.1522	1.6946	**0.466**
outlet	0.66	0.75	1.23	1	5.4	1199.8	0.011	1.8025	**1.16**	0.1522	1.6946	**0.196**
Average									**1.55**			**0.331**

The reduction in efficiency per year for concentration of sediment particle 0.659 kg/m3 for Kaligandaki A hydropower plant corresponding the predicted erosion rate 1.55 mm/yr is 0.331%. The leakage loss in Francis turbine is considered as 50% of the erosion loss hence the total reduction in efficiency per year is 0.497%.

4.2.4.2 Total Loss

The total loss in cost is the sum of loss in energy per year due to erosion and leakage, loss in generation during maintenance and repair and maintenance or replacement cost calculated as in Table 4.24.

Table 4.24 Calculation of Total Loss for Kaligandaki A HPP

Loss in amount due to reduction in efficiency and Leakage		
Reduction in efficiency due to erosion	%	0.3311
Leakage Loss (Approx. 50 % of loss due to erosion)	%	0.1655
Total Loss in Efficiency per year	%	0.4966
Annual design energy	GWh	842
Loss in energy per year due to erosion and leakage	GWh	4.18166
Tariff per kW	US Cent	7.1519
	US $	0.071519
Loss in amount	US $	299068.31
Loss in generation during maintenance		0
Maintenance is done during dry season so the discharge will be only sufficient to run single turbine, therefore maintenance can be done in alternate turbine.		
Loss in maintenance cost		
Cost for material	US $	51818.18
Incentives to worker and staff	US $	1717.93
Total loss in maintenance	US $	53536.11

Loss in amount due to reduction in efficiency and Leakage	US $	299068.31
Loss in generation during maintenance	US $	0
Loss in maintenance cost	US $	53536.11
Total Loss in Amount	US $	**352604.42**
	INR	**24,329,705**

(1 US $ = INR 69.00)

The total loss in amount obtained is 24.33 M INR per year for the Kaligandaki A HPP for predicted erosion rate 1.55 mm/yr with sediment concentration 0.659 kg/m3 corresponding reduction in efficiency 0.331% per year.

4.2.5 Efficiency Reduction and Total Loss in Trishuli Hydropower Plant

4.2.5.1 Efficiency Reduction

The Table 4.25 shows erosion rate and the loss in efficiency percentage determined from IEC-62364 (2013) erosion model.

Table 4.25 Determination of Erosion rate and loss in efficiency for Trishuli HPP

Runner	Factors					Const		Const		Constant		Reduction in efficiency per year (n%)= a1*(Er)^b1
	C kg/m3	K hardness	K shape	K m	Kf	a	Size (mm)	b	Er (mm /yr)	a1	b1	
Inlet	0.39	0.76	1.28	1	9.0	1199.8	0.022	1.8025	**4.27**	0.1522	1.6946	**1.781**
outlet	0.39	0.76	1.28	1	5.4	1199.8	0.022	1.8025	**2.56**	0.1522	1.6946	**0.749**
Average									**3.42**			**1.265**

The reduction in efficiency per year for concentration of sediment particle 0.395 kg/m3 for Trishuli hydropower plant corresponding the predicted erosion rate 3.42 mm/yr is 1.265%. The leakage loss in Francis turbine is considered as 50% of the erosion loss, hence the total reduction in efficiency is 1.894% per year.

4.2.5.2 Total Loss

The total loss in cost is the sum of loss in energy per year due to erosion and leakage, loss in generation during maintenance and repair and maintenance or replacement cost calculated as in Table 4.26.

