Journal of Multi Disciplinary Engineering Technologies
Volume 18, Issue 01

Progressive Effect of Silt Erosion on Hydro Turbines- A Comprehensive Review

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Abstract

A hydro turbine is an essential component of the hydroelectricity system used to convert the the falling water's kinetic energy into mechanical energy. These turbines are highly sensitive to silt erosion, a process that involves the wearing out of solid structures of turbines by silt particles counteracting with fluids such as water. The erosion and abrasive wear cause a reduction in the turbine efficiency and its ability to maintain efficient operation and maintenance in the long run that gives rise to economical losses. This review examines the mechanisms of silt erosion, its impact on turbine performance, and strategies for mitigation. Parameters related to silt erosion which are the causes of efficiency loss have also been discussed. Recent studies highlight the importance of understanding sediment characteristics, erosion rates, and advanced materials in enhancing turbine resilience.

Keywords: Silt Erosion, Hydro Turbines, Renewable Energy

1 Introduction

Hydropower remains a prominent renewable energy source, accounting for approximately 16% of global electricity generation [1]. With an increasing focus on sustainable energy solutions, the integrity of hydro turbines is under scrutiny, particularly regarding their vulnerability to silt erosion. Silt erosion occurs when suspended particles in water flow which mainly cause the wear and tear on the turbine components, ultimately leading to decreased efficiency and increased maintenance costs [2]. In this paper the authors have considered the study of Himalayan region and the problem of erosion in the hydro turbine component through sand-laden river water. The erosion problem generally exists for all types of turbines. The influence of heavy rain during monsoon period cause

Published on: November, 2024

land erosion and landslide. This cause huge sediment in river due to fragile geographical composition of the Himalayan range. Sediment is also a result of rock break up that happens through the processes of chemical and mechanical weathering. As estimated by [3], about 20 billion tonnes of earth material is eroded by rivers and streams and transported to the sea at present and about 1.5 to 6 billion tonne of it comes from the Indian subcontinent. This is a worrying trend for most small hydropower plants as majority of them are run-of-river type sited in steep hilly regions. The amounts of sediments in water during rainy season is quite high, up to 20000 ppm and eradicating all sediments before it passes through turbine is quite hard. The sediment mainly comprised of Quartz (70–98%), which is abrasive with Moh's scale of 7, and feldspar with Moh's scale of 6 that extensively deteriorates the wearing parts of the machines. In impulse turbines, high wear and tear is observed on nozzle, bucket, and seal ring while in reaction turbines faceplate, guide vane, runner blade, and seal rings are worst for wear. Erosion wear in hydraulic machines changes the shape of the blades; the vibration of these machines increases; fatigue is caused; efficiency decreases, and system failure is likely to occur [4]. Hydropower stations are classified into three categories based on the extent of damage: Intensive – annual, substantial – every three years, moderate – costs of special efforts and resources every 15-20 years [5].

2 Sediment

Intense rainfall during monsoon session causes land erosion and landslides and results into sedimentation of rivers here mainly because of the geotechnical structure of the Himalayan stretch. Sediment is built as a result of disintegration of rocks where processes of chemical and mechanical weathering take place. River sediments are formed of three classes of sediments, mainly clay, silt and sand, gravel with a specific gravity of 2.6. These sediments, as stated earlier, typically have particle size distribution that is determined using sieve analysis and the Visual Accumulation Tube (VAT) method [6]. According to their transport behaviour in river hydraulics, sediment particles are categorised as either the bed load or suspended load particles. Small fragments that they drag along the riverbed by sliding, rolling or jumping are known as the bed load which however has a much higher speed than the flowing water. Suspended load on the other hand refers to broken fragments of rocks and all matter that is in the water but is transported at almost the same velocity as the water. A portion of the suspended load is deposited in settling basins or reservoirs while the rest flows through turbines: this results into wearing off of turbines [6]. Depending on the river involved, river sediments involve a particle size distribution illustrated below in table 1.

