Sediment Management at the Proposed Kaiha 2 Hydropower Project, Mano River Basin, Liberia

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Table of Contents

List of Figures

List of Tables

Abbreviations

km	kilometers
LHS	Liberian Hydrological Services
m	meter
m^3	cubic meter
m^3/s	cubic meters per second
Mm^3	million cubic meters
MW	megawatt (1 million watts of power)
MWh	megawatt-hour (energy of 1 megawatt of power delivered for 1 hour)
RREA	Rural & Renewable Energy Agency
s	second
t	metric ton (1 t = 1000 kg = 2,205 pounds)
yr	year

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EXECUTIVE SUMMARY

The proposed 2.5 MW Kaiha-2 run-of-river hydropower development project is proposed immediately upstream of the Kaiha River waterfall located about 4.75 km south-southwest of the Village of Mbaloma. It will develop approximately 13 m of head and utilize Kaplan type turbines. This study was undertaken to assess the sediment impacts to the project and to recommend appropriate actions.

Sediment data are non-existent in this area.. However, a combination of site observations, reference to the professional literature, and application of an Africa-specific sediment yield equation, all point to very low sediment loads. Because of the low head, silt and clay will not affect the turbine. Also, observations at the site indicate that the load of silt and clay will be very low. Most of the sediment load will be in the form of quartz sand, with a mean diameter of approximately 0.5 mm based on sediment samples from Kaiha River. Sediment load from the 1129 km^2 watershed tributary to the proposed intake was estimated on the order of 24,500 t/y, equivalent to a volume loss of 16,300 m^3/year when sedimented in the proposed reservoir.

Construction of a 7.5 m tall dam is proposed to provide additional head, to provide regulating storage, and to divert water into the intake structure. Because topographic data are lacking it is not known how far this reservoir will extend upstream or how much volume will be impounded. However, the high sinuosity of the river above the dam, together with elevation data from Google Earth imagery, indicate very low gradient and thus a significant reservoir volume. The sand will accumulate in this reservoir in the form of a delta which will advance toward the dam. Without any data, an educated guess is that this delta will not greatly affect the regulating volume and will not reach the dam within the first 20 years of operation.

The project Feasibility Study (Multiconsult 2015) indicates a 1 to 2 m variation in the reservoir level for daily flow regulation. Reservoir behavior simulations prepared in this analysis suggest that by year 2038 regulating storage will no longer be necessary to maximize power production from this plant. By the time this delta reaches the dam, it is expected that the power demand will have grown to the extent that regulation storage will no longer be useful. This will occur because the power demand during all hours of the day will have grown to exceed the plant capacity of 2.5 MW, due to either growth of local power demand (as projected in the Feasibility Study) or because the local grid may become interconnected to a larger (national) power grid. When this happens it will not be necessary to consider maintaining reservoir storage; the only sediment issue will be to minimize the sand load on the turbines.

Schematic layouts for the intake structure have been presented in Figure 17, Figure 18, and Figure 19. This design will be capable of managing the sediment when the delta reaches the dam. It will also facilitate the handling of floating woody debris which may pose problems from the very start of operations. From the standpoint of project feasibility, sedimentation is not an issue. The recommended intake arrangement and operating strategy should adequately address the anticipated sedimentation problems, especially given the low sediment loads in this river basin.

More important than sediment is the considerable uncertainty concerning the accuracy of the hydrologic data. The power computations that resulted from the analysis contained in this study are significantly lower than those presented in the Feasibility Study, because of the flow data that was provided. Validation of the hydrologic dataset should be the primary focus of the hydrologist's work on this project.

The most important recommendations are summarized below:

- Hydrologic data. The hydrologist should focus on validating the available hydrologic data and checking the gaging methodology, computational procedures and hydrologic data management.
- Topography. A longitudinal profile should be made along the Kaiha River running upstream of the falls, until reaching the river bed reaches the elevation of the spillway weir on the proposed dam. A minimum of 6 cross-sections, spaced at intervals of not more than 500 m along the length of the reservoir, should be measured to estimate the reservoir volume.
- Sediment data. Collection of suspended sediment data should be performed during the wet season (the only time of year that there is significant sediment transport) by taking vertically-integrated samples across the full cross-section following the procedure outlined in Edwards and Glysson (1999). The sediment load should be size classed as either "sand" or "fines".

- Project design. To facilitate the handling of sediment and woody debris, the intake should be designed taking into consideration the design recommendations given in Section 7.

- Reservoir monitoring. The reservoir cross-sections should be re-surveyed at 5-year intervals after project construction to monitor the rate of reservoir sedimentation. The longitudinal profile should be resurveyed every year using hand-held GPS and measuring the water depth at 100 m intervals points with the reservoir held at its full level.

- Turbine abrasion. The concentration of sediment sand exiting turbines (a well-mixed zone) should be sampled on a once daily basis once the sandy delta approaches to within 500 m of the intake. This sampling will help the operators keep track of the sediment load, which may become quite high once the sand reaches the intake if the sediment sluice is not operated regularly. This monitoring will help identify the operational procedures which are most useful in minimize the sediment load and resultant abrasion to the turbines.

The complete set of recommendations are given in Section 8 of this report.

1. INTRODUCTION

1.1. Authorization

This report was prepared under the scope of "Consultancy Services for Sedimentation Specialist" of the Liberia Renewable Energy Access Project:

Contract Reference No: RREA/LIR/CONS/07

Project ID: P149683

The project coordinator at the Rural and Renewable Energy Agency (RREA) was Ms. Eunice P. Dahn.

1.2. Project Overview

This consultancy centers on the evaluation of sediment and related issues at the proposed 2.5 MW Kaiha 2 run-of-river (RoR) hydropower plant, to be located on the Kaiha River in the upper portion of the Mano River basin. A map showing the approximate location of the project is presented in Figure 1. The coordinates of the proposed dam are: 8.0015 ° N latitude, 10.2100° W longitude.

The project envisions 2 Kaplan turbines operating with about 13 m of gross head, and delivering power into a micro-grid which will also be constructed as part of the project. Because hydropower is insufficient to meet the full demand during the dry season, when flow in the river approaches zero, the system will also have a diesel generation facility. A 7.5 m tall dam is being designed as part of the intake structure to provide additional head and also provide storage for daily power peaking.

1.3. Scope of Services

The Terms of Reference for this consultancy are summarized below:

The consulting services ("the Services") include to assist the Rural and Renewable Energy Agency (RREA) in performing the following:

- *Review the results of sediment load assessment and safe yield analysis of the river. If need be, carry out preliminary assessment of sediment inflows in the river. A site visit could be required.*

Figure 1: Project location map.

- *Review the adequacy of the adopted design for all hydraulic structures and equipment with respect to (i) sediment inflows analysis, (ii) equipment design, (iii) plant operation.*
- *Propose adequate sediment management plan for the project, including modifications in project layout and/or equipment specifications to cope with sediment influx.*
- *Propose action plan to re-instate sediment measurement stations and increase accuracy of data available in the near future.*

Additional topics were also addressed, as required to provide a more complete basis for project design.

The study objective is to identify project design and operational strategies that will support sustained long-term hydropower from this site while minimizing adverse and environmental impacts.

2. METHODOLOGY

2.1. Data Collection and Data Availability

The following reports and data sources were made available for this analysis:

- LHS web site. Daily, streamflow and related hydrologic data since 2012 are available from the Liberian Hydrological Services web site (lhsliberia.com) for several gage stations, but none of the available gages are located in the Mano River basin, including the Kaiha River and other tributaries. The closest gage to the project site is the gage at Lofa Bridge (8194 km^2 catchment). Published internet data cover the period 1/6/2012 – 26/7/2016. Additional (more recent) data were requested during the meeting at LHS on May 17 but has not yet been provided.
- Kaiha . Daily stage data and several stage-discharge data measurements by ADCP were provided for calendar years 2013 – 2016, for the two stations on the Kaiha River (Kolba City and Kolahun), both located above the falls. Reportedly, the Kolba City gage is more accurate. However, to date no information on the location (lat/long or catchment area) has been made available for the Kolba City gage. These data are available at Kolahun, but the daily stage record has not been made available.
- Multiconsult. 2016. *Pre-Feasibility Studies of Selected Mini Hydropower Projects in Liberia: Kaiha 2 HPP Feasibility Report*, a report to Norwegian Water Resources Directorate.

  This document includes feasibility–level drawings, which have been made available in electronic format.
- Innovation Energie Développement Consultants. 2015. *Pre-feasibility study of MW-sized hybrid isolated mini-grids in Lofa County, Liberia.* Task Reports 1, 2 and 3. Report prepared with World Bank funding for the Rural and Renewable Energy Agency, Monrovia, Liberia
- Japan International Cooperation Agency (JICA). 1975. *Basic Studies on Hydro-electric Power Development in the Republic of Liberia*. Report to Government of Liberia.
- Multiconsult. 2016. *Kaiha 2 Hydropower Plant and Transmission Grid Environmental and Social Impact Assessment Scoping Report*. Report submitted to Environmental Protection Agency (EPA) Liberia.

- Liberia Energy Support Sector. 2011. *Identification of Potential Hydropower Sites in Bong, Nimba and Lofa Counties*. (This study identified the Kaiha falls as only a 0.5 MW project.)
- Anon. 1981. *Rainfall Data Book of Liberia (From Inception Till 1980)*. Mimeo download http://lhsliberia.com/wp-content/uploads/2.-Rainfall-Data-Book-of-Liberia.pdf on May 17, 2017.
- Miscellaneous. Various hydrologic tables, figures and maps were obtained from the Internet.

A meeting was held with LHS personnel on May 17. A field visit was performed during 18-20 May to observe site conditions and collect a sample of Kaiha river sediment deposits (sand).

2.2. Data Not Made Available

This draft report has been prepared without having received from the Liberian Hydrological Services (LHS) the following data: location and catchment area for streamflow data for the Kolba City gage, and the daily streamflow data for the Kolahun gage. The daily time series of flows used in the Multiconsult 2016 pre-feasibility study was also not available. There is considerable uncertainty as to the streamflow data that was provided.

