# TECHNO-ECONOMIC ASSESSMENT STUDY FOR ROGUN HYDROELECTRIC CONSTRUCTION PROJECT

## PHASE II: PROJECT DEFINITION OPTIONS

## Volume 2: Basic Data

## Chapter 6: Sedimentation

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# 1 OBJECTIVES AND CONTEXT

The proposed Rogun project is a large reservoir dam in a natural context where the annual sediment rates are recorded to be very high. Consequently the project is prone to be affected by sedimentation processes, the reservoir created being favorable to particle settling.

This therefore requires the viability of the proposed alternatives to be assessed taking into account the impact of sedimentation, in particular on the reservoir capacity and on operational constrains. It also raises the necessity to address the general concern about the long-term behavior of large reservoirs and identify an appropriate end of the life strategy to be implemented to ensure long-term sustainability of the project.

The present note comprises a complete review of existing data on the characteristics and quantity of the solid particles transported by Vakhsh River, including an analysis of investigation campaigns carried out in the past at Nurek reservoir. This allows a reasonable estimate at this stage of the studies of the yearly solid runoff at Rogun.

The second part of the Chapter is review of the state of the art sediment management options used worldwide and their applicability to the Rogun project.

The third part outlines a proposed sediment management plan for Rogun project during the operation phase, ensuring that all alternatives are designed for the longest possible economic life together with safe operation. Considerations are also given to an end-of-life strategy to ensure sustainability and safety of the Rogun project in the long run.

## 2 REFERENCES

Various documents dealing with sedimentation at Rogun and Nurek are available: reports, note, tables… Here below are listed the one that have been made available to the Consultant.

[1] Project of completion of Rogun HPP – report n°1861-2-2-2 : Natural conditions, Hydro meteorological conditions, Hydroproject Institute (HPI), 2009.

[2] Bankable feasibility study for Stage 1 Construction Completion– Vol 3D Hydrology, Lahmeyer International GmbH, 2006.

[3] Note called “Calculation of Vakhsh rive solid run off”, Ministry of Water, 2012.

[4] Note called “Characteristics of Amudarya river”, Barki Tojik ,2012

[5] Report on the engineering hydrology of the Nurek reservoir, Tajik State Design and survey research institute "Hydroenergoproject", Dushanbe 2001

[6] Excel file containing solid run off measurements at various gauging station (Darband, Sariguzar,Tutkaul, Chorsod..), Hydromet Institute of Duschambe, 2012

General documents about the sedimentation issue have been published, here below are listed the one used by the Consultant.

[7] Sedimentation and Sustainable Use of Reservoirs and River Systems, bulletin n°147, ICOLD, 2009.

[8] Reservoir conservation, the RESCON approach, A.Palmieri, F.Shah, G.W. Annandale, A.Dinar, the World Bank, 2003

[9] The feasibility of flushing sediment from reservoirs, E.Atkinson, 1996

[10] Design of small dams-Appendix A: Reservoir sedimentation, USBR. 1987

[11] Reservoir Sedimentation Handbook, G.L. Morris, J. Fan, McGraw-Hill, 1998

[12] Schleiss, A., and Oehy, C., 2002. Verlandung von Stauseen und Nachhaltigkeit. Wasser, Energie, Luft-Eau, Énergie, Air, 94 (7/8), 227 – 234.

# 3 VAKHSH RIVER SEDIMENT CHARACTERISTICS

## 3.1 General information

The solid runoff in the Vakhsh River mainly forms due to wash away of silt from river basins and to a significantly smaller extent due to river bed degradation. The sediments are carried away with glacier streams and with melting snow and rainwater.

The river water in the Vakhsh system features high turbidity. The highest turbidity occurs in the flood seasons with two maxima occurring in May in the period of intensive seasonal snow melting and in July-August in the period of glacier melting. The lowest turbidity is observed in winter months.

## 3.2 Grain size distribution

***Data available***

The grain size distribution of both the suspended load and the bed load at Rogun are given in the Table 3.1 and Table 3.3. Those values are presented both in the Lahmeyer report [2] and the HPI report [1]. It comes from the Hydrometeorological institute of Tajikistan and their analysis of observations at various gauging station.

| D, mm | 1-0.5 | 0.5-0.25 | 0.25-0.1 | 0.1-0.05 | 0.05-0.01 | <0.01 |
|---|---|---|---|---|---|---|
| % | 1.17 | 1.19 | 13.99 | 21.25 | 19.60 | 42.80 |

**Table 3.1 : Suspended load - Grain size distribution**

| D, mm | 500-250 | 250-120 | 120-80 | 80-40 | 40-20 | 20-10 | 5-1.2 | <1.2 |
|---|---|---|---|---|---|---|---|---|
| % | 3.0 | 17.8 | 14.2 | 27.1 | 19.6 | 4.1 | 2.9 | 8.0 |

**Table 3.2 : Bed Load - Grain size distribution**

Several grain size distributions, defined thanks to measurements done during the flood 1992 and during the year 1979, are shown in the HPI report [1] for the suspended load.

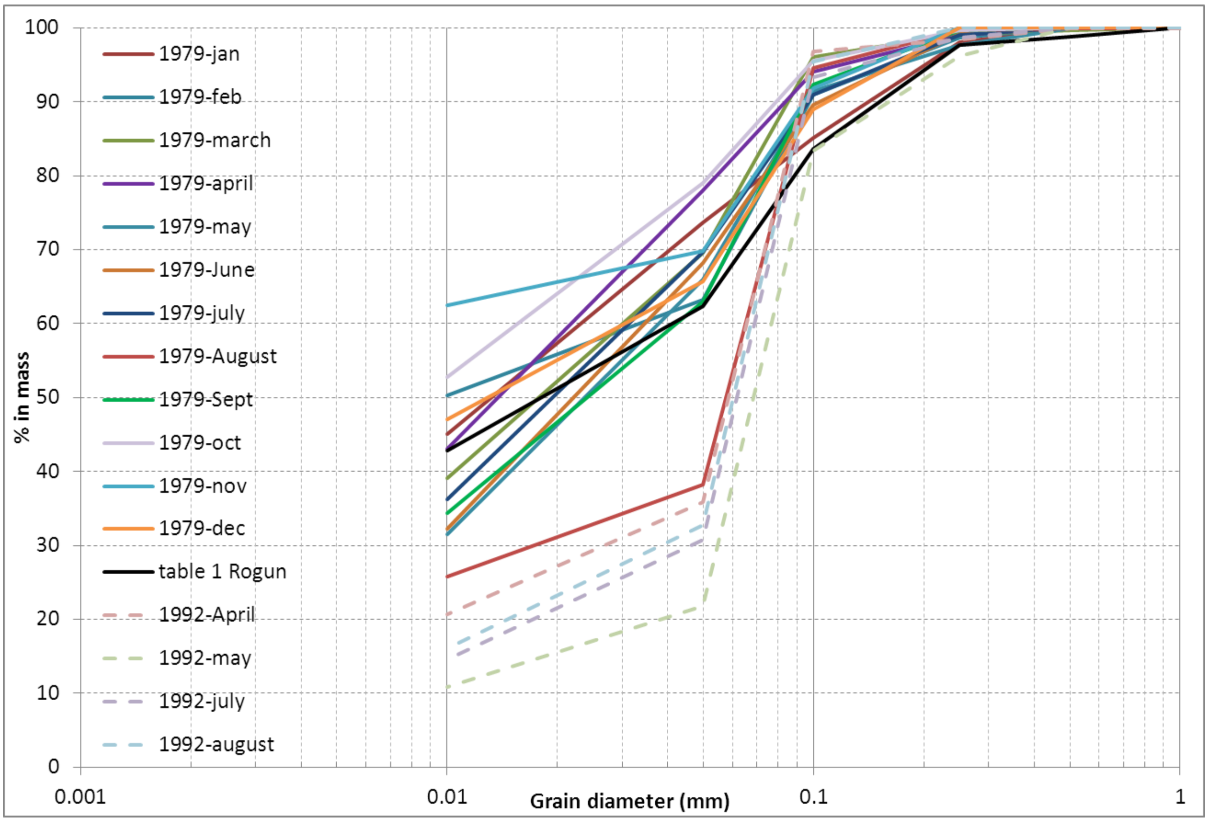


**Figure 3.1: Suspended load - Grain size distribution**

***Assessement***

The Figure 3.2 shows the values presented in Table 3.1 and Table 3.2 plotted on the same chart. The black curve is the total grain size distribution of the Vakhsh sediment assuming that the bed load represents 15% and the suspended load 85% of the total solid run off.

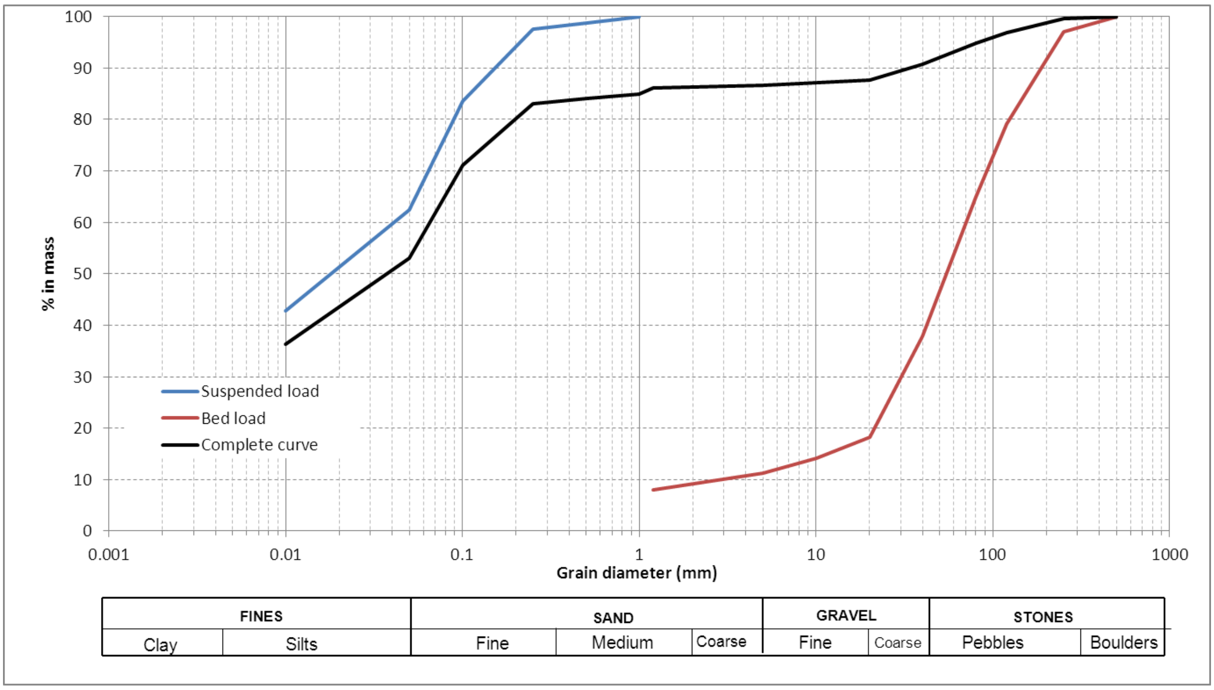


**Figure 3.2 : Chart of grain size distribution**

The black curve presents a flat area covering almost all the sand part of the chart. This would mean that there is almost no sand in the sediment material transported by the Vakhsh River. This cannot reasonably represent the reality.