Table 1 Different particle size sediment [6]

Particle Type	**Size (mm)**
'Clay'	Less than 0.002
'Silt'	0.002 - 0.06
'Sand'	0.06 - 2
'Gravel'	2 - 60
'Cobbles'	60 - 250
'Boulders'	More than 250

In the Himalayan region, the sediment multiplied due to:

- The young geology – immature, soft and loose,(Himalayas are World's youngest mountain — just 15 million years)
- Glacial Silt in the snowmelt season
- Tropical climate- long and hot summer changes to very heavy monsoon.
- Landslides.
- Climatological disturbances – droughts and then floods.
- Heavy grazing pressure.

- Faulty methods used for cultivation.
- Uncontrolled felling of trees.

2.1 Factors for Sediment Erosion

Sediment erosion results from the relative motion of sediment particles that are being transported by water together with the hydraulic components on which they impinge. The area of erosion reduction depends on the properties of the erodible material, the transport medium, and the substrate type [7]. These factors are categorized into three distinct groups:

- **Operating conditions:** Velocity, acceleration, impingement angle, sediment concentration
- **Flowing medium and eroding particles:** Type of particles, size, shape, hardness, and their composition.
- **Target:**Chemical composition, elasticity, hardness, surface topography.

2.2 Sediment's Properties

Particles' characteristics are vital to determine with regard to sediment erosion, whereas insufficient information about the sediment's amount and properties defines the capability of scientific investigations of the detrimental effects of sedimentation [8]. Literature reveals that harder particles cause more wear than softer particles [9]. Also, particle angularity has been distinguished as the parameter influencing the increase of erosive wear rate [10]. Each of the above parameters is also introduced into numerical models of erosive wear to make the prediction of the damage more accurate [8]. Particulate properties can stay inherent or become altered according to operation parameters. Knowledge of these characteristics is crucial for assessing, minimising, and avoiding erosion. The impacts of key particle characteristics are presented and discussed in the sections below.

2.2.1 Particle Size

Particle size can be characterized primarily in two dimensions: mass and length. At a given velocity, one could measure the kinetic energy of a particle and since mass is proportional to the $diameter^3$. Hence,
$Erosionrate \propto Diameter^3$
Mainly, those of sizes beyond 0.2 to 0.25 mm are mainly dangerous to human health. It has been established that sediment particles as large as the fine sand which has Moh hardness of less than 5, can occasion considerable wear [7]. The distribution of particle size is often studied using the sieving technique and the Visual Accumulation Tube (VAT) [11]. If the particle size is small, then it's called cutting or abrasive wear and if the size of the particle is large and gives rise to material deformation through elastic deformation and fatigue. Table 2 shows the acceptable particle sizes for various types of turbines used in this present study.

Table 2 Allowable silt size for various turbines [12]

Turbine	Allowable Maximum Silt Size(mm)
Pelton turbine	0.15-0.20
Francis turbine	0.20-0.25
Kaplan turbine	0.2-0.5

2.2.2 Particle Shape

Particle shape is known to be decisive in erosion rates; however, few research papers address particle-shape dependency of erosion. Apart from the erosion rates, the particle shape influences considerably the shear strength, density, permeability, compressibility, and sediment transport capacity. Particle shapes are generally defined as round, angular, or semi-round on the basis of participants' perceptions. Chert and other particles with architectural irregularities or sharp edges are more truthful and will consequently raise the erosion rate, while rounded or blunt-edged manufactured rubble encompasses more gloss and brings down the erosion rate.

2.2.3 Particle Hardness

The degree of erosion that occurs is dependent on the hardness of the particles present in the flowing liquid. Where offenders are harder than the substrate, severe erosion takes place. However, if the particle is softer, erosion can only occur where the substrate has relatively low fracture energy [13]. That is why the ratio of the hardness of the particle to that of the substrate plays an essential role in controlling the erosion rate. In particular, 75% of the sediment obtained from the Himalayan region is quartz, which has a hardness value of 7 on Moh's scale. This high hardness tends to aggravate erosion in these areas.