2.3. Basis of Analysis and Limitations

There are very few data available for this project. The only discharge data are available for the recent period following the civil war. Streamflow data from prior years for all rivers in Liberia were lost during the war. There are no sediment data of any type available in Liberia, and very scanty references in the professional literature.

Daily discharge data are available from two gages near the project site, but data deficiencies at both sites (Kolba City and Kolahun) prevent the data from being used to construct a reliable daily flow series for the proposed intake site.

The analysis has been performed within the limitations of these data constraints. Project design recommendations have been developed based on conditions expected to prevail at the site based on interpretation of the available data, professional literature, and experience from other sites.

3. EXISTING DESIGN PARAMETERS FOR THE PROJECT

3.1. Design Parameters in 2016 Feasibility Report

Only a conceptual feasibility level design has been prepared to date (Multiconsult 2016). The overall project plan view is shown in Figure 2. This figure has been prepared from the DWG (Autocad) file submitted with the feasibility study, and the values of the contour intervals have been added by our office based on the topographic data contained as an appendix in that report.

There are several inconsistencies in the conceptual design information presented in the feasibility study.

- The Feasibility Study states on page 1 of the summary that the project will have, "*1 m drawdown in the reservoir for use in peaking hours*", but the drawing titled "Dam and Intake Longitudinal Section" shows 2 m drawdown. Because there are no topographic data for the reservoir, and thus no stage-storage curve, both values (1 m and 2 m) are simply educated guesses.
- Varying values for the hydraulic head are also given, varying from 11 to 13 m.

These inconsistencies underscore the conceptual nature of the project design at this point. This reflects the lack of basic data, and particularly the lack of topographic data for the reservoir area.

The Feasibility Study outlined the following principal power generating components:

- 7.5 m high concrete gravity dam and intake structure upstream of the Kaiha waterfall. The spillway crest elevation of the dam (maximum operating level) is given as 450.5 and the design flood level is 453 m (Dam and Intake Cross-Sections drawing).
- Based on the topography (Figure 2), the last contour below the falls is given as 436.5, for an elevation difference of 14 m. Taking into consideration the need to elevate the plant above the wet season downstream river level, plus pipeline losses, a gross head of 13 m cited in the Feasibility Study is probably an appropriate value to use at this point.
- The dam will create a regulating reservoir which will enable water to be stored overnight during low flow periods, to be used to generate electricity during periods of high power use in during the daytime and evening hours.

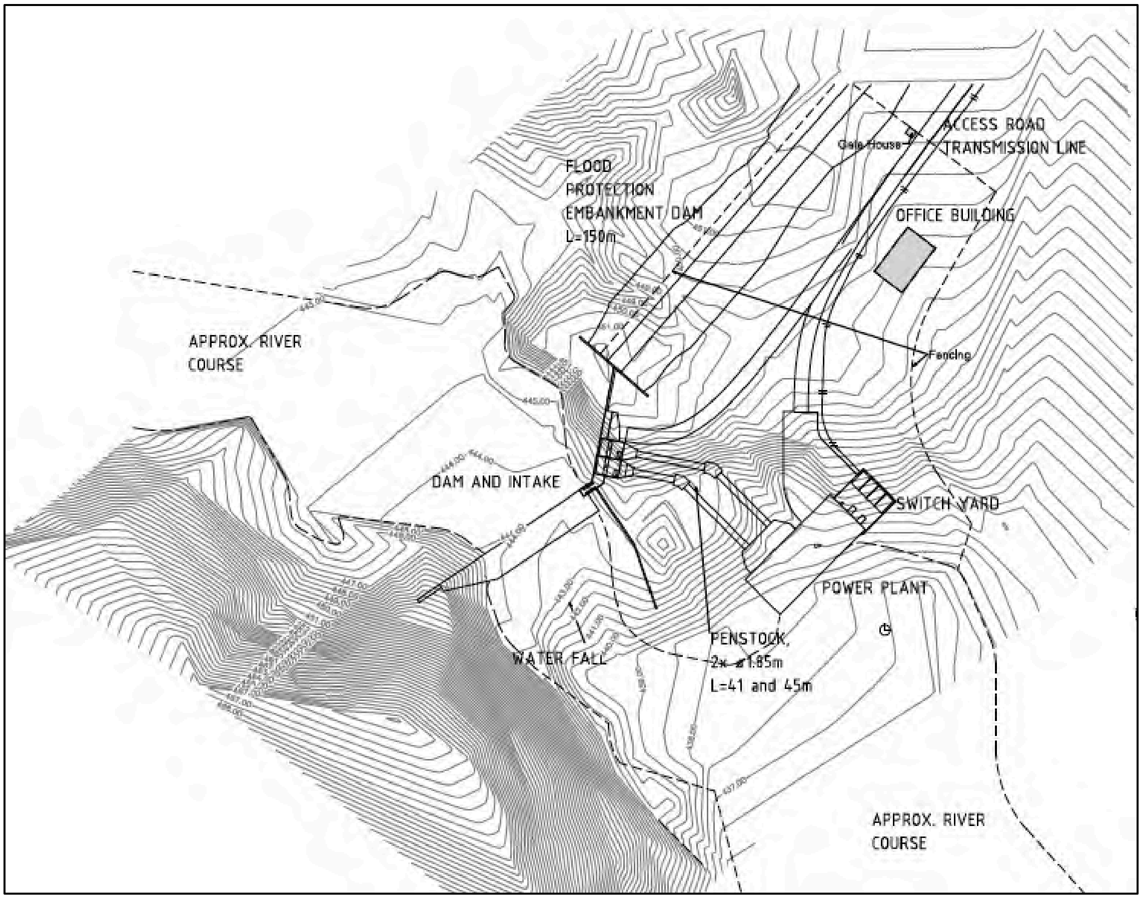


Figure 2: Conceptual plan view of the project from the Feasibility Study.

- The schematic design calls for an earthen embankment to prevent overflow of the left abutment during the design flood.
- A short penstock with steel pipes connecting the intake to the power station
- A power station is located downstream of the waterfall and rapids, to be equipped with two Kaplan turbines.

The project's non-generation components include construction of a new 5.5 km access road running south-southwest from the Village of Mbaloma (latitude 8.042° N, longitude 10.195° W) to the project site, plus the power transmission and distribution infrastructure.

Salient features of the project are summarized below in tables extracted from the Multiconsult Pre-feasibility report.

Table 10: Project Salient Features

Item	Value
Power Production	
Design Discharge	23.2 m3/s
Gross Head	13 m
Installation	2.5 MW
Dam and intake	
Type of Dam	Concrete Gravity dam
Height of Dam	7.5 m
Type of Spillway	Overflow
Crest Length of Spillway	49.4 m
Intake bay	2 no
Waterway	
Penstock length	41 m and 45 m
Penstock Diameter	2 x Ø 1.85 m
Power House	
Type	Surface
Number of Units	4 S-turbines
Tailrace length	8 m

Table 13: Elevation profiles at main structures

Elevations:	(masl)
Dam and Intake	
Dam top	453.5
Dam spillway crest	450.5
Design flood water level (MWL)	453.3
Bottom outlet sill	443.3
Intake sill	444.2
Forebay invert bed	443.4
Top penstock invert level	445.5
Power Plant	
Machine hall	437.5
Machine hall upper level	442.0
Mean tail water level	437.5
Deign flood tail water level	441.5

According to the Feasibility Study (page 5) the Kaiha 2 hydropower project has the potential to generate an average of 17.5 GWh/year (varying in dry and wet years), but it will feed into the distribution system only 7.5 GWh in the first year and 16.5 GWh in the 20th year, following the growth in demand. Unmet demand is estimated to grow from 0.3 to 4.0 GWh/year over the 20 year study period, which will be covered by a diesel generation plant, with 3 MW generating capacity in the initial year and increasing to 4 MW in year 20. This assumes regulating storage will be available in the reservoir.

The project cost, as outlined in the Feasibility Study (page 6), is given below in 2016 USD:

- *14.9 mill. USD for the hydropower plant. With an installed capacity of 2500 kW, the total estimated cost entails a generation cost of 5.98 USD/MW.*
- *5.9 mill. USD for the transmission line including extension options.*
- *20.8 mill. USD for the transmission line together with the hydropower plant,*
- *The hydropower plant annual operation and maintenance cost is set to 2.5% of the investment cost, while at 2% for the transmission grid.*

4. HYDROLOGY AND SEDIMENT YIELD

4.1. Basin Characteristics

The Kaiha (or Zeliba) River forms the upper part of the Mano river basin, and the Kaiha catchment is very elongated and extends up to the Guinea border.

The catchment area tributary to the Kaiha 2 HPP dam site is reported in the Feasibility Study as 1129 km^2 based on topographic analysis of 30 m resolution NASA Shuttle Radar Topography Mission data. The elevation at the project site is about 445 m, and the maximum elevation in the catchment is about 850 m. Other than the area of the falls, the river slope is low, with a meandering reach that starts about 1 km upstream of the falls.

Satellite photography indicates that much of this catchment area is covered by forests, but substantial deforestation for slash-and-burn agriculture was evident from both the GoogleEarth images and on the ground (Figure 3). Some of the deforestation and burning extends up to the river bank.

Figure 3: Slash and burn agricultural system in the watershed above the proposed Kaiha 2 power intake.

Figure 4: Deforestation and burning to the edge of the river bank, Google Earth image dated 3/2/2015.