The Figure 3.1 presenting the grain size distribution of the river suspended load at various months and year shows an important scattering of the measured suspended load grain sizes.

## 3.3 Specific weight

All measurements and assessment of solid run off are done in terms of weight. The transformation in volume is done thanks to the specific weight of the sediment.

***Data available***

In the various documents, there is no mention of any laboratory test to measure this density. Nevertheless, the different values found in the previous studies are reproduced in the following table:

| Reference | Suspended load | Bed load | Total |
|---|---|---|---|
| HPI 2009 [1] | 1.15 | 2.60 | - |
| Lahmeyer BFS [2] | - | - | 1.39 |
| Ministry of Water 2012 [3] | - | - | 1.34 |

**Table 3.3 : Specific weight (t/m$^3$)**

***Assessment***

2.6 t/$m^3$ is the average value of rock specific weight.

Usual values of solid run off specific weight range between 1.2 and 1.4 t/$m^3$. Values stated by Lahmeyer [2] and the ministry of Water [3] are in the upper bond of this range.

The value of 1.15 t/$m^3$ considered for the suspended load is doubtful; the usual range of suspended load specific weight is 1.4 t/$m^3$.

## 3.4 Concentration

***Data***

The sediment concentration is measured at several gauging stations and presented in several documents:

- [6]: suspended load measurements at Goluvnaya, Tigrova, Chorsod, Sariguzar, Darband and Tutkaul. The station with the longest serie is Tutkaul with monthly data from January 190 to December 1943 and from May 1947 and April 1967.
- [2]: suspended load measurements at Tutkaul, Sariguzar, Surkhob, Chorsod, and the bedload at Tutkaul.
- [1]: suspended load measurements at several gauging station, and the bed load measurement at Tutkaul.

In addition, in [1], HPI presents a long series of monthly solid discharge (suspended and bed load) at Rogun site. Those series have been computed thanks to several record stations in the Vakhsh River basin: Tutkaul (1942-1944, 1948-1972), Nurabad (1976-1978, 1980-1982), and Kichrog (1984-1986, 1990-1993). When data are missing, the series have been completed thanks to a correlation law between the solid and the liquid monthly discharge. The next figures are extracted from [1] and present the correlation found between the suspended load and the water discharge, and between the bed load and the water discharge.

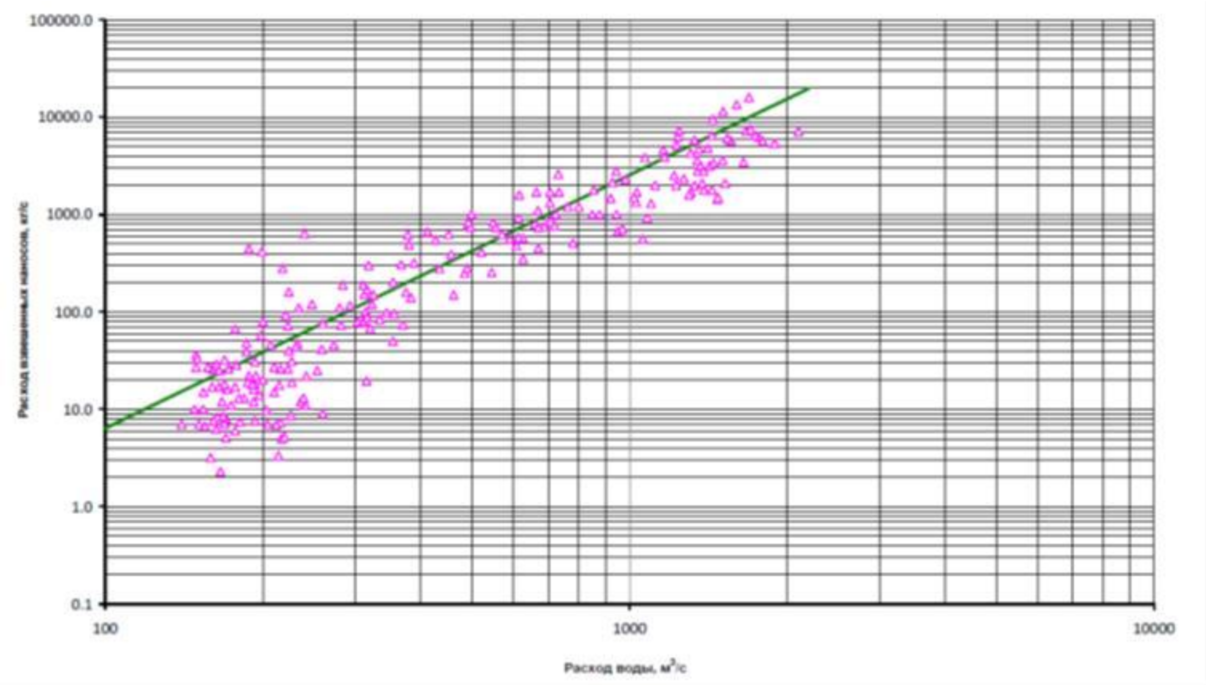


**Figure 3.3 : Suspended load (kg/s vs m$^3$/s)- Source [1]**

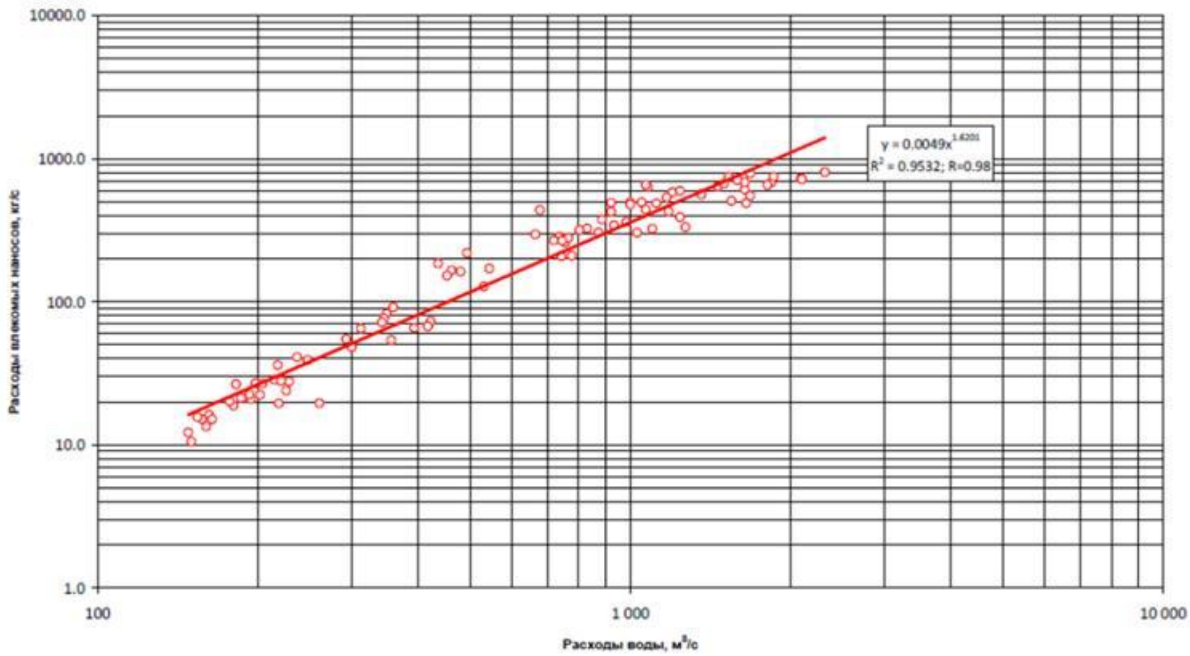


**Figure 3.4 : Bed load (kg/s vs m$^3$/s) - Source [1]**

### *Assessment*

Suspended load data from [2] and [6] are similar: when a measure at a given station and a specific date is available on both sources, the value is the same. Bed load data presented in [1] and [2] are identical. The suspended load measurement presented in [1] and reproduced in Figure 3.3 gather measurements from several stations (Tutkaul, Nurabad and Kichrog) and therefore cannot be compared to the Tutkaul measurement presented in [2] and [6].

All the data presented in the various documents are consistent with each other. Nevertheless, the sampling procedure is not detailed in any document which makes difficult to assess the reliability of the suspended load measurements.

It is said in the text [1] that bed load movements starts when the liquid discharge overpasses 300 $m^3/s$ and that the measurements of bed load is impossible when the liquid discharge is over 500 $m^3/s$. Data presented in the Figure 3.4 are doubtful since there are measured points over 500 $m^3/s$ and under 300 $m^3/s$.

On the next figures, the HPI completed series and the measured data are compared. It can be seen that a large number of points are exactly aligned, which means that they have been calculated based on the solid/liquid run off correlation found. Those are theoretical values and not actual measures. The actual data measured and shifted from their measurement location to Rogun site represents a small part of the whole series. The representativeness of the series is therefore limited as calculated values distort the sample.