2.2.4 Concentration

Flux may be defined as the number of particles loitering per volume or as the number of particles hitting a surface per time and area on planar geometry. This parameter has considerable influence on the rates of the erosive wear. The local erosion rate is seen to increase proportionally with increasing flux rate up to a certain value of flux rate; beyond this threshold value, contradictory phenomenon of particle particle interaction which includes phenomena like bouncing and impact of newly arriving particle leads to erosion rate reduction. His focus can also be defined as the ratio expressed in percentages of the number of particles per given mass or volume of the fluid. Concerning river sedimentation, it has the units of grams per litre (g/L), but it often used in parts per million (ppm) by weight. That is why for the practical use, it is quantified as one kilogram per cubic meter of water or 0.1

2.2.5 Speed of Erosive Particle

The erosion of material occurs due to plastic deformation and cutting action and ratio of these damages depends upon impingement angle and velocity of particle. Up to a certain velocity which is called Critical or Threshold velocity, the particle cannot skid in the surface due to friction and cutting action does not take place [13]. As the velocity increases higher than the critical velocity, both types of damages occur, which increases the erosion rate drastically. Most often used expression for relation between the erosion rate and velocity is
$Erosion \propto Velocity^n$
Where value of n depends upon the material and other operating condition [8].

2.2.6 Impingement Angle

It is defined as the angle between the eroded surface and the trajectory of particles just before the impact. Ductile material has severe erosion in low impingement angle. The maximum erosion is shown at $10^o - 30^o$. For the brittle material the erosion rate increases as the angle of impingement increases and is highest at normal impingement. The erosion can be termed as 'ductile mode of erosion' when it is maximum at low angle and 'Brittle mode of erosion' when erosion is maximum at higher impingement angle [14]. Maximum erosion rate for brittle material is higher than that for ductile material.

3 Mechanism of erosion in Hydro Turbines

Hydro turbines have the following difficulties; runner blade damage through silt erosion, runner and draft tube wear and corrosion through cavitation, hydro turbine instability at partial gate opening,

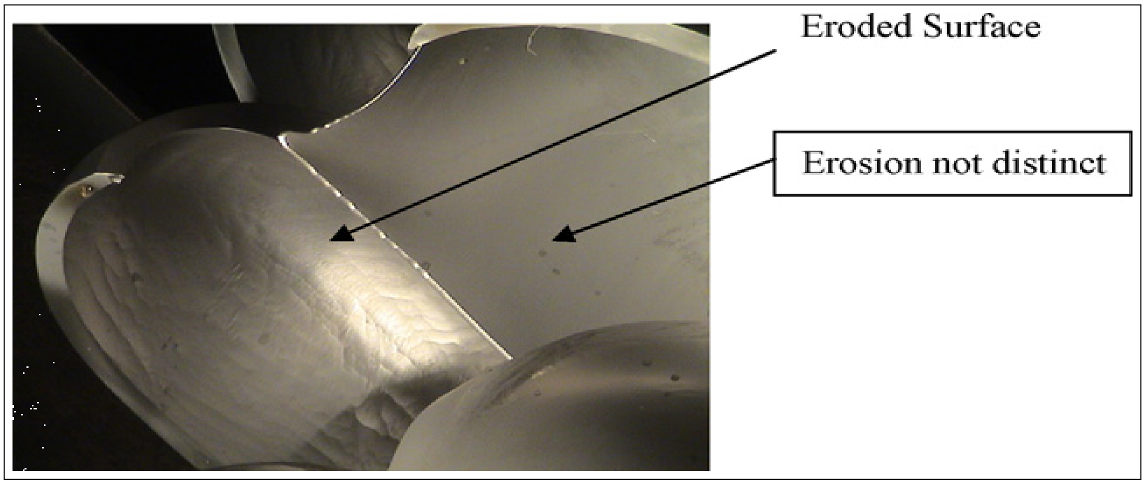

Fig. 1 Eroded blade [15]

