UNIVERSITY of RWANDA COLLEGE OF SCIENCE AND TECHNOLOGY ACE-ESD AFRICAN CENTER OF EXCELLENCE IN ENERGY FOR SUSTAINABLE DEVELOPMENT

TITLE: INVESTIGATION ON THE COMBINED EFFECT OF SEDIMENT EROSION AND CAVITATION IN HYDRAULIC TURBINES
CASE STUDY OF GICIYE I AND GIHIRA HYDROPOWER PLANTS IN RWANDA

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A dissertation submitted in fulfillment of the requirements of the Degree of Masters of Science in Renewable Energy, African Center of Excellence in Energy for Sustainable Development(ACE-ESD), College of Science and Technology, University of Rwanda.

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Declaration

I declare that this Dissertation contains my own work except where specifically acknowledged, and it has been passed through the anti-plagiarism system and found to be complaint and approved final version of the dissertation.

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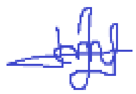
Signed: 

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Abstract

Normally, a proper hydraulic design of turbine components should results in cavitation free geometry. However, a cavitation-free design is demonstrated to be subjected to cavitation when the surface integrity changes because of sediments erosion. The reason for this is that both occurences are more likely to happen in areas with high water velocity. Some of the deteriorated turbines show signs of sediment erosion as well as cavitation. It is difficult to study and analyse the synergetic effect of sediments erosion and cavitation.

The effects of individual sediments erosion or cavitation have been studied in a number of experments and theoretical researches. However, there has been relatively little research on the synergestic effects of cavitation and sediments erosion. For completing the research gap, an invistigation on combined effects of sediments erosion and cavitation was conducted. Two hydropower plants on high sediments loaded rivers were selected as a case study. The selected hydropower plants are Giciye I on Giciye river and Gihira on Sebeya river in Rwanda.

In this work, different approaches have been used such as data collection, laboratory testing, data recording and observation test.

The collected data and results were analysed and discussed.The results showed that both sebeya and Giciye river have sediments. The particles that reach the turbines at Giciye I hydropower plant are sand and fine, with 97% sand and 3% fine, and 84% sand and 16% fine at Gihira hydropower plant. It was observed that high vibration signals were found and corresponding decrease of efficiency resulting from the increase in sediment erosions and cavitation. These resulted in repetitive turbines breakdown.

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List of Acronyms and abbreviations

µm: micrometers

ASTM: American Society for Testing and Materials

CC: curvature coefficient

CU: Uniformity coefficient

dB: Decibel

EUCL: Energy Utility corporation Limited

g: Gram

Gs: specific gravity

HVOF: High Velocity Oxygen Fuel spraying

KW: Kilo Watt

L: liters

m: meters

m^3/s: cubic meter per second

mg: milligram

mL: milliliters

mm: millimeters

MW: Mega Watt

^oC: degree Celsius

RMT: Rwanda Mountain Tea

TSS: Total Suspended Solid

USCS: unified soil classification system

CHAPTER ONE: INTRODUCTION

1.1 Background

1.1.1 General

Due to its topography Rwanda is known as a country of thousand hills. The Central, North and Western of Rwanda is dominated by high mountains. Rwanda is considered as a part of Albertine Rift Mountains of the East African Rift. Highest points are found in the chain of volcanoes that include Karisimbi volcano which is the highest point at 4,507 meters.

The Centre of Rwanda is dominated by rolling hills, while the Eastern is dominated by plains, swamps and savanna.

The economic and social development for any country is accelerated by electricity availability. Therefore, it is very important for any country to have a reliable and stable power generations for meeting the power demand [1].

Hydropower plants development in Rwanda has showed a tremendous progress over last decades. The total power installed capacity in the country is equal to 238.368 MW; 50.6% of the total capacity is from hydropower plants. In order to achieve this progress, private investors and Independent Power producers were involved in energy sector by the Government of Rwanda [2]

Even if there are potential for hydropower plants development in Rwanda, some technical challenges are present like sediment in rivers, turbines' erosion and cavitation. The origin of erosion and sedimentation problems is the climatic and physical conditions in the area where Rwanda is located. Most of rivers in the tropical region are full of sand and other sediments especially in rainy season [3].

1.1.2 Sediment erosion problem

Sediment erosion is globally among the problem related to the operation and maintenance of hydropower plants especially turbines. Hydropower plants which are located on rivers which have sediments, their hydraulic turbines are subjected to erosive and abrasive wear.

Turbine wear results both efficiency and life span reduction of the turbine as well problems in operation and maintenance and leads to the economic losses.

Most of hydropower plants that are built on sediments loaded rivers encounter serious problems related to sediments erosion in their first year of operation.

Storage and run of river hydropower plants are affected by sediment erosion but the problems' nature is different. Run of river hydropower plants take water directly from the river even if desilting basins are built for trapping the sediments, they suffer from wear of their turbines even in their first year of operation. Whereas storage hydropower plants, reservoir capacity depletion over a certain period of time due to the deposit of sediments.

Dealing with sediment is a great challenge for new hydropower plants projects in a sediment loaded rivers as they require the construction of additional infrastructure for avoiding the sediments [4].

For dealing with sediments, desilting basins and sediment flushing systems are designed in way that they can trap the sediments of big size and allow sediments less than 0.2mm, however the sediments of less than 0.2mm cause erosion to turbine components especially high head turbines. All those design make the hydropower plant projects in sediment loaded rivers very costly.

Sediments particles in a moving fluid have a high kinetic energy, when they strike metal surface they create wear by cutting or deformation the metal surface.

High head Pelton and Francis turbines are mostly affected by sediment erosion compare to low head Kaplan and propeller turbines. For impulse turbines the most affected parts are runner buckets, nozzles and their needles while for reaction turbines the most affected parts are guide vanes, runner blades and sealing rings. However, in a high sediment loaded river, turbines components with low velocity of water like spiral casing, draft tube and main inlet valve are also affected by sediment erosion.

1.1.3 Cavitation

Cavitation is a phenomenon in a liquid that occurs when flow-induced pressure reduction leads the liquid/water to begin evaporating into air bubbles present in the liquid/water.
At a pressure known as cavitation inception pressure, the cavitation process begins. Because bubbles occur as a result of the injection of heat, the cavitation process appears to be comparable to boiling. Erosion may occur if the bubbles collapse on or near a solid surface.

Cavitation is most common in hydraulic reaction turbines like Francis turbines, but it should also happen in impulse turbines like Pelton turbines in practice. The area where the cavities are left at a low pressure and collapsed to the blade surface is where cavitation erosion occurs in turbines.

Cavitation effect in hydraulic turbines, decrease the turbine efficiency and lifespan of the turbine without forgetting the increase of operation and maintenance costs of hydropower plant [5].
Different studies have done on the effect of the individual sediment erosion or individual cavitation phenomenon in hydraulic turbines but few studies were done on the combination effect of sediment erosion and cavitation.

1.2 Statement of the Problem

Sediment erosion and cavitation phenomenon are the most problems in hydraulic turbines operations and maintenance.
Generally, the geometry of a good-designed hydraulic turbine and its components must be cavitation free, however with the presence of sediment erosion the original surface is changed and the cavitation free turbine and its component are found subjected to cavitation.

Rwanda is located in tropical region where most of rivers are full of sediments which are caused by soil erosion, fragile rocks and landslides. Most of the rivers in Rwanda are characterized by flow variations which trigger the cavitation. Sediments erosion and cavitation are the main challenges on operation and maintenance of hydropower plants in Rwanda, the efficiency of the turbine decreases with the increase in the sediment wear and cavitation and finally result the breakdown of hydraulic turbines.

The origin of erosion and sedimentation problems is the climatic and physical conditions in the area where Rwanda is located. Most of rivers in the tropical region are full of sand and other sediments especially in rainy season [6]

1.3 Objectives

1.3.1 Major Objective

The main objective is to observe a relationship between sediment erosion and cavitation in hydraulic turbines and establish the operating strategy for hydraulic turbines that are operating in sediment water.

1.3.2 The Specific Objective

For achieving the main objective of the study the following specific objectives are drawn:

- Determine the sediment size in Giciye and sebeya rivers and their effect on the performance of the turbines.
- Identification of combined effect of sand erosion and cavitation in hydraulic turbines.
- Interlink the effect of sediment erosion to cavitation phenomenon in hydraulic turbines.

1.4 Scope of the study

The scope of this study is only focused on the combined effect of sediment erosion and cavitation in hydraulic turbines on Sebeya and Giciye rivers.

Two rivers, Sebeya and Giciye with high sediments were observed in order to find out the sediment characteristics. A visual check of turbines and their components was done on one hydropower plant at each river, Gihira hydropower plant on Sebaya river and Giciye I hydropower plant on Giciye river. All technical aspects were studied in a way that pursuing the achievement of the objectives mentioned in the previous point

1.5 Outcomes and Significance of the Study

1.5.1 Outcomes of the Study

This is study contributes to a particular knowledge on:

- Understanding on how the sediment erosion triggers the cavitation in hydraulic turbines,
- Operation and maintenance strategy of hydropower plant which are located on sediment loaded rivers,
- Selection of appropriate material for turbine design and construction,
- Corrective and preventive maintenance of eroded turbines.

1.5.2 Significant of the Study

The findings of this study are a great benefit to the following:

a) Hydropower Plants Developers

Information from the study enable people who are engaged into the development of hydropower plants to improve their operation and maintenance strategies in order to protect their turbines against sediment erosion and cavitation. Data gathered are useful to the plant owners and operators and help them to understand how sediment erosion triggers the cavitation of turbine after a certain period of operation.

b) Turbines Designer and Manufacturers

The results help turbines designers and manufacturers to select the appropriate geometry and shape which is resistive to sediment erosion and cavitation. They will be able to select the appropriate coating materials to be used for protecting their turbines.

c) Future Researchers

Many researchers have conducted different studies on the effect of the individual sediment erosion or individual cavitation phenomenon but very little studies have been done in a combined effect of sediment erosion and cavitation. This study equips future researchers to gain knowledge in the combined effect of sediment erosion and cavitation in hydraulic turbines.

Data collected can help researchers in energy sector to link theoretical knowledge with the practical knowledge.

CHAPTER TWO: LITERATURE REVIEW

This chapter reviews the existing literature related to the wear of the material, sediment erosion, erosion of hydraulic machinery, cavitation in hydraulic turbines and Synergy between particle erosion, cavitation and corrosion.

2.1 Wear of materials

Erosion is the wear of a hydro turbine caused by silt. Different studies have used different names to characterize the material removal mechanism from hydraulic turbines [7]; consequently, before dealing with sediment erosion and cavitation in hydraulic machines, it is critical to have a general understanding of wear, its types, and mechanisms.

Generally, wear is described as a gradual loss or deterioration of material as a result of mechanical interaction between components.

According to ASTM G40-88 wear is defined as a damage to a solid surface, often involving progressive loss of material, caused to relative motion between that surface and a contacting substance or substances. Material displacement on a given body that does not result in a net change in volume or weight should also be considered as wear [7].

2.1.1 Classification of wear

Wear should be classified and categorized in a variety of ways. In the 1950s, corrosion, surface fatigue, abrasive, and adhesive wear were considered as the four major categories of wear, and more than 95 percent of wear cases in machinery were attributed to those four major types of wear [7].

Brekke et all in [7] attempted to identify six separate primary wear mechanisms and discovered that all six wear mechanisms have one thing in common: the loss of solid components from rubbing surfaces.

Meng and Ludema in [8] discovered a semblance of agreement on the definitions of terminology used by most of researchers on wear mode or process and mechanisms.

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According to Meng and Ludema in [8], erosion is the wear of hydraulic turbines caused by sediment-laden water. Even if there is modest abrasion in some turbine components owing to particle entrapment, erosion and cavitation are the most common causes of turbine damage.

2.1.2 Wear rate

Distinct types of wear have different mechanisms, locations, and magnitudes of damage. As a result, the wear process is commonly defined in terms of wear rate, but due to the aforementioned variances, using a uniform technique for quantifying wear rate is extremely difficult. The depth or volume of material removed per unit of sliding or rolling distance is the usual means of defining the wear rate of a surface [8].

According to the ASTM G40-88 standard, "the rate of material removal or dimensional change due to wear per unit of exposure parameter, for example, quantity of material removed (mass, volume, thickness) in unit of sliding distance or unit of time". The majority of wear rate data is derived through friction and wear. Such information is dependent on the material pair, which is usually expressed as a dimensionless wear coefficient. The relative magnitude of the wear statistics reported in the literature is more relevant than their absolute values [8].
It is difficult to use the data for erosion of hydraulic turbines because of the differences in nature and rate of material removal.

2.2 Erosion

Impacts of solid or liquid particles against a solid surface induce erosive wear, also known as erosion. These particles are confined in the flow medium and have enough kinetic energy to harm even metal surfaces. Liquid particles are carried by the gas medium, whereas solid particles are carried by the liquid or gas media. Liquid droplet erosion is one type of erosion, whereas solid particle erosion is another. Despite the fact that erosion has become a distinct sort of wear mechanism, it is still misconstrued as a type of abrasive wear.

Erosion can occur in a variety of machines in the power plant, aircraft, process, and mining industries and others. Because of the sediment in the water, the turbines in hydropower components deteriorate. Sediment erosion, on the other hand, affects components such as pipes, valves, and sensors in off-shore industries, process industries, sewage systems, and mining sectors.

Different investigations [8] have demonstrated that component erosion cannot be entirely eliminated. The study of material features and failure causes, on the other hand, aids in understanding how to reduce material damage caused by erosion.

2.2.1 Mechanisms of particle erosion

Thermal, chemical, and mechanical activities are the primary causes of material separation as debris in erosion. However, the methods for achieving such actions varies.

Solid particle erosion is caused by four primary mechanisms: cutting, fatigue, brittle fracture, and melting. Cutting activities can alternatively be classified as cutting by cutting edge penetration or plastic deformation until failure. The hierarchy of these processes is depicted in Figure 2.1.

There are seven types of solid particle erosion: abrasive erosion, surface fatigue, brittle fracture, ductile deformation, surface melting, macroscopic erosion, and atomic erosion.

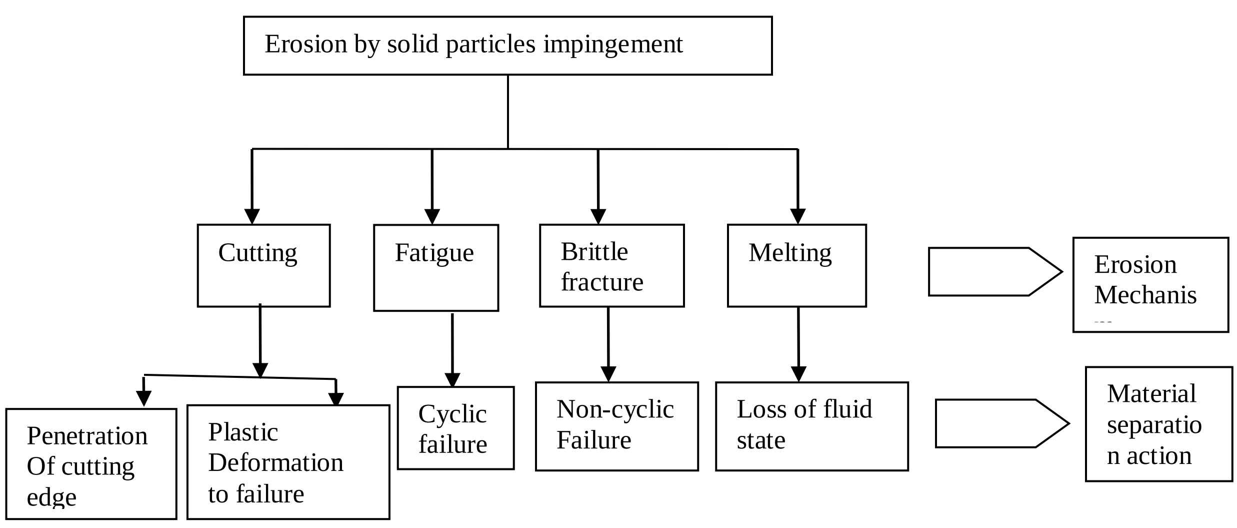


Figure 2. 1 Mechanism of solid particle erosion [9]

Cutting (abrasive) erosion

Abrasive erosion occurs when particles impact the surface at a low impingement angle, as shown in figure 2.2.a, and remove the material via cutting action. When abrasive grains touch a surface, they roll or glide, causing erosion by abrasion or cutting. The substance is removed by scouring or scraping the particles' sharp edges, resulting in brief track-length scars.

