SECTION 8 : SEDIMENT REMOVAL

8.1 INTRODUCTION

The issue of sediment transport was addressed in **Section 4**, which also provided a summary of the results of the sediment sampling work carried out in the Okavango Delta and more recently at Divundu. Sediment removal from the weir basin was identified as one of the most important requirements that must be satisfied to ensure the continued natural functioning of the Okavango River and Delta systems.

Two methods of sediment removal have consequently been identified: sluicing of sediments or bypass pumping. Each of these methods is discussed in **Sections 8.2 and 8.3** below together with a discussion on their relative impacts on electricity generation and on the environment

8.2 SLUICING

8.2.1 THEORY AND MECHANISMS

The principle behind sluicing is that for 10½ to 11 months of each year the weir would be operated at FSL. Then for 4 to 6 weeks during the high flow period, the gates would be opened fully in order to draw down the level in the basin to the natural water level (almost as if the weir was not there). With the rapid drop in the water level, the velocities will increase dramatically, thereby removing all sediments that have accumulated within a few hundred metres of the weir.

Experience gained on a number of international dam projects has shown that as the velocities increase further upstream in the basin due to the rapid drawdown, bedload sediments will be mobilised and transported through the dam. Sluicing of sediments that have accumulated in a dam or weir basin, is efficient during high flood periods, and particularly if a reservoir capacity of 2% of the MAR is not exceeded, because the sluicing volume is a function of the reservoir capacity. This will continue until the flow through the dam has attained its natural flow condition. From this point on, the natural velocities will still increase until the flood has reached its peak, whereafter they will start dropping only marginally as the flood hydrograph starts tailing off on its declining limb. The high velocities will ensure that the accumulated sediments are mobilised and removed from the weir basin.
In order to optimise sediment transport through the weir, the ideal time for sluicing would be during the peak flow each year. The peak discharge is, however, very variable and in practice it is impossible to predict when the peak will occur. It can only be determined after the event. However, in principle, the aim would be to sluice the impoundment during the highest flow period each year. When ecological impacts of sluicing are taken into account, the ideal time for sluicing may be during the rising or declining limb of the hydrograph – taking into account, for example, ecological factors that cause fish to spawn or migrate. Determining the

optimum time for sluicing would therefore require further detailed investigation of both sediment transport and ecological issues.

At this stage the mechanics of sediment transport and the characteristics of the Okavango River still require further research. Some tests have been carried out to determine the magnitude of sediment load (both suspended and bedload) in the framework of this pre-feasibility study (**section 4.3**), but additional investigations on the mode of sediment transport in the river need to be undertaken during the next phase of the project. These will include extensive sediment sampling programmes and model testing to evaluate the effectiveness of sluicing. Model tests may also be complemented by, or compared with, the results of numerical modelling techniques using one, two or three dimensional analysis software.

The volumes of sediment transported and the relationship to discharges in the Okavango Delta have been established through continuous investigations by McCarthy et al. These values however, cannot be applied automatically to the river at Divundu. Even if initial sampling results indicate that the results obtained from tests carried out in the Delta are similar, additional long-term sampling will have to be carried out to establish the relationship between flood intensity and hence flow velocity, and sediment transport. Based on the results of these measurements, separate rating curves for bedload and suspended load should be developed.

Therefore at the present stage, a reliable estimation of sediment volumes transported by the river is not possible. Consequently, there are no data available relating to the critical discharge for inception of movement of sediment particles or sediment rating curves. Different sediment sluicing scenarios were consequently evaluated for the determination of mean annual energy production.
However, since the forecast of the flood peak and consequently the optimum sluicing period is uncertain, sluicing procedures will require careful consideration. The starting/ending of sluicing procedures as a function of a critical discharge is based on the theory that the volume of sediments transported is a function of the volume of the river discharge.

As only indicative information is presently available from the field measurements, the energy calculations used for the financial and economical evaluation were carried out for the following two scenarios only:

- Sluicing for a fixed duration of 4 weeks each year during the flood
- Sluicing for a fixed duration of 6 weeks each year during the flood

The impacts of these sluicing scenarios on electricity production are discussed below.

8.2.1.1 Monthly Distribution of Energy

Efficient sluicing of sediments from the head of the weir basin to just downstream of the weir, is one of the most essential aspects that must be complied with to ensure environmental acceptability of the project. As the bulk of sediment is expected to be transported during the flood period, it is proposed, in the case of sluicing, to open the spillway gates completely for a period of four weeks. During this time no energy will be produced, with either the Hydromatrix turbines alternative, or with the Bulb turbine alternative. **Figure 8-1** shows the mean monthly distribution of energy production of the Hydromatrix turbine as a function of the 1950 to 1998 flow series. The calculations for the weir at Site 5, are carried out for a FSL of 1010,0 m.a.m.s.l. In this case, it has been assumed that the sluicing duration will be for a period of 4 weeks during the flood season. As can be seen in **Figure 8-1**, the mean monthly energy production drops from 10 GWh (January) to 4 GWh (April). The distribution of the mean monthly energy production of the bulb unit is basically similar to the one shown in **Figure 8-1**, therefore it is not shown separately in this context.