4.2. Flood Hydrology

The project must be designed to withstand an extraordinary flood, the "design flood". The design flood must pass through the dam's spillway without overtopping any non-overflow section of the dam, and must do so with the sediment sluice closed. Also, the powerhouse should be located high enough so it will not be flooded by the rise in flood level within the river below the falls. The Feasibility Study (Sec. 3.2) adopted an average flood specific runoff of 160 l/s/km^2 at the Kolahun gage, which corresponds to 181 m^3/s at Kaiha 2 based on the ratio of watershed areas. A peak-to-annual flood ratio of 2.5 was suggested, resulting in a peak flood on the order of 450 m^3/s. Section 3.2 "Floods" in the Feasibility Study states:

> *Due to the limited amount of data available estimation of extreme floods in the catchment is challenging. In order to find approximate dimensions of spillways, powerhouse elevations etc. we have prepared some rough flood estimates for the Kaiha 2 site.*
>
> *In the catchment we have observations of the floods of 2014 and 2015, in addition we have observations of the 2012 and 2013 floods from Lofa River. We*

also have observations of the 2013 flood at the Sembehun site but this is an uncertain estimate due to the quality of the rating curve.

The floods of 2014 and 2015 at Kolahun were 75 m^3/s and 152 m^3/s respectively, the 2013 flood was similar to the 2014 flood if we compare with Sembehun data, scaling from Lofa we get somewhat higher results. Based on this we have chosen an average flood of 120 m3/s or 178 l/s/km2, the corresponding value from Lofa is 141 $l/s/km^2$ with very little variation between years. Given the larger area at Kaiha 2 compared with the Kolahun gauge we have chosen to use an average flood of 160 $l/s/km^2$, corresponding to 181 m^3/s at Kaiha 2.

The scaling factor between average floods and large floods vary considerably and we have no data available from Liberia to provide any guidance, we have seen factors of around 2.5 in catchments of similar geography and believe this could be a reasonable first estimate, this yields a flood at Kaiha 2 of 450 m^3/s. We have chosen so far not to assign a specific probability due to the significant uncertainty involved.

Recommendation 1: Establishing an appropriate value of the design flood is a critically important parameter for project design, and should is one of the primary objectives of the Hydrology Study.

4.3. Daily Discharge Data

Daily streamflow discharge data are used to determine the power available from the project. LHS personnel reported that there are two streamflow gages on the Kaiha River: Kolahun and Kolba City. Data for the gage locations and intake are given in Table 1. However, the Multiconsult Pre-feasibility Study reports different gage locations (Table 2). The gage at the Kolahun site was visited (Figure 5), and a photo was provided of the Kolba City gage location by LHS (Figure 6) but the Kolba gage site was not visited.

Table 1: Geographic Data for Locations Along Kaiha River.

Parameter	Kaiha Falls	Kolahun Gage	Kolba City Gage
Catchment area, km^2	1129	673	?
Catchment area ratio	1.678	1.0	
Latitude N	8.002	8.278	?
Longitude W	10.211	10.078	?

Table 2: Stream gages on Kaiha River reported in Table 2 of Multiconsult 2016 (Sec 3.1).

No.	Name	Latitude	Longitude	No. of flow measurements	Data period	Area km²
01MA001	Kaiha River at Kolahun	8.278	-10.078	26	07.01.2014-	673
01MA002	Kaiha River at Sambehun	8.228	-10.125	20	18.05.2013-	731

According to LHS personnel, the most reliable gage data for the Kaiha 2 site are the data from the Kolba City gage because the Kolahun gage is affected by backwater from an irrigation weir. However, location information for the Kolba City gage could not be obtained, and the stage and discharge field measurement data provided for the Kolahun and Kolba City gages were identical, which is clearly impossible if they are at different locations.

There are actually two bridges at Kolahun, with a smaller bridge (presumably that shown in Figure 6) located only 1.5 km (straight line) upstream of the Kolahun bridge shown in Figure 5. In view of the above, and without receiving further clarification, the Kolba City gage was taken as given above. Its streamflow data were adjusted to the Kaiha 2 site based on the ratio of mean discharges (Section 4.4).

Figure 5: Kolahun bridge gage site, looking upstream, staff gage visible on the abutment on the right side of the photo (downstream side of the bridge).

Figure 6: Kolba City bridge streamgage location (photo provided by LHS).

Daily stage (water level) for the Kolba City gage were provided from January 7, 2014 to December 31, 2016, together with a table of simultaneous stage and discharge measurements. These were used to construct the stage-discharge rating curve in Figure 7, which was used to then compute the daily flow time series shown in given in Figure 8.

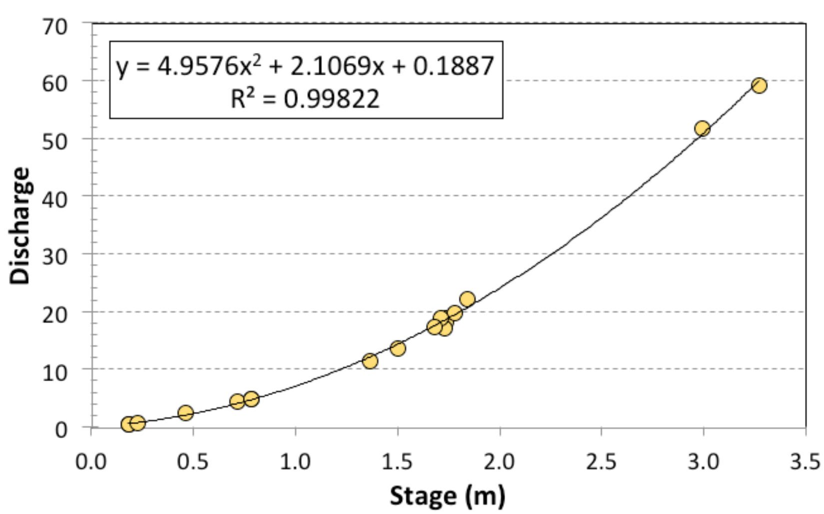


Figure 7: Stage-discharge rating curve developed for Kolba City gage.

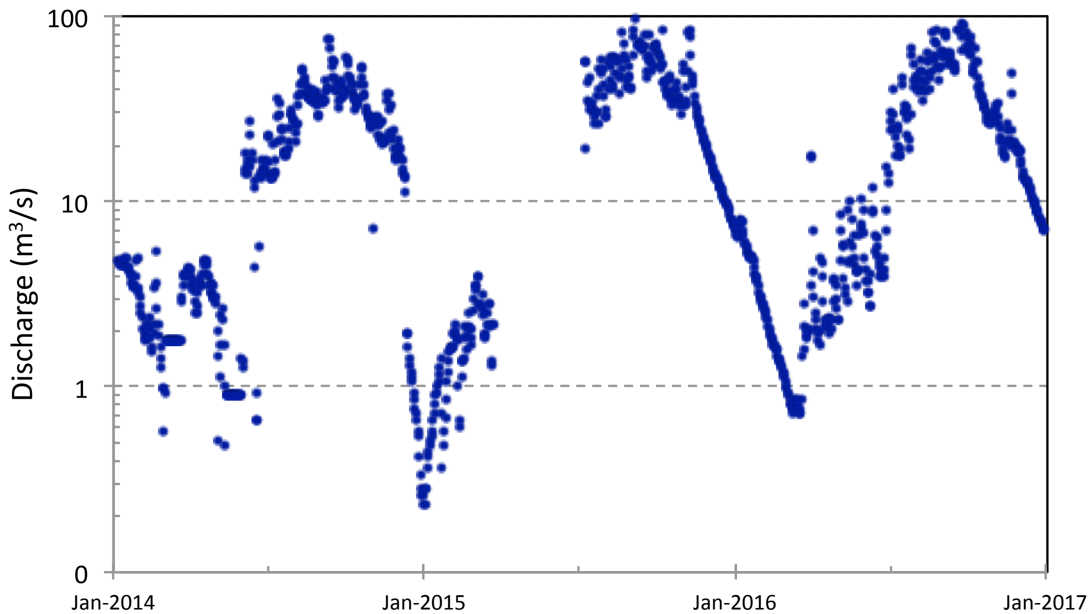


Figure 8: Daily discharge time series at Kolba City. Average discharge is 14.0 m^3/s.

4.4. Adjustment of Daily Discharge to the Kaiha 2 Site

These discharges given above were compared to the computations provided in the Multiconsult Pre-feasibility study (Section 3.1 "Hydrology"), which reported an average discharge of 20.2 m^3/s for Kaiha River at Kolahun for the period January 2013 – February 2016. This is much higher than the 14.0 m^3/s discharge computed for the data in Figure 8.

There are obviously problems with the data that were provided, and the daily flow data used by Multiconsult were also not available.

Recommendation 2: It is recommended that the RREA communicate directly with MultiConsult and obtain an electronic (spreadsheet) copy of the daily discharge time series they used in their analysis, and copies of any original data files associated with these data.

Multiconsult presented a summary of hydrologic data, reproduced as Table 3. The average flows reported in that table at Kaiha 2 are 33.9 m^3/s, while the average flow for the data in Figure 8 is 14.0 m^3/s. To scale the daily flows given in Figure 8 upward to match the average flow reported by Multiconsult at the Kaiha 2 intake location, the daily flows provided in Figure 8 are multiplied by a factor of 33.9/14.0= 2.42.

Table 3: Summary hydrologic data from Table 6 in Multiconsult (2016).

	Area	Annual Runoff	Average Flow		1 % Low Flow	
Site	km^2	Mm^3	m^3/s	$l/s/km^2$	m^3/s	$l/s/km^2$
01MA001 Kaiha River at Kolahun	673.4	637	20.2	30.0	0.20	0.30
Kaiha 2 HPP	1129	891	33.9	30.0	0.34	0.30

The Multiconsult report also pointed out that there is a considerable area of uncertainty in the low flow data:

> *Average flow for these years was 20.2 m^3/s, yielding a specific runoff of 30 $l/s/km^2$. The 5 % low flow was at 0.82 m^3/s. Minimum flow was close to zero, this is however very uncertain data as it is well below the lowest measurement used to establish the rating curve. The lowest measured flow was 0.51 m^3/s in March 2016.* (page 26)

They stated that the available pre-civil war data reported low flow values that were significantly higher than the flows reported in the post-war period.