Table 4.26 Calculation of Total Loss for Trishuli HPP

Loss in amount due to reduction in efficiency and Leakage		
Reduction in efficiency due to erosion	%	1.2648
Leakage Loss (Approx. 50 % of loss due to erosion)	%	0.6324
Total Loss in Efficiency per year	%	1.8973
Annual design energy	GWh	163.00
Loss in energy per year due to erosion and leakage	GWh	3.0925
Tariff per kW	US Cent	7.15190
	US $	0.071519
Loss in amount	US $	221174.39

Loss in generation during maintenance		0
Maintenance is done during dry season so the discharge will be only sufficient to run single turbine, therefore maintenance can be done in alternate turbine.		
Loss in maintenance cost		
Cost for material	US $	16227.27
Incentives to worker and staff	US $	1204.57
Total loss in maintenance	US $	17431.84

Loss in amount due to reduction in efficiency and Leakage	US $	221174.39
Loss in generation during maintenance	US $	0.00
Loss in maintenance cost	US $	17431.84
Total Loss in Amount	US $	**238606.23**
	INR	**16,463,830**

(1 US $ = INR 69.00)

The total loss in amount obtained is 16.46 M INR per year for the Trishuli HPP for predicted erosion rate 3.42 mm/yr with sediment concentration 0.395 kg/m^3 corresponding reduction in efficiency 1.265% per year.

4.3 REVENUE LOSS

In Nepal from December to May months is declared as dry season months and June to November as wet season months. Dry season months rate is Nepalese rupees 8.4 and wet season rate is Nepalese rupees 4.8. The corresponding dry and wet energy rate is applied to calculate revenue loss. The marketable dry energy is 2.96 GWh and marketable wet energy is 17.58 GWh for study area. Summarized total loss in amount as per reduction in efficiency by abrasive erosion is shown in Table 4.27 is illustrated in Figure 4.14.

Table 4. 27: Summarized total energy reduction in amount as per reduction in efficiency due to abrasive erosion.

SN	Name of HPP	Total reduction in efficiency due to abrasive erosion of turbine (% per year)	Total Loss (M INR)
1	Marsyangdi	0.49	14.2
2	Middle Marsyangdi	1.64	35.5
3	Upper Marsyangdi A	0.10	3.8
4	Trishuli	1.89	16.5
5	Kaligandaki A	0.49	24.3

Total loss in amount has increased with increased in reduction of turbine efficiency due to abrasive erosion in relation with energy loss. Among all five HPP, the Middle Marsyangdi HPP has found higher total loss in amount with 35.5M INR with higher value of energy reduction of 1.64% per year likewise the Upper Marsyangdi A HPP has least value of total reduction on efficiency 0.10mm/yr resulting total loss 3.8 M INR per year.

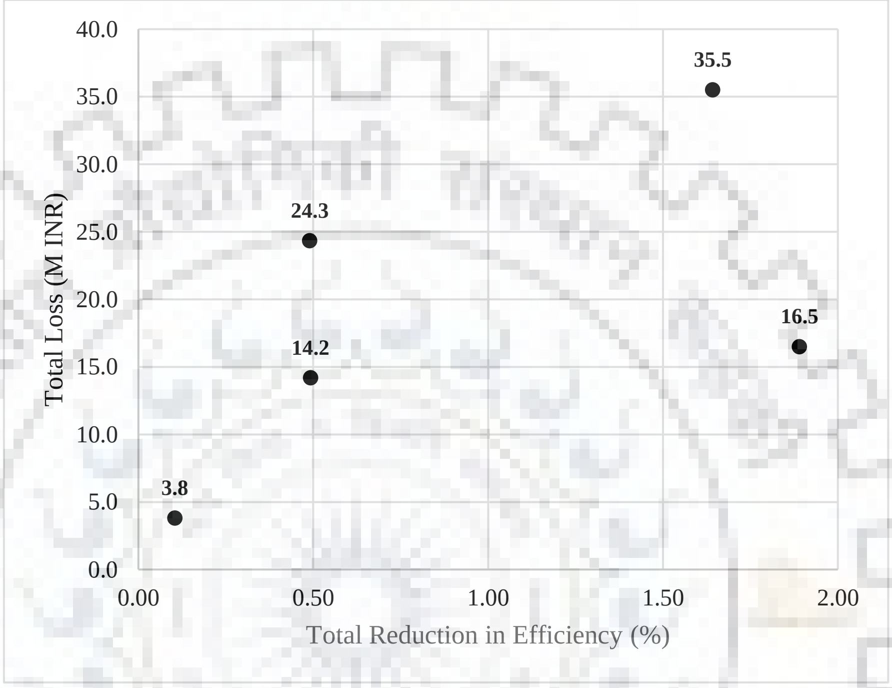

Figure 4.14 Total reduction in efficiency due to abrasive erosion and total loss for HPPs

Energy loss and revenue loss each year due to the reduction of turbine efficiency by abrasive erosion for all five case is listed in table 5.28 and illustrated in Figure 4.15.