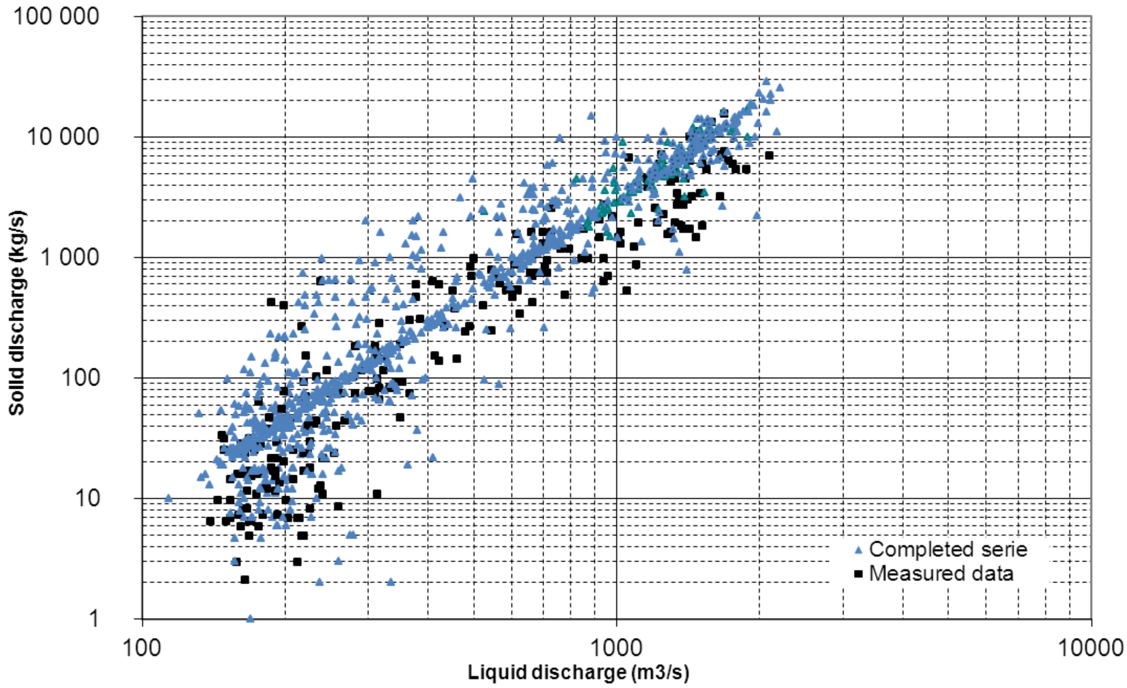


**Figure 3.5 : Suspended load - HPI data [1]**

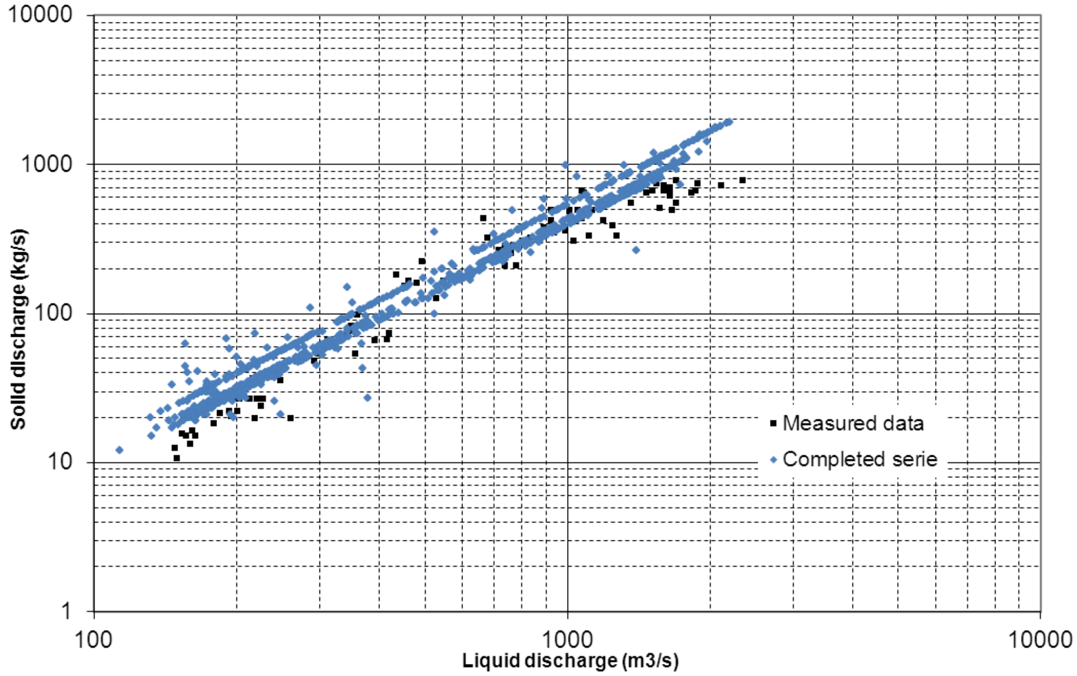


**Figure 3.6 : Bed load - HPI data [1]**

# 4 NUREK RESERVOIR EXPERIENCE

## 4.1 Available information

Since its impounding in 1972, Nurek reservoir catches sediments from the Vakhsh River. According to the various documents, several surveys have been carried out over the years to investigate the sedimentation of Nurek reservoir: in 1989, 1994 and 2001.

The next table and graphs shows the main results of those surveys.

| | Volume (km$^3$) | | | |
|---|---|---|---|---|
| **Storage** | **1972** | **1989** | **1994** | **2001** |
| **Total** | 10.50 | 8.66 | 7.96 | 8.63 |
| **Live** | 4.50 | 3.40 | 3.06 | 4.27 |
| **Dead** | 6.00 | 5.26 | 4.90 | 4.36 |

**Table 4.1 : Evolution of Nurek reservoir capacity**

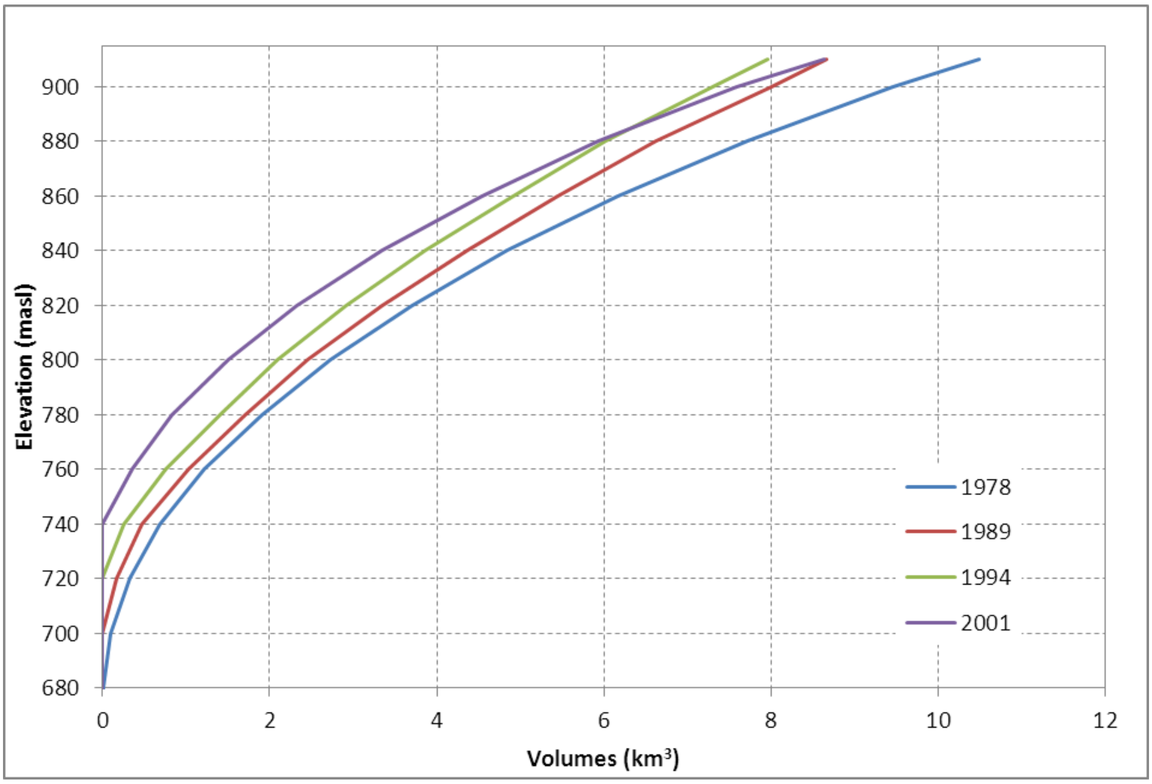


**Figure 4.1 : Evolution of Nurek reservoir capacity**

No documentation is available on the characteristics of the sediments filling Nurek. It is understood that a specific study is being undertaken on that topic. It is prime importance for understanding the future sedimentation conditions of Rogun reservoir.

## 4.2 Assessment

According to these surveys, the reservoir capacity at the full supply level, 910 masl:

- decreased by 108 $Mm^3$/year from 1972 to 1989,
- decreased by 115 $Mm^3$/year between 1994 and 1989,
- decreased by 64 $Mm^3$/year between 2007 and 1972,

Even taking into account bank transformations, the increase of capacity reported between 1994 and 2001 is difficult to explain:

- in the report on Nurek reservoir [5], the erosion of banks is evaluated at 77 $Mm^3$ for the total period 1972-2001, ie 2.66 $Mm^3$/year.
- Lahmeyer [2] make a reference to the report of the 1994 survey where it is stated that the volume of bank transformation is 21 $Mm^3$ between 1989 and 1994, ie 4.2 $M^3$/year.

**Therefore, the most reliable periods of measurements are 1972-1989, when Nurek reservoir was filled by 108 $Mm^3$/ year.**

## 4.3 Further campaign

For long term sustainable sediment management of the Rogun reservoir, a clear understanding is required not only on the annual sediment transport volume and the corresponding loss of storage but also on the configuration of the sediment deposition patterns over the life of the project. To obtain this kind of information, the Nurek reservoir sedimentation process since its impoundment in 1972 could be a good source. It is almost like a large scale hydraulic model and it could provide us with all the information required to predict and manage some of the aspects of long term sedimentation of the Rogun reservoir. A good understanding of the evolution of the reservoir sedimentation at Nurek is therefore very important to design a precise sediment management plan in phase 3. It would be necessary to retrieve all the available historical sedimentation data of the existing Nurek reservoir.

***Bathymetric survey of the reservoir sedimentation***

It is important to assess and understand the actual aspects of sedimentation process of the Nurek reservoir as the last survey was carried out in 2001, i.e., 12 years ago. Consequently, we would propose that a bathymetric survey using multi beam echo sounding be carried out for the part of the reservoir which has been subjected to significant sedimentation. This would enable assessment of the general reservoir sedimentation patterns as a function of the variations in the reservoir cross sections, annual water levels and the corresponding river discharge hydrographs.

***Longitudinal and transversal cross sections of the sediment deposition in the reservoir***

Measurement of the longitudinal and transversal cross sections would enable us to assess the overall magnitude of sedimentation to-date. At the same time determine the topset and foreset slopes of the deposited sediment materials. Simultaneously the reservoir water level and river discharge should be recorded to determine the corresponding flow velocities in the longitudinal direction. Identification at the same time if there are areas with surface back eddies influencing the flow velocities and sediment deposition patterns.

***Bed samples of deposited sediments***

Grab samples (preferably during high river discharges) from the surface of the deposited sediments in the reservoir at every 1000 m interval along three longitudinal alignments. One along the center line of the reservoir and the other two at equidistant from the centerline and the bank.

***Core samples along the topset and foreset slopes***

If possible collect core samples along the topset and foreset slopes of the deposited sediments in the reservoir. Such sampling would enable assessment of the annual progression of the delta and also the segregation and deposition patterns of different particle sizes transported by the river. Locations of core sample data collection will be defined after evaluation of the grab samples.

***Annual reservoir water level variations and corresponding river discharges***

Information regarding the annual reservoir water level variations and the rate at which the water level was lowered and raised over the last 32 years with indications (if possible) on corresponding river discharges.

***Measurement of suspended sediment concentration and particle size distribution at different depths along the reservoir for various river discharges***

This would enable understanding of the transport patterns and assessment of the suspended sediment concentrations and corresponding particle sizes along the reservoir as the flow velocities decrease with measurement of corresponding water temperatures.

# 5 ESTIMATION OF YEARLY SOLID RUNOFF AT ROGUN

## 5.1 From Gauging station measurements

***Data available***

In [1], HPI has computed the yearly solid discharge as the average of all monthly solid discharge of the series constructed. It gives a long term yearly solid run off of 87.8 Mt (bed and suspended loads).

In [3], the author uses the Tutkaul station measurements and performs a frequency analysis on the yearly mean solid discharge to extract the 50% probability event. The yearly solid run off extracted with this method is 90.45 Mt.

***Assessment***

As explained in 3.4, the suspended and bed load series presented by HPI in [1] are extrapolated series based on a limited number of actual measurements.

On the other hand, the calculation made in [3] of the yearly solid run off is based on actual Tutkaul measurements. Tutkaul is located downstream of Rogun site, approximately at Nurek location.