Fig. 2 Hydro-abrasive particle damage on the trailing edge of a Francis turbine [11]

guide bearing failures, and water leakage through guide vane seals, turbine guide bearings, and gland seals. Sand erosion is most effectual on the Pelton turbines of high head and the medium head Francis turbines. These two low head Kaplan and propeller turbines are not immune to erosion in their river operating environment loaded with sediments. In impulse turbines, critical part such as buckets, nozzles and spear valves are highly liable to be damaged as shown in Figure 1. Likewise, reaction turbines are susceptible to erosion on the following parts including guide vanes, faceplates of the rotor, runner blades as shown in Figure 2 and seal rings.

Components operating in comparatively low velocity fields include inlet valves, spiral casings, draught tubes and wheel pits which also get eroded due to sand transport of water. In most cases, scouring in small units is more intensive than in large units despite similar head and water velocity in the turbines. This is due to a smaller radius of curvature and hydraulic radius that prevailed in small units making more particles to be set in contact with the surface and undergo higher acceleration.

The shape of the erodent particles can have a big influence on erosion and the method shows that it is hard to accurately predict quantitatively for natural particles due to their random nature. Figure 3 categorises the kinds of erosion detected in turbines; this shows that many forms of erosion exist in such turbines and that the overall conditions that foster erosion are diverse.

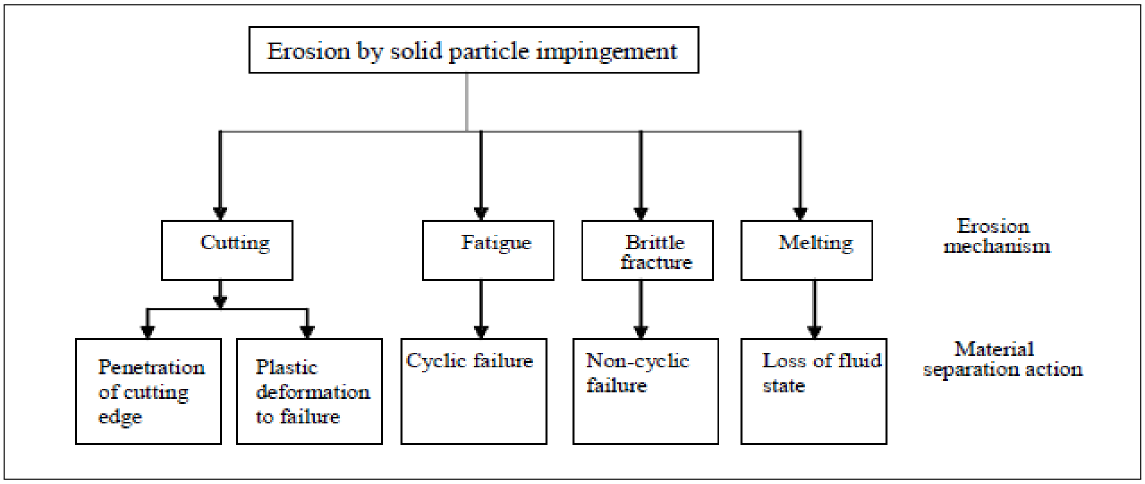

Fig. 3 Classification of Erosion in turbines[16]

Problems in power station 'operation and maintenance' due to silt are as stated below[17]:

- Frequent clogging of strainers.
- Blockage and perforation of cooler tubes.
- Damage to cooling water pumps and valves.
- Recurring failure of turbine shaft seals.
- Malfunctioning of drainage and dewatering systems, along with sump siltation.
- Increased leakage through runner labyrinths, causing elevated top pressure.
- Wear and tear of guide vane bushes and their cup seals.
- Failure of seals in intake and main inlet valves.
- Sealing issues in hydro-mechanical gates, including intake and draft tube gates.