Table 4. 28: Energy loss and revenue loss each year by reduction of turbine efficiency by abrasive erosion.

Name of Hydropower plant	**Marsyangdi**	**Middle Marsyangdi**	**Upper Marsyangdi**	**Trishuli**	**Kali Gandaki A**
Total loss in efficiency due to abrasive erosion of turbine (% per year)	0.49	1.64	0.10	1.89	0.49
Marketable dry energy in GWh	2.96	2.96	2.96	2.96	2.96
Marketable dry energy loss in GWh	0.015	0.049	0.003	0.056	0.015
Cost loss in dry season (INR)	**206,506**	**1,725,414**	**11,698**	**923,076**	**352,882**
Marketable wet energy in GWh	17.58	17.58	17.58	17.58	17.58

Marketable wet energy loss in GWh	0.086	0.29	0.02	0.33	0.09
Cost loss in wet season (INR)	**1,226,479**	**10,247,558**	**69,476**	**5,482,323**	**2,095,835**
Total Revenue loss (INR)	**1,432,985**	**11,972,971**	**81,174**	**6,405,399**	**2,448,717**

Total revenue loss each year due to the reduction of turbine efficiency by abrasive erosion of turbine has increased with increased in their total energy loss among all five HPP, the Kaligandaki A HPP has found to be higher revenue loss as in Figure 4.15.

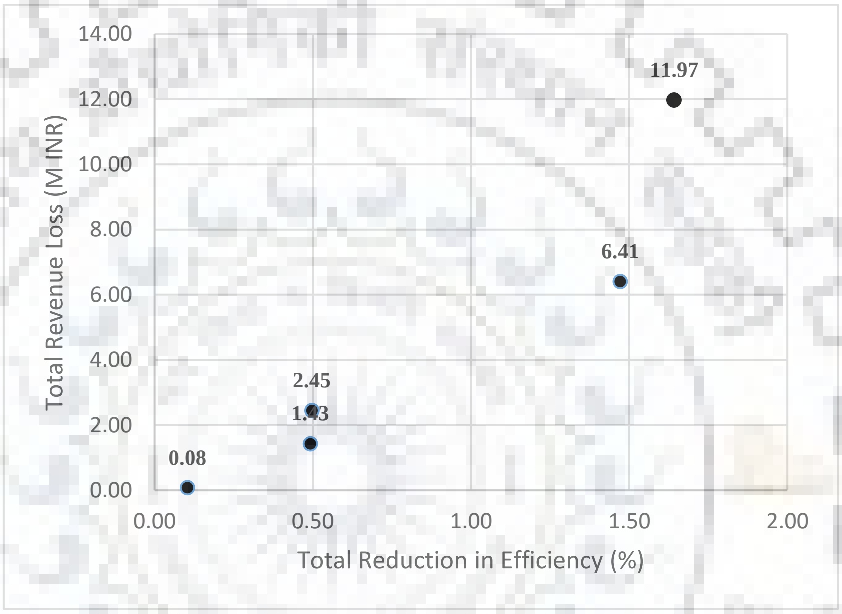

Figure 4.15 Total Reduction in efficiency due to abrasive erosion and total revenue loss for HPPs

4.4 SUMMARIZED FINDINGS

The abrasion erosion rate and corresponding reduction in efficiency of all five cases has been summarized in Table 4.29.