## 5.2 Empirical method

***Data***

In Lahmeyer and HPI reports, results of studies carried out by others agencies are presented. Their solid run off calculation is based on three empirical methods:

- Wash away intensity from the catchment area;
- Turbidity-catchment height relation curve;
- Suspended load modulus of runoff.

With these methods, the bed load is assumed at 30% of the suspended load.

| **Method** | **Suspended load** (Millions of tonnes) | **Bed load** (Millions of tonnes) | **Total** (Millions of tonnes) | **Ratio bed vs suspended load** |
|---|---|---|---|---|
| As per wash away intensity from the catchment area | 79.0 | 23.7 | 102.7 | 30% |
| As per turbidity-catchment area height relation curve | 92.8 | 27.8 | 120.6 | 30% |
| As per suspended load modulus of run off | 95.9 | 28.8 | 124.7 | 30% |

**Table 5.1 : Yearly solid run off calculation - Empirical method**

### 5.3 Comparison and conclusion

| **Method** | **Suspended load** (Millions of tonnes /year) | **Bed load** (Millions of tonnes/year) | **Total** (Millions of tonnes/year) | **Ratio bed vs suspended load** |
|---|---|---|---|---|
| Gauging station and interpolation (HPI [1]) | 78.6 | 9.2 | 87.8 | 12% |
| Tutkaul gauging station (Ministry of water resources [3]) | - | - | 90.5 | - |
| 1978 project | 80.8 | 3.6 | 84.4 | 4.5% |
| 1993 studies | 79.4 | 7.9 | 87.3 | 10% |
| As per wash away intensity from the catchement area | 79.0 | 23.7 | 102.7 | 30% |
| As per turbidity-catchement area height relation curve | 92.8 | 27.8 | 120.6 | 30% |
| As per suspended load modulus of run off | 95.9 | 28.8 | 124.7 | 30% |
| | | | | |
| *Mean* | *84.4* | *16.8* | *99.7* | |
| *Standard deviation* | *7.8* | *11.2* | *16.8* | |

**Table 5.2 : Annual solid run off**

Various methods agree on the yearly suspended load with a value in the range of [79;96] millions of tonnes per year.

Depending on the method, the bed load volume is comprised between 5% and 30% of the suspended load volume.

Finally, the total yearly solid run off is comprised between 87 and 125 millions of tonnes depending on the method used.

As said in the paragraph 4.2, the reservoir of the Nurek HPP has being filled by approximately 100 $Mm^3$ per year on the period of most reliable data. Even with a rather low sediment density as 1.35, the matching weight is 135 millions of tonnes, ie more than the upper bound of the estimated range of total yearly solid run-off. With a sediment density of 1.4, the matching weight is 140 millions of tonnes.

**Finally, the total yearly solid run-off of the Vakhsh River is ranged in between 87 and 140 millions of tonnes per year, or between 62 and 100 Million $m^3$ per year.**

**This range of uncertainty cannot be narrowed at this stage of the studies. For the purpose of its study, and as a conservative approach, the value of 100 $Mm^3$ /year is considered as a representative assumption of sediment solid run-off.**

**During the next phase of the study, the evaluation of the Vakhsh solid run off should be completed by using stae of the art sediment sampling to reduce the range of uncertainties on the yearly solid run off.**

# 6 REVIEW OF AVAILABLE SEDIMENT MANAGEMENT SOLUTIONS

## 6.1 Inventory of possible measures:

To ensure the project safety and sustainability, several possible measures to reduce impact of sedimentation can be considered.

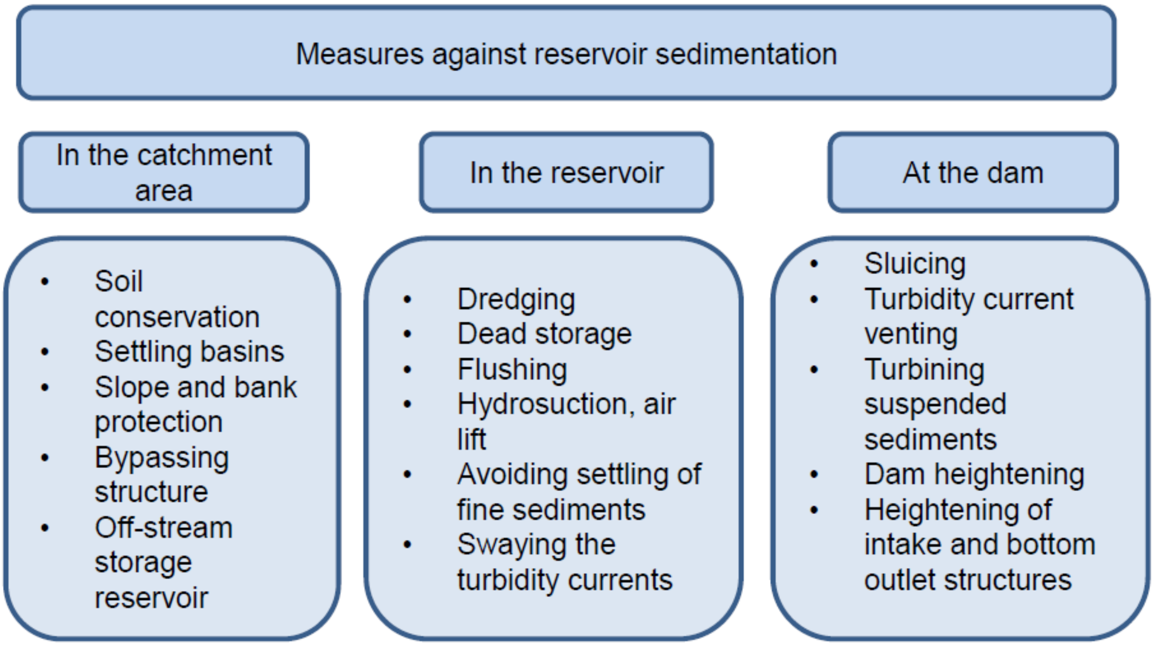


**Figure 6.1 : Inventory of possible measures for sediment management (after Schleiss and Oehy, 2002)**

The following possible mitigation measures and their applicability to the specific Rogun conditions are being reviewed in the following paragraphs:

- Reducing sediment inflows with:
  - watershed management
  - upstream check structures
  - reservoir bypass
  - off-channel storage
- Managing sediments within the reservoir with:
  - adequate operating rules
  - tactical dredging
- Evacuation of sediments from the reservoir with:
  - Flushing

## 6.2 Reducing sediment inflows

### 6.2.1 Watershed management

Watershed management has been proved to be efficient in reducing soil erosion in some cases where the catchment area was limited and vegetation type adequate.

*In the case of Rogun, the catchment area is out of proportion and moreover the soil is naturally poor and not suitable for afforestation or specific farming technics (bunding, terracing…) as farming in the Rogun catchment is limited to cattle raising.*

### 6.2.2 Upstream check structures

The upstream check structures option would consist in trapping or storing the sediment inflows on Vakhsh tributaries upstream of the Rogun reservoir. It requires emptying the trap from its sediment after each flood.

*In the case of Rogun, the main tributaries should be equipped to have significant effect. The amount of sediment to trap and to clean after the flood is important and would require important means: even if half of the total inflows can be trapped, it means that 30 $Mm^3$ of sediment should be clean and transport by trucks each year. It would require equipment and workers larger than during the dam construction where approximately 5 $Mm^3$ (71 $Mm^3$ in 15 years) of material will be transported from the borrow areas and placed in the dam each year.*

*This solution cannot be applied in Rogun given the amount of sediment to evacuate.*

### 6.2.3 Off-channel storage

The off-channel storage consists in diverting the river during high sediment transport period into specific reservoir outside of the river channel, in a small tributary for instance.

*In the case of Rogun, the topography is not suitable for such solution: because tributaries are steep slope valleys, the storage areas in their upper part are very small compared to the annual solid run off.*

### 6.2.4 Reservoir bypass

This solution consists in diverting the sediment flood around of the reservoir: during high floods the river would be diverted from the reservoir to a specific water way that reaches the main river downstream of the dam.

This technic is feasible when the site topography is suitable is allows to construct limited diversion structures. A successful example is the Nagle dam in South Africa (see Figure 6.2).


**Figure 6.2 : Nadle dam (South Africa) - Reservoir by pass**

*In the case of Rogun, the fairly straight shape of the reservoir makes this solution difficult: as shown in Figure 6.3, a similar concept will need at least a 30 kilometre long tunnel through the right bank to only lengthen the life of the downstream half of the reservoir. This is unprecedented in the past experience of such structures. Moreover the cross section of such tunnels should be large enough to safely pass the sediment loaded floods and would involve large maintenance costs challenging the economic feasibility of such a structure.*

*Moreover discharging the sediment load in Nurek reservoir would only shift the problem to Nurek project. And in addition, the annual sediment load is not concentrated in a short period of time, but it is spread over the whole wet season. Bypassing the whole wet season will prevent the reservoir yearly filling.*

*The technical problems associated with sediment scour and the high cost of such large and long tunnel suggest that a by-pass tunnel will not be feasible.*

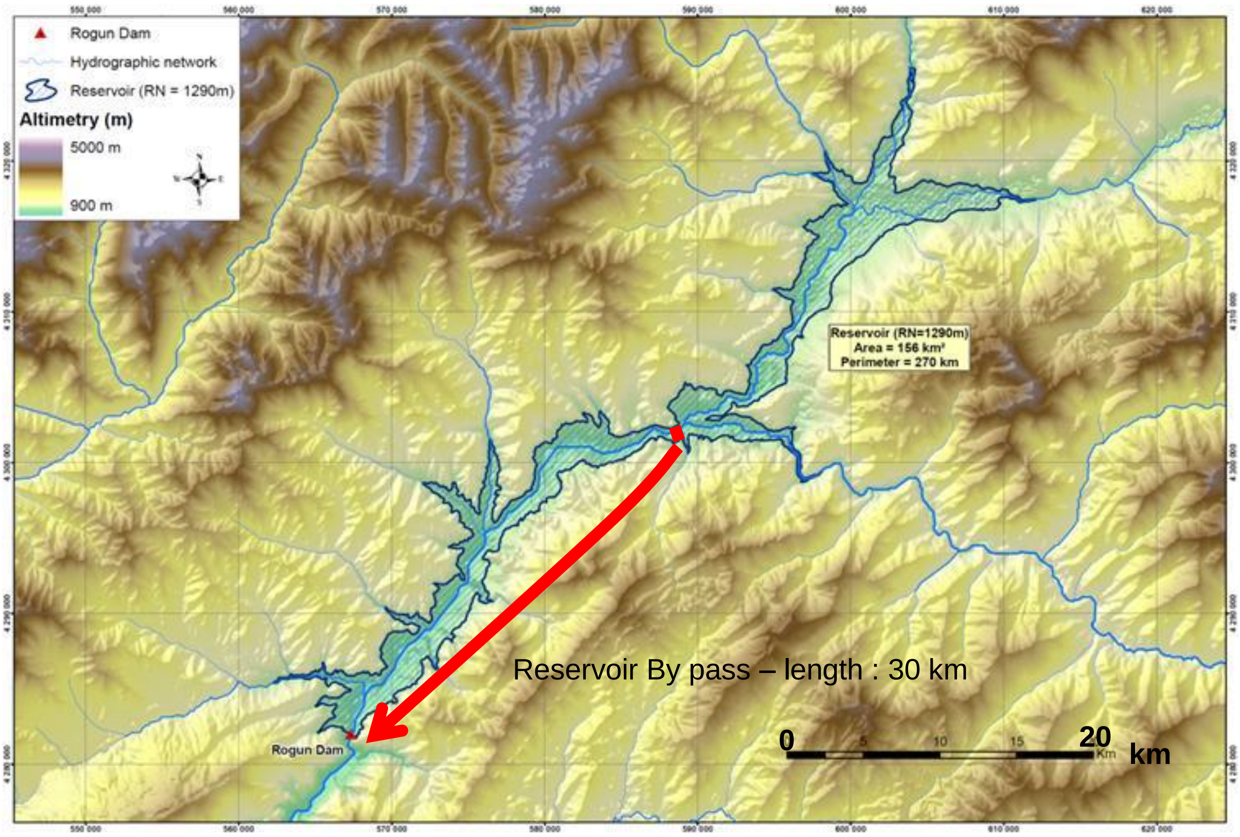


**Figure 6.3 : Tentative layout - Rogun sediment by pass**

## 6.3 Managing sediment within the reservoir

### 6.3.1 Adequate operating rules

Reservoir sedimentation and the progression of the sediment delta towards the dam can be controlled to a certain extent by controlling the reservoir operating conditions (including modification of the level of the intakes during the life of the project to extend the generation phase).