Surface fatigue

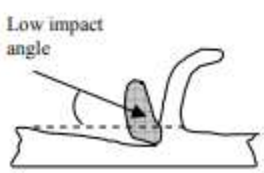
This erosion mechanism is analogous to wear on rolling surfaces caused by surface strain. The surface cannot be plastically deformed when particles strike it with a large impact angle but low speed, as shown in figure 2.2.b. Instead, after repeated pounding, the surface becomes weak due to fatigue action, and cracks appear. After repeated blows, the particles will be separated from the surface.

Plastic deformation

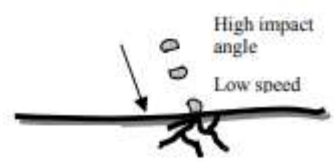
When particles impact the elastic surface at a medium speed and a large impingement angle, flakes form around the striking point, causing plastic deformation of the surface, as shown in figure 2.2.c. The particles will detach as debris after repeated strikes on the flakes.

Brittle fracture

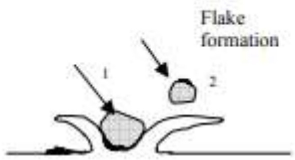
Brittle fracture occurs when particles impact the brittle surface with a significant impingement angle at a medium velocity (Figure 2.2.d). Brittle fragmentation is more common if the particles are sharp, and the particles detach from the material by subsurface cracking.



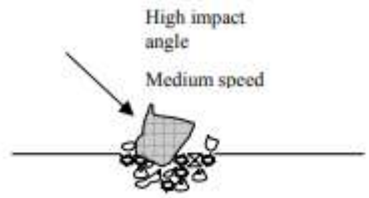
a) Cutting (abrasive) erosion mechanism



b) Fatigue erosion mechanism



c) Plastic Deformation



d) Erosion by brittle fracture

Figure 2. 2 Material separation actions [8]

2.2.2 Factors affecting erosion

There are a variety of elements that distinguish different types of erosion mechanisms and regulate erosion rates. These elements can be divided into three categories [9].

They are factors that are linked to:

1. Operating conditions: velocity, acceleration, impingement angle, flux rate or concentration, flow medium and temperature.
2. Eroding particles (sand or liquid droplets): size, shape, hardness, material.
3. Substrates (target materials): chemistry, elastic property, hardness, surface morphology.

2.3 Sediment

River sediments are the particles that cause erosion of turbine components in hydropower plants. Clay, silt, sand, and gravel make up the river sediments, which have a specific gravity of about 2.6[8]. Based on sediment transport, sediment particles in river water are categorized as bed load or suspended load. Bed load refers to all particles that travel close to the bed by sliding, rolling, or jumping. These particles have a significantly lower velocity than flowing water, whereas suspended load refers to all particles that are carried away in suspension by flowing water and have a velocity that is close to that of flowing water. A portion of the suspended load settles in settling basins or reservoirs, while the rest passes through turbines, producing component erosion.

As demonstrated in table 2.1, river sediments comprise a variety of different particle sizes. Turbine erosion is mostly caused by a sand percentage of the silt. The sand can be classified as fine if its size is between 0.06 and 0.2 mm, as medium if the size is between 0.2 and 0.6 mm, lastly as coarse if the size is between 0.6 and 2 mm [9].

Particle transport mechanisms, in addition to particle characteristics, play a role in erosion models. The mobility of such particles is mostly determined by particle properties (density, shape, and size) as well as fluid properties (velocity, turbulence, viscosity).

Table 2. 1 Classification of river sediment [9].

Particle	Clay	Silt	Sand	Gravel	Cobbles	Boulders
Size(mm)	<0.002	<0.002-0.06	0.06-2	2-60	60-250	>250

The particles sink in still water due to gravity, which is counteract by buoyancy or upthrust. The mass of the particle and the viscosity of the fluid determine the sinking speed. Turbulence separates particles from the rest of the flow and lifts them from the bed, whereas transit velocity moves particles in the flow direction. The Reynolds number (Re) is low, resulting in laminar flow, which is ideal for particle settling.

Similarly, water flowing around the particle creates drag in the flow direction. Forward movement is impeded by solid friction between the particle and the bed. Dissolved air or air bubbles can also prevent particles from settling, resulting in water color due to particle suspension. The centrifugal force and the Coriolis force are important destabilizing forces when particles move along a curved path while the system is rotating (including global rotations).

The numerical study of exact interactions between all connected components is difficult. Sediment movement studies may reveal the area of the attack on the turbine, which can help focus on the best position for an erosion-resistant coating in the turbine.

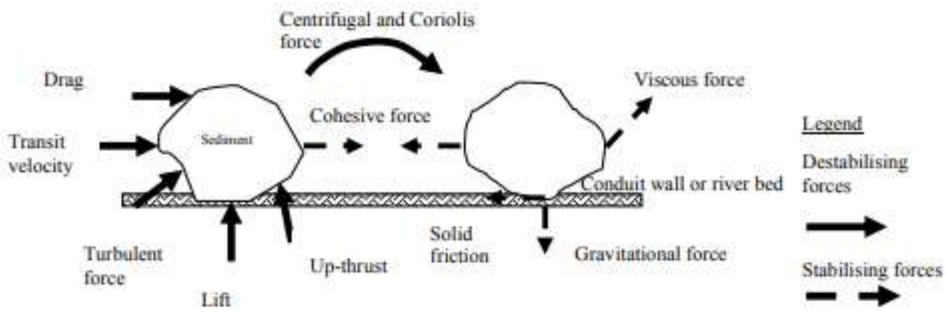


Figure 2. 3 Forces acting on the particles in the flow field [9]

2.4 Erosion of hydraulic machinery

Hydraulic machinery is divided into two categories: turbines and pumps. In the case of turbines, the energy is available in the form of water's potential or kinetic energy, which is dependent on the mass of the water and the available head. Mechanical energy, on the other hand, should be used to move the water to a greater level. At the expense of reaction to the turbine structure, the energy available in the water is converted into mechanical energy in the form of turbine rotation. Similarly, the pump impeller's physical movement puts force on the fluid.

Any material in the water exert force on the turbine or pump, which the material must withstand. Sand is a very important component of the water with such an application. The surface of the turbine and pump should be sturdy enough to withstand any forces caused by solid particles without deformation or failure. One type of wear is the deformation or dimensional change of a turbine or pump surface. In the literature, names like erosion, hydraulic abrasion, abrasion, and hydro-abrasion have been used to describe the progressive change in the form and state of the surface caused by particles in the water. Erosion is the best terminology which is mostly used among others for describing this phenomenon.

Hydraulic machines can be categorized in a variety of ways based on their construction, operating principle, and range of use. Both rotary and reciprocating mutual dynamic action between the machine and fluid are possible. The abrasive character of the damage caused by fluid born particles in reciprocating machines differs from that seen in rotating machines.

Based on the principle of energy conversion, water turbines are divided into impulse and reaction turbines. Reaction turbines include the Francis, Kaplan, and bulb turbines. Pelton and turgo are both impulse turbines. For smaller units, cross flow turbines are two-stage impulse turbines.
It is difficult to tell the difference between different types of erosion on hydraulic apparatus at a micro level. According to the visual appearance, hydraulic turbine erosion is categorized into six categories, as indicated in Table 2.2 [10].

This classification may be useful in determining the nature of erosion damage as well as maintenance plans. On the other hand, depending on the difference in flow velocity and particle impingement angle, erosion in hydraulic turbines is divided into three categories: I, II, and III (Table 2.2) [11].
The erosion test of specimens placed at various turbine components was used to construct this classification. This classification might be confusing or misleading because the same turbine component, such as the blade, can have various types of erosion at the leading and trailing edges. The erosion of hydraulic machinery caused by sediment-laden water can be properly characterized based on particle and fluid flow conditions [7].

- Micro erosion
- Secondary flow vortex erosion
- Acceleration erosion

Micro erosion occurs on the surface of turbine components when small particles with a grain size of less than 60 µm move at a high velocity. High turbulence in the boundary layers causes these particles to rotate rapidly, generating many ripples in the flow direction. Fish scale and orange peel patterns are also used to describe erosion patterns. This form of erosion can be seen in the guide vane and runner blade as they approach the outlet and needle.

Flow in the second stage obstacles in the flow field or secondary flow in the corners of conduits produce secondary flow vortex erosion. Any impediment in the flow field induces secondary flow, which generates a horseshoe vortex around cylindrical objects such as guide vane shafts. Similarly, the Pelton wheel's needle has a vortex behind the ribs that support it, hence vortex erosion occurs in the straight line behind the ribs. This form of erosion is also caused by vortices in the corners of conduits, such as guide vanes-facing plates and blades-band. The combined action of the boundary layer and the change in flow acceleration causes such vortices and secondary flow.

Particles separated from the flow direction by their acceleration normal to the flow direction contact the surface, generating a collision in the water conduit surface. Large particles, such as those more than 0.5 mm, cause serious damage to Francis turbine and Pelton bucket conduits, blades, and guide vanes.

Hydraulic machines with high Reynolds numbers, such as 10^6 -10^8, are typically subjected to all three types of erosion. The next sections examine the damage to specific components of the main types of turbines.

Table 2. 2 Turbine erosion classification [10].

S/N	Type	Description
1	Mettalic luster	Shining surface with no traces of paint, scale or rust
2	Fine scaly erosion	Surface with rare, separately located and skin-deep minute scales
3	Scale erosion	Surface entirely covered with skin-deep fine scale
4	Large-sized scaly erosion	Surface entirely covered with deep and enlarged scales
5	In-depth erosion	Surface covered with deep and long channels
6	Through hole	Erosion of entire material

Table 2. 3 Classification of erosion [11].

Type of erosion	Location	Flow velocity	Impingement angle
I	Spiral casing draft tube	Low	Small
II	Runner blade Guide vane	High	Small
III	Wearing ring	High	Large due to vortex and turbulence

2.5 Cavitation in hydraulic machinery

Cavitation erosion is commonly referred to simply as cavitation, which ignores the fact that cavitation can occur without generating erosion. Cavitating draft tube flows for example, and cavitation that is not severe enough to produce metal fatigue and erosion. While erosion is an obvious hazard of cavitation, there are other consequences that could be just as costly. All cavitation problems in a reaction turbine, on the other hand, are almost always caused by the apparatus being used outside of its design parameters [12].

2.5.1 Characteristics of Cavitation in Hydraulic Machinery

While the underlying process of gas cavities forming as a result of a substantial fall in dynamic pressure is the same in real and ideal laboratory circumstances, cavitation in turbines has a few additional aspects to consider. Cavitation bubbles may be mitigated by re-entry to high pressure zones, and hence collapse, because cavitation occurs in a flowing flow. The impact of a cavity collapse is determined by the place where it occurs. While some types of cavitation produce bubble collapse near the machine's surface, which can lead to pitting, cavitation can also happen in the free stream where the collapse is not as erosive [12].

Free-floating bubbles in the flow or on the blade surface are not generally related with erosion, but they will collapse when exposed to high pressure gradients. This is usually due to a lack of available submergence for the turbine.

Cavitation linked to the turbine leading edge is one of the more aggressive forms of cavitation observed in the flow. Several mechanisms are possible, including stable and transparent sheet cavitation that steadily loses vortices with low impact energies. Cloud cavitation is a more erosive type with turbulent cavity interfaces. The aperiodic shedding is created by an unstable cavity.

When vortices created by different incidence angles across the leading edge cause flow rotation, this is known as inter-blade vortex cavitation. The vortices may form at the meeting of the blade and the crown. This type of cavitation is most common in free streams, although it can cause erosion if the vortex tip collides with the blade. The vortex cavitation may also create severe vibration at full load.

2.5.2 Cavitation in Francis Turbines

The development of cavitation in Francis turbines is influenced by a number of factors. To begin with, the runner dimensions are lowered in the design phase to save money, resulting in a higher runner circumferential velocity and a lower cavitation number. Part-load operation is also more common in hydropower facilities, and the runner design is not designed to reduce cavitation. Due to regular operation in off-design circumstances, hydropower facilities with a substantial range in available head will be subject to cavitation difficulties [13].

In Francis turbines, there are five different types of cavitation that can be developed [13]:

- **Leading edge cavitation on runner blades**

Leading edge cavitation can develop when operating with heads that deviate from the design head, such as in hydropower plants with large reservoir level variations. Cavitation on the suction side of the blade can occur when using a higher head than the design head, whereas cavitation on the pressure side can occur when using a lower head than the design head. Pressure pulsations and erosion on the runner blades may result from this sort of cavitation.

- **Travelling bubble cavitation**

Traveling bubble cavitation is caused by bubbles that originate from the blade suction side and can cause severe blade surface degradation as well as noise. This type of cavitation occurs when the runner is operated at high local velocities, resulting in full load operation. It is determined by the machine's submergence and the system's net positive suction head.

- **Inter-blade Vortex cavitation**

During partial load operation, flow separation at the inlet edge and the creation of a vortex between the runner blades are possible. Inter-blade vortex cavitation will not produce significant erosion or vibration unless the cavitation vortex comes into contact with the runner surface.

- **Trailing edge vortex cavitation**

Cavitation bubbles formed by a vortex on the trailing edge of the runner blade collapse further downstream in the draft tube, raising pressure. There is no significant cavitation erosion when the bubble collapses in the absence of any substance. However, if cavitation happens further upstream in the runner, a bubble collapse on the runner blade surface produces erosion damage.

- **Draft tube swirl with a cavitating vortex core**

At part load operation, the draft tube swirl is visible below the runner cone, rotating in the same direction as the runner. The rotational frequency, also known as the Rheingans frequency, is usually roughly 1/3 of the runner's rotating speed [11]. Cavitation in the draft tube swirl does not produce erosion, but it does cause considerable low frequency pressure pulsations, which cause loud noise and vibration in specific component load operating ranges. Low-frequency pressure pulsations can also travel upstream of the runner, causing power variations.

In the gap between the shroud and the stationary lower cover, where the pressure is low and the runner's peripheral velocity is high, cavitation can also develop. Cavitation may also be a cause of dynamic pressure on the runner blades, in addition to the erosion stated. Lift oscillations will result from the shedding of sheet cavitation on the blades, which can cause fatigue.

2.6 Synergy between particle erosion, cavitation and corrosion

The velocities of hydraulic machinery and offshore sector components are increasing all the time, resulting in early component failure due to a combination of flow-dependent erosion and corrosion. The presence of solid particles in the flow, as well as cavitation, add to the difficulty. One of the top five corrosion problems in offshore sectors is combined erosion-corrosion [14]. Hydraulic machines are subjected to the combined effect of sediment erosion, cavitation and corrosion. Even while there may be a mixed reaction to combined actions, it is more likely to degrade protective layers and increase corrosion rate.