Table 4.29 Summarized findings of abrasion value for HPPs

SN	Name of HPP	Erosion rate (mm/yr)	Reduction in Efficiency (%)
1	Marsyangdi	1.54	0.328
2	Middle Marsyangdi	3.14	1.095
3	Upper Marsyangdi A	0.61	0.069
4	Trishuli	3.42	1.265
5	Kaligandaki A	1.55	0.331

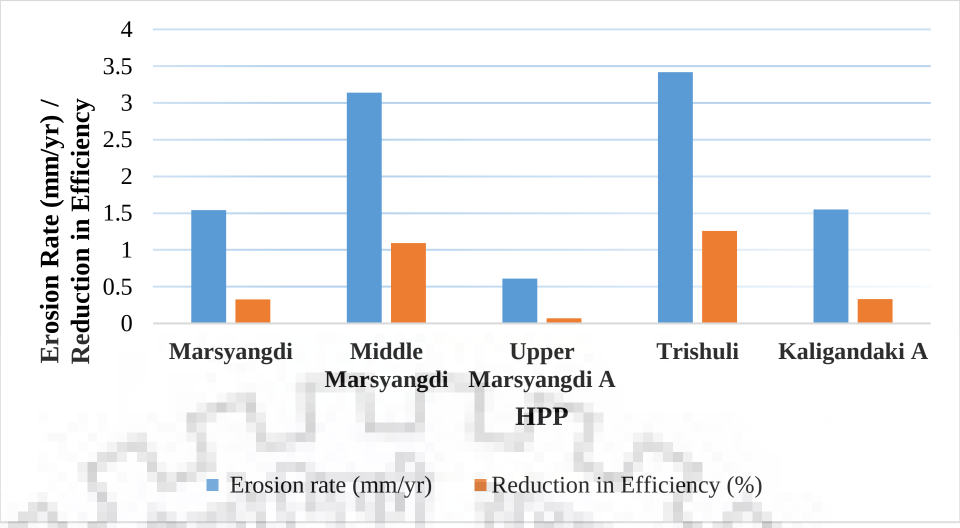

Figure 4.16 Erosion rate and total reduction in efficiency due to abrasive erosion for five HPPs

I. Although three hydropower are in same Marsyangdi river basin, rate of abrasive erosion in Middle Marsyangdi Hydropower Plant is found to be more than Marsyangdi and Upper Marsyangdi ‘A’ Hydropower Plant. This is due to higher particle size of sediment concentration at Middle Marsyangdi HPP. Likewise, remaining two Kaligandaki A HPP and Trishuli HPP have also the higher value of abrasive erosion because of difference in catchment characteristics, concentration of sediment passing through turbine, particle shape, particle size, and mineral content.

II. In all hydropower plants more than 80 % of the sediment load passes through turbine during monsoon season from May to September.

III. Erosion in runner inlet, runner outlet and other turbine parts is not uniform in all five projects.

IV. Among all five HPP, the value of abrasive erosion rate of Trishuli HPP has found highest value and the Upper Marsyangdi A HPP has least value and corresponding percentage reduction in efficiency.

CHAPTER - 5

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSIONS

From the detailed study elaborated in each chapter following conclusions are drawn.

- For all five hydropower plants comprising three river basins, the mineral particles contains the large extent of Quartz as a hard minerals ranging from 44.6% in Upper Marsyangdi HPP to 68.32% in Kaligandaki HPP.
- According to IEC-62364 (2013) the shape of sediment particles in HPP found to be sub angular as their aspect ratio (b/l ratio) lies in between 1 to 2 whereas, the factor K_{Shape} for Upper Marsyangdi HPP is taken as unity. The sub-angular shaped sediment particles are prone to more abrasive erosion.
- The Erosion in runner inlet, runner outlet and other turbine parts is not uniform in all cases.
- From five case studied, the higher abrasion erosion rate has found to be the larger value of corresponding percentage reduction in efficiency and hence the total loss in terms of energy generation. Among five cases, Trishuli HPP is found have highest erosion rate 3.42 mm/yr with higher reduction in efficiency 1.265% per year causing about 16.5M INR losses due to abrasive erosion. Whereas, Upper Marsyangdi A HPP have lower erosion rate 0.61mm/yr with corresponding lower reduction in efficiency 0.069% per year resulting only 3.8 M INR losses due to abrasive erosion.
- The Middle Marsyangdi HPP has found highest amount of revenue loss with 11.97 M INR associated with energy generation among the five hydropower projects while the least value of total loss in revenue only 0.08M INR is found in Upper Marsyangdi HPP.
- Decreased erosion rate, reduces direct cost related to turbine erosion and revenue loss on account of reduced turbine efficiency. While saving in operation and maintenance cost of turbines and accessories along with revenue loss, proper management of mitigation measures are to be ensured by designing proper sediment removal structures, and optimizing plant operation.