At Tarbela dam in Pakistan the reservoir is about 90 km long and in about 30 years the foreset slope has advanced within 10 km of the power intake and sand is already entering the power discharge. The reservoir level is lowered each year by about 70 m and at the onset of the flood season high velocity flow over the topset slope of the deposited sediment mostly fine sand helped the foreset slope to move downstream at a very fast rate, about 2.5 km/year.

According to the reservoir operation studies, the yearly reservoir drawdown is 30 m for the highest alternative (10% of the maximum reservoir depth), 50 m for the medium (17%) and 80 m for the lowest alternative (33%). The higher is the alternative, the less sensitive to yearly drawdown it would be.

*However for sustainable sediment management of such a large reservoir, it is in any case advisable to adjust the operating rule of the reservoir to the sedimentation pattern. This includes raising the level of the intakes while the sediment level at the foot of the dam is raising to extend the life of the generation system. The proposed sediment management plan during operation is described in the next paragraph.*

*Interpretation of the Nurek reservoir sedimentation will provide us with actual sedimentation rates, its configuration and progression rates of the foreset slopes over the last 40 years. This information would enable a good prediction of short term (Stage 1) evolution of the Rogun reservoir sedimentation.*

### 6.3.2 Tactical dredging

The tactical dredging consists in localized dredging of the most critical area: power intakes, spillways intakes. The volume removed is here much lower than the yearly run off (silt and clay fraction is allowed to pass through) this can lengthen the life span of the reservoir.

*In the case of Rogun, such dredging can only be localized after several decades, when the sediment foreset get close to the power intakes. However, given the annual load of sediments, tactical dredging might not bring significant effect on protecting the intakes against clogging.*

## 6.4 Evacuation of sediments from the reservoir

### 6.4.1 Reservoir Flushing

Flushing consists in using a low level tunnel to remove sediment already deposited in the reservoir thanks to the flow velocity and transport it downstream of the dam.

Such solution can be very efficient in narrow and small reservoirs: in that case the flushing is made until the complete drawdown of the reservoir. The “report of feasibility of Flushing sediment from reservoirs” written by Atkinson in 1996 [9] presents some reservoirs that have been successfully flushed; there initial capacities are all below 15 $hm^3$ (100 times less than Rogun).

*Such a complete flushing is not possible in the case of Rogun given the size of the reservoir: emptying 13 000 $hm^3$ (or even 5 000 hm3) of water in a flood season is not possible due to water use regulation within Amudarya basin which forbid to store important amount of water that would be required for refilling the reservoir after empty flushing. Moreover, the important discharge necessary to flush the reservoir will not be turbined, and the energy produced significantly decrease: 13000 hm3 over a year gives an average discharge of 400 $m^3/s$ that is approximately the River modulus.*

*However, a partial drawdown can be used to clear the area close to the power intakes and lengthen the life span of the power house equipment.*

*A tunnel set just below the power intakes and discharging in the Obishur River has been initially envisaged with the layout described in the following figure. Special care should be given to the behavior of the localized foreset in front of the power intakes slope instability and sand wave into the power water ways.*

*However, this solution was deemed not properly behaving; due to the fact that it should have worked under high head, say not less than 110 m for the alternative FSL 1290, being the inlet position located at least some 30 m below the power intakes. Some other drawbacks were noted, linked also to the nature of the Obi-Shur creek, which is the only possible point of discharge for a tunnel starting from the power intakes area.*

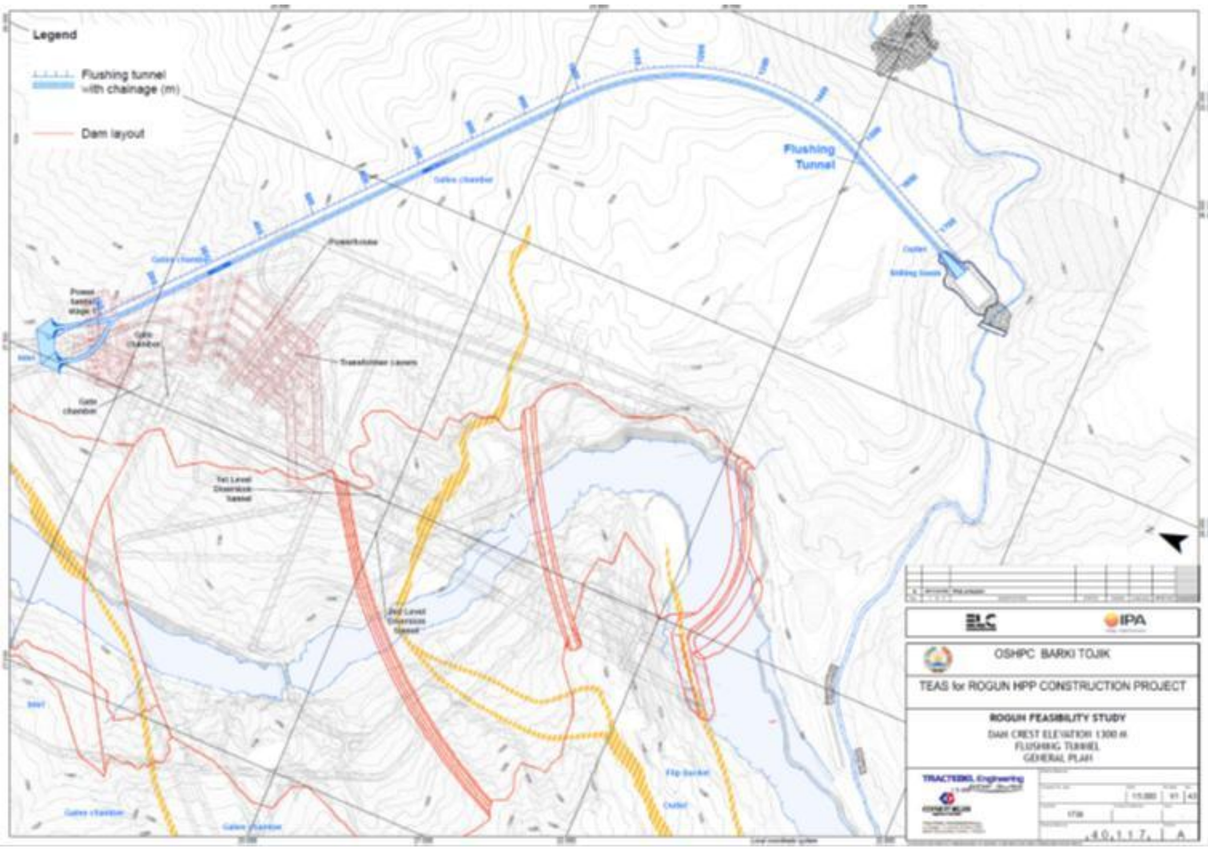


**Figure 6.4 : Tentative layout - Flushing tunnel**

## 6.4.2 Sluicing and density current venting

Sluicing consists in discharging the loaded flow through the outlets before it settled in the reservoir.

*Sluicing has been proved to be efficient in certain large dams all over the world. But, both the sediment type, and the dam type make it not applicable to Rogun. Large sluicing gates cannot be set at the bottom or at mid-level of Rogun reservoir to cross the dam as it is an embankment dam and, moreover, the total head at the gate would exceed the acceptable head (in the range of 50 to 60m) to avoid serious gate vibration and/or cavitation.*

Density current venting consists in making use of the current created by the reservoir water density gradient to transport the sediment downstream of the dam, through specific tunnels or through the turbines.

*In the case of Rogun, turbidity current could be discharged through the turbines using the multi-level water intake presented in §7.1.4. and in the hydraulics of the project components (Volume 3, Chapter 3, Appendix 4). Indeed, the intakes are set lower than required by the normal reservoir operation. This particularity could allow discharging the turbidity current that might occur in the bottom of the reservoir through the turbines.*

*At best, such device could allow the removal of the fine part of the sediment, approximately 40% in volume of the whole sediment load. It will therefore not allow balancing the solid in and outflow but it would slow down the reservoir storage depletion.*

*Discharging the density current through the turbines is a promising way of slowing down the Rogun reservoir depletion, and should be studied in further stage of the study when a detailed model would be elaborated and calibrated on an accurate set of data from Nurek reservoir.*

*The abrasiveness of the fine sediment transported by the Vakhsh river should also be studied to assess the feasibility of discharging the density current through the turbines and evelaute the impact of such operation on the hydro mechanical equipment.*

*It is to be highlighted that, given the large uncertainties on the parameters driving this phenomena (average yearly run off, amount of fine, density, amount of turbidity currents that will reach the intakes, impact on Nurek storage, etc…), the Consultant has not considered the release of turbidity currents through the turbines in determining the operational life of each alternatives as used in the economic analysis of the project alternatives.*

### 6.4.3 Mechanical removal

Sediment extraction by dredging, hydro-suction or dry excavation is performed on several reservoirs in the world. In France at Serre Ponçon and Sautet dams large scale coarse bed load is being extracted since many years.

Serre Ponçon storage capacity is 1.3 km$^3$, ie 10% of Rogun capacity. And the yearly solid run-off is estimated to 350 000 tonnes, ie less than 1% of Rogun solid run-off.

**Figure 6.5 : Coarse sediment removal of the Sautet dam (France)**

*Here, the volume of annual solid run off is too large for such a method: assuming that 300 000 m$^3$/month (rather high speed material placing on the dam) of material can be removed during the 6 dry months, it makes 1.8 hm$^3$, ie less than 3% of the total yearly solid run off.*

*Therefore, mechanical removal is not a feasible solution in the case of the Rogun dam.*

## 6.5 Replacing lost storage

In the case of Rogun raising the dam is not a foreseen solution, as it already reaches the practical limitation, especially in terms of flood management, and energy dissipation.