The interplay between various flow regimes and corrosion is depicted in figure 2.4. Erosion-corrosion refers to the space between corrosion-slurry impingement, corrosion-cavitation, and corrosion-turbulent flow. Flow-induced corrosion and rest with erosion-corrosion, on the other hand, are described as interactions between turbulent and laminar flow, where mechanical processes are dominant. Erosion takes precedence over cavitation and corrosion as flow velocity increases [14].

Synergic effect refers to the increase in overall weight loss that cannot be explained by pure corrosion (without particles) or pure erosion (mechanical processes - with solids) [14].

The synergism in erosion-corrosion can be split into erosion enhanced corrosion ($\Delta W_{Corrosion}$) or corrosion enhanced erosion ($\Delta W_{Erosion}$) and hence total erosion can be written as:

$$W_{Total} = W_{Erosion} + W_{Corrosion} + \Delta W_{Erosion} + \Delta W_{Corrosion} \qquad \text{Eq. 2.6.1}$$

Where,

$$\Delta W_{Erosion} + \Delta W_{Corrosion} = Synergy \qquad \text{Eq. 2.6.2}$$

Total synergy is the sum of $\Delta W_{Erosion}$ and $\Delta W_{Corrosion}$, among which $\Delta W_{Erosion}$ is dominating in case of transport of solid slurry. The combined effect of cavitation might be incorporated in ΔWE as erosion or mechanical effect synergy. In the case of hydropower turbines, river water is typically no corroding, hence the erosion-corrosion synergy is minimal. However, in the case of galvanic effect, corrosion can be a factor due to a poor selection of materials with widely disparate electrochemical potentials.

Particle erosion can strip corrosion film and influence on corrosion rate by different mechanisms, such as:

- Increased mass transport by high turbulence levels caused by surface roughening
- Removal of oxides or corrosion scales exposing fresh reactive material, prohibiting film formation and acceleration corrosion rates
- Local acidification in erosion pits

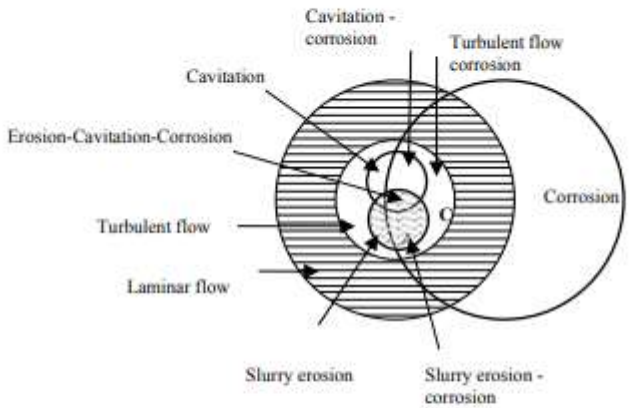


Figure 2. 4 Interaction of erosion-cavitation-corrosion [14].

CHAPTER THREE: METHODOLOGY

For achieving the objectives of this study different approaches have been used. These include: field data collection, laboratory testing, field data recording and observation test.

3.1 Field work sediments observation and laboratory tests methods

3.1.1 Sampling methodology

Two rivers were taken as samples for observing their behaviors in terms of sediments, those rivers which were chosen as samples are Sebeya river and Giciye river. Sediment Samples were taken for laboratory tests in order to determine the sediments size and their classification.

Three samples were taken at intake and tailrace of Giciye hydropower plant and Gihira hydropower plant.

Samples taken at the intake of Giciye 1 hydropower plant (Giciye river):

Sample one: Surface water (top water)

Sample two: Middle point water

Sample three: Bottom water

Sample four: 1 liter of water

Samples taken at the tailrace of Giciye 1 hydropower plant (Giciye river):

Sample one: Surface water (top water)

Sample two: Middle point water

Sample three: Bottom water

Sample four: 1 liter of water

The same samples were taken at Gihira hydropower plant (Sebeya river).

All samples were taken at time that both Gihira and Giciye hydropower plants were operating at 90% of their designed water flow which is 3.2m^3/s, 4m^3/s respectively.

List of the tools used

1. Small plastic water bucket
2. One-liter plastic bottle

a) Sampling at the intake

b) Sampling at the tailrace

c) Samples taken

Picture 3.1 sampling

3.1.2 Laboratory tests

The following test were done in the soil mechanics laboratory of University of Rwanda, College of Science and Technology, Department of Civil, Environmental and Geomatics Engineering.

- Sieve Test
- Specific gravity
- Hydrometer
- Total Suspended Solid (TSS)

3.1.2.1 Sieve test and Sieve Analysis

Sieve test and sieve analysis were done by taking reference to the International Standard ASTM C136 which is the American Society for Testing and Materials, standard test method for sieve analysis of fine and coarse aggregates.

The sieve test method is used for determining the particle size distribution of fine and coarse aggregates by sieving.

For performing this test, a sample of dry aggregate also known as mass is taken and was separated through a series of sieves of progressively smaller openings for determination of particle size distribution.

Sediments classification was done by using ASTM D 2487-17 which is the standard practice for classification of soils for engineering purposes (unified soil classification system) [15].

List of the tools used:

- Balance
- Sieves
- Mechanical Sieve Shaker
- Oven

Picture 3.2 drying of samples in the oven

Picture 3.3 sieving test

3.1.2.2 Specific Gravity

By definition specific gravity is the ration of mass of an aggregate to the mass of a volume of water equal to the volume of the aggregate particles. It is also known as the absolute volume of the aggregate. The sampling and testing was done by taking reference to the ASTM C128-15 International standard test method for relative density (Specific density) and absorption of fine aggregate [15].

A total of 24 hours was spent immersing the aggregate sample in water. It is taken out of the water, weighed, and the water evaporated off the surface of the particles. The sample is then weighed while submerged in water. The sample is then oven-dried and weighed for the third time. It is feasible to determine specific gravity and absorption using the weights acquired and the formulas in this test technique.

List of the tools used:

- Balance
- Sample container
- Water Tank
- Sieves

Picture 3.5 specific gravity test

3.1.2.3 Hydrometer and particle size analysis

Particle size analysis was done by taking reference to ASTM D422 which is the standard test method for particle size analysis of soils.

According to the ASTM D 422 standard the distribution of particle sizes larger than 75 µm (retained in the No 200 sieve) is determined by sieving, while the distribution of particle sizes smaller than 75 µm is determined by a sedimentation process, using a hydrometer for having the necessary data.

For having a deep particle size analysis, a hydrometer test was done in this study.

List of tools used:

- A sensitive balance up to 0.01 g
- Stirring Apparatus
- Hydrometer
- Sedimentation cylinder
- Thermometer
- Sieves
- Water bath/Constant temperature room
- Beaker
- Timing device

Sodium metaphosphate was used as a dispersing agent.

Picture 3.6 hydrometer test

3.1.2.4 Total suspended solids test (TSS test)

Sampling was done by using ASTM D4411-03 standard guide for sampling fluvial sediment in motion.

The total suspended solids test is in done by referring to the ASTM D5907 – 18 standard test methods for filterable matter (total dissolved solids) and non-filterable matter (Total suspended solids) in water. However, for samples of water taken in open channel this standard is not used. For open channel water like the case study of this research, the ASTM D3977-97 standard test methods for determining sediment concentration in water samples is used.

These test methods of ASTM D3977-97 cover the determination of sediment concentration in water samples taken at the intake and tailrace of both Giciye I and Gihira hydropower plants.

The supernatant water is poured or pumped away once the sediment has settled. The volume of leftover water sediment mixture is measured in order to apply a dissolved solids correction later. After drying, the sediment is weighed.

List of tools used:

- Beakers
- Filter
- Laboratory Balance

Picture 3.8 TSS test

3.2 Technical inspection and visual check

A technical inspection in Giciye I hydropower plant and Gihira hydropower plant is done. The parts inspected are turbines and their components mostly are runners, nozzles, nozzle bars and wicked gates. In Giciye I hydropower plant pelton turbines are installed while in Gihira hydropower plant there is Francis turbines.

Photos of damaged area due to sand erosion and cavitation were taken. Therefore, the classification of erosion in the turbines was done based on visual analysis

3.3 Determination of combined effect of sediment erosion and cavitation in hydraulic turbines

For determining the combined effect of sediment erosion and cavitation on the turbines; vibration and noise sensors were installed on Giciye I turbines for comparing the measured values after 5 years of operation with the ones recorded after one month of installation of new runners, nozzles and other accessories.

A regular recording of vibration and noise data was done in period equal to one month. Data were recorded on hourly basis but a daily average was calculated for the analysis.

Operation and maintenance logbooks of Gihira and Giciye I hydropower plants were consulted to check if there had been any breakdown due to the combined effect of sediment erosion and cavitation.

For verifying the turbine performance, water flow data and active power were recorded and the data recorded were compared to the ones recorded after the installation of new mechanical equipment.

CHAPTER FOUR: RESULTS AND DISCUSSIONS

4.1 Sediment erosion

4.1.1 Sediment laboratory test results

a) Sieve analysis (ASTM C136)

Giciye I intake surface (top) water

Total dry initial mass(g): 568.53

Fineness Modulus: 2.92

Gravel: 1

Sand: 98

Fine: 1

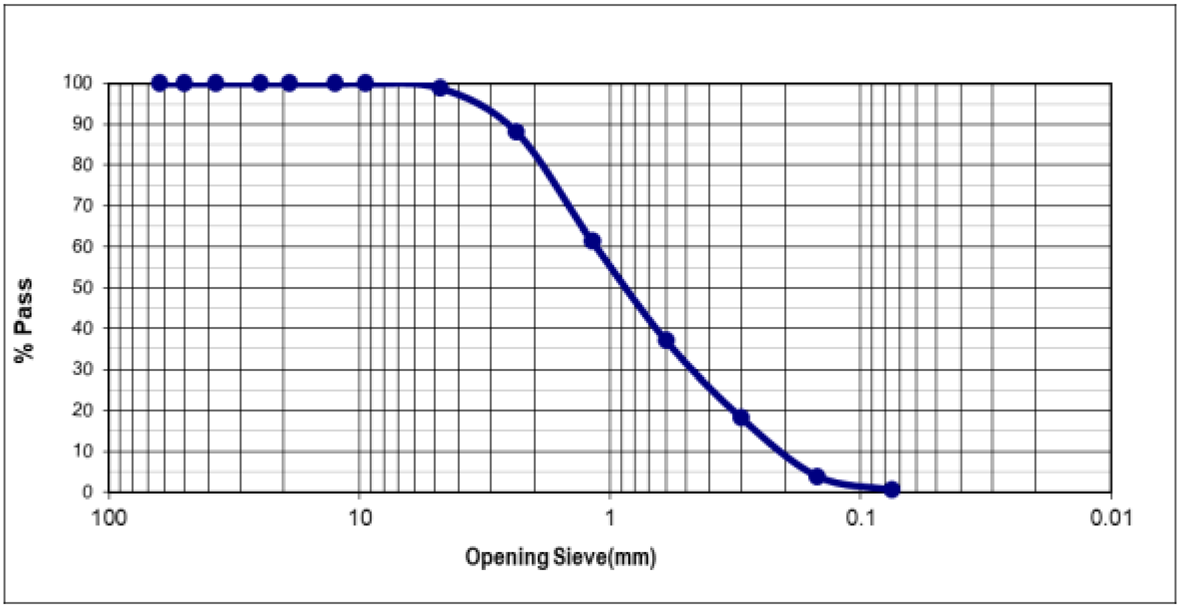


Figure 4. 1 Percentage pass vs sieve opening chart of Giciye intake top water

A total dry mass of 568.53g was taken at the top water of the intake of Giciye I hydropower plant was used as a sample to pass in the sieving test. The tests results showed that the sediment tested are composed by 1% of gravel, 98% sand and 1% of fine.

The figure 4.1 is the distribution curve which was used as a graphical representation of the data obtained during the seiving test.

These results showed that the Giciye river is having sediments which are dominated by sand.

Giciye I intake middle point water

Total dry initial mass (g): 762.4

Fineness Modulus: 3.95

Gravel: 15

Sand: 85

Fine: 0

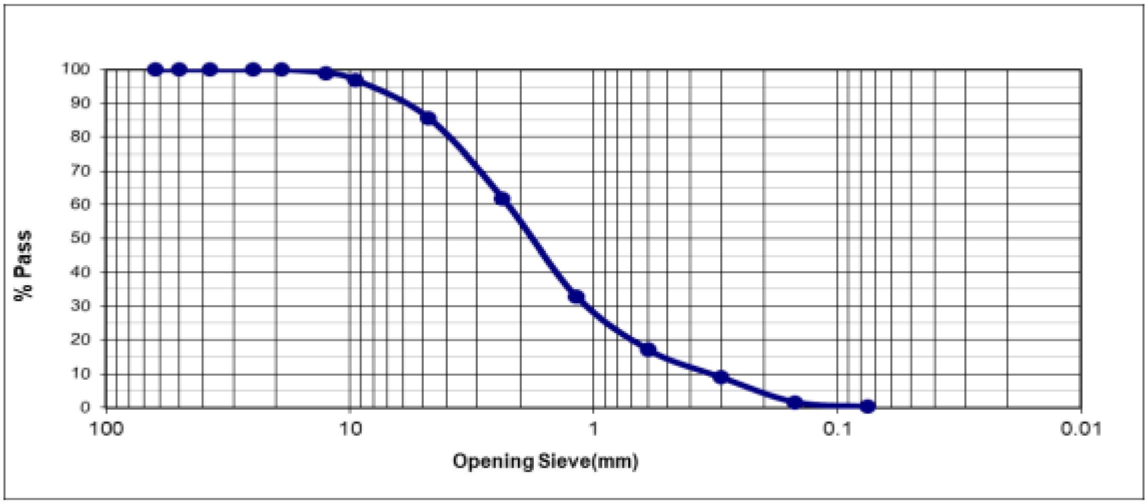


Figure 4. 2 Percentage pass vs sieve opening chart of Giciye intake middle point water

A total dry mass of 762.2g was taken at the middle point water of the intake of Giciye I hydropower plant was used as a sample to pass in the sieving test. The tests results showed that the sediment tested are composed by 15% of gravel, 85%.

The figure 4.2 is the distribution curve which was used as a graphical representation of the data obtained during the seiving test.

These results showed that the Giciye river is having sediments which are dominated by sand.