5.2 RECOMMENDATIONS

Based on the study following is recommended for future works:

1. Data should obtained from real time sediment monitoring units.

2. For better design, CFD for turbine erosion should be carried out for different range of discharge and sediment inflow concentration and for its components.
3. Different researchers have developed empirical relations to estimate the hydro abrasive erosion in hydraulic turbines but their reliability is limited and thus requires more work to be carried out.
4. Operation optimization to reduce sediment abrasion can only be achieved by the combined research of engineers, scientists, researcher of academic institutes, consultants and operators of hydropower.

REFERENCES

1. Abgottspon A., Staubli T., Felix D., Albayrak I., Boes R.M., "Hydro-Abrasive Erosion of Pelton Buckets and Suspended Sediment Monitoring", Proceeding Hydro Vision International, USA 2013.

2. Athar, M., Jamil M., and Ghazala, G., "A New Relationship for Sediment Removal Efficiency of Vortex Chamber Type Sediment Extractor," in ISH Journal of Hydraulic Engineering, vol. 11, pp. 111-131, 2012.

3. Bajracharya, T. R., Acharya, B., Joshi, C. B., Saini, R. P. and Dahlhaug, O. G., "Sand Erosion of Pelton Turbine Nozzles and Buckets: A Case Study of Chilime Hydropower Plant," in Wear, vol. 84, pp. 264 -177, 2008.

4. Bastola, A. K & Neopane, H. P., "Mineral Analysis and Erosion Potential of Sediment Samples from Nepalese Hydro Power Plant," in Journal of Machinery Manufacturing and Automation, vol. 3, pp. 50-55, 2014,

5. Bishwakarma, M. B., Støle, H., "Real-Time Sediment Monitoring in Hydropower Plants," J. Hydraul. Res., 46 (2), pp. 282-288, 2008. 10.1080/00221686.2008.9521862

6. Boes, R. M., "Real-Time Monitoring of SSC and PSD in the Headwater way of a High-Head Hydropower Plant," in: Proceeding 33rd IAHR Congress, Vancouver, Canada, pp. 4037–4044, 2009.

7. Brekke, H., "Design of Hydraulic Machinery Working in Sand Laden Water in Abrasive Erosion and Corrosion of Hydraulic Machinery," Imperial College Press, ed C G Duan and V Y Karelin London, pp 155-181, 2002.

8. Chaudhary, C. S., "Impact of high sediment on hydraulic equipment of Marsyangdi Hydropower plant", in Proc. Int. seminar on sediment handling technique, Kathmandu. Pp 16-19, 1999.

9. Chhetry, B. and Rana, K., "Effect of Sand Erosion on Turbine Components: A Case Study of Kali Gandaki "A" Hydroelectric Project (144 MW), Nepal; HYDRO NEPAL, Issue No. 17, pp 24-33, 2015.

10. DoED, “Monthly Progress Report, October. Department of Electricity Development, Nepal”, (http://doed.gov.np/monthly/progress-reports) accessed on 5th November, 2018, 3:15 PM.

11. Felix, D., Albayrak, I., Abgottspon, A., Boes, R., and Gruber, P., “Suspended Sediment and Pelton Turbine Wear Monitoring: Experimental Investigation of various Optical and Acoustic Devices and Beginning of the Case Study at HPP Fieschertal,” in Proceeding, 17th Intl. Seminar on Hydropower Plants (Vienna-hydro), ISBN 978-3-9501937-8-7. Vienna, Austria, pp. 483-494, 2012.