*On the other hand, the construction of new dams could be foreseen, even though it does not solve the issue of sediment management but only shifts it upstream. The technical and economic feasibility of sites upstream of Rogun dam has still to be assessed and that is beyond the scope of this study. This option does not provide any long term solution to the sedimentation issue on the whole cascade as it only delays the problem of dams filled with sediments on the long run.*

# 7 SEDIMENT MANAGEMENT PLAN FOR ROGUN PROJECT

## 7.1 Operation phase of the project

### 7.1.1 Storage depletion throughout the life of the project

Within the reservoir life span, the depletion of storage is progressive. The distribution of the deposited sediment in the reservoir and its evolution within time is a well-known phenomenon even though its quantification is complex. The next figure presents a typical distribution of deposited sediment along the reservoir.

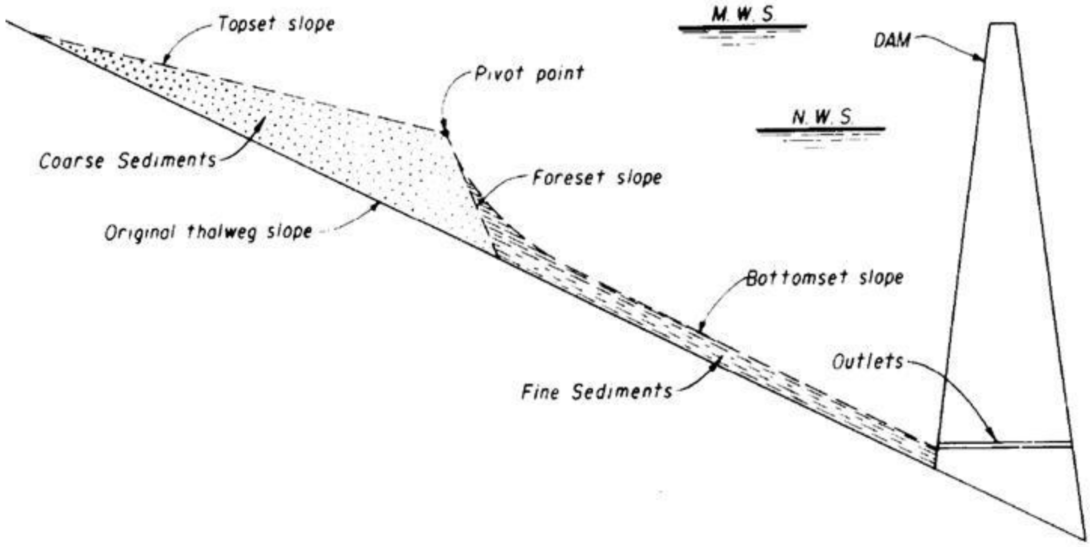


**Figure 7.1 : Typical sediment deposition profil (source USBR)**

At the upstream tail of the reservoir, the coarse sediment deposited as the river water velocity decreases. The finer the element is, the smaller is its entrainment velocity and the closer to the dam it deposits.

The foreset slope is created by the reservoir level variation: the rapid drawdown of the reservoir decreases the stability of the deposited sediment that tends to slide toward the dam and increase the bottomset thickness.

This shows that the active storage depletion starts at the beginning of the reservoir operating life. The reservoir is not filled horizontally from the bottom to the top.

Based on a yearly solid run off of 100 hm3, the reservoir storage capacity curve can be calculated thanks to the method proposed by the US Bureau of Reclamation (1987) [10], based on "Revision of the Procedure to Compute Sediment Distribution in Large Reservoirs" by J.M. Lara (USBR,1962). This procedure is a simplified one that does not take into account the variation of the trap efficiency and sediment deposit pattern over time. This simplified method is sufficient for the level of this study and with respect to the other uncertainties, especially on the yearly solid run off estimation.

In further stage of the study, Rogun reservoir sedimentation pattern will be predicted using a sediment transport modelling, using information from the Nurek reservoir for calibration. At Nurek, very precise information for about 40 year's sedimentation (1972 – 2013) could be found and this is a fairly long-term. So a very precise back analysis of Nurek sedimentation could be done and applied to the Rogun reservoir configuration.

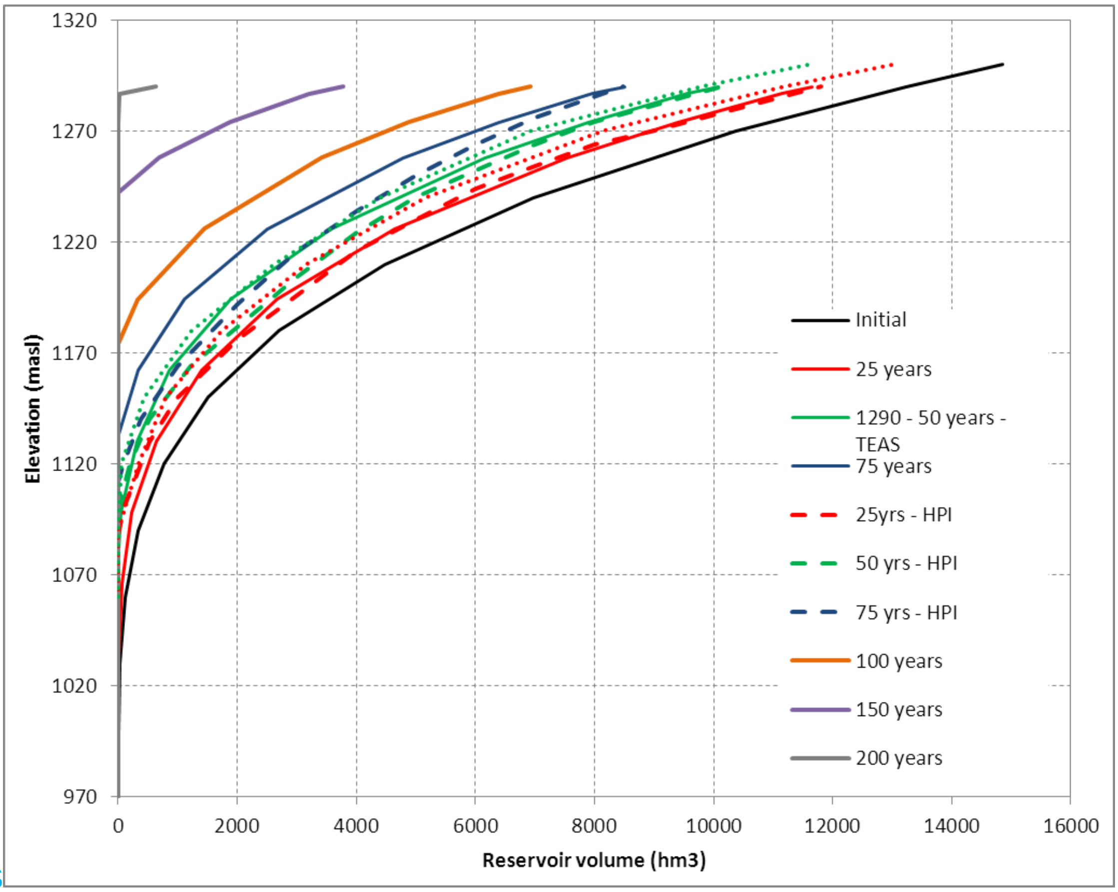


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**Figure 7.2: Rogun reservoir storage capacity curve – FSL=1290 masl**

### 7.1.2 Early generation

An early generation phase is planned during the construction period of the Rogun project, it will be necessary to adapt the water supply to the Units 5 & 6 for various reservoir levels.

The consequence of power generation using low reservoir water level when the storage volume is small is that the risk of sediment intrusion into the power discharge might be high. Especially due to the high seismicity in the region and liquefaction of the foreset slope might induce a sand wave capable of destroying the turbine water intake as in the case of Ambuklau Power Intake in the Philippines.

The following devices designed by HPI aims at protecting the power house from sediment entry during the early generation phase.

- First a specific intake feeding units 5 and 6 is used from elevation 1055 masl to 1160 masl, it has a special design that make it useable for the all range of reservoir level from 1055 to 1160 masl (see

- Figure 7.3).
- 2 final intakes are set at elevation 1152 masl and start to be used 10 years after the river diversion.
- 4 others are set at 1175 masl.

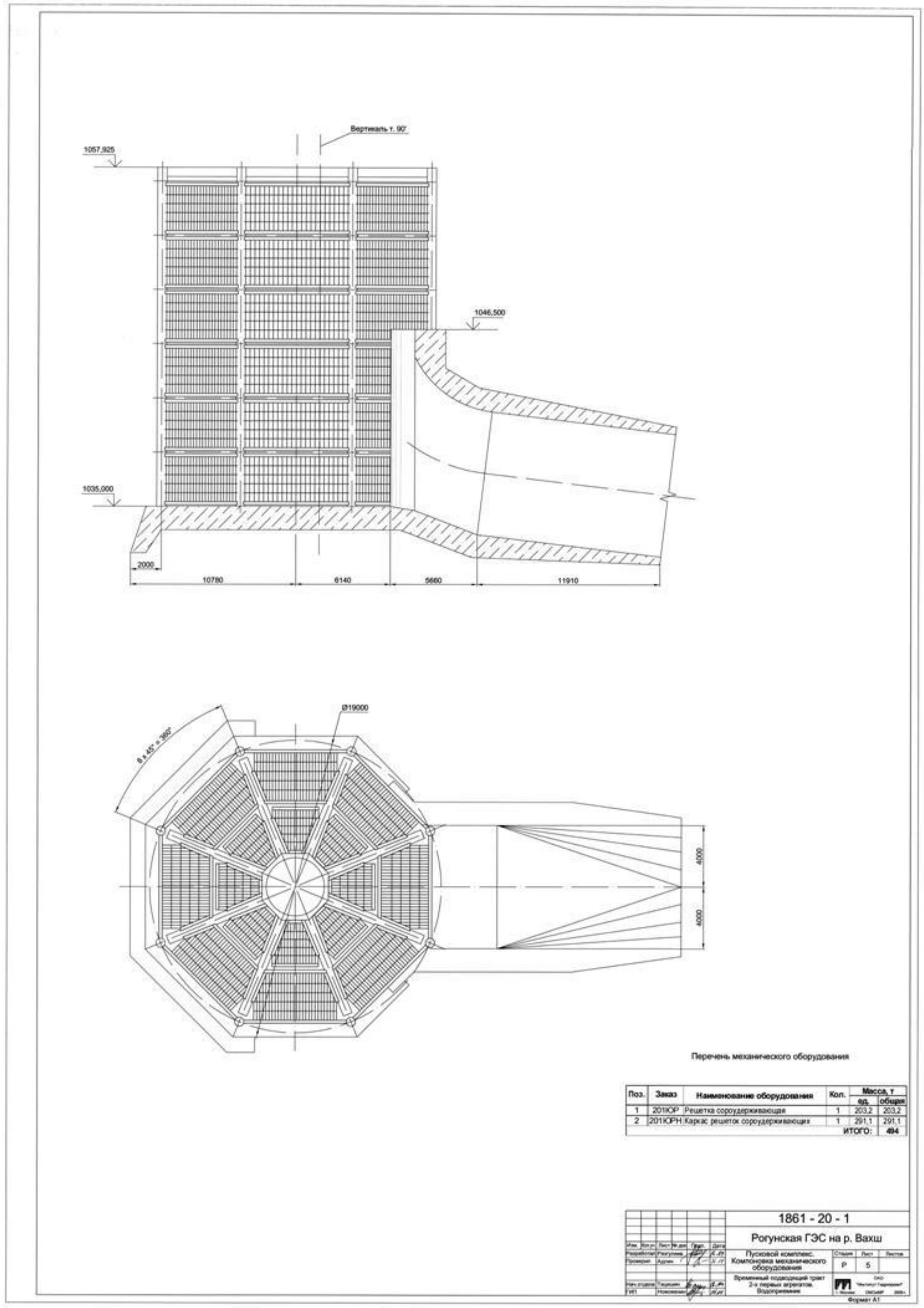

**Figure 7.3 : HPI drawing - Temporary power intake**

### 7.1.3 Impact on regulation capacity and energy generation

Energy generation will be impacted as soon as the active storage volume starts to be reduced by the sediment deposited in the reservoir.