Also, the average annual power that was computed (subsequently) using the data available for this study is considerably lower than computed by MultiConsult using their dataset. This makes it very important to confirm and rectify the hydrologic data deficiencies.

Recommendation 3: The problems encountered with the hydrologic data points to an area of considerable uncertainty. The hydrologic consultant should give top priority to sorting out and verifying the hydrologic data on which the power plant feasibility has been predicated, including field verification of the methodology for collecting data and office procedures for processing stage and discharge data. Also look at the extreme low flows when water levels may fall below the bottom of the installed staff gage (as reported in the field).

As a note, the extreme low flow data are actually of little importance from the standpoint of power generation because at very flows, below about 1.5 or 2 m^3/s, there will not be sufficient flow to operate a single turbine.

5. SEDIMENT

5.1. Sediment Yield

On a continental basis, only arid Australia has a lower sediment yield than Africa. By global standards, sediment yields in Africa are low compared to other areas of the world, even in moist hilly areas such as Lofa County, due to the presence of generally limited topographic relief together with predominately hard igneous rock, erosion-resistant soils, and generally good vegetative cover.

Based on a sediment yield map for all of Africa, the sediment yield in the project area will fall in the range of 10 – 100 $t/km^2/yr$ (this map was given as Fig. 13 in Vanmaercke et. al. 2014). For all of Liberia that study reported only a single measured value for sediment yield, 189 $t/km^2/yr$, for a site in the extreme southern part of the country. Data are similarly sparse for Guinea.

Based on all African data, the same paper by Vanmaercke et. al. presented a multiple regression model for predicting sediment yield in Africa:

$$SY_{predicted} = 1.49*e^{1.24PGA} * MLR^{0.66} * e^{-0.05TreeCover} * Ro^{0.24}$$

Where SY = sediment yield ($t/km^2/yr$); PGA = peak ground acceleration due to earthquake having a 10% exceedance probability in 50 years (m/s^2); MLR = average topographic height difference within a 5 km radius (m); TreeCover = percent of ground with tree cover (%), and Ro = average annual runoff depth (mm).

To apply this equation to the watershed above Kaiha falls, earthquake acceleration was taken as 0.4 m/s^2 based on (Grünthal et.al. 1999)[1], MLR was estimated at 100 m, TreeCover was estimated at 50% based on Google Earth images, and Ro = 946 mm/yr based on the estimate of 30 $l/s/km^2$ presented in the Multiconsult Feasibility Study (recall Table 3). The parameter values and resulting value of sediment yield are summarized below:

Peak Ground Acceleration (PGA), m/s^2	0.4
MLR, avg. height difference within 5 km radius	100
TreeCover (% of catchment), %	50
Ro, avg. annual runoff depth, mm/yr	946
Computed sediment yield, $t/km^2/yr$	21.7
Computed sediment LOAD, t/yr for 1129 km^2 watershed	24,500

The authors noted that their equation explained only 40% of the observed variability in sediment yield across Africa, with 74% of the predictions producing values within a factor of 5 from the observed value (i.e. between 20% and 500% of the observed value), while 88% fell within a factor of 10 of the observed value. As evident from these statements, this is only a very rough estimate of sediment yield.

[1] Acceleration map can be viewed at http://www.gfz-potsdam.de/en/section/seismic-hazard-and-stress-field/projects/previous-projects/probabilistic-seismic-hazard-assessments/gshap/.

5.2. Land Use Intensification and Erosion Control

Slash-and-burn agricultural practices have relatively small impact on sediment yield if performed on a low-intensity basis with long recovery periods (e.g. 50+ years). However, intensification of land clearing in the Kaiha basin seems to be a trend, and this can greatly increase the rate of erosion and sediment yield. This may be particularly true if the land is converted to grazing rather than allowing reforestation to occur.

In general, the best approach to preventing widespread land degradation is to focus intensive agricultural practices onto the best soils, and promote less-invasive activities (such as forestry) on less-productive and more erosion-prone sloping soils. The intensive agricultural practices may consist of organic-type agriculture which employs methods to greatly enhance yield, or it may include the utilization of commercial agricultural inputs. The utilization of green manure as a source of nutrients and soil amendment to enhance fertility – in lieu of burning – is particularly important. Also, use of techniques such as green manure to enhance the soil will increase the moisture holding capacity, a benefit not obtained from burning. Successful programs have focused on developing model farms in different districts, starting with small scale interventions. As these small interventions are perfected and proven out, then bring other farmers to the model farm so that by word of mouth and hands-on activities these improved techniques can be disseminated throughout the community. These practices do not need to be limited to field crops; they may include greenhouses (plastic roofs) to control rainfall on more delicate crops, fish ponds, food processing (value added) activities, etc.

Interventions to aid farmers obtain more economic productivity from a smaller land area should not be limited to cultivation practices only. It should also include improved post-harvest handling, storage, packaging, shipping, and better access to markets. Taken together, both cultivation and post-cultivation practices can aid the farmer to make more profit from a smaller area of land, reducing the pressure to cut and burn forests. Activities such as enhancement of the tree stock in forests may also be promoted to increase the value from soils which, due to their slopes, should not be cultivated.

Finally, these interventions with farmers should <u>not</u> be oriented to achieving erosion control be the primary benefit. For improved soil conservation practices to be sustainable, the primary beneficiary must be the farmer. It is necessary to provide practices which enable the farmer to earn more money and have greater economic security. The technological practices provided to achieve these ends should, as a by-product, also enhance soil conservation, but for these soil-conserving techniques to be sustained the farmer must realize benefits.

Recommendation 4: Promote development and dissemination of improved agricultural practices (both cultural and post-harvest) and associated activities which enable farmers to obtain more economic benefit from the more intensive utilization of the best agricultural soils, thereby reducing the pressure to cut and burn erosion-prone forest lands with steeper soils.

5.3. Road Construction as a Sediment Source

Roads can be a major source of sediment supply that is delivered to rivers, especially given the steep topography and the gullying observed in some of the existing dirt roads (Figure 9).

Figure 9: Four-wheel drive vehicle stuck in a gullied road.

Road-related erosion is derived from cut slopes, fill slopes, drainage features (ditches and culvert crossings), and from the road surface itself. Given the generally good rainfall and vigorous vegetative growth, there is good potential to minimize erosion from all but the road surface itself, and also to capture eroded sediment in vegetated areas. A recent reviews of literature on road-related and other erosion sources are given by Seutloali and Beckedahl (2015) and Labrière et.al. 2015.

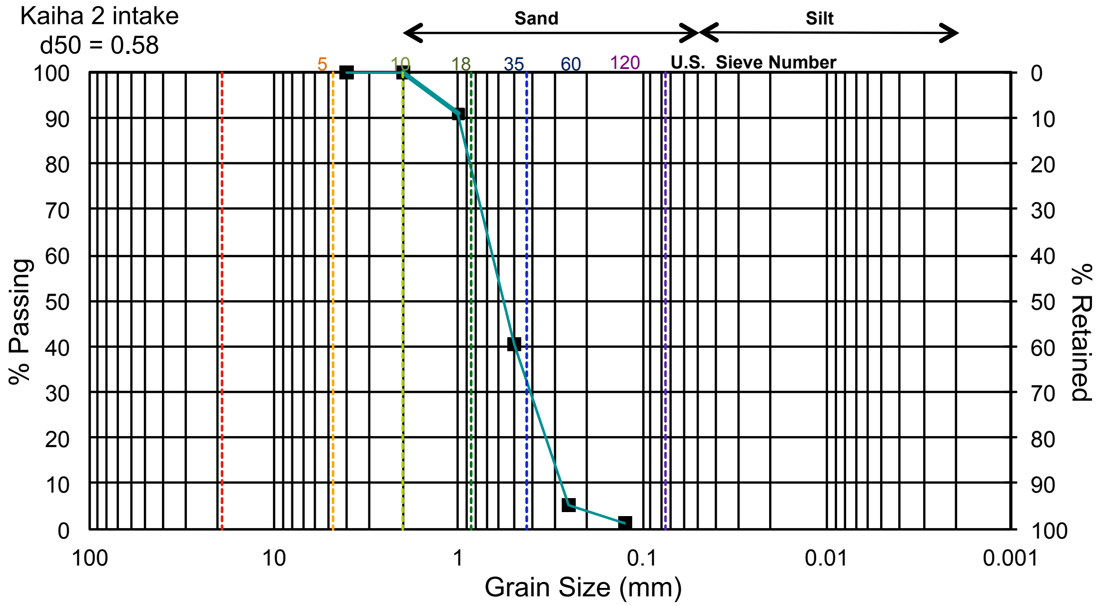
Recommendation 5: Develop and apply basic road construction and drainage standards to minimize erosion of dirt roads with the dual objective of reducing road maintenance costs while also reducing the amount of sediment delivered into waterways.

5.4. Sediment Characteristics

The Kaiha River bed has repeated bedrock outcrops along its length. It transports sand either as bed or suspended load, depending on the flow velocity. The river is colored by tannic acids but was not observed to transport silt or clay. The appearance of the river immediately upstream of the falls is shown in the panoramic photo in Figure 10.

Figure 10: Panoramic photo of Kaiha River just above the falls.

Careful examination of overbank areas subject to seasonal flooding in the vicinity of the proposed intake showed only thin pockets of sand in a very few locations, and then only in very limited quantities. Two sand samples were collected, one of them by sampling multiple locations along the left side of the river immediately above the falls, and the second from sand extracted from a lateral bar just below the Kolahun bridge gage site. The bed material at the Kolahun site was visually coarser than the material on the bar, and similar to the material sampled above the falls. Particle size distributions for both are given in Figure 11, and the grain size nomenclature is given below.