12. Felix, D., Albayrak, I. and Boes, R. M., “Laboratory Investigation on Measuring Suspended Sediment by Portable Laser Diffractometer (LISST) focusing on Particle Shape,” Geo-Mar Lett, Vol -33, pp. 485 – 498, 2013. DOI: 10.1007/s00367-013-0343-1

13. Felix, D., Albayrak, I., Abgottspon, A. and Boes, R. M., “Hydro-Abrasive Erosion of Hydraulic Turbines caused by Sediment” in Proceeding 28th IAHR Symposium on Hydraulic Machinery and Systems, Grenoble, France, IOP Conf. Series, 2016.

14. Felix, D., “Experimental Investigation on Suspended Sediment, Hydro-Abrasive Erosion and Efficiency Reductions of coated Pelton Turbines”, PHD Dissertation, Eth, Zurich, 2017. https://doi.org/10.3929/ethz-b-000161430

15. Galay, V. J., Schreier, H. and Bestbier R., "Himalayan Sediments Issue and Guidelines," Water and Energy Commission Secretariat, Nepal, 47, 2000.

16. IEC 6236: 2013, "Hydraulic machines – Guide for dealing with hydro-abrasive erosion in Kaplan, Francis, and Pelton turbines," The International Electrotechnical Commission, Switzerland.

17. Jha, B., "Report on Sediment Monitoring Activities at Upper Marsyangdi 'A' Hydropower Plant," Annual Report, Nepal electricity Authority, Nepal. Pp 55, 2017.

18. Kayastha, G.P. “Silting problems in hydro power plants in Nepal,” in Proceeding 1st International Conference on Silting Problems in Hydropower Plants, New Delhi, pp 23-30, 1999.

19. Li, D., Li, Y., Wang, Z., Wang, X. and Li, Y., 2016, “Quantitative, SEM-based Shape Analysis of Sediment Particles in the Yellow River,” International Journal of Sediment Research- 31, Pp. 341–350, 2016. DOI: 10.1016/j.ijsrc.2016.05.006

20. Liu, J., Lu, L., and Zhu, L. “Experiment study on sediment erosion of Pelton Turbine Flow Passage Component Material”. In IOP Conference Series: Earth and Environmental Science, 15:32055. Beijing, China: IOP Publishing, 2012.

21. Mann, B. S., “High-Energy Particle Impact Wear Resistance of Hard Coating and their Application in Hydro Turbines,” Wear, Vol- 237, pp. 140-146, 2000.

22. Mosonyi, E., "Water Power Development High- Head Power Plants," Nem Chand and Bros, Roorkee, India, 2009.

23. Neopane, H.P., Dahlhaug, O. G., and Thapa, B., “An Investigation of the Effect of Particle Shape and Size in Hydraulic Turbines in Waterpower,” International Conference, XVI 09, USA. 2009.

24. Neopane, H. P., “Sediment Erosion in Hydro Turbines”, PhD [dissertation] Norwegian University of Science and Technology, 2010. Retrieve from http://ntnu.diva-portal.org/smash/get/diva 2:326677.

25. Neopane, H. P., Dahlhaug, O. G., and Eltvik, M., “Numerical Prediction of Particle Shape factor effect on Sediment Erosion in Francis Turbine blades in Hydropower”, the 6th International Conference on Hydropower, Tromso, Norway, Vol-10, 2010.

26. Neopane, H. P., and Sujakhu, S., “Particle Size Distribution and Mineral Analysis of Sediments in Nepalese hydropower plant: A Case Study of Jhimruk Hydropower Plant”, in Kathmandu University Journal of Science and Technology, Vol. 9 (1), pp 29-36, 2013.

27. NEA, Nepal, "Annual Report on Sediment Monitoring Activities at Marsyangdi Hydropower Station," Nepal Electricity Authority, pp. 57, 2017.