Material degradation mechanisms encompass a wide range of processes, but they can generally be categorized into three fundamental types: Mechanical and Chemical treatment, heat treatment and cold treatment. These are the causes of material separation in the form of debris during erosion even though the routes to get to them are different. Solid particle erosion is governed by four primary mechanisms: we take erosion, cutting, fatigue, brittle fracture, and melting as the major types of wear that take place during the operation of a machine. Cutting actions can further be divided into two forms: cutting by the use of a sharp tool and cutting through deformation resulting in failure. The organisational structure of these processes is shown in figure 3.

The authors in [16] identify seven potential mechanisms for solid particle erosion: Abrasive erosion, surface fatigue, brittle fracture, ductile deformation, surface melting, macroscopic, and atomic erosion. Nonetheless, out of all these, it is only the first four mechanisms, namely abrasion-erosion, fatigue, deformation-plasticity, and brittle fracture, that are of importance within the hydraulic machinery since they are the ones that show the extent of material wear within these applications.

3.1 Abrasive Wear

The kind of wear examined in hydraulic machinery parts results from the abrasion in effect from the perpetual impact of solid particles with the surface. Ideally upon impact the kinetic energy of particulate matter is converted to the work that actually deforms the material of the machines. The residual strains resulting in the present of a rough trace, similar to tearing of a layer separate from the metal mass, depends on the action pattern, crystalline structure and heterogeneity of the metal.

Even if only elastic deformation is produced in single particle/surface impacts, repeated parallel particle interactions give rise to surface failure by fatigue mechanisms. Micro – cut's come about out of many more impacts and interaction of the abrasive particle on to the metal surface. This hydraulic abrasion mechanism shows that material loss in hydraulic components is proportional to the kinetic energy of the particles that cause the erosion, and the number of abrasive particles in the flow carrying medium.

Abrasive wear by grits or hard asperities is similar to cutting with a series of cutting tools or with a file. Particles or grits reduce material through micro-cutting, micro-fracture, grain pullout or by causing fatigue from successive deformations as presented in figure 4.

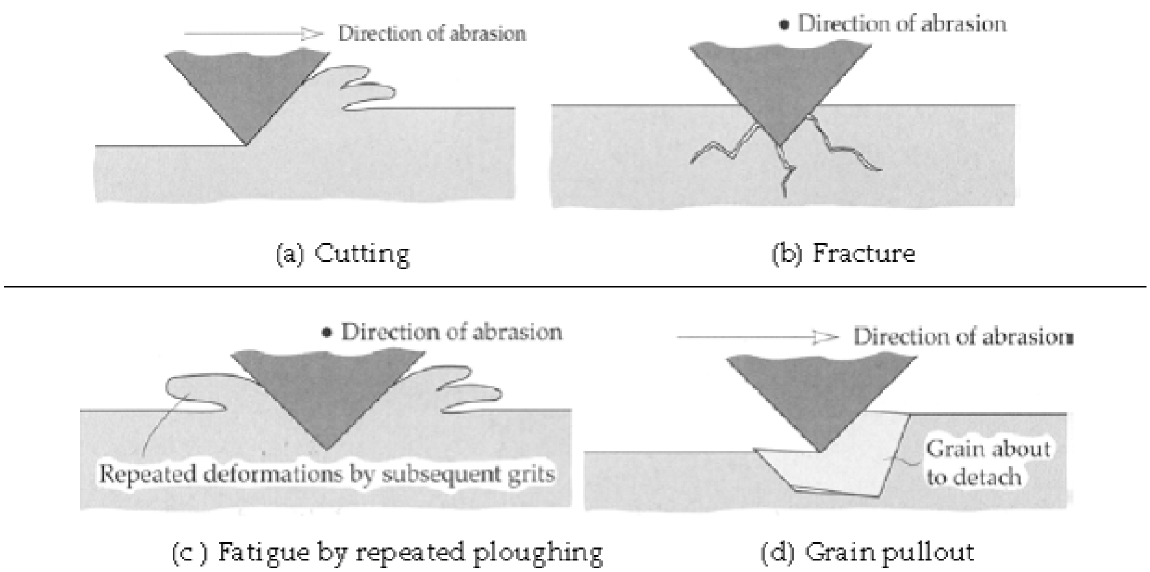

Fig. 4 Abrasion wear [16]