Giciye I intake bottom water

Total dry initial mass (g): 846.02

Fineness Modulus: 3.53

Gravel: 7

Sand: 92

Fine: 0

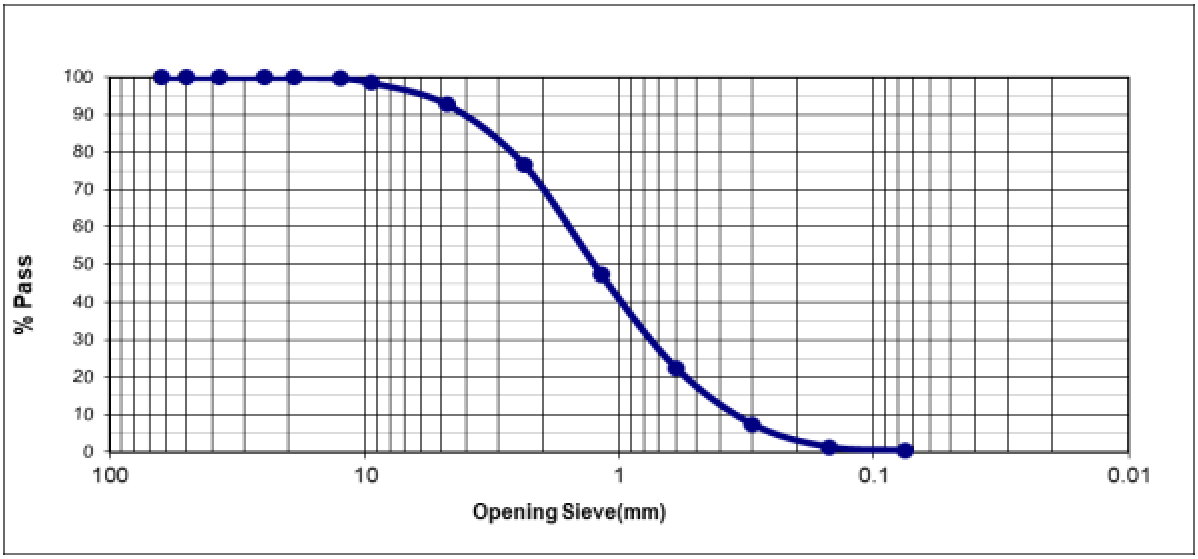


Figure 4. 3 Percentage pass vs sieve opening chart of Giciye intake bottom water

A total dry mass of 846.02g was taken at the bottom point water of the intake of Giciye I hydropower plant was used as a sample to pass in the sieving test. The tests results showed that the sediment tested are composed by 7% of gravel and 92% of sand.

The figure 4.3 is the distribution curve which was used as a graphical representation of the data obtained during the seiving test.

These results showed that the Giciye river is having sediments which are dominated by sand.

Giciye I tailrace Surface (Top) water

Total dry initial mass (g): 442.08

Fineness Modulus: 0.83

Gravel: 0

Sand: 96

Fine: 4

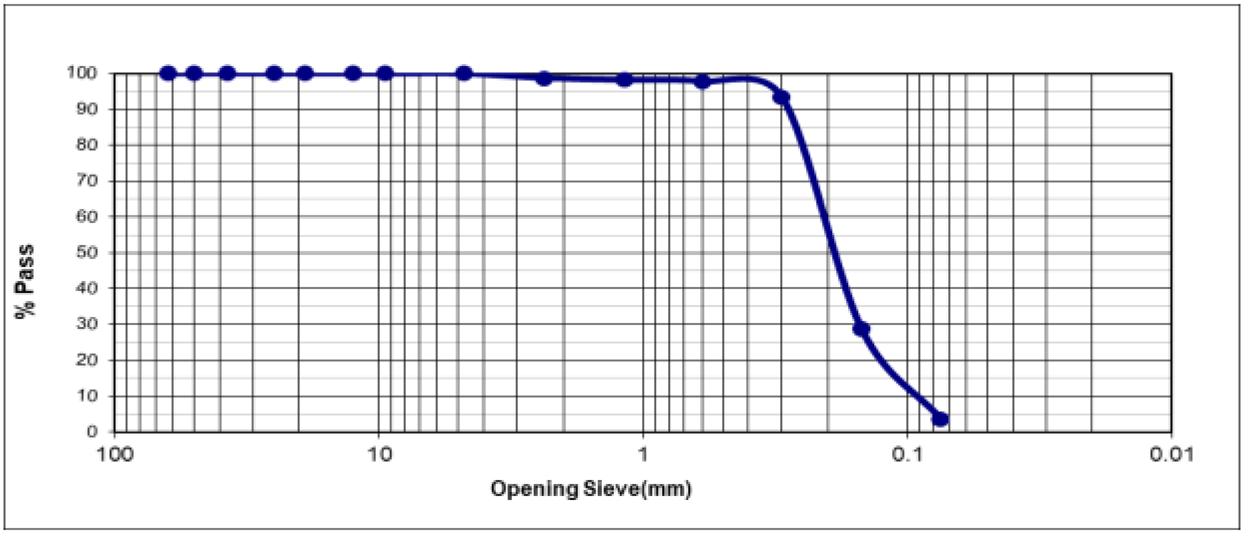


Figure 4. 4 Percentage pass vs sieve opening chart of Giciye tailrace top water

A total dry mass of 442.08g was taken at the top point water of the tailrace of Giciye I hydropower plant was used as a sample to pass in the sieving test. The tests results showed that the sediment tested are composed by 96% of sand and 4% of fine.

The figure 4.4 is the distribution curve which was used as a graphical representation of the data obtained during the seiving test.

These results showed that the Giciye river is having sediments which are dominated by sand.

The tested sediment are the one which are in the water that reaching the turbine and its components. Sand results the turbine components erosion.

Giciye I tailrace middle point water

Total dry initial mass (g): 414.59

Fineness Modulus: 0.93

Gravel: 1

Sand: 96

Fine: 1

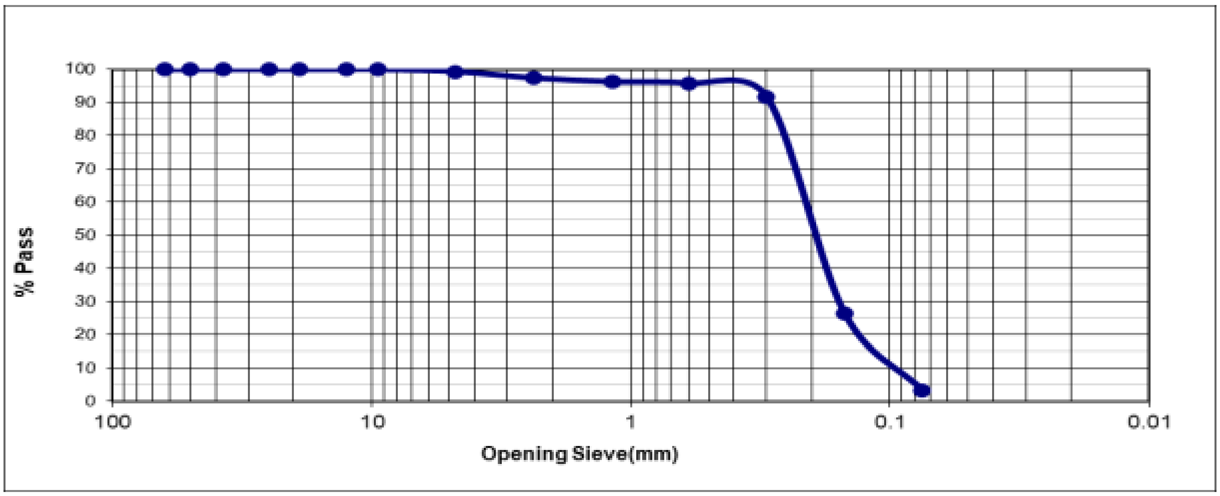


Figure 4. 5 Percentage pass vs sieve opening chart of Giciye tailrace middle point water

A total dry mass of 414.59g was taken at the middle point water of the tailrace of Giciye I hydropower plant was used as a sample to pass in the sieving test. The tests results showed that the sediment tested are composed by 1% gravel , 96% of sand and 1% of fine.

The figure 4.5 is the distribution curve which was used as a graphical representation of the data obtained during the seiving test.

These results showed that the Giciye river is having sediments which are dominated by sand.

The tested sediment are the one which are in the water that reaching the turbine and its components. Sand results the turbine components erosion.

Giciye I tailrace Bottom water

Total dry initial mass (g): 538.68

Fineness Modulus: 1.13

Gravel: 0

Sand: 98

Fine: 2

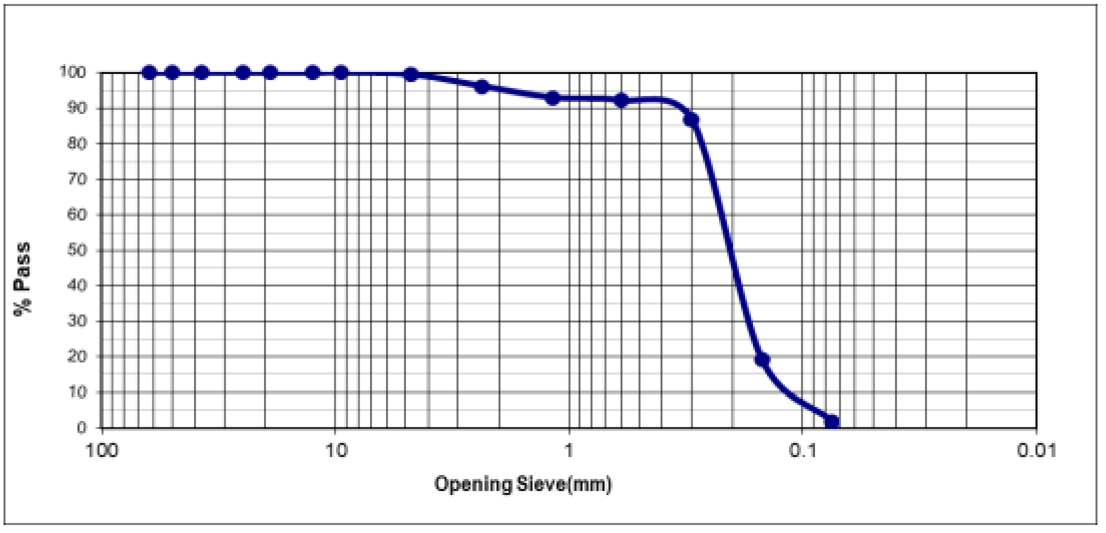


Figure 4. 6 Percentage pass vs sieve opening chart of Giciye tailrace bottom water

A total dry mass of 538.68g was taken at the bottom point water of the tailrace of Giciye I hydropower plant was used as a sample to pass in the sieving test. The tests results showed that the sediment tested are composed by 98% of sand and 2% of fine.

The figure 4.6 is the distribution curve which was used as a graphical representation of the data obtained during the seiving test.

These results showed that the Giciye river is having sediments which are dominated by sand.

The tested sediment are the one which are in the water that reaching the turbine and its components. Sand results the turbine components erosion.

SEBEYA intake surface (top) water

Total Dry initial Mass (g): 452.57

Fineness Modulus: 0.77

Gravel: 0

Sand: 94

Fine: 6

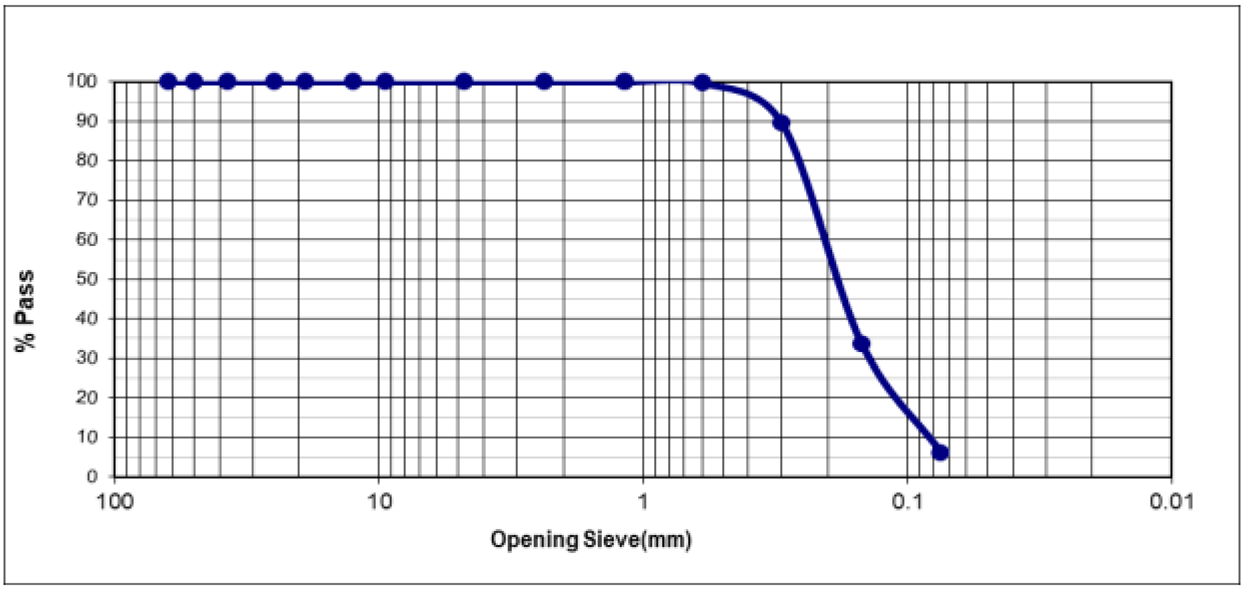


Figure 4. 7 Percentage pass vs sieve opening chart of Sebeya intake top water

A total dry mass of 452.57g was taken at the top water of the intake of Gihira hydropower plant was used as a sample to pass in the sieving test. The tests results showed that the sediment tested are composed by 94% sand and 6% of fine.

The figure 4.7 is the distribution curve which was used as a graphical representation of the data obtained during the seiving test.

These results showed that the Sebeya river is having sediments which are dominated by sand.

SEBEYA intake middle point water

Total dry initial mass (g): 537.79

Fineness Modulus: 0.79

Gravel: 0

Sand: 94

Fine: 6

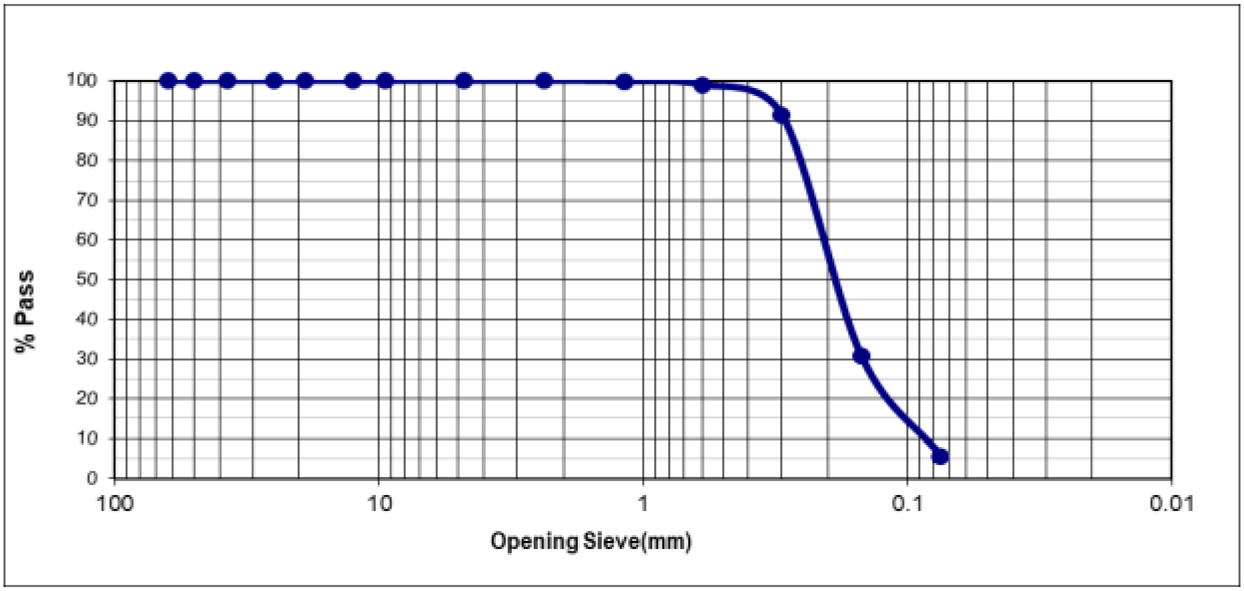


Figure 4. 8 Percentage pass vs sieve opening chart of Sebeya middle point water

A total dry mass of 537.79g was taken at the middle point water of the intake of Gihira hydropower plant was used as a sample to pass in the sieving test. The tests results showed that the sediment tested are composed by 94% sand and 6% of fine.