(http://nea.org.np/publications/ annual/monthly reports); accessed on 12 May, 2019, 3:00 pm.

28. NEA, Nepal, “Annual Report,” Nepal Electricity Authority, August, 2018.

29. Padhy, M. K., and Saini R. P., "A Review on Silt Erosion in Hydro Turbines," in Proceedings Renewable and Sustainable Energy Reviews, Vol. 12, pp. 1974–1987, 2008.

30. Padhy, M. K., and Saini, R. P., “Effects of Size and Concentration of Silt Particles on Erosion of Pelton Turbine Buckets”, Energy, Vol. 34-10, pp. 1477-1483, 2009.

31. Padhy M.K., Saini R.P., “Study of Silt Erosion on Performance of a Pelton Turbine”, Energy; 36(1):141-7, 2011.

32. Padhy M.K., SainiR.P., “Study of Silt Erosion Mechanism in Pelton Turbine Buckets”, Energy 2012;39: 286-293, 2012.

33. Pandit, H. P., Shakya, N. M., Stole H. and. Garg, N. K., "Sediment Exclusion in Himalayan Rivers Using Hydrocyclone," ISH Journal of Hydraulic Engineering, vol. 14:2, pp. 118-133, 2008. No. 10.1080/09715010.2008.10514909,.

34. Perrig, A., and Farhat, P. F. A. D. M., “Hydrodynamics of the Free Surface Flow in Pelton Turbine Buckets“, PhD Thesis, A La Faculte Des Sciences et Techniques de lingenieur, Docteur Es93715, 242, 2007. https:// doi.org/10.5075/epfl-thesis-3715.

35. Rai, A. K., and Kumar, A., “Continuous Measurement of Suspended Sediment Concentration: Technological Advancement and Future Outlook,” Measurement,Vol 76, pp. 209-227, 2015. https://doi.org/10.1016/j.measurement.2015.08.013.

36. Rai, A. K. and Kumar, A., “Analysing Hydro Abrasive Erosion in Kaplan Turbine: A Case Study from India,” Journal of Hydrodynamics, Vol-28(5): pp. 863-872, 2016. DOI: 10.1016/S1001-6058(16)60687-X

37. Rai, A. K., Kumar, A., Hies, T. and Nguyen, H. H., “Field Application of a Multi-Frequency Acoustic Instrument to Monitor Sediment for Silt Erosion Study in Pelton Turbine in Himalayan Region, India,” IOP Conference Series: Earth and Environmental Science, Vol 49, 2016. 122004 doi:10.1088/1755-1315/49/12/122004

38. Rai, A. K., and Kumar, A., “Sediment Monitoring for Hydro Abrasive Erosion: A Field Study from Himalayas, India,” International Journal of Fluid Machinery and Systems, Vol-10(2):146-153, 2017. DOI: 10.5293/IJFMS.2017.10.2.146- ISSN 1882-9554.

39. Rai, A.K., Kumar, A. and Staubli, T., “Financial Analysis for Optimization of Hydropower Plants regarding Hydro Abrasive Erosion: A study from Indian Himalayas,” 29th IAHR Symposium on Hydraulic Machinery and Systems. Kyoto, Japan, September 16-21, 2018. Paper No.- IAHR2018-152.

40. Rajkarnikar, B., Neopane, H.P., Thapa, B.S.,”Comparative study of sediment erosion on alternative designs of Francis runner blade”,International Journal of Fluid Machenary and System. Vol-8(3), 2015. DOI: 10.5293/IJFMS.2015.8.3.183

41. Ravisankar R., Senthikumar G., Kiruba S., Chandrasekaran A. and Jebakumar P.P., “Mineral Analysis of Coastal Sediment Samples of Tuna, Gujarat, India,” Indian Journal of Science and Technology Vol. 3, pp. 7, 2010.

42. Rygg, J.R., “CFD Analysis of a Pelton Turbine in Open FOAM”, MS Thesis, Trondheim, Norwegian University of Science and Technology, Faculty of Engineering Science and Technology, Department of Energy and Process Engineering, 2013.