In the case of the coupled operation of the Rogun and Nurek reservoirs, the following will progressively happen as sediments are trapped in the Rogun reservoir:

- Phase 1: As losses in the active storage capacity increase, the amplitude of the yearly oscillation of reservoir levels (necessary for the regulation of river discharges) increases to compensate the loss in storage capacity. Discharge regulation (increase of winter discharge) is not affected but heads in late winter get reduced. Energy can be consequently slightly affected if the head loss is significant compared to the total head.

- Phase 2: When the lowering of reservoir level (necessary for discharge regulation) is too important, the optimum coupled operation of Rogun and Nurek is to be reviewed : the Nurek reservoir starts its contribution to the flow regulation, getting its winter head reduced. Energy generation is consequently reduced.

The timing of these different operation phases is difficult to assess at this stage of the studies, particularly due to the uncertainties in the estimate of the average sediment load. However, several simulations have been run to assess the energy production at various time steps assuming that the total sediment load for this exercise is 100 $Mm^3$/yr and that all sediments are trapped in Rogun (no allowance for turbidity currents as a conservative approach).

The next graph plots the timely variation of Rogun minimum reservoir level and the timely variation of firm energy produced by Rogun and Nurek. This simplified approach allows assessing the Rogun reservoir life span with respect to its regulation capacity and energy production.

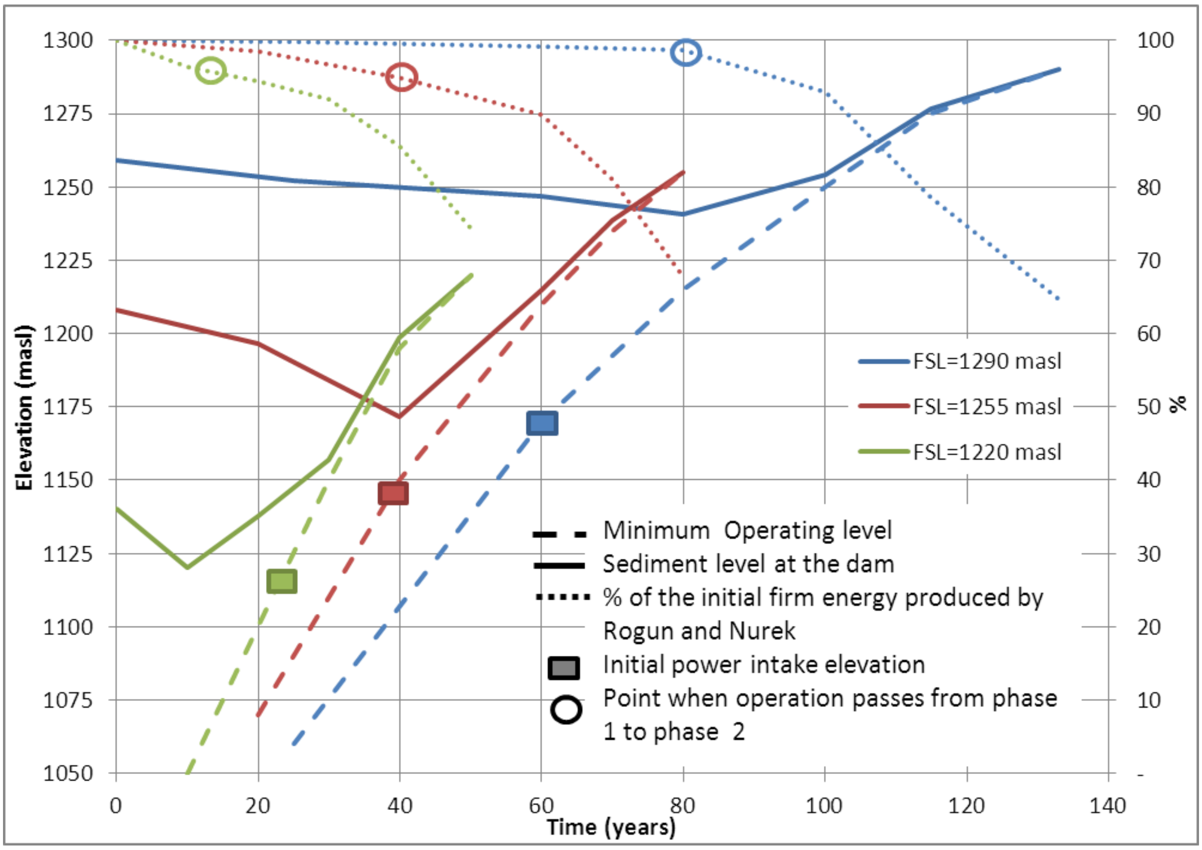


**Figure 7.4: Evolution of optimum minimum reservoir level, firm energy and sediment level with time, for a sediment load of 100 $Mm^3/yr$**

The phases described above can be evaluated on the graph.

For the three alternatives, the first phase (when the minimum reservoir level slowly decreases) is progressive and the impact on the energy is limited. The higher the dam is, the longer this phase lasts and the smaller is the energy loss.

As a conclusion it can be said that the energy production starts to be significantly impacted (for instance 5% loss):

- after 20 years for the lowest alternative;
- after 40 years for the medium alternative;
- after 90 years for the highest alternative.

Then during Phase 2 when the minimum operating level starts to rise again, the energy curve keep decreasing slowly, and a slope change happens when the new reservoir bottom reaches the minimum level. Then, the curve is sharper, and the energy decreases quickly as the Rogun loses it regulation capacity.

### 7.1.4 Power intakes raising

In parallel to the depletion of storage capacity and the modification of the Rogun-Nurek coupled operation, the other phenomenon that can impact the energy production is the possible plugging of the power intakes with sediments.

Power intakes elevations should be low enough to satisfy the early generation requirements during the dam construction. A sensitivity analysis is performed on the power intakes life span in Table 7.1.

| **Dam alternative (FSL)** | **1290** | **1255** | **1220** |
|---|---|---|---|
| *Elevation (Initial intake sill)* | *1172* | *1140* | *1115* |
| Life span (years) (with 60/100 $hm^3$/year) | 90/60 | 60/40 | 30/25 |

**Table 7.1 : Sensitivity analysis and power intake life span without remedial measure**

By placing this date on the former graph, it can be seen that the intake plugging will occur long time before the regulation capacity depletion for the two highest alternatives. Without any special design or remedial measure, the energy production would be limited by the intake life span.

Therefore, the Consultant proposes a special intakes design that will lengthen the powerhouse lifespan. The power intake sill remains at the same elevation, but a concrete structure is anchored on the bank slope, and is equipped with several gates at several elevations. This will allow opening and closing the gates as the sediment rises, and adapt the power intake elevation as necessary. A simplified sketch is presented below, details of the structures are presented in the Hydraulic chapter (Vol 3 Chapter 3 Appendix 4).

This structure could also allow discharging the possible turbidity current through the turbines as described in the hydraulic chapter. But this phenomenon is not accounted for in the determination of the life of each alternative, as it is difficult at this stage to evaluate the exact amount of suspended loads that could be discharged annually through the turbines and because the impact on the hydro-mechanical equipment is not assessed.

Thanks to this device that virtually allows to raise the intake level, the life span of the energy production is extended and adapted to the reservoir life span. In the last upper meter of the reservoir, the flow will not be naturally de-silted by the reservoir. Therefore it has been considered that this structure can be used until the sediment reaches the FSL minus a safety margin of 15 m. The following table presents the Rogun power production lifespan that have been considered in the economic and financial studies of the alternatives:

| **Dam alternative (FSL)** | **1290** | **1255** | **1220** |
|---|---|---|---|
| Life span (years) (with 100 $hm^3$/year) | 115 | 75 | 45 |

**Table 7.2 : Power intake life span with raising intake**

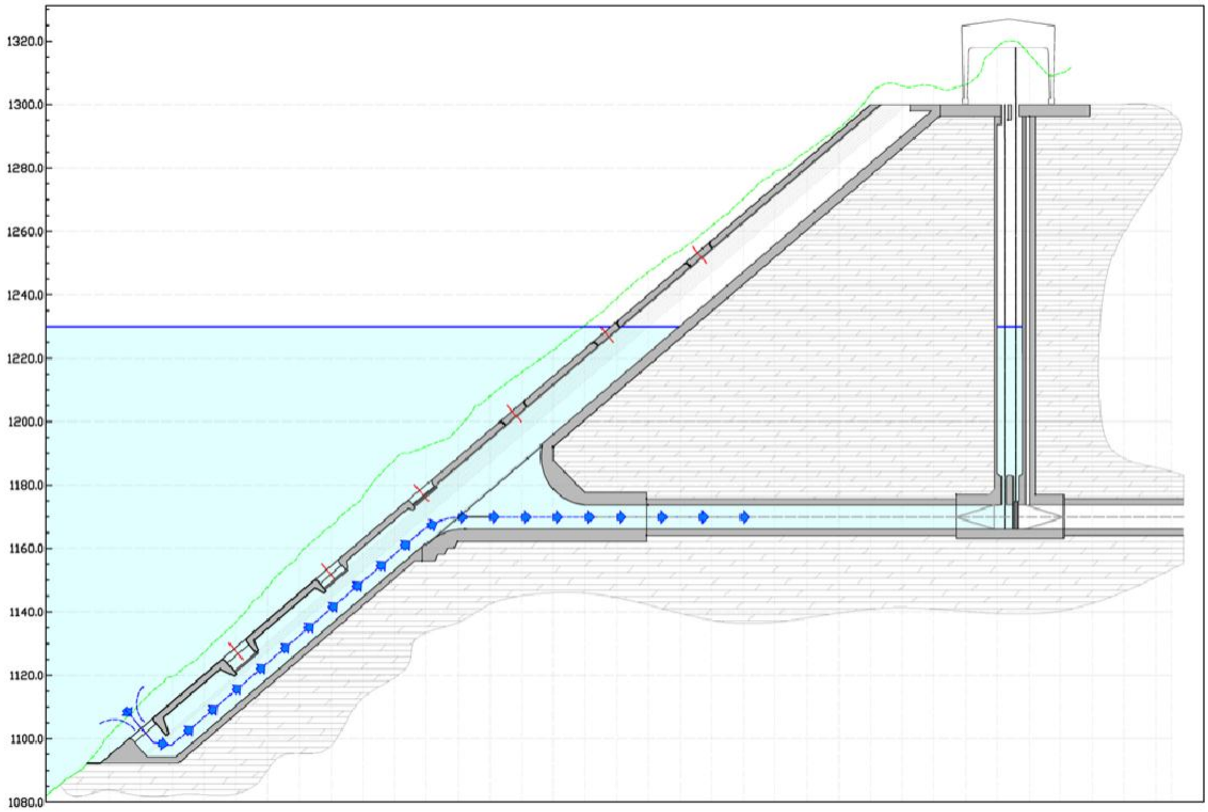


**Figure 7.5 : Power intake scheme for extended life span**

### 7.1.5 Impact on electro-mechanical equipment

The Rogun electro-mechanical equipment will be impacted by the sediment load only after a long operation period: the reservoir acts as a desilting device and the water passing through the turbines will be clear of sediment as long as the intake sill is not reached. This is experience today in the Nurek reservoir.