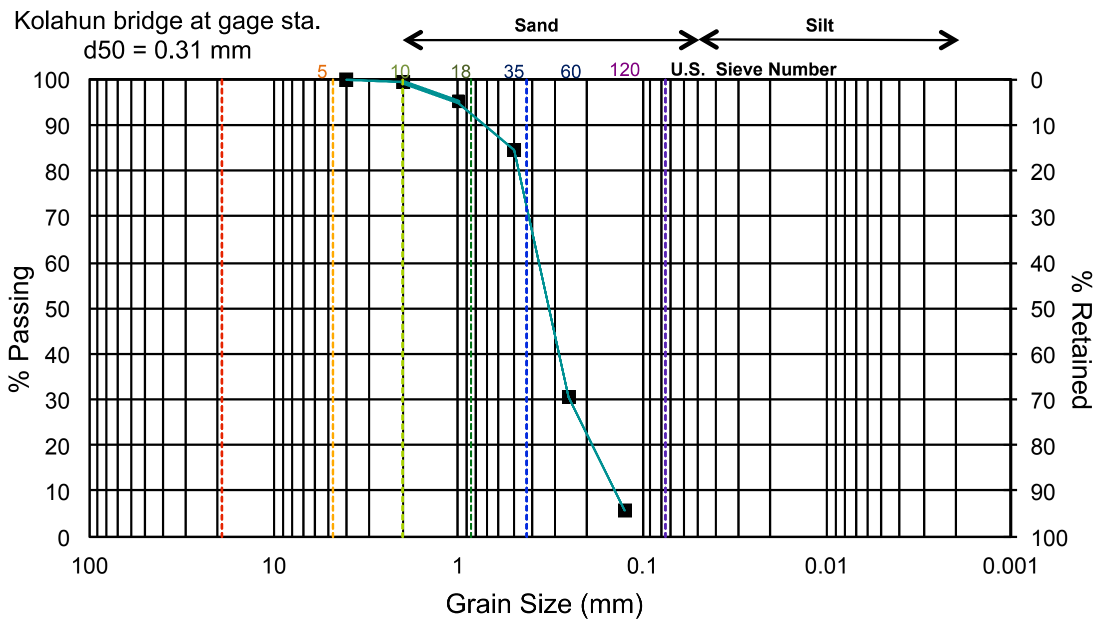


Figure 11: Particle size distribution of sediment samples. TOP – Kaiha River above the falls, proposed intake location. BOTTOM – Kaiha River, finer sediment from lateral bar below Kolahun bridge.

Category	Smallest Dia. (mm)	Largest Dia. (mm)
Clay	0.0005	0.004
Silt	0.004	0.062
Sand	0.062	2
Gravel	2	64

Both samples consisted entirely of sand sized material, all of it apparently quartz, as seen in Figure 12. There was almost no sand smaller than 0.1 mm and gravel was also absent.

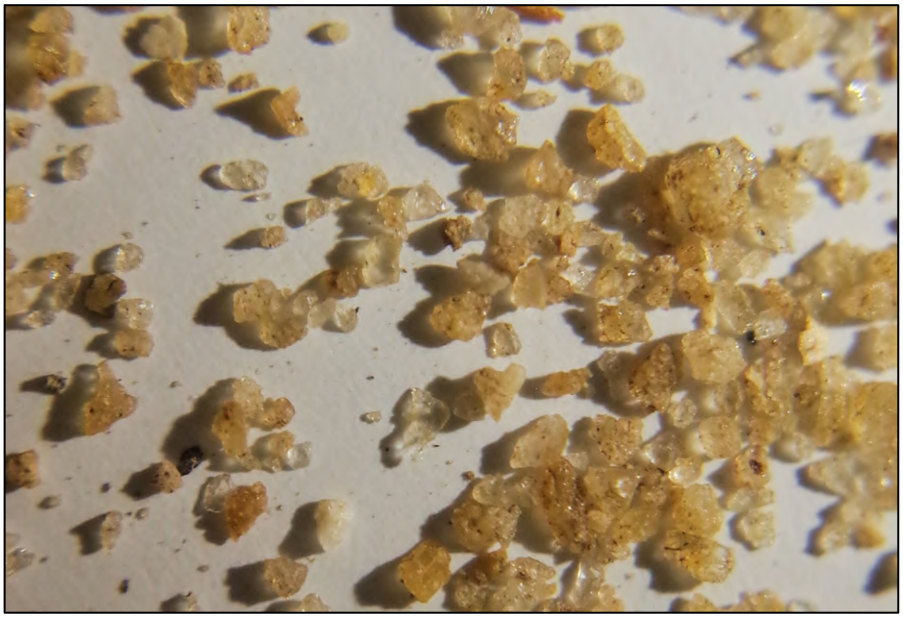


Figure 12: Photograph of sand from Kaiha River at intake location.

At the river there was no evidence of any amount of silt or clay deposition on the river bed or overbank areas, and the amount of sand deposition was extremely limited. However, Google Earth photography does show sand bars at some locations in the meandering reach of the Kaiha River from Kolahun downstream to the falls. Nevertheless, all the field and photographic evidence suggesting that the sediment load is very small, which is consistent with the low amounts of sediment yield predicted by the empirical equation in Section 5.1.

5.5. Bulk Density and Rate of Storage Loss

A regulating reservoir is proposed at the Kaiha 2 intake. To estimate the rate of storage loss in the regulating reservoir it is necessary to convert sediment load (mass) into an equivalent volume of sediment deposit. Representative values of dry bulk density[2] for sand deposits in a reservoir (also known as specific weight) are given below:

Geiger (1963)	1.36 to 1.60
Strand and Pemberton (1987)	1.55

2 Dry bulk density is the amount of sediment per cubic meter of sediment deposit in a reservoir.

Adapting a value of 1.5 t/m^3, a range of possible rates of storage loss are given in Table 4. Inflowing sand will be 100% trapped in the reservoir unless sediment management techniques such as flushing are implemented. Sediment yield may be greatly increased above current low levels by road construction and deforestation within the catchment. The time to fill the regulating pool cannot be computed at this point because, lacking topographic data, the pool volume cannot be calculated.

Table 4: Potential Range of Storage Loss Rates in Kaiha 2 Regulating Reservoir.

Specific Sediment Yield, t/km^2/yr	Sediment Load, t/yr	Volume Loss, m^3/yr	Years to Fill Regulating Pool
22	24,500	16,300	?
100	112,900	75,267	?

Note: Sediment load computed for 1129 km2 watershed tributary to Kaiha 2 dam given in Table 1.

5.6. Sedimentation of the Reservoir Volume

The general pattern of reservoir filling is illustrated conceptually in Figure 13. Because the sediment consists of sand, and because the reservoir will be held normally full (nearly constant high water level with limited variation for daily regulation), the sand will settle rapidly as soon as it enters the reservoir. The deposited sand will create a delta which will gradually advance downstream and eventually reach the dam and power intake.

The volume of the reservoir that will be created by the dam is currently unknown. At this point we do not even have a longitudinal profile along the Kaiha River which would indicate how far upstream the reservoir will extend, which is the most basic information needed to make a highly preliminary estimate of the reservoir volume.

The Kaiha River above the dam has a very sinuous meandering reach, and for a distance (valley length) of about 2.5 km above the falls, the river has a sinuous channel length of about 4.9 km, resulting in a sinuosity value of ~2. This is a geomorphic indicator that the river slope is quite shallow upstream of the proposed dam, suggesting it may be possible to impound a significant storage volume because the river slope is relatively flat. This means that there will be a relatively large storage volume available to store inflowing sediment, thereby retarding the rate of delta progression toward the dam.

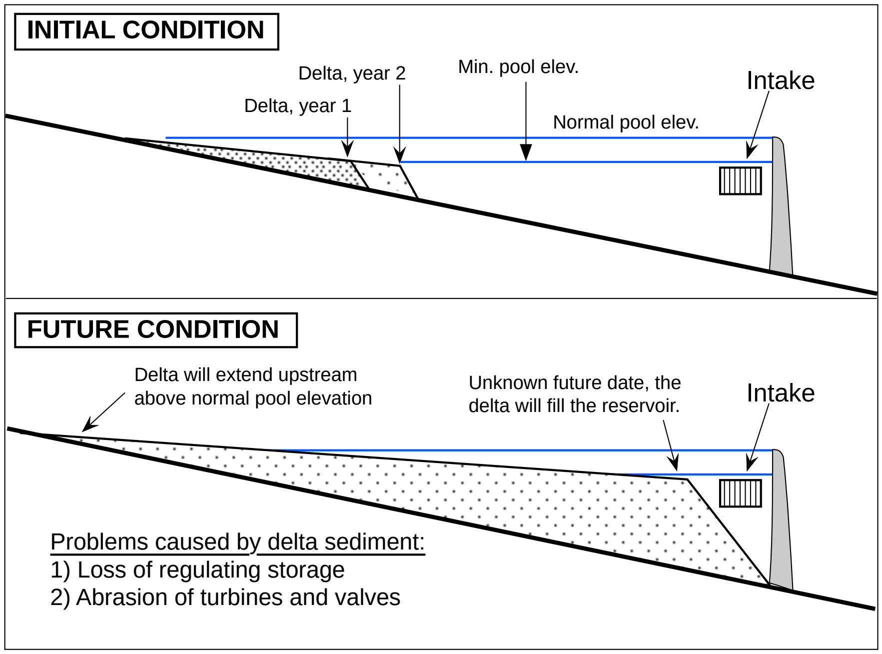


Figure 14: Conceptual pattern of filling of the Kaiha 2 reservoir.

Absent data on the sediment load and the reservoir volume, it is not possible to make any type of reasonable engineering calculation to estimate of the time required before the delta face reaches the intake. However, based entirely on engineering judgment and the conditions observed in the field, I do not believe that sediment will be a problem within the first 20 years of operation.

Recommendation 6: Prior to undertaking the project final design, it will be important to obtain basic topographic data to better determine the reservoir geometry. This may be obtained by constructing a longitudinal profile along the existing river, and using approximately 6 topographic cross sections (maximum distance of 500 m between cross-sections) to better define the reservoir configuration and volume. Additional topographic data are also required at the dam to better define closure of the reservoir at the maximum design flood stage.