The figure 4.8 is the distribution curve which was used as a graphical representation of the data obtained during the seiving test.

These results showed that the Sebeya river is having sediments which are dominated by sand.

SEBEYA intake bottom water

Particle size analysis (ASTM D422)

Gravel: 0

Sand: 89

Fine: 11

Hydrometer: 151H

Test Temperature: 24°C

Meniscus correction Cm: 0

Reading in dispersant solution: -5

Particle density: 2.65

Viscosity of water: 0.8909

Dry initial weight(g): 0.00

Dry weight washing (g): 0

D10: 0.006

D30: 0.01

D60: 0.05

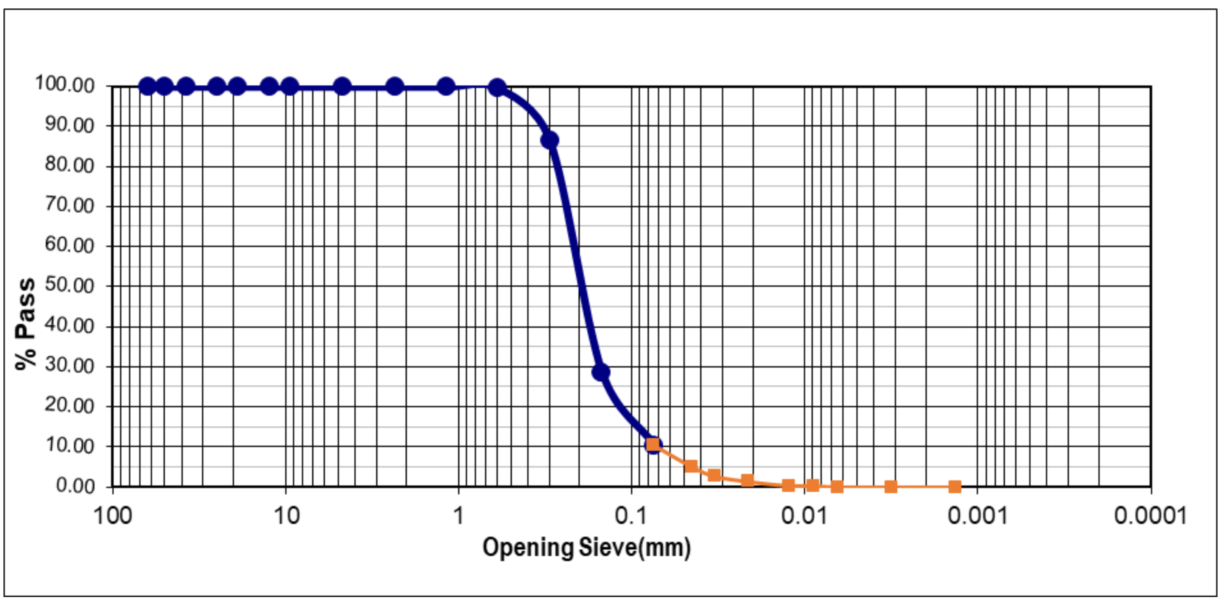


Figure 4. 9 Percentage pass vs sieve opening chart of Sebeya intake bottom water

A total dry mass of 444.33g was taken at the bottom point water of the intake of Gihira hydropower plant was used as a sample to pass in the sieving test, for deep analysis the sediments of size below 0.075mm were taken for hydrometer test. The tests results showed that the sediment tested are composed by 89% sand and 11% of fine.

The figure 4.9 is the distribution curve which was used as a graphical representation of the data obtained during the seiving test and hydrometer test.

These results showed that the Sebeya river is having sediments which are dominated by sand.

SEBEYA tailrace surface water

Particle size analysis (ASTM D422)

Gravel: 0

Sand: 77

Fine: 22

Hydrometer: 151H

Test Temperature: 24^{o}C

Meniscus correction Cm: 0

Reading in dispersant solution: -5

Particle density: 2.65

Viscosity of water: 0.8909

Dry initial weight(g): 0.00

Dry weight washing (g): 0

D10: 0.006

D30: 0.01

D60: 0.05

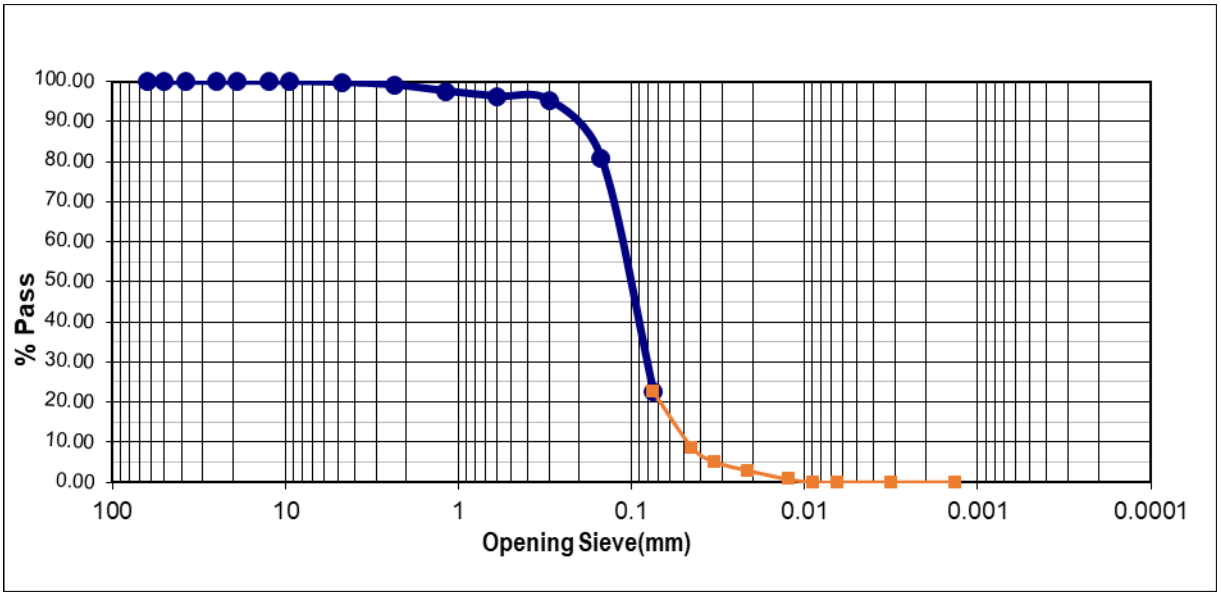


Figure 4. 10 Percentage pass vs sieve opening chart of Sebeya tailrace top water

A total dry mass of 459.32g was taken at the top point water of the tailrace of Gihira hydropower plant was used as a sample to pass in the sieving test, for deep analysis the sediments of size below 0.075mm were taken for hydrometer test. The tests results showed that the sediment tested are composed by 77% sand and 22% of fine.

The figure 4.10 is the distribution curve which was used as a graphical representation of the data obtained during the seiving test and hydrometer test.

These results showed that the Sebeya river is having sediments which are dominated by sand.

The tested sediment are the one which are in the water that reaching the turbine and its components. Sand results the turbine components erosion.

SEBEYA middle point water

Particle size analysis (ASTM D422)

Gravel: 0

Sand: 88

Fine: 11

Hydrometer: 151H

Test Temperature: 24^{o}C

Meniscus correction Cm: 0

Reading in dispersant solution: -5

Particle density: 2.65

Viscosity of water: 0.8909

Dry initial weight(g): 0.00

Dry weight washing (g): 0

D10: 0.006

D30: 0.01

D60: 0.05

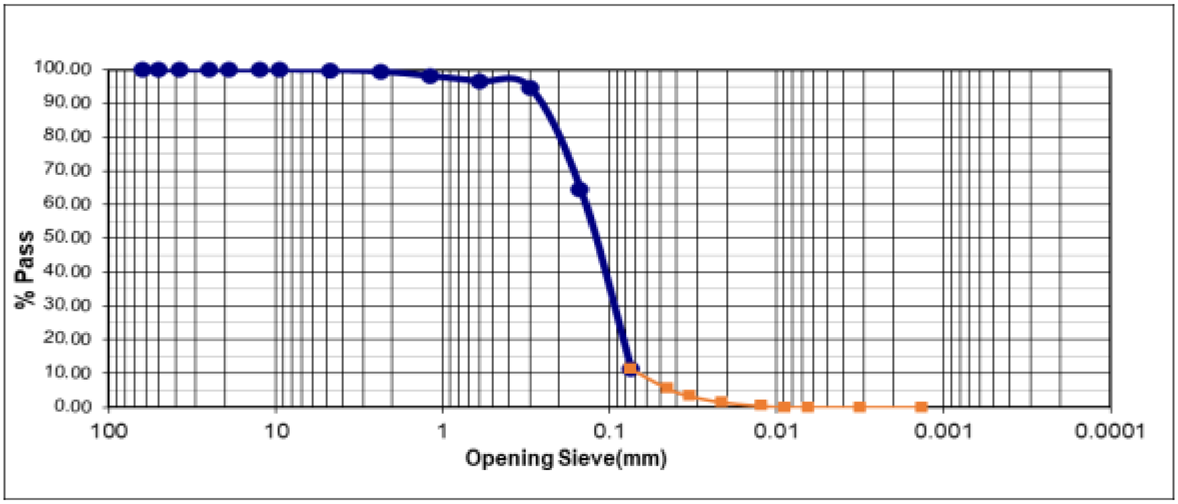


Figure 4. 11 Percentage pass vs sieve opening chart of Sebeya tailrace middle point water

A total dry mass of 605.11g was taken at the middle point water of the tailrace of Gihira hydropower plant was used as a sample to pass in the sieving test, for deep analysis the sediments of size below 0.075mm were taken for hydrometer test. The tests results showed that the sediment tested are composed by 88% sand and 11% of fine.

The figure 4.11 is the distribution curve which was used as a graphical representation of the data obtained during the seiving test and hydrometer test.

These results showed that the Sebeya river is having sediments which are dominated by sand.

The tested sediment are the one which are in the water that reaching the turbine and its components. Sand results the turbine components erosion.

SEBEYA bottom water

Particle size analysis (ASTM D422)

Gravel: 0

Sand: 89

Fine: 11

Hydrometer: 151H

Test Temperature: 24^{o}C

Meniscus correction Cm: 0

Reading in dispersant solution: -5

Particle density: 2.65

Viscosity of water: 0.8909

Dry initial weight(g): 0.00

Dry weight washing (g): 0

D10: 0.006

D30: 0.01

D60: 0.05

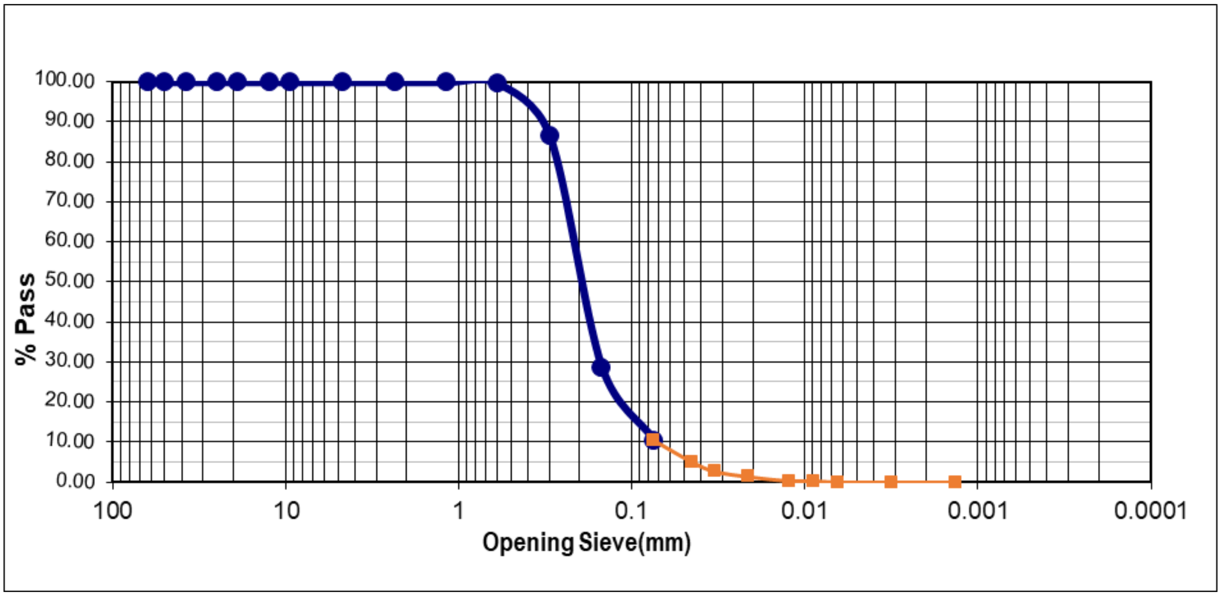


Figure 4. 12 Percentage pass vs sieve opening chart of Sebeya tailrace bottom water

A total dry mass of 444.33g was taken at the middle point water of the tailrace of Gihira hydropower plant was used as a sample to pass in the sieving test, for deep analysis the sediments of size below 0.075mm were taken for hydrometer test. The tests results showed that the sediment tested are composed by 88% sand and 11% of fine.

The figure 4.12 is the distribution curve which was used as a graphical representation of the data obtained during the seiving test and hyrometer test.

These results showed that the Sebeya river is having sediments which are dominated by sand.

The tested sediment are the one which are in the water that reaching the turbine and its components. Sand results the turbine components erosion.

b) Specific gravity test (ASTM D128)

Table 4. 1 Specific gravity test results

Sampled area	Specific gravity
Giciye I intake surface (top) water	2.654
Giciye I intake middle point water	2.655
Giciye I intake bottom water	2.670
Giciye I tailrace surface water	2.642
Giciye I tailrace middle point water	2.650
Giciye I tailrace bottom water	2.659
Sebeya intake surface water	2.715
Sebeya intake middle point water	2.722
Sebeya intake bottom water	7.731
Sebeya tailrace surface water	2.662
Sebeya tailrace middle point water	2.674
Sebeya bottom water	2.682

c) TSS test results (ASTM D3977-97)

Table 4. 2 Total suspended solids test results

Sample	Unit	Values
Sebeya intake (Gihira hpp)	mg/L	1760
Sebeya tailrace (Gihira hpp)	mg/L	9780
Giciye intake (Giciye I hpp)	mg/L	1380
Giciye tailrace (Giciye I hpp)	mg/L	1080

Table 4. 3 Summary of the laboratory test results and soil classification according to USCS (ASTM D2487)

	GICIYE I INTAKE BOTTOM WATER	GICIYE I INTAKE MIDDLE P WATER	GICIYE I INTAKE SURFACE(TOP)WATER	GICIYE I TAILRACE BOTTOM WATER	GICIYE I TAILRACE MIDDLE P WATER	GICIYE I TAILRACE SURFACE (TOP) WATER	SEBEYA INTAKE BOTTOM WATER	SEBEYA INTAKE MIDDLE P WATER	SEBEYA INTAKE SURFACE(TOP) WATER	SEBEYA TAILRACE BOTTOM WATER	SEBEYA TAILRACE MIDDLE P WATER	SEBEYA TAILRACE SURFACE(TOP)WATER
Gravel	7	14	1	0	1	0	0	0	0	2	0	0
Sand	92	85	98	98	96	96	89	94	94	83	88	77
Fine	0	0	1	2	3	4	11	6	6	15	11	22
D10	**0.4**	**0.3**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
D30	**0.8**	**1.1**	**0.5**	**0.2**	**0.2**	**0.2**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
D60	**1.7**	**2.3**	**1.1**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.1**	**0.1**	**0.1**
Cc	**1.0**	**1.5**	**1.0**	**1.1**	**1.1**	**1.1**	**1.3**	**1.1**	**1.0**	**1.3**	**1.4**	**1.2**
Cu	**4.8**	**6.7**	**5.4**	**2.2**	**2.3**	**2.4**	**2.9**	**2.5**	**2.6**	**2.7**	**2.9**	**2.5**
Symbol	**SP**	**SW**	**SP**	**SP**	**SP**	**SP**	**SP-SM**	**SP-SM**	**SP-SM**	**SM**	**SP-SM**	**SM**
Name	**Poorly graded sand**	**Well graded sand**	**Poorly graded sand**	**Poorly graded sand**	**Poorly graded sand**	**Poorly graded sand**	**Poorly graded sand with silt**	**Poorly graded sand with silt**	**Poorly graded sand with silt**	**Silty Sand**	**Poorly graded sand with silt**	**Silty Sand**
Gs	**2.670**	**2.655**	**2.654**	**2.659**	**2.650**	**2.642**	**2.731**	**2.722**	**2.715**	**2.682**	**2.675**	**2.662**

4.1.2 Laboratory test results discussions

For both Giciye I and Gihira hydropower plants, the laboratory test results of samples taken at different levels showed that the particles are of big size and with high solid suspension at the intake than the tailrace. The difference is explained by the installed decantation basins (sand trap) at both hydropower plants between their intake and the forebay tank.