When turbidity currents reach the special intake structure a decision will need to be made on whether to pass the suspended sediments through the turbines or exclude them by using a higher level intake gate. Additional tests are required to fully understand the characteristics of the suspended material in turbidity currents. This will assist in assessing the merits of passing it through the power station versus the potentially negative impact on the electro-mechanical equipment.When the coarse material will reach the upper position of the special intake:

- the equipment will be eroded by the coarse sediments and the powerhouse should be put out of operation;
- or a specific desilting device is to be designed and put in operation to keep using Rogun as a run-off-the-river hydro power project.

In both cases, the long term sediment management shall then be put in place to ensure balance between inflows of sediments and outflows and ensure long term safety. This is detailed in the following paragraph.

## 7.2 Long term sediment management and sustainability:

### 7.2.1 End of life definition:

As already mentioned above, based in the estimated range of run off, the ultimate reservoir life span (when the powerhouse is put out of operation with a final intake level at FSL – 15 m) can be calculated for each alternative (see Table 7.3).

| | **Total volume (hm3)** | **100 $Mm^3$/year** |
|---|---|---|
| **FSL=1290 masl** | 13 300 | 115 years |
| **FSL=1255 masl** | 8 600 | 75 years |
| **FSL=1220 masl** | 5 200 | 45 years |

**Table 7.3 : Estimated Rogun reservoir ultimate life span**

### 7.2.2 End-of-life sediment management:

Rogun project under its current design has foreseen shaft spillways with submerged intakes. The inherent risks in such concepts are cavitation caused by high velocities and degradation caused by introduction of abrasive sediments. Such risk will be unacceptable after decades when coarse sediments will be carried into spillways tunnels and could cause structural failure.

The risks of cavitation without abrasive material may be satisfactorily solved by means of an adequate hydraulic design and with the help of aeration. Several high head dams with surface spillways such as Bratsk and Karun and morning glory spillway at Glenn Canyon which suffered severe cavitation problems are now performing satisfactorily by added aeration systems.

Therefore, submerged intakes can be safely used in the first decades of the Rogun operation as long as clear water is discharging, if adequate aeration features have been designed.

But, at some point of time if abrasive materials enter the tunnel spillways, important damages would occur.

Moreover, as per the Consultant’s flood management design, these tunnels spillways are meant to protect Rogun and the whole downstream cascade from the PMF thanks to the Rogun reservoir routing capacity. As the reservoir routing capacity will reduce with time, this protective function has been designed to be effective during a limited period.

Therefore, a free surface overflow spillway with adequate aeration and dissipation device would be a mandatory solution at long-term in order to safely pass the design flood when spillway tunnels will be put out of operation by sedimentation.

The Consultant developed a design for such surface spillway that is detailed in the Hydraulic report (Vol3 Chapter 3 Appendix 4). The dissipation device is made of successive stilling basins that allow controlling the water velocity in the channel down to acceptable values.

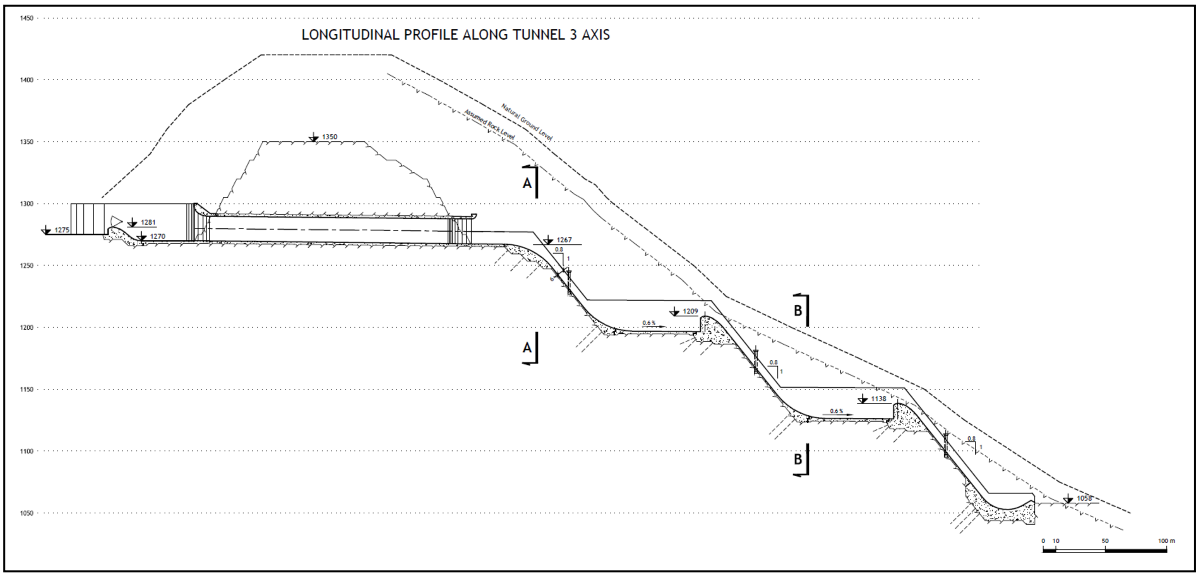


**Figure 7.6 : Proposed surface spillway longitudinal profile**

At the long term, this surface spillway could also discharge the solid inflows and manage the sediment balance, when the plant and the other spillway facilities will be put out of operation. This could be a solution to manage coarse sediment in the longer term and to avoid extreme dam safety issues. It would require large operation and maintenance costs during the first years of operation with coarse material passing through every flood season.

An ultimate end of life closure option could be to remove the gates from the surface spillway allowing the sediments to carve an incised channel through the spillway and underlying rock over a period of several decades. This scenario envisages that the incising river would bypass the dam structure, which would be abandoned and slowly release the sediments downstream. Other options may be considered at an horizon of 100 years and more to cope with long term safety of the abandoned structure, but the surface spillway can be considered as a potential answer to avoid extreme safety scenarios in the event that no other re-engineering solution is found in the long term future for the Rogun project.

## 7.3 Vakhsh cascade

Presently, the sediment load of the Vakhsh River is trapped into the Nurek reservoir. In the future, if Rogun is not constructed, Nurek will be progressively filled with sediment. At mid-term some structures will be impacted (power intake, bottom spillway for instance) and at long term the project safety will be questioned.

At that time, the Vakhsh River will not have any regulation capacity which would largely decrease the energy produced in winter.

Flood evacuation at Nurek will also be an issue as Nurek spillway system consists mainly of tunnel spillways that, as explained above, cannot handle sediment- loaded water. The total discharge capacity of Nurek will in that case be much lower than the PMF value.

Construction of Rogun will largely decrease the Nurek reservoir sediment filling rate, ensuring the river regulation for a significant additional time period of time, and delay the need of rehabilitation of the flood evacuation system with respect to the sedimentation issue.

This is an important feature of Rogun project with respect to the overall sustainability of the Vakhsh cascade.

# 8 CONCLUSIONS

During the first decades of the life of the project, the full sediment inflow will get deposited in the reservoir. According to the reservoir operation study performed, the reservoir level variation is limited compared to the reservoir depth. Therefore, it will not impact significantly the produced energy. This phase will last approximately 20 years, 40 and 90 years respectively for the dam alternatives 1220, 1255 and 1290 masl.

Because of the necessity of the early generation, the intakes are set lower than required by the normal reservoir operation. While the sediment level keeps rising, the design of the power intakes allows progressively raising them from their initial level, following the rise of the sediments level and avoiding their early plugging. This system could also be used for fine suspended sediments to be discharged through the turbines, but further investigations and modeling are required to estimate the amount of sediment that could be discharged through Rogun).

During this phase of raising the power intakes, the energy production will progressively get reduced as the river regulation will be progressively decreased and completed by Nurek regulation which is initially proposed to be operated as a run of the river project.

Based on the estimated range of solid run-off, the ultimate reservoir life span is 45, 75 and 115 years for respectively the dam alternatives 1220, 1255 and 1290 masl.

Regarding the flood evacuation, the tunnel spillways and the reservoir routing capacity will be able to protect Rogun and the cascade for a limited period. Then, the complete surface spillway should be ready to operate and ensure the safe flood evacuation.

In the long term, the reservoir will be completely filled with sediments and the annual solid load will be discharged through the surface spillway. There will be important maintenance works each year to repair the damages caused by the sediment transportation in the spillway channel, but the dam safety will be ensured. After several decades of this situation an end of life closure scenario could be envisaged, involving the proposed surface spillway as a river bypass structure avoiding extreme catastrophic scenarios.

# 9 RECOMMANDATIONS AND FURTHER STEPS

The range of the solid run-off of the Vakhsh River is 60-100 $Mm^3$. The evaluation of Vakhsh solid run off should be completed by using state of the art sediment sampling and by doing a detailed sediment study in the Nurek reservoir prior to the detailed design phase.

Depending on the alternatives the ultimate life span of the whole reservoir is in the range of 50-80 years for the lowest alternative, 80-140 for the medium and 130-210 years for the highest alternatives.

Man will not be able to control the sediment transportation of the Vakhsh River, at best it can delay and/or limit its impact on the proposed Rogun project and propose an end of the life solution, ensuring sediment balance when the dam will be abandoned.

At this stage of the study and given the data available, some general recommendations in terms of design and operation can be made:

- A complete surface spillway is necessary as long-term measure to safely pass the floods and their solid load.
- Reservoir operation of both Rogun and Nurek will be adapted as the sediment deposits in the Rogun reservoir.
- A multi-level power intake should be constructed to lengthen the powerhouse and reservoir life span.
- Ultimately, a desilting device could be designed to keep operating Rogun as a run-off-the-river hydropower plant while discharging the excess sediment load through the proposed surface spillway.

Further studies and physical hydraulic modelling would be required to design a complete sediment management plan that should be making use of Nurek experience. Therefore, the following is recommended:

- Thorough analysis of Nurek sedimentation thanks to new surveys including echo sounding bathymetry, core sampling, measurement of suspended sediment concentration and particle size distribution;
- Detailed simulation of the Nurek and Rogun sedimentation pattern, including behaviour of possible turbidity currents;
- Analysis of the possible impact on the permanent equipment resulting from passing turbidity currents through the multi-level intakes; whenever the studies indicate unacceptable adverse impact, the multi-level intakes would be used only to continue operating the plant while sediments will be already higher than headrace tunnels inlets;
- Optimization of sediment management for the whole cascade..