Recommendation 7: Collection of suspended sediment data should be performed during the wet season (the only time of year that there is significant sediment transport) taking vertically-integrated samples across the full cross-section, following the procedure outlined in Edwards and Glysson (1999). Sampling should be undertaken from a bridge. The sediment load should be reported in two size classes, “sand” and “fines”.

Recommendation 8: Once the project is in operation, sedimentation should be monitored each year by making an annual trip in a boat from the dam upstream as far as possible, with the reservoir full, measuring water depth along the original (now flooded) river channel at intervals of approximately 100 m. Make measurements in the straight portion of the channel, and not in the river bends. The location of each measurement point can be recorded using a hand-held GPS unit (horizontal accuracy to about 5 m). It is recommended that the measurement points be pre-selected and recorded by GPS prior to filling the reservoir to avoid sites with rocks which will give an irregular bottom depth, and to revisit these same sites at each subsequent sediment survey. These survey sites should be selected before filling the reservoir, selecting areas of relatively flat bottom and devoid of large stones, in straight reaches of the river between meander bends.

Recommendation 9: Provide access to the upstream portion of the reservoir to permit sand to be extracted from the reservoir for construction purposes. This is probably the most effective sediment management measure that can be undertaken. If a significant amount of concrete construction occurs, this measure alone may be sufficient to completely control sediment accumulation in the reservoir.

6. REGULATING STORAGE VOLUME

6.1. The Purpose of Regulating Storage

Daily regulating storage at a run-of-river hydropower plant is used during low flow periods, to shut off the plant and capture flow during periods of low energy demand (e.g. after 11:00 PM), so that this water can be used to operate the plant at full capacity during periods of peak demand (e.g. afternoon and evening). However, this type of operation is advantageous only in certain situations:

- When power is delivered into an energy market which offers higher prices during periods of peak power demand, or
- When power is delivered into a mini-grid and the power plant needs to track the load as it varies over the day, <u>and</u> there are overnight periods when power production exceeds demand <u>plus</u> peak demand periods when power production cannot meet the demand.

Under either of these two conditions water can be stored overnight and used to produce power during the peak demand period.

The Kaiha 2 hydropower plant will feed into a mini-grid, but given the extremely low flows that are anticipated in the river (as low as 1 m^3/s at the intake site), to have a reliable power grid it will be necessary for the proposed diesel plant to have the capacity to supply the entire system when the river flow is too low to operate a single turbine. Under this scenario, the diesel plant will be able to track the load throughout the day, and the hydropower plant would provide energy on an as-available basis, thereby reducing the need to burn diesel fuel.

However, within a range of streamflow values the capacity of the hydropower plant will exceed the overnight energy demand. To maximize the amount of hydropower energy (and minimize the amount of diesel fuel used), it will be necessary to store water overnight, when the power load is less than the hydropower plant capacity, and to pass this water through turbines during the peak load hours. This is the scenario that is analyzed below to determine the volume and value of regulating storage at the Kaiha 2 plant.

6.2. Need to Compute the Benefit of Regulating Storage

The amount of daily regulating storage volume was not calculated in the Feasibility Study; it only cited a variation in pool level on the order of 1 to 2 meters for the purpose of daily regulation, but without a stage-storage curve for the proposed reservoir, these values simply represent a guess.

At Kaiha 2, with its load of inflowing sand, it will be difficult to maintain the regulating storage volume in the long run. It will require that reservoir emptying and flushing events be coordinated with large flood discharges, and it will also require large-capacity radial gates. This represents a level of cost and complexity that is not normally justifiable in a small 2.5 MW plant such as Kaiha 2. This makes it important to determine the benefits of regulating storage volume at Kaiha 2 to determine if these added costs and complexities are justifiable.

6.3. Procedure for Computing Regulating Storage Benefit

Because the sediment load is anticipated to be low, sedimentation will have little impact on the regulating storage volume during the first years of plant operation. Therefore, this analysis is performed based on the conditions that are anticipated at year 2038, the end of the energy projection period used in the MultiConsult report.

The daily operation of the plant, and the role of daily regulating storage has been analyzed using the daily load curve for the mini-grid reproduced in Figure 15 and the projected year 2038 peak daily power demand of 3.8 MW.

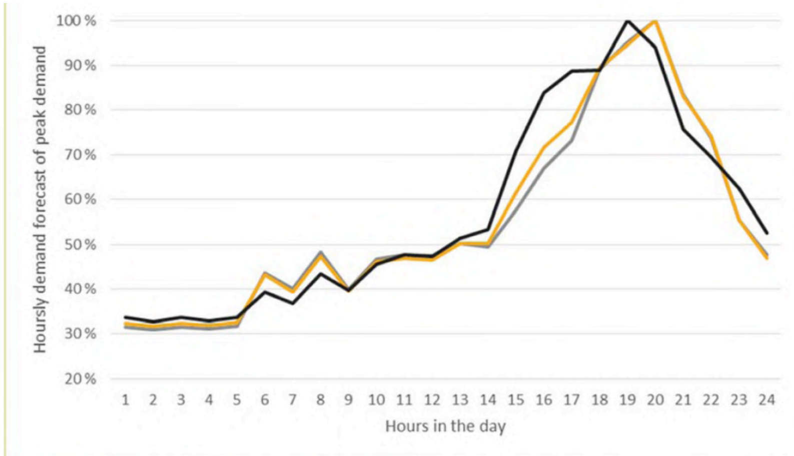


Figure 23: Hourly demand forecast relative to peak demand

Figure 15: Hourly load curve (Figure 23 in the Feasibility Study).

The daily operation of the hydropower plant is shown schematically in Figure 16 with respect to the year 2038 load curve, illustrating how the plant operation varies as a function of streamflow. It also shows a situation when daily regulating storage can increase power production and how this storage volume is used. It also shows situations when regulating storage volume provides no benefit whatsoever.

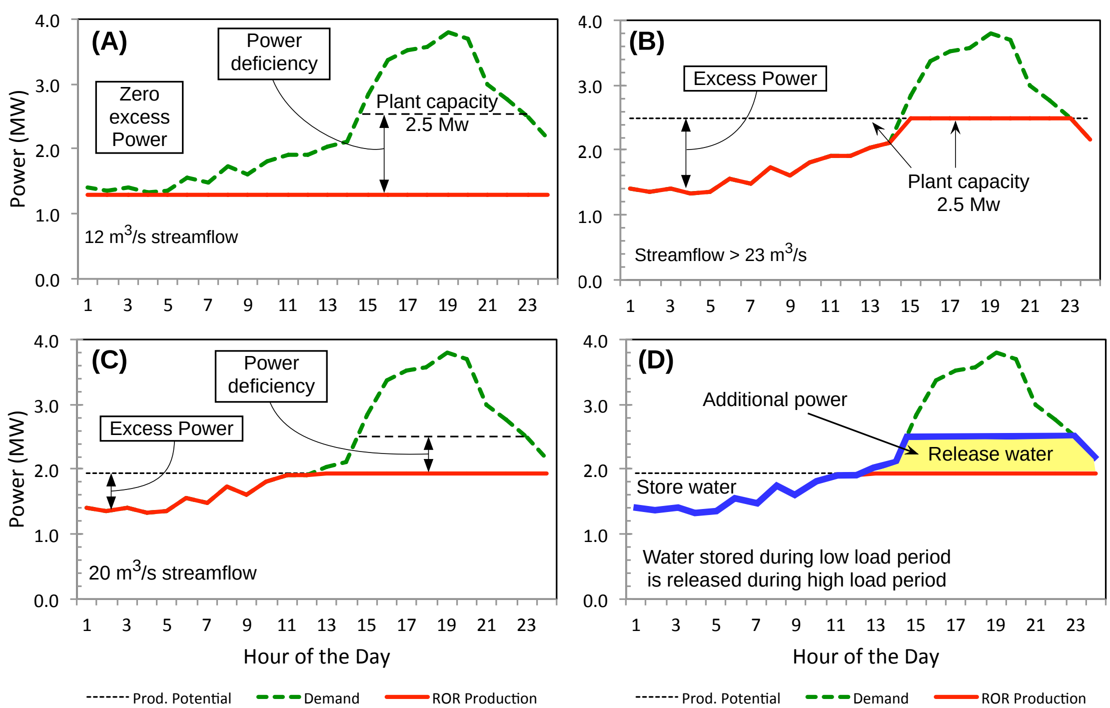


Figure 16: Graphs of hourly run-of-river hydropower production vs. hourly power demand, and the power production potential based on flow in the river. Graphs computed for 3.8 MW peak demand (year 2038).

Each of the panels in Figure 16 is explained below:

- Figure 16A shows a low flow condition when there is not enough water to exceed the load (power demand) at any time in the day or night. In this case the plant is operating at a constant rate for 24 hours, with production limited by the river flow rate. Although the plant has sufficient design capacity (2.5 MW) to meet the power deficiency shown in the graph, there is insufficient water available. In this situation regulating storage provides no benefit.
- Figure 16B shows the condition when streamflow exceeds 23 m^3/s and the hydropower plant is operating at full capacity during hours of peak load. Excess power is available at night, but this cannot be shifted over to meet the daytime peak load because the plant is already operating at its full capacity of of 2.5 MW. In this situation regulating storage provides no benefit.
- Figure 16C shows the condition when flows are between the two values shown previously. Remembering that water = power, the plant does have excess power (water) overnight, and if regulating storage is available this water can be stored and released during the daytime to operate the plant at its full 2.5 MW capacity. In this situation storage is useful because it can store water at night, and deliver this water to the power plant during periods of high power load, thus allowing it to operate at full power for a limited number of hours each day. Because the overnight water is now captured and used, instead of simply flowing over the dam during the night, the power production is increased as a result of the regulating storage.
- Figure 16D traces power plant operation using a heavy blue line, showing the periods of water storage and release in the regulating reservoir pool corresponding to panel C. Because the nighttime water is now captured and used during the day, additional power can be produced as compared to the condition without regulating storage.