43. Sangal, S., Singhal, M.K., and Saini, R.P., “Hydro Abrasive Erosion in Hydro Turbines: A Review,” International Journal of Green Energy, 2018. Https: //doi.org/10.1080/15435075. 2018.1431546

44. Sharma, S. K., "Sediment Management in Himalayan Rivers," Hydro Vision, copy right HCl Publication, ISBN-0444-89235-4, pp 1-12, 2006. www.hcipub.com

45. Stachowiak, G. W., and Batchelor, A.W., “Engineering Tribology,” Elsevier, ISBN-0444-89235-4, pp 960, 1993.

46. Thakur, R., Khurana, S., Kumar, A., and Khurana, S., "Experimental Examined of Effect of Silt Erosion on Overall Performance of Pelton Buckets," in Engineering Science and Technology: An International Journal, vol. 7, no. 3, pp. 47-53, 2017.

47. Thapa, B., Shrestha, R., Dhakal, P. and Thapa, B.S.,“Sediments in Nepalese hydropower projects, in Proceeding of International conference on the great Himalayas: Climate, Health, Ecology, Management, and Conservation,” Kathmandu, Nepal, January, pp. 12-15, 2003.

48. Thapa, B., “Sand Erosion in Hydraulic Machinery,” Ph.D. Thesis 1-226, Norwegian University of Science and Technology (NTNU), 2004. https:// doi.org/0.

49. Thapa, B., and Brekke H., “Effect of Sand Particle Size and Surface Curvature in Erosion of Hydraulic Machinery and Systems”, IAHR Symposium on Hydraulic Machinery and Systems, Stockholm, 2004.

50. Thapa, B., Shrestha, R., Dhakal, P. and Thapa, B.S., “Problems of Nepalese Hydropower Projects due to Suspended Sediments, Aquatic Ecosystem Health and Management,” Vol-8:3, pp. 251-257, 2005. DOI: 10.1080/14634980500218241.

51. Thapa, B.S., Thapa, B., and Dahlhaung O.G., “Current Research in Hydraulic Turbines for Handling Sediments,” Energy 47 pp 62-69, 2012.

52. Tsuguo, N. “Estimation of repair cycle of turbine due to abrasion caused by suspended sand and determination of desilting basin capacity.” In Proceedings of International Seminar on Sediment Handling Technique, NHA, Kathmandu, 1999.

ANNEXURE

Annex A Questionnaire for Data Collection

PROJECT WISE DATA	
A. Project Details	
Name of Respondent	
Name of River	
Name of Scheme	
Installed capacity	
Design head	
Design discharge	
Plant load factor	
Annual generation-Design	
- Actual	
Water conductor system	(From intake to tail race, Layout if possible)
Intake type	
Silt excluder type	
Longitudinal Slope of river	
Type of valves	
Type of gates	
Type of turbine &No. of Units	

B. SEDIMENT RELATED	
Peak season	
Major history	
Shut down time	With Reason(Sediment/Maintenance/or any other)

Generation loss	
Measurement (yes/no)	(With technique used, Method of sample collection, instrument used and depth chosen,method of parameter determination)
Frequency	
Location	
Incoming sediment	
Sediment concentration	
Sediment size	
Shape	
Mineral content	
Hardness	
Effuelent sediment from desilting tank	
Sediment concentration	
Sediment size	
Shape	
Mineral content	
Hardness	

C. SEDIMENT PORBLEMS TO HYDROMECHANICAL EQUIPMENTs	
Turbine	(frequency of repair and timing, site of repair - any other factors, inventory for maintenance - spare runner etc., method of measurement of thickness loss,template,)
	(method of repair - welding etc., lost quantity of material - how to find)
Runner	
Guide Vane	

Gates	
Valves	
Penstock	
Draft Tube	
Nozzle	
Seat rings	
Cooling Systems	

D. MAINTENANCE COST AND FREQUENCY	
Hydro Mechanical component	(Maintenance, Repair& Replacement cost, corrective measures and remedial steps taken & cost involved)
Civil Works	