3.2 Erosive Wear

Abrasion can be described as several variants of wear processes that depends on particle material, particle impact angle, impact velocity and particle size. In the case where the particles are hard and the solid, the wear process may seem somewhat like the abrasive wear. However, in the case where liquid particles are the erodents then abrasion does not take place; the wear arises from cyclic stress due to impact.

As used herein, the term "erosive wear" generally means various modes when relatively small particles come into contact with mechanical parts. They are pragmatically defined and not tied to a conceptual understanding of the wear processes involved. As previously described, the main types of erosive wear and their severities are illustrated in the figures 5 and 6 to demonstrate the many ways that an erosion surface can manifest itself in mechanically rubbed surfaces.

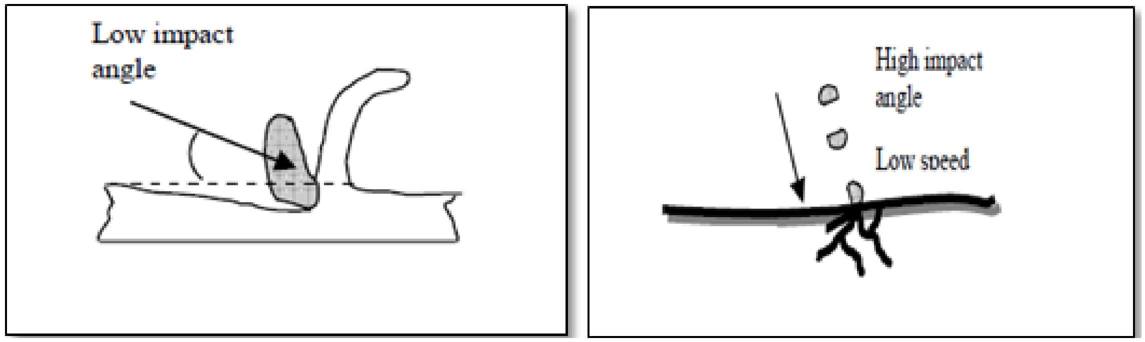

Fig. 5 Cutting erosion and Surface fatigue [16]

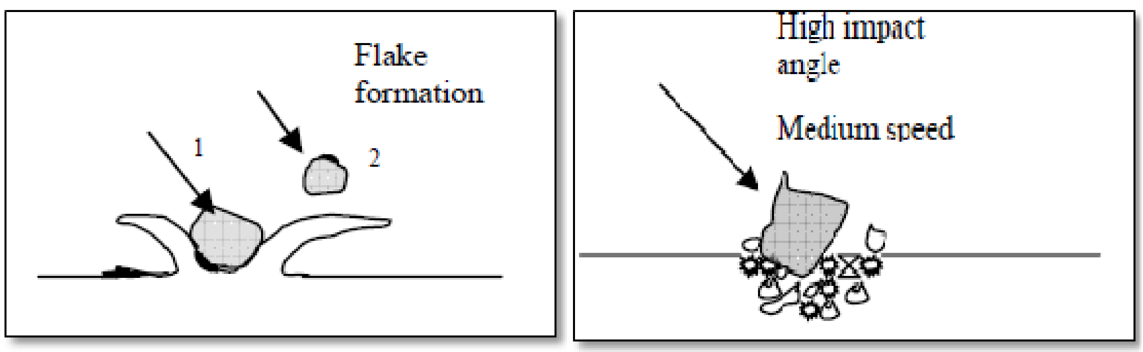

Fig. 6 Plastic deformation and Brittle fracture [16]