As should be apparent from the graphs, regulating storage is of value only within a certain range of flows. If the flow is either high or low, regulating storage produces no benefit whatsoever. At other flow rates storage produces very little benefit. Consider the case of Figure 16A. Increasing the river flow by 1 m^3/s – from 12 to 13 m^3/s – would provide only a very small amount of excess water for storage to produce additional power during the day.

6.4. Results of Regulating Storage Calculations

The amount of additional power that could be generated was estimated based on the daily flow data previously shown in Figure 8, after adjustment by a factor of 2.42 as previously described in Section 4.4. As the result of evaluating nearly 3 years of daily data, for a year 2038 peak power demand of 3.8 MW, the following conclusions were obtained:

- Streamflow falls within the range that any degree of flow regulation would be possible approximately 28% of the days,
- Regulating storage will increase annual power production by only about 1%,
- The maximum usable regulating storage volume will be approximately 150,000 m^3, and
- As the power demand continues to increase beyond the 3.8 MW peak hour demand, the benefit of power regulation will further decline (assuming that a peak-hour pricing structure is not used).

Given the very limited utility gained from regulating storage under the conditions anticipated at the Kaiha 2 plant under the 2038 demand scenario, the added expense of facilitating reservoir flushing by installing large radial gates, and operating the plant under an empty flushing regime during periods of peak flow, will not be justified. In fact, the amount of power lost by taking the plant out of production for 2 days of flushing each year when the river is at flood stage, will be approximately equivalent to the annual power gained through daily flow regulation. Clearly, in the case of Kaiha 2 there is little justification for sustaining regulating storage, especially since the primary objective will be to simply maximize total annual energy production to produce a corresponding decrease in fossil fuel use.

Recommendation 10: The water level in the reservoir may be regulated to increase power production during lower flow periods, but this will not generate enough additional power to justify the expense and complexity of preparing the dam to flush sediment to maintain a regulating storage volume in the long term. Furthermore, since the benefit of regulation will continuously decline as the power demand increases (assuming peak-hour pricing is not used), the provision of measures for hydraulic flushing or other measures to preserve daily regulating storage is not justified at this site.

7. DESIGN RECOMMENDATIONS FOR INTAKE

7.1. Design Considerations

The intake should be designed to meet several performance objectives:

- Flood management. Pass floods and their associated debris without clogging or damaging the intake.
- Debris management. Pass trash and floating debris, and facilitate the means to efficiently clean trash racks which protect the turbines from these debris.
- Control bed level. Pass sediments downstream by operating the sediment sluice intermittently, to maintain the river bed at the lowest level possible in front of the intake. This will minimize sediment entrainment in the flow of water diverted into the turbines.
- Sediment exclusion. Locate and configure the intake within the river's geomorphic environment to maximize the exclusion of suspended sediment from diverted water.

While the sediment load (sand) is not anticipated to be large, it will eventually fill the reservoir to the crest of the fixed weir and, without a means to flush out the area of the intake, a large sand load will eventually begin abrading the turbines.

Google Earth photography shows a considerable amount of trees that have fallen into the river, especially at the eroding exterior of river meanders, and people familiar with the river also indicated that it can transport considerable woody debris during floods. The need to exclude debris must also be considered as an integral part of the intake design.

7.2. Intake Conceptual Configuration

The conceptual plan view of the intake is shown in Figure 17 and section views are shown in Figure 18 and Figure 19.

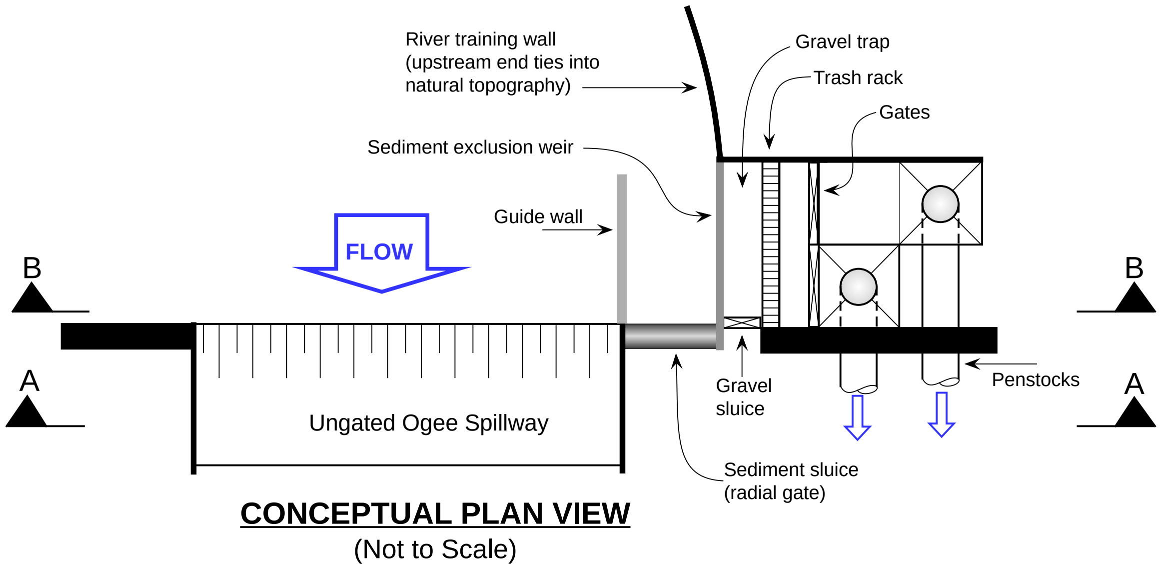


Figure 17: Conceptual plan view of recommended intake configuration.

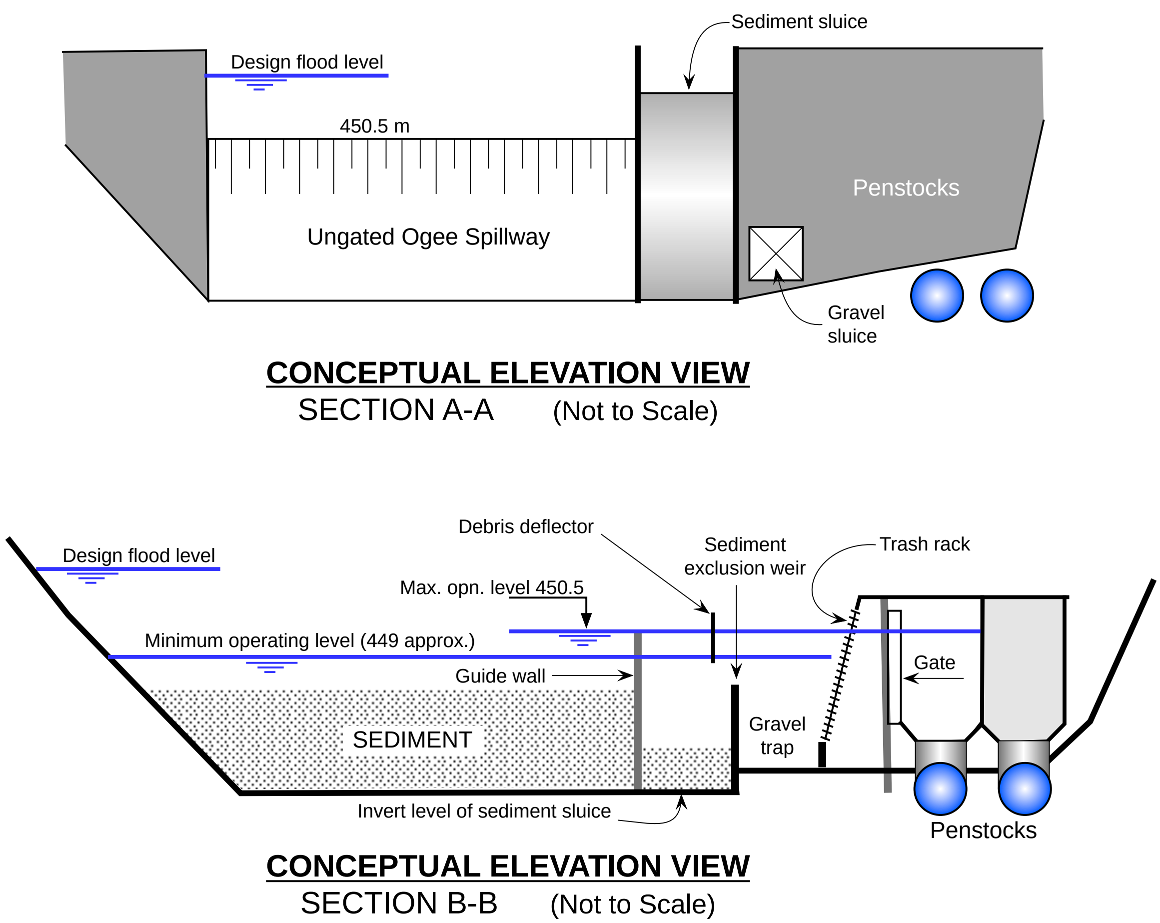


Figure 18: Intake conceptual cross-sections (section locations shown in Figure 17).