According to what is written in technical documentation of those designed decantation basins, they must trap all particles of 0.3mm and above, whereas the laboratory test results showed that some particles of a diameter above 0.3mm are reaching the turbines of both hydropower plants.

According to sieving test analysis, the particles reaching the turbine at Giciye I hydropower plant are sand and fine, with 97% sand and 3% fine, and 84% sand and 16% fine at Gihira hydropower plant.

According to ASTM D 2487-17 which is the standard practice for classification of soils for Engineering purposes (unified soil classification system), the particles found are the following group:

- Well graded sand
- Poorly graded sand
- Poorly graded sand with silt
- Silty Sand

Erosive wear of hydro turbines is a complicated phenomenon that is influenced by a variety of factors including silt size, hardness and concentration, water velocity, and base material qualities. The erosion of the turbine's base material and parts causes a change in flow pattern, efficiency losses, vibrations, and consequently the failure of hydro turbines.

Other researchers have conducted similar research with different case studies and found the following:

Thapa et al. in [14] used a case study of the 60 MW Khimti hydropower plant to explore the impact of suspended sediments on hydropower projects. The hydroelectric plant was designed with settling basins to filter 85 percent of all particles with a fall diameter of 0.13 mm and 95 percent of all particles with a fall diameter of 0.20 mm due to the significant amount of sediments present. In July 2000, the hydropower plant was commissioned, after three years of operation (July, 2003), the investigation on the turbine components' damages was done.

The investigators noticed that the turbine bucket and needles had a significant level of degradation. Despite the settling basins' satisfactory performance, particles smaller than the design size flowed through the turbines, causing damage. The bucket thickness was lowered by around 1 mm near the bucket's root, which is significant in terms of strength and hence the component's reliability. Similarly, the bucket's splitter was degraded from its initial straight edge to a saw tooth shape.
Similarly, the bucket's splitter was degraded from its initial straight edge to a saw tooth shape.
The splitter's sharp edge had dulled, and the width had increased to around 4 mm, lowering the turbine's efficiency [14].

Yan investigated the effects of silt abrasion in various Chinese hydropower plants and came at the conclusion saying that abrasion is considerable for all particles smaller than 0.05 mm, but risen dramatically for larger size particles [16].

During his research, Pradhan noticed that the traditional design criteria for trapping 0.2 mm size sediment particles in run-of-river hydropower plants in steep sediment-laden rivers did not appear to work satisfactorily. In general, projects suffered from severe erosion caused by silt, which resulted in damage to runners [17].
Other researchers in the field found that abrasion is considerable for all particles smaller than 0.05 mm, but risen dramatically for larger size particles [16],

According to the particles laboratory test results and in comparison in similar studies, the turbines and their components of both Giciye I and Gihira hydropower plants are experiencing sediment erosion, which is caused by strong turbulence in the high jet velocity, which causes the particles to oscillate and rotate in circles, causing collisions with the steel.

4.1.3 Classification of turbine erosion in Giciye I and Gihira hydropower plants

For classifying and analyzing the turbine erosion, a visual check at different parts of the turbines and photos were taken for deep analysis.

4.1.3.1 Giciye I hydropower plant

Giciye I hydropower plant is a runner of river hydropower plant located in Rwanda, Western Province, Nyabihu District, Rurembo Sector. The hydropower plant is in operation since 5th June, 2014 with installed capacity of 4 MW. Currently is working with two vertical Pelton turbines.

The following are important technical parameters:

Types of turbines: Vertical Pelton turbine

Gross Head: 127 m

Net head: 124.85 m

Design Flow: 4 m^3/s

Penstock water pressure reaching the turbine: 12.48 bars

Penstock length: 341 m

Penstock pipe type: steel pipe

Generator type: Synchronous

Number of turbines: 2

As said above the plant is in operation since June, 2014. However, the runner, nozzles, nozzle bars and other accessories were damaged and replaced by other with HVOF coating after one year and half of operation due to sediment erosion and cavitation.

The following photos are showing the combined effect of sediment erosion and cavitation to runner, and nozzles after 5 years of operation:

Picture 4.1 Combined effect of sediment erosion and cavitation to the runner blades

Picture 4.2 Combined effect of sediment erosion and cavitation to the turbine nozzles

The analysis for classifying the erosion in Giciye I hydropower plant was done by taking reference to the following table:

Table 4. 4 Turbine erosion classification [10].

S/N	Type	Description
1	Mettalic luster	Shining surface with no traces of paint, scale or rust
2	Fine scaly erosion	Surface with rare, separately located and skin-deep minute scales
3	Scale erosion	Surface entirely covered with skin-deep fine scale
4	Large-sized scaly erosion	Surface entirely covered with deep and enlarged scales
5	In-depth erosion	Surface covered with deep and long channels
6	Through hole	Erosion of entire material

By taking reference to the above table 4.4, in Giciye I hydropower plant, runner blades are facing a fine scaly erosion whereas nozzles are facing through hole erosion

4.1.3.2 GIHIRA Hydropower plant

Gihira hydropower plant is on Sebeya river and it is located in Rwanda, Western Province, Rubavu District, Rugerero Sector. It is a runner of river hydropower plant which is in operation since 1986 with installed capacity of 1.8 MW. Gihira hydropower plant was handed over to an independent power producer called Rwanda Mountain Tea on 25th September, 2015 through a concession agreement signed between RMT and EUCL. From 8th August, 2017 until 24th October, 2017, RMT did renovation of Gihira hydropower plant, including the change of electromechanical equipment. The power plant has two installed horizontal Francis turbine.

The following are important technical parameters of Gihira hydropower plant:

Installed capacity: 1.8Mw

Types of turbines: Horizontal Francis turbine

Gross Head: 66.1m

Net head: 63.45m

Design Flow: 3.2 m^3/s

Penstock water pressure reaching the turbine: 6.34 bars

Penstock length: 185 m

Penstock pipe type: underground steel pipe

Generator type: Synchronous

Number of turbines: 2

The following pictures are showing the combined effect of sediment erosion and cavitation of runner, wicked gates and sealing rings after 3 years and half of operation:

Picture 4.3 Combined effect of sediment erosion and cavitation to runner status

Picture 4.4 Combined effect of sediment erosion and cavitation to wicked gates

Picture 4.5 Combined effect of sand erosion and cavitation to sealing ring

According to what have been seen during the turbine technical inspection and the information from the table 4.4, runner blades, wicked gates and sealing rings of Gihira I hydropower plant are facing a fine scaly erosion.

Using laboratory testing method and visual testing methods, all confirmed that the turbines are facing sediment erosion effect.

4. 2 Combined effect of sediment erosion and cavitation

The combined effects of sediment erosion and cavitation in hydraulic turbine are of two types, hydraulic effects and mechanical effects. The major hydraulic effect is a low turbine efficiency due to water flow instability whereas mechanical effects are vibration, noises and surface erosion. For identifying the combined effects, a case study of Giciye I hydropower plant was taken. Water flow, active power, vibration and unit sound were recorded in a period of one month.

The following are the data recorded:

Table 4. 5 Unit 2 data recorded after one month of operation (Giciye I hydropower plant)

Days	**Water flow (m^3/s)**	**Active Power (Kw) after 1 month of operation**	**vibration (mm/s) after 1 month of operation**	**sound meter (dB) after 1 month of operation**
Day 1	1.62	1620	1.3	65
Day 2	1.7	1700	1.4	67
Day 3	1.69	1690	1.3	67
Day 4	1.67	1670	1.3	66
Day 5	1.67	1670	1.3	66
Day 6	1.65	1650	1.2	66
Day 7	1.6	1600	1.3	65
Day 8	1.67	1670	1.3	66
Day 9	1.69	1690	0.3	67
Day 10	1.69	1690	1.3	67
Day 11	1.58	1580	1.1	63
Day 12	1.59	1590	1.1	65
Day 13	1.59	1590	1.1	65
Day 14	1.69	1690	1.3	67
Day 15	1.58	1580	1.3	65

Day 16	1.59	1590	1.3	65
Day 17	1.58	1580	1.3	64
Day 18	1.69	1690	1.3	67
Day 19	1.67	1670	1.2	68
Day 20	1.59	1590	1.1	65
Day 21	1.58	1580	1.1	64
Day 22	1.59	1590	1.1	65
Day 23	1.58	1580	1.1	64
Day 24	1.69	1690	1.3	67
Day 25	1.79	1790	1.5	69
Day 26	1.8	1800	1.5	70
Day 27	1.9	1900	1.6	72
Day 28	1.92	1920	1.6	72
Day 29	1.9	1900	1.6	72
Day 30	1.8	1800	1.5	70
Day 31	1.9	1900	1.6	72

Table 4. 6 Unit 2 data recorded after 5 years of operation (Giciye I hydropower plant)

Days	Water flow (m^3/s)	Active Power (Kw) after 5 year of operation	vibration (mm/s) after 5 year of operation	sound meter (dB)after 5 year of operation
Day 1	1.62	1570	4	80
Day 2	1.7	1610	4.1	82
Day 3	1.69	1600	4	81
Day 4	1.67	1590	3.9	80
Day 5	1.67	1590	4	80
Day 6	1.65	1570	3.9	80
Day 7	1.6	1530	3.8	78
Day 8	1.67	1590	4	80
Day 9	1.69	1600	4.1	80
Day 10	1.69	1600	4.1	81
Day 11	1.58	1500	3.7	78
Day 12	1.59	1550	3.9	79
Day 13	1.59	1560	3.9	80
Day 14	1.69	1590	4	81
Day 15	1.58	1500	3.6	77
Day 16	1.59	1550	3.7	78
Day 17	1.58	1500	3.6	77
Day 18	1.69	1600	3.1	81
Day 19	1.67	1590	4	80
Day 20	1.59	1550	3.8	79
Day 21	1.58	1500	3.6	77
Day 22	1.59	1550	3.8	78
Day 23	1.58	1500	3.6	77
Day 24	1.69	1600	4	80
Day 25	1.79	1700	4.1	83
Day 26	1.8	1750	4.2	84
Day 27	1.9	1800	4.3	86
Day 28	1.92	1850	4.5	87
Day 29	1.9	1800	4.3	86
Day 30	1.8	1750	4.2	84
Day 31	1.9	1800	4.3	86

The above data in tale 4.5 and table 4.6 were recorded on hourly basis and a daily average was calculated and presented in the table.

4.2.1 Power production loss

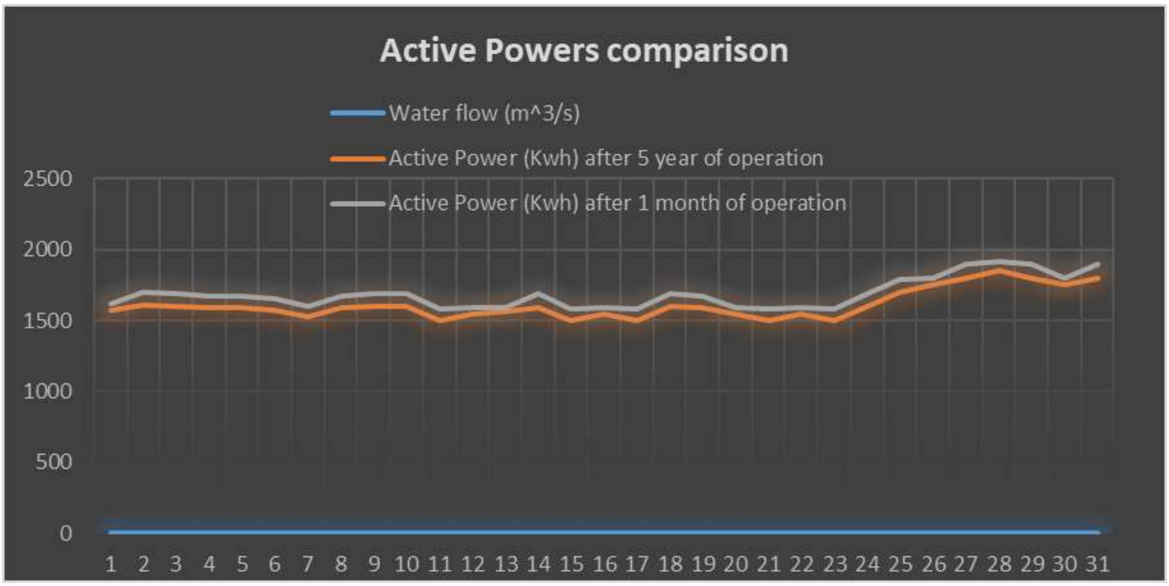


Figure 4. 13 Active powers production comparison

By comparing the active power production after one-month hydropower plant operation with the one after 5 year of operation, it is found that with the same water flow, the active power is decrease by 4.5% due to the combined sediment erosion and cavitation. This mean that the annual production energy is decreased by 4.5% which is a significant economic loss to the power plant owners.

4.2.2 Vibration

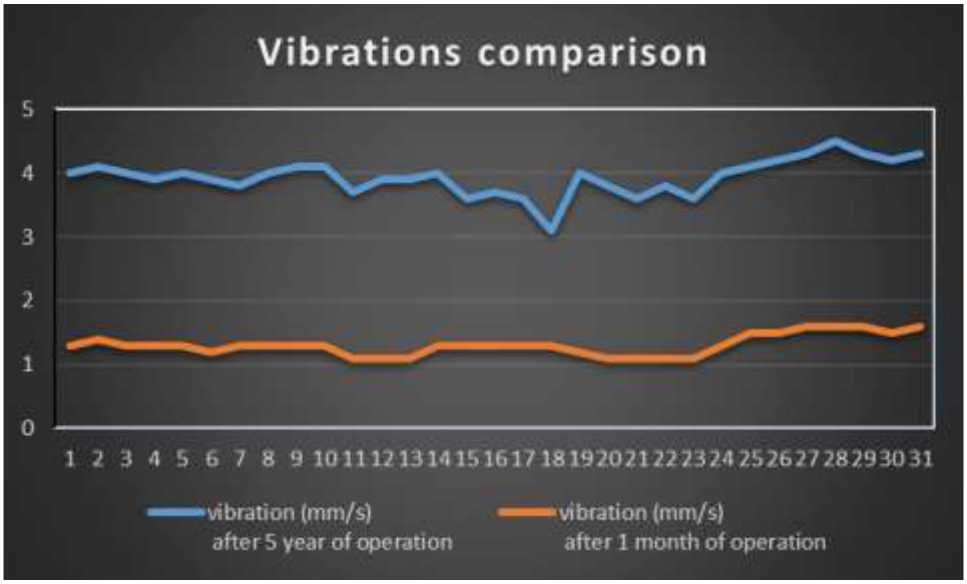


Figure 4. 14 Vibrations comparison

By comparing the vibration after one-month hydropower plant operation with the one after 5 year of operation, it is found that, the vibration is increased by 203%. There are many factors which should contribute to the increment of vibration such as damage of bearings, insufficient clearance between stationary and rotating parts but the major factor is extreme force fluctuations caused by cavitation and sediment erosion.