- **Cutting erosion** According to Figure 5, the material removal when particles impacts on the surface at low angle, termed as impingement angle, happen through a cutting edge kind which is called as abrasive erosion. Abrasive particles move away in rolling or sliding motion as in various impacts of abrasion or cutting takes places. They are characterised by short track-length scars on the surface in which material is removed by scouring or scraping due to the sharp edges of the particles.
- **Surface fatigue** Surface fatigue erosion is illustrated in Figure 5 where particles penetrate and impact a surface at a high angle of incidence but at relatively low velocity. It is similar to wear due to the surface fatigue on rolling surfaces of components and developed substrates. In this case, the surface does not yield as it undergoes plastic deformation; rather it decays with periodical fatigue actions. After impacts, cracks appear and then steadily the material particles of the surface start falling after several strikes.
- **Plastic deformation** It is observed from Figure 6, when particles collide with an elastic surface at medium speed and large impact angle the material undergoes plastic deformation on the surface and forms a flake around the impacted point. These flakes with repeated impacts spall off as the material de-laminates as debris.
- **Brittle fracture** The brittle fracture erosion is the next type of erosion, which is characterised by striking a brittle surface with large impact angles and at a medium velocity as indicated in Figure 6. It also indicates that if the particles are sharp, brittle fragmentation is probable; thereby loosening of material by subsurface cracking is likely to occur.

3.3 Methods for encountering Silting Problem

A three-dimensional approach is recommended to address silting issues in hydro power plants, which includes the following strategies:

- Treating the catchment area to reduce the silt load.
- Implementing effective desilting mechanisms to prevent silt entry.
- Utilizing silt-resistant equipment to endure the abrasive effects of silt.

Catchment area treatment methods, while effective in reducing silt load, are often time-consuming and expensive. These methods are generally unsuitable for immediate solutions. Biological measures include activities like plantation and pasture development. Engineering measures encompass techniques such as constructing check dams, check walls, contour bunding, gully plugging, wire crating, benching and terracing, rock bolting, creating contour drains, and establishing a network of drainage wells.

Although silt trap provisions are commonly employed, they involve significant civil costs and may not always deliver optimal results. Therefore, a reassessment of existing designs is necessary, taking into account their historical performance, alongside the development of innovative approaches to desilting operations.

4 Conclusion and Future Scope

Silt erosion degrades the efficiency and profitability of hydro turbines in many applications. Silt particles are abrasive and therefore cause degradation of the material, thus decreasing efficiency of energy conversion as well as increasing the rate of maintenance. It is important to check the occurrence of erosion so that effective and simple measures could be implemented. Studies into the durability of parent materials as well as research into protective coatings and new designs of turbines have been found to offer a lot of improvement in operation under silt-laden water. The flow management procedures and sediment handling technology contribute greatly to eradicating the negative impacts of silt erosion. With the increasing global trend towards the adoption of renewable energy, hydropower retains a definitive place in the stable of renewable technologies. Thus, further development of the technique for measuring sensory attributes is a crucial requirement, but making it stable and precise under adverse conditions. Preservation of hydro turbines from silt erosion will improve their durability, while efforts towards sustaining their cost-efficiency and environmentally friendly character define hydropower sustainability. For future studies, the integration of engineering developments, sediment management strategies, and monitoring techniques should form the centre of further studies to resolve this major problem. With such approaches prioritized, one would hope for hydropower to firmly hold its position among the most preferred energy solutions in the global setting without necessarily suffering huge compromises in both environmental impacts and operational characteristics.

Declarations

- The authors received no specific funding for this study.
- The authors declare that they have no conflicts of interest to report regarding the present study.
- No Human subject or animals are involved in the research.
- All authors have mutually consented to participate.
- All the authors have consented the Journal to publish this paper.
- Authors declare that all the data being used in the design and production cum layout of the manuscript is declared in the manuscript.

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