Key features of the intake are outlined below:

a) The **guide wall** separates the ogee spillway from the sediment sluiceway. This wall creates high-velocity flow along the entire front of the sediment exclusion weir when the sediment sluice is opened.

b) The **sediment exclusion weir** takes water from the top of the water column, where suspended sand concentration is lower and the suspended grain size will also be smaller. Also, a debris deflector may be constructed at the exclusion weir to minimize entrance of woody debris (see Figure 19).

c) The **trash rack** is located downstream of the exclusion weir. At this location the water should be able to approach the trash rack in a perpendicular direction, as desirable, even when the sediment sluice is partially open.

d) A bottom-opening **sediment sluice** is opened as necessary to clear sediment from in front of the exclusion weir, or it may be partially opened during high flows if this provides better sediment control. The operating schedule for this sluice should be based on operational experience, and may change as the sediment load grows over time. Use of a radial gate is recommended to minimize the problem of sediment and debris trapping in the guide slots that are required for a vertical gate. While the bottom-opening nature of this gage facilitates sediment release, it will trap floating debris. A flap gate may be installed on the top of this gate to release floating debris.

e) The **gravel trap** serves several purposes. Because there appears to be so little gravel in this river, it will probably trap very little gravel. However, it will act as a hydraulic stilling basin in front of the trash rack, allowing the flow to approach the rack in a perpendicular direction, avoiding flow shear across the face of the screen, and also providing a zone of less turbulent flow which will facilitate cleaning of the trash rack.

f) The **gravel sluice** is used to periodically flush out the gravel trap.

g) The **penstock** configuration is only conceptual, and will need to be finalized by the designer based the requirements of fitting the intake to the site topography. It is shown with a separate vertical gate controlling the entrance to each penstock so that one may be shut down for maintenance during the dry season while the other continues to operate. Alternative geometries could be used to achieve a similar purpose.

h) The general concept of a **debris deflector** is schematically shown in Figure 19. Because some debris will be submerged, the deflector will not be 100% effective. The debris captured on the trash rack may be similar to those seen in Nepal (Figure 20). If the trash rack is not kept clean it can become clogged to the point that as much as 1 meter of head loss is generated, as in Figure 21. That is why the ability to efficiently and rapidly clean the trash rack is important.

A photograph of a hydropower intake (under construction) having features similar to those recommended here is shown in Figure 22.

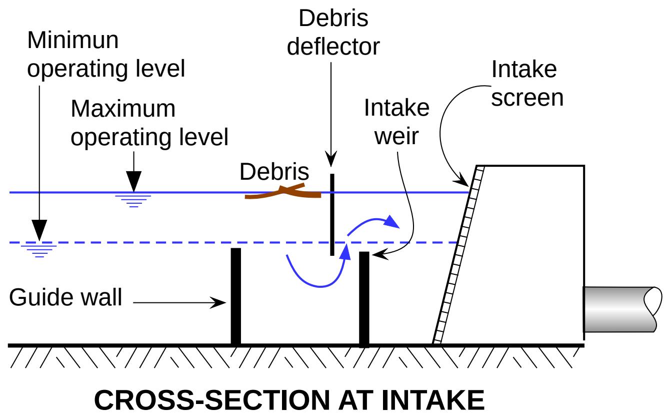


Figure 19: General concept of deflector for floating debris.

Figure 20: Photograph of debris removed from trash rack on Kali Gandaki hydropower plant in Nepal.

Figure 21: Headloss across trash rack due to clogging by debris.

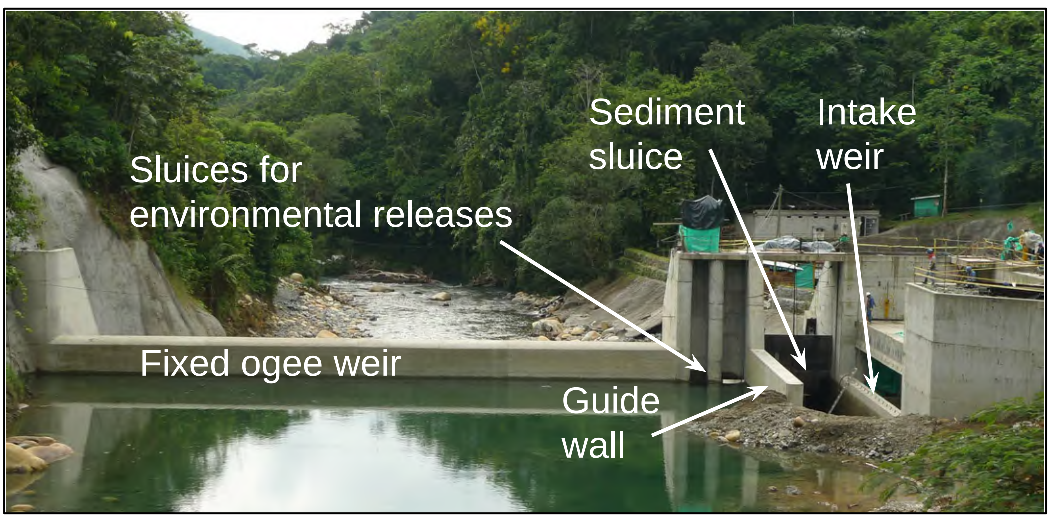


Figure 22: Photograph of intake weir having a configuration similar to that proposed in Figure 17 and Figure 18.

7.3. Intake Geomorphic Location

The intake should be located on the exterior of the river curve. At this location the secondary current established by the curvature in the river will cause the water on the surface of the river (with lower suspended sand concentration) to be carried into the intake, The recommended configuration is schematically illustrated in Figure 23.

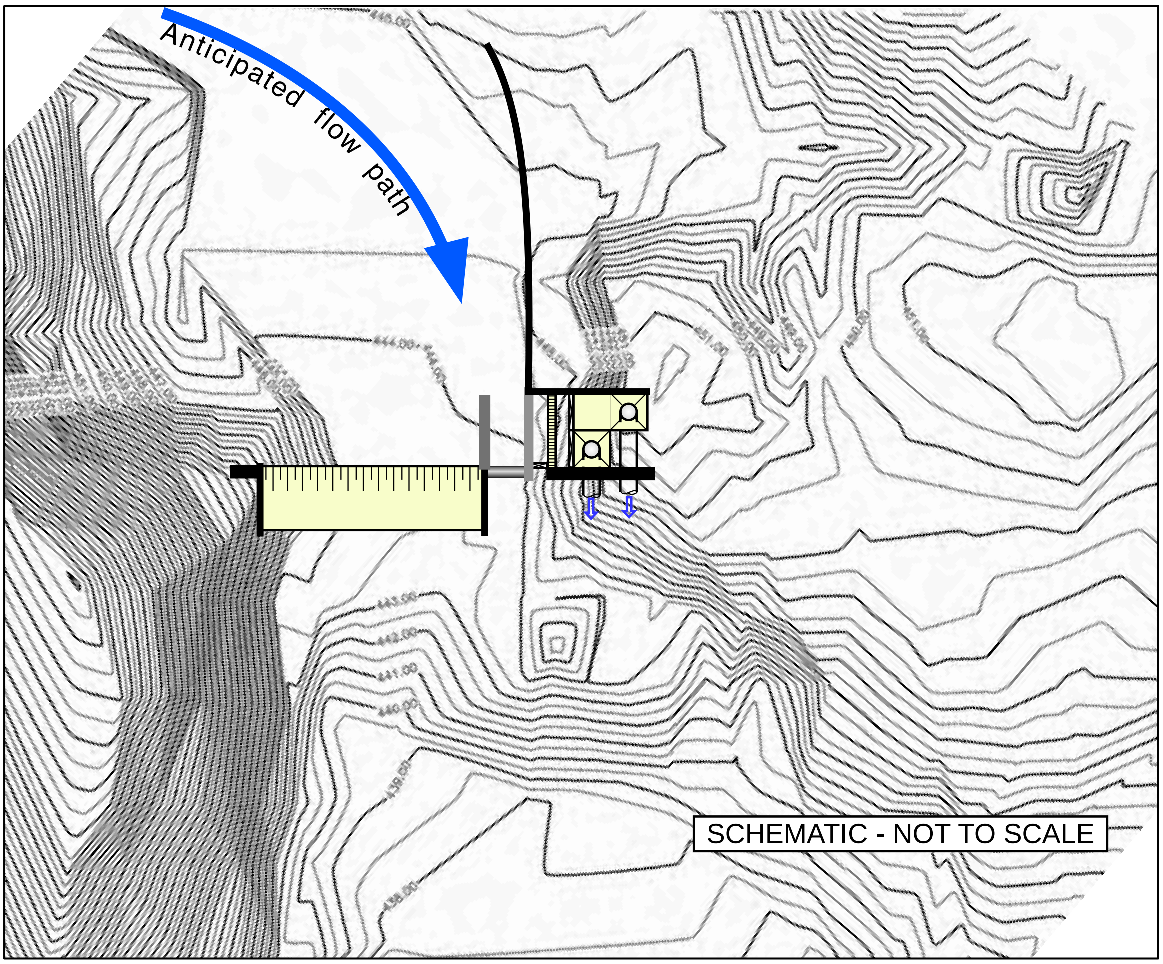


Figure 23: Geomorphic location of the intake.

7.4. Project Operation and Monitoring

No sand it anticipated to reach the intake until the face of the delta reaches that area, and then the sand load will suddenly become very high. When the delta reaches the intake area it will be necessary to open the sediment sluice to periodically remove sand from the area in front of the intake, thereby maintaining a deep area into which sand can settle instead of entering the intake.

It is difficult to accurately measure sand concentration because it settles rapidly and therefore has a non-uniform concentration within the water column. This will be especially true for the coarse Kaiha River sand. Therefore, to evaluate the effectiveness of the intake operation in excluding sand, it is recommended that daily monitoring of sand concentration be performed by sampling the water exiting the turbine. This is an area of high turbulence which will probably be most representative of the average sand concentration. By monitoring sand at this point and correlating it to the frequency of operation of the sediment sluice at the intake, it will be possible to fine-tune intake operation to minimize sediment entrainment into the turbine.

Recommendation 11: In the design and construction of the turbines, provide a port for extracting water samples from an area of high turbulence exiting the turbine for the purpose of monitoring sand concentration.

Recommendation 12: Turbine abrasion. The concentration of sediment sand exiting turbines (a well-mixed zone) should be sampled on a once daily basis once the sandy delta approaches to within 500 m of the intake. This sampling will help the operators keep track of the sediment load, which may become quite high once the sand reaches the intake if the sediment sluice is not operated regularly. This monitoring will help identify the operational procedures which are most useful in minimize the sediment load and resultant abrasion to the turbines.

Monitoring recommendations for the reservoir have been provided in Section 5.6 and are not repeated here.

8. RECOMMENDATIONS

The recommendations previously given are repeated below along with their page number:

9. REFERENCES

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