Vibrations contribute to the decrement of the life span of the turbine and its accessories without forgetting their contribution to the repetitive breakdowns of the turbines parts. You cannot avoid completely the vibration in hydraulic turbines but it should be minimized.

4.2.3 Noises

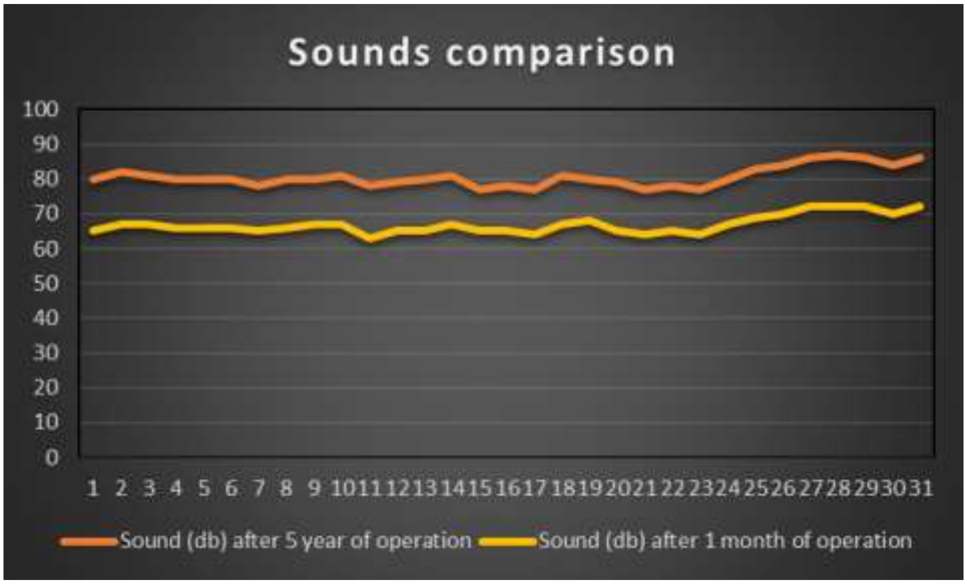


Figure 4. 15 comparison of sound

By comparing the sound after one-month hydropower plant operation with the one after 5 year of operation, it is found that, the sound/noises is increased by 20%.

The noise is primarily produced by the turbine blades moving through the water. This results in a swishing sound, as well as noise from the turbine machinery, that is synchronized to the rotation of the blades. The extreme force fluctuations caused by cavitation and sediment erosion increases the turbine sound/ noises.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The investigation's results shown that turbine components are subjected to a combined effect of sediments erosion and cavitation especially in high sediments loaded rivers. Surface roughness due to sediment erosion in high velocity regions might cause cavitation erosion in a cavitation free geometries.

Combined effect of sediment erosion in hydro turbines cannot be totally avoided, however it can be minimized to a certain level that is economically acceptable. Many researchers have used experimental and analytical studies to independently investigate the sediments erosion effects and cavitation effects in hydro turbines. Few studies on the combined effect of sediments erosion and cavitation with typical case studies were conducted.

Despite design changes in turbine components and the use of coating materials on turbine components, some investigators have concluded by saying that the improvement in most situations is not considerable. Therefore, further experimental and theoretical research is needed for a deep investigation on the combined effect of sediment erosion and cavitation and draw possible and sustainable solutions for those effects.

5.2 Recommendations

Sediments characteristics in the river are changing with seasons, for deep sediment analysis I recommend for future researchers to take water samples during rainy seasons and dry seasons so that they can make a comparison in order to have a good analysis and sediments classification.

Future researchers are also recommended to increase the active power, water flow, noises and vibration recording time from one month to one year for being able to analyze the combined effect of sediment erosion and cavitation at different stage of production caused by the river flow fluctuation along the whole year.

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Appendices

1. Table of sieve test of Giciye I intake surface water

ASTM	Sieve opening (mm)	Partial retained Weight (g)	Cumulative Refusal Weight (g)	% retained	% Pass	% Partial retained
2.1/2"	**63**	0	0.0	0	100	0
2"	**50**	0	0.0	0	100	0
1.1/2"	**37.5**	0	0.0	0	100	0
1"	**25**	0	0.0	0	100	0
3/4"	**19**	0	0.0	0	100.00	0
1/2"	**12.5**	0	0.0	0	100.00	0.00
3/8"	**9.5**	0	0.0	0	100.00	0.00
4	**4.75**	0	6.0	1	98.95	0.00
10	**2.36**	0	67.2	12	88.18	0.00
16	**1.18**	0.4	219.5	39	61.39	0.07
30	**0.6**	7.6	357.8	63	37.07	1.34
50	**0.3**	404.7	465.2	82	18.18	71.18
100	**0.15**	384.4	546.0	96	3.97	67.61
200	**0.075**	24.1	565.6	99	**0.52**	4.24
Pan		**5.6**	568.5	100	0.00	0.98

2. Table of sieve test of Giciye I intake middle point water

ASTM	Sieve opening (mm)	Partial retained Weight (g)	Cumulative Refusal Weight (g)	% retained	% Pass	% Partial retained
2.1/2"	**63**	0	0.0	0	100	0
2"	**50**	0	0.0	0	100	0
1.1/2"	**37.5**	0	0.0	0	100	0
1"	**25**	0	0.0	0	100	0
3/4"	**19**	0	0.0	0	100.00	0
1/2"	**12.5**	0	7.4	1	99.02	0.00
3/8"	**9.5**	0	22.9	3	97.00	0.00
4	**4.75**	0	109.3	14	85.67	0.00
10	**2.36**	0	290.3	38	61.92	0.00
16	**1.18**	0.4	511.8	67	32.88	0.05
30	**0.6**	7.6	632.1	83	17.09	1.00
50	**0.3**	404.7	694.5	91	8.91	53.08
100	**0.15**	384.4	750.5	98	1.57	50.42
200	**0.075**	24.1	760.7	100	**0.22**	3.16
Pan		**5.6**	762.4	100	0.00	0.73

3. Table of sieve test of Giciye I intake bottom water

ASTM	Sieve opening (mm)	Partial retained Weight (g)	Cumulative Refusal Weight (g)	% retained	% Pass	% Partial retained
2.1/2"	**63**	0	0.0	0	100	0
2"	**50**	0	0.0	0	100	0
1.1/2"	**37.5**	0	0.0	0	100	0
1"	**25**	0	0.0	0	100	0
3/4"	**19**	0	0.0	0	100.00	0
1/2"	**12.5**	0	1.8	0	99.79	0.00
3/8"	**9.5**	0	11.4	1	98.66	0.00
4	**4.75**	0	61.1	7	92.78	0.00
10	**2.36**	0	198.7	23	76.51	0.00
16	**1.18**	0.4	445.2	53	47.37	0.05
30	**0.6**	7.6	655.6	77	22.51	0.90
50	**0.3**	404.7	783.3	93	7.41	47.84
100	**0.15**	384.4	834.8	99	1.33	45.44
200	**0.075**	24.1	842.3	100	**0.44**	2.85
Pan		**5.6**	846.0	100	0.00	0.66

4. Table of sieve test of Giciye I tailrace surface water

ASTM	Sieve opening (mm)	Partial retained Weight (g)	Cumulative Refusal Weight (g)	% retained	% Pass	% Partial retained
2.1/2"	**63**	0	0.0	0	100	0
2"	**50**	0	0.0	0	100	0
1.1/2"	**37.5**	0	0.0	0	100	0
1"	**25**	0	0.0	0	100	0
3/4"	**19**	0	0.0	0	100.00	0
1/2"	**12.5**	0	0.0	0	100.00	0.00
3/8"	**9.5**	0	0.0	0	100.00	0.00
4	**4.75**	0	0.0	0	100.00	0.00
10	**2.36**	0	5.4	1	98.78	0.00
16	**1.18**	0.4	7.9	2	98.22	0.09
30	**0.6**	7.6	9.7	2	97.80	1.72
50	**0.3**	404.7	29.0	7	93.44	91.54
100	**0.15**	384.4	314.6	71	28.85	86.95
200	**0.075**	24.1	426.1	96	**3.61**	5.45
Pan		**5.6**	442.1	100	0.00	1.27

5. Table of sieve test of Giciye I tailrace middle point water

ASTM	Sieve opening (mm)	Partial retained Weight (g)	Cumulative Refusal Weight (g)	% retained	% Pass	% Partial retained
2.1/2"	**63**	0	0.0	0	100	0
2"	**50**	0	0.0	0	100	0
1.1/2"	**37.5**	0	0.0	0	100	0
1"	**25**	0	0.0	0	100	0
3/4"	**19**	0	0.0	0	100.00	0
1/2"	**12.5**	0	0.0	0	100.00	0.00
3/8"	**9.5**	0	0.0	0	100.00	0.00
4	**4.75**	0	2.7	1	99.36	0.00
10	**2.36**	0	11.0	3	97.35	0.00
16	**1.18**	0.4	15.5	4	96.27	0.10
30	**0.6**	7.6	17.5	4	95.77	1.83
50	**0.3**	404.7	34.3	8	91.74	97.61
100	**0.15**	384.4	305.0	74	26.44	92.72
200	**0.075**	24.1	401.0	97	**3.27**	5.81
Pan		**5.6**	414.6	100	0.00	1.35

6. Table of sieve test of Giciye I tailrace bottom water

ASTM	Sieve opening (mm)	Partial retained Weight (g)	Cumulative Refusal Weight (g)	% retained	% Pass	% Partial retained
2.1/2"	**63**	0	0.0	0	100	0
2"	**50**	0	0.0	0	100	0
1.1/2"	**37.5**	0	0.0	0	100	0
1"	**25**	0	0.0	0	100	0
3/4"	**19**	0	0.0	0	100.00	0
1/2"	**12.5**	0	0.0	0	100.00	0.00
3/8"	**9.5**	0	0.0	0	100.00	0.00
4	**4.75**	0	2.6	0	99.52	0.00
10	**2.36**	0	20.7	4	96.17	0.00
16	**1.18**	0.4	37.8	7	92.98	0.07
30	**0.6**	7.6	42.3	8	92.16	1.41
50	**0.3**	404.7	71.3	13	86.77	75.13
100	**0.15**	384.4	436.0	81	19.07	71.36
200	**0.075**	24.1	528.4	98	**1.90**	4.47
Pan		**5.6**	538.7	100	0.00	1.04

7. Table of sieve test of Sebeya intake surface water

ASTM	Sieve opening (mm)	Partial retained Weight (g)	Cumulative Refusal Weight (g)	% retained	% Pass	% Partial retained
2.1/2"	**63**	0	0.0	0	100	0
2"	**50**	0	0.0	0	100	0
1.1/2"	**37.5**	0	0.0	0	100	0
1"	**25**	0	0.0	0	100	0
3/4"	**19**	0	0.0	0	100.00	0
1/2"	**12.5**	0	0.0	0	100.00	0.00
3/8"	**9.5**	0	0.0	0	100.00	0.00
4	**4.75**	0	0.0	0	100.00	0.00
10	**2.36**	0	0.0	0	100.00	0.00
16	**1.18**	0.4	0.0	0	100.00	0.09
30	**0.6**	7.6	1.4	0	99.68	1.68
50	**0.3**	404.7	47.3	10	89.56	89.42
100	**0.15**	384.4	299.5	66	33.83	84.94
200	**0.075**	24.1	424.2	94	**6.27**	5.33
Pan		**5.6**	452.6	100	0.00	1.24

8. Table of sieve test of Sebeya intake middle point water

ASTM	Sieve opening (mm)	Partial retained Weight (g)	Cumulative Refusal Weight (g)	% retained	% Pass	% Partial retained
2.1/2"	**63**	0	0.0	0	100	0
2"	**50**	0	0.0	0	100	0
1.1/2"	**37.5**	0	0.0	0	100	0
1"	**25**	0	0.0	0	100	0
3/4"	**19**	0	0.0	0	100.00	0
1/2"	**12.5**	0	0.0	0	100.00	0.00
3/8"	**9.5**	0	0.0	0	100.00	0.00
4	**4.75**	0	0.0	0	100.00	0.00
10	**2.36**	0	0.0	0	100.00	0.00
16	**1.18**	0.4	0.9	0	99.83	0.07
30	**0.6**	7.6	5.5	1	98.98	1.41
50	**0.3**	404.7	46.4	9	91.36	75.25
100	**0.15**	384.4	372.4	69	30.76	71.48
200	**0.075**	24.1	507.1	94	**5.70**	4.48
Pan		**5.6**	537.8	100	0.00	1.04

9. Table of sieve and hydrometer test of Sebeya intake bottom water

ASTM	Sieve opening (mm)	Partial retained Weight (g)	Cumulative Refusal Weight (g)	% retained	% Pass	% Partial retained
2.1/2"	**63**	0	0	0.00	100.00	**0**
2"	**50**	0	0	0.00	100.00	**0.00**
1.1/2"	**37.5**	0	0	0.00	100.00	**0.00**
1"	**25**	0	0	0.00	100.00	**0.00**
3/4"	**19**	0	0	0.00	100.00	**0.00**
1/2"	**12.5**	0	0	0.00	100.00	**0.00**
3/8"	**9.5**	0	0	0.00	100.00	**0.00**
4	**4.75**	0	0	0.00	100.00	**0.00**
8	**2.36**	0	0	0.00	100.00	**0.00**
16	**1.18**	0	0	0.00	100.00	**0.00**
30	**0.6**	1.27	1.27	0.29	99.71	**0.29**
50	**0.3**	57.76	59.03	13.29	86.71	**13.00**
100	**0.15**	257.35	316.38	71.20	28.80	**57.92**
200	**0.075**	81.22	397.6	89.48	10.52	**18.28**
Font		46.73	444.33	100.00	0.00	**10.52**
			3.21		K	**0.01301**

Time (min)	Hydrometer Reading R'h	True Reading Rh	Effective depth L (cm)	Correct Hydrometer Reading R	% of Soil in suspension	Diameter (mm)
					10.52	**0.075**
1	21	21.0	11.9	16.0	5.067262	**0.0449**
2	14	14.0	12.9	9.0	2.702540	**0.0330**
5	10	10.0	13.2	5.0	1.351270	**0.0211**
15	7	7.0	13.5	2.0	0.337817	**0.0123**
30	7	7.0	14.2	2.0	0.337817	**0.0090**
60	6	6.0	14.7	1.0	0.000000	**0.0064**
250	6	6.0	14.8	1.0	0.000000	**0.0032**
1440	6	6.0	15.2	1.0	0.000000	**0.0013**

10. Table of sieve and hydrometer test of Sebeya tailrace surface water

ASTM	Sieve opening (mm)	Partial retained Weight (g)	Cumulative Refusal Weight (g)	% retained	% Pass	% Partial retained
2.1/2"	**63**	0	0	0.00	100.00	**0**
2"	**50**	0	0	0.00	100.00	**0.00**
1.1/2"	**37.5**	0	0	0.00	100.00	**0.00**
1"	**25**	0	0	0.00	100.00	**0.00**
3/4"	**19**	0	0	0.00	100.00	**0.00**
1/2"	**12.5**	0	0	0.00	100.00	**0.00**
3/8"	**9.5**	0	0	0.00	100.00	**0.00**
4	**4.75**	1.3	1.3	0.28	99.72	**0.28**
8	**2.36**	2.77	4.07	0.89	99.11	**0.60**
16	**1.18**	7.27	11.34	2.47	97.53	**1.58**
30	**0.6**	5.83	17.17	3.74	96.26	**1.27**
50	**0.3**	4.33	21.5	4.68	95.32	**0.94**
100	**0.15**	66.95	88.45	19.26	80.74	**14.58**
200	**0.075**	267.57	356.02	77.51	22.49	**58.25**
Font		103.30	459.32	100.00	0.00	**22.49**
			3.21		K	**0.01301**

Time (min)	Hydrometer Reading R'h	True Reading Rh	Effective depth L (cm)	Correct Hydrometer Reading R	% of Soil in suspension	Diameter (mm)
					22.49	**0.075**
1	18	18.0	11.9	13.0	8.668783	**0.0449**
2	13	13.0	12.9	8.0	5.056790	**0.0330**
5	10	10.0	13.2	5.0	2.889594	**0.0211**
15	7	7.0	13.5	2.0	0.722399	**0.0123**
30	6	6.0	14.2	1.0	0.000000	**0.0090**
60	6	6.0	14.7	1.0	0.000000	**0.0064**
250	6	6.0	14.8	1.0	0.000000	**0.0032**
1440	6	6.0	15.2	1.0	0.000000	**0.0013**

11. Table of sieve and hydrometer test of Sebeya tailrace middle point water

ASTM	**Sieve opening (mm)**	**Partial retained Weight (g)**	**Cumulative Refusal Weight (g)**	**% retained**	**% Pass**	**% Partial retained**
2.1/2"	**63**	0	0	0.00	100.00	**0**
2"	**50**	0	0	0.00	100.00	**0.00**
1.1/2"	**37.5**	0	0	0.00	100.00	**0.00**
1"	**25**	0	0	0.00	100.00	**0.00**
3/4"	**19**	0	0	0.00	100.00	**0.00**
1/2"	**12.5**	0	0	0.00	100.00	**0.00**
3/8"	**9.5**	0	0	0.00	100.00	**0.00**
4	**4.75**	1.14	1.14	0.19	99.81	**0.19**
8	**2.36**	2.35	3.49	0.58	99.42	**0.39**
16	**1.18**	8.62	12.11	2.00	98.00	**1.42**
30	**0.6**	9.34	21.45	3.54	96.46	**1.54**
50	**0.3**	11.19	32.64	5.39	94.61	**1.85**
100	**0.15**	181.47	214.11	35.38	64.62	**29.99**
200	**0.075**	322	536.11	88.60	11.40	**53.21**
Font		69.00	605.11	100.00	0.00	**11.40**
			3.21		K	**0.01301**

Time (min)	**Hydrometer Reading R'h**	True Reading Rh	Effective depth L (cm)	Correct Hydrometer Reading R	% of Soil in suspension	**Diameter (mm)**
					11.40	**0.075**
1	21	21.0	11.9	16.0	5.494118	**0.0449**
2	15	15.0	12.9	10.0	3.296471	**0.0330**
5	10	10.0	13.2	5.0	1.465098	**0.0211**
15	7	7.0	13.5	2.0	0.366275	**0.0123**
30	6	6.0	14.2	1.0	0.000000	**0.0090**
60	6	6.0	14.7	1.0	0.000000	**0.0064**
250	6	6.0	14.8	1.0	0.000000	**0.0032**
1440	6	6.0	15.2	1.0	0.000000	**0.0013**

12. Table of sieve and hydrometer test of Sebeya tailrace bottom water

ASTM	Sieve opening (mm)	Partial retained Weight (g)	Cumulative Refusal Weight (g)	% retained	% Pass	% Partial retained
2.1/2"	**63**	0	0	0.00	100.00	**0**
2"	**50**	0	0	0.00	100.00	**0.00**
1.1/2"	**37.5**	0	0	0.00	100.00	**0.00**
1"	**25**	0	0	0.00	100.00	**0.00**
3/4"	**19**	0	0	0.00	100.00	**0.00**
1/2"	**12.5**	0	0	0.00	100.00	**0.00**
3/8"	**9.5**	0	0	0.00	100.00	**0.00**
4	**4.75**	0	0	0.00	100.00	**0.00**
8	**2.36**	0	0	0.00	100.00	**0.00**
16	**1.18**	0	0	0.00	100.00	**0.00**
30	**0.6**	1.27	1.27	0.29	99.71	**0.29**
50	**0.3**	57.76	59.03	13.29	86.71	**13.00**
100	**0.15**	257.35	316.38	71.20	28.80	**57.92**
200	**0.075**	81.22	397.6	89.48	10.52	**18.28**
Font		46.73	444.33	100.00	0.00	**10.52**
			3.21		K	**0.01301**

Time (min)	Hydrometer Reading R'h	True Reading Rh	Effective depth L (cm)	Correct Hydrometer Reading R	% of Soil in suspension	Diameter (mm)
					10.52	**0.075**
1	21	21.0	11.9	16.0	5.067262	**0.0449**
2	14	14.0	12.9	9.0	2.702540	**0.0330**
5	10	10.0	13.2	5.0	1.351270	**0.0211**
15	7	7.0	13.5	2.0	0.337817	**0.0123**
30	7	7.0	14.2	2.0	0.337817	**0.0090**
60	6	6.0	14.7	1.0	0.000000	**0.0064**
250	6	6.0	14.8	1.0	0.000000	**0.0032**
1440	6	6.0	15.2	1.0	0.000000	**0.0013**

13. Table of specific gravity of Giciye I intake surface (top) water

Test number	**1**	**2**	**3**
Mass of Pycnometer (g)	162.70	171.30	172.90
Mass of the pycnometer and water	657.30	665.90	667.40
Temperature (°C)	20.1	20.1	20.1
Density of water (g/mL)	0.99819	0.99819	0.99819
Temperature Coefficient (K)	0.99998	0.99998	0.99998
Volume of Pycnometer	495.4968	495.4968	495.3967
Mass of oven dry specimen	59.70	58.80	60.10
Mass of pycnometer, water, and soil solids (g)	694.50	702.50	704.90
Specific gravity at soil solids the test temperature	2.653	2.649	2.659
Specific gravity of soil solids at 20°C	2.653	2.649	2.659
Average Specific Gravity	**2.654**		

14. Table of specific gravity of Giciye I intake middle point water

Test number	**1**	**2**	**3**
Mass of Pycnometer (g)	166.80	184.70	174.40
Mass of the pycnometer and water	660.50	679.10	667.80
Temperature (°C)	20.1	20.1	20.1
Density of water (g/mL)	0.99819	0.99819	0.99819
Temperature Coefficient (K)	0.99998	0.99998	0.99998
Volume of Pycnometer	494.5952	495.2965	494.2947
Mass of oven dry specimen	59.50	59.80	59.90
Mass of pycnometer, water, and soil solids (g)	697.50	716.40	705.20
Specific gravity at soil solids the test temperature	2.644	2.658	2.662
Specific gravity of soil solids at 20°C	2.644	2.658	2.662
Average Specific Gravity	**2.655**		

15. Table of specific gravity of Giciye I intake bottom water

Test number	**1**	**2**	**3**
Mass of Pycnometer (g)	184.40	165.50	172.90
Mass of the pycnometer and water	679.20	660.10	667.40
Temperature (°C)	20.1	20.1	20.1
Density of water (g/mL)	0.99819	0.99819	0.99819
Temperature Coefficient (K)	0.99998	0.99998	0.99998
Volume of Pycnometer	495.6972	495.4968	495.3967
Mass of oven dry specimen	59.80	59.80	60.10
Mass of pycnometer, water, and soil solids (g)	716.80	697.40	704.90
Specific gravity at soil solids the test temperature	2.694	2.658	2.659
Specific gravity of soil solids at 20°C	2.694	2.658	2.659
Average Specific Gravity	**2.670**		

16. Table of specific gravity of Giciye I tailrace surface water

Test number	**1**	**2**	**3**
Mass of Pycnometer (g)	165.10	184.10	171.80
Mass of the pycnometer and water	660.70	667.60	665.80
Temperature (°C)	20.1	20.1	20.1
Density of water (g/mL)	0.99819	0.99819	0.99819
Temperature Coefficient (K)	0.99998	0.99998	0.99998
Volume of Pycnometer	496.4987	484.3767	494.8958
Mass of oven dry specimen	59.90	60.50	60.30
Mass of pycnometer, water, and soil solids (g)	697.80	705.00	703.60
Specific gravity at soil solids the test temperature	2.627	2.619	2.680
Specific gravity of soil solids at 20°C	2.627	2.619	2.680
Average Specific Gravity	**2.642**		

17. Table of specific gravity of Giciye I tailrace middle point water

Test number	**1**	**2**	**3**
Mass of Pycnometer (g)	161.50	171.50	170.50
Mass of the pycnometer and water	657.40	667.30	665.90
Temperature (°C)	20.1	20.1	20.1
Density of water (g/mL)	0.99819	0.99819	0.99819
Temperature Coefficient (K)	0.99998	0.99998	0.99998
Volume of Pycnometer	496.7992	496.699	496.2983
Mass of oven dry specimen	59.90	60.40	59.60
Mass of pycnometer, water, and soil solids (g)	694.50	705.00	703.10
Specific gravity at soil solids the test temperature	2.627	2.661	2.661
Specific gravity of soil solids at 20°C	2.627	2.661	2.661
Average Specific Gravity	**2.650**		

18. Table of specific gravity of Giciye I tailrace bottom water

Test number	**1**	**2**	**3**
Mass of Pycnometer (g)	162.20	173.10	171.80
Mass of the pycnometer and water	657.50	666.90	665.80
Temperature (°C)	20.1	20.1	20.1
Density of water (g/mL)	0.99819	0.99819	0.99819
Temperature Coefficient (K)	0.99998	0.99998	0.99998
Volume of Pycnometer	496.1981	494.6954	494.8958
Mass of oven dry specimen	59.70	60.00	60.30
Mass of pycnometer, water, and soil solids (g)	694.60	704.30	703.60
Specific gravity at soil solids the test temperature	2.642	2.655	2.680
Specific gravity of soil solids at 20°C	2.642	2.655	2.680
Average Specific Gravity	**2.659**		

19. Table of specific gravity of Sebeya intake surface water

Test number	**1**	**2**	**3**
Mass of Pycnometer (g)	164.90	184.70	173.50
Mass of the pycnometer and water	660.60	679.00	667.80
Temperature (°C)	20.1	20.1	20.1
Density of water (g/mL)	0.99819	0.99819	0.99819
Temperature Coefficient (K)	0.99998	0.99998	0.99998
Volume of Pycnometer	496.5988	495.1963	495.1963
Mass of oven dry specimen	60.00	60.10	59.90
Mass of pycnometer, water, and soil solids (g)	698.30	717.10	705.70
Specific gravity at soil solids the test temperature	2.691	2.732	2.723
Specific gravity of soil solids at 20°C	2.691	2.732	2.723
Average Specific Gravity	**2.715**		

20. Table of specific gravity of Sebeya intake middle point water

Test number	**1**	**2**	**3**
Mass of Pycnometer (g)	164.60	171.90	184.30
Mass of the pycnometer and water	660.30	667.50	678.90
Temperature (°C)	20.1	20.1	20.1
Density of water (g/mL)	0.99819	0.99819	0.99819
Temperature Coefficient (K)	0.99998	0.99998	0.99998
Volume of Pycnometer	496.5988	496.4987	495.4968
Mass of oven dry specimen	59.70	60.10	60.40
Mass of pycnometer, water, and soil solids (g)	697.80	705.70	717.20
Specific gravity at soil solids the test temperature	2.689	2.744	2.733
Specific gravity of soil solids at 20°C	2.689	2.744	2.733
Average Specific Gravity	**2.722**		

21. Table of specific gravity of Sebeya intake bottom water

Test number	1	2	3
Mass of Pycnometer (g)	166.50	185.10	173.10
Mass of the pycnometer and water	660.30	679.30	667.70
Temperature (°C)	20.1	20.1	20.1
Density of water (g/mL)	0.99819	0.99819	0.99819
Temperature Coefficient (K)	0.99998	0.99998	0.99998
Volume of Pycnometer	494.6954	495.0961	495.4968
Mass of oven dry specimen	60.00	60.10	59.90
Mass of pycnometer, water, and soil solids (g)	698.50	717.20	705.70
Specific gravity at soil solids the test temperature	2.752	2.707	2.735
Specific gravity of soil solids at 20°C	2.752	2.707	2.735
Average Specific Gravity	**2.731**		

22. Table of specific gravity of Sebeya tailrace surface water

Test number	1	2	3
Mass of Pycnometer (g)	171.62	170.40	161.85
Mass of the pycnometer and water	666.80	665.90	657.40
Temperature (°C)	20.1	20.1	20.1
Density of water (g/mL)	0.99819	0.99819	0.99819
Temperature Coefficient (K)	0.99998	0.99998	0.99998
Volume of Pycnometer	496.0779	496.3985	496.4486
Mass of oven dry specimen	59.78	60.16	59.75
Mass of pycnometer, water, and soil solids (g)	704.00	703.60	694.70
Specific gravity at soil solids the test temperature	2.647	2.679	2.661
Specific gravity of soil solids at 20°C	2.647	2.678	2.661
Average Specific Gravity	**2.662**		

23. Table of specific gravity of Sebeya tailrace middle point water

Test number	1	2	3
Mass of Pycnometer (g)	162.80	172.90	171.40
Mass of the pycnometer and water	657.80	667.70	666.20
Temperature (°C)	20.1	20.1	20.1
Density of water (g/mL)	0.99819	0.99819	0.99819
Temperature Coefficient (K)	0.99998	0.99998	0.99998
Volume of Pycnometer	495.8976	495.6972	495.6972
Mass of oven dry specimen	60.10	60.30	59.90
Mass of pycnometer, water, and soil solids (g)	695.40	705.40	703.80
Specific gravity at soil solids the test temperature	2.671	2.668	2.686
Specific gravity of soil solids at 20°C	2.671	2.668	2.686
Average Specific Gravity	**2.675**		

24. Table of specific gravity of Sebeya bottom water

Test number	**1**	**2**	**3**
Mass of Pycnometer (g)	162.00	172.10	170.80
Mass of the pycnometer and water	657.00	667.10	665.40
Temperature (°C)	20.1	20.1	20.1
Density of water (g/mL)	0.99819	0.99819	0.99819
Temperature Coefficient (K)	0.99998	0.99998	0.99998
Volume of Pycnometer	495.8976	495.8976	495.4968
Mass of oven dry specimen	59.80	60.00	59.90
Mass of pycnometer, water, and soil solids (g)	694.50	704.90	702.80
Specific gravity at soil solids the test temperature	2.682	2.703	2.662
Specific gravity of soil solids at 20°C	2.682	2.703	2.662
Average Specific Gravity	**2.682**		