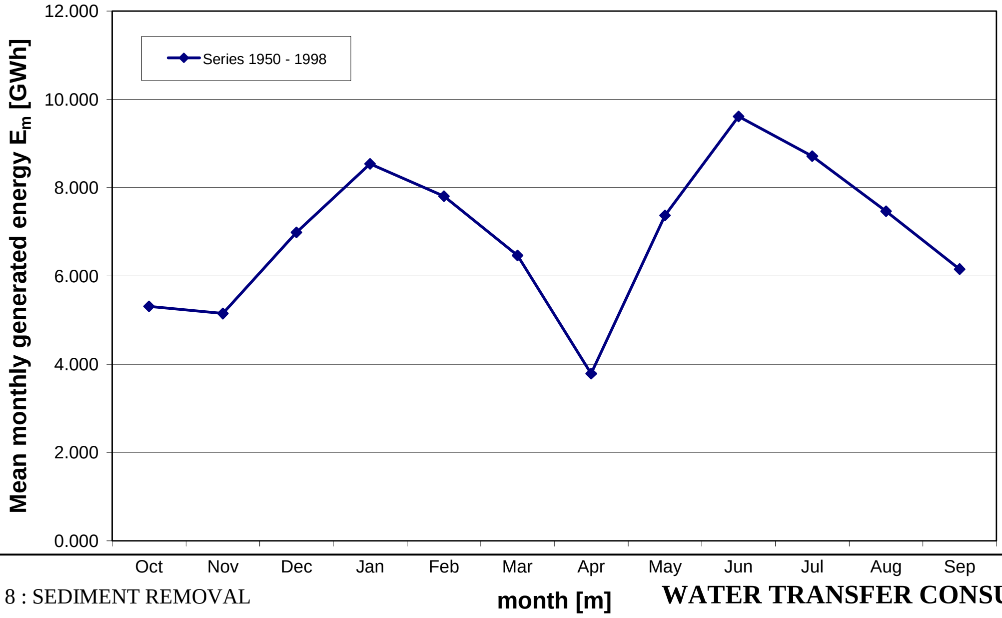

Figure 8-1 : Mean Monthly Energy Production of the Hydromatrix Turbine at Site 5

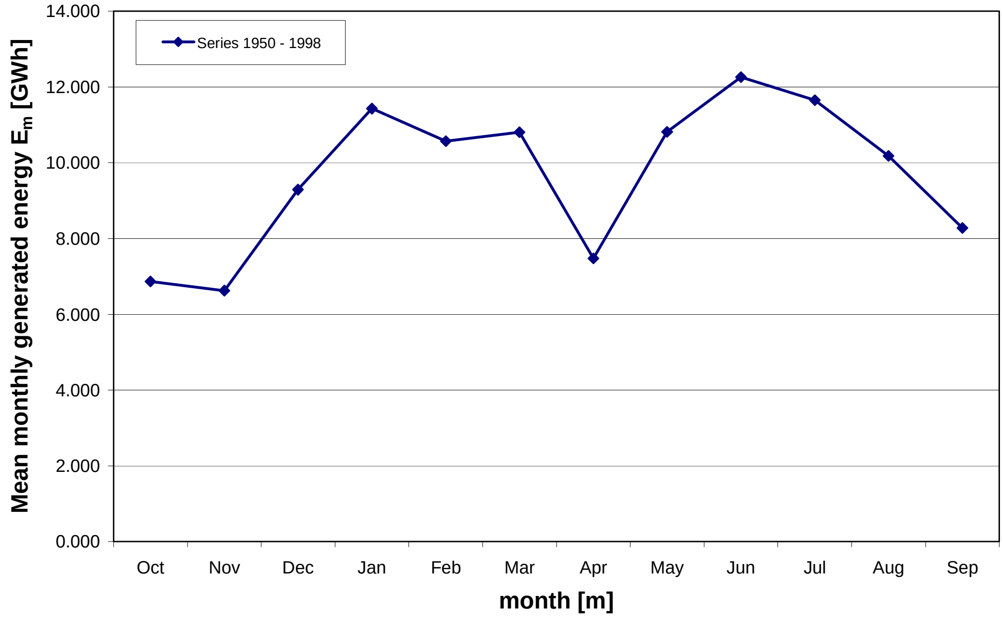

Figure 8-2 : Mean Monthly Energy Production of the Hydromatrix Turbines/ Bulb Turbines Combination at Site 2

Figure 8-2 shows the variation in energy production for the combination Hydromatrix turbines and Pit Units with canal development in the case of Site 2. The main advantage of this layout is the fact that during the sluicing period the available head of the Popa Falls can be utilised for power generation. However, the available head would be reduced to the natural head between Site 2 and the Popa Falls. The mean monthly energy production in the month of April would increase slightly compared to the aforementioned layouts of Hydromatrix or Bulb units at Site 5. The drop of energy production in April is due to the fact that part of the river flow would be discharged through the bulb turbines via the headrace canal during the sluicing procedure. Since the available head of the Popa Falls is approximately 3 to 4 m, the total output of the canal development hydro power plant will not exceed 8 GWh/month.

8.2.1.2 Loss of Energy

Figures 8-1 and 8-2 clearly show the effect that sluicing has on energy production during the peak flow period. The loss of energy depends on the available head of the hydropower layout, which is illustrated in **Table 8-1** below. Approximately 10 GWh would be lost during a sluicing period of 4 weeks.

Table 8-1 : Annual Loss of Energy due to a 4 Week Sluicing Period

Gross Head [m]	Energy Loss [GWh]
6.5	6
8.5	10
11	14

Table 8-2 gives the results of an analysis carried out for the case where the sluicing period is 6 weeks, i.e., only two weeks more than for the four week sluicing option. Between 3,5 GWh` and 8,2 GWh would be lost in addition to the losses shown in **Table 8-1** above by extending the sluicing period by two weeks.

Table 8-2 : Additional Loss of Energy due to 2 Weeks Extension of the Sluicing Period

Gross Head [m]	Energy Loss [GWh]
6.5	3.5
8.5	5.5
11	8.2

Figure 8-3 shows the monthly energy production at Site 5 for a FSL of 1010,0 m.a.m.s.l. and a sluicing period of four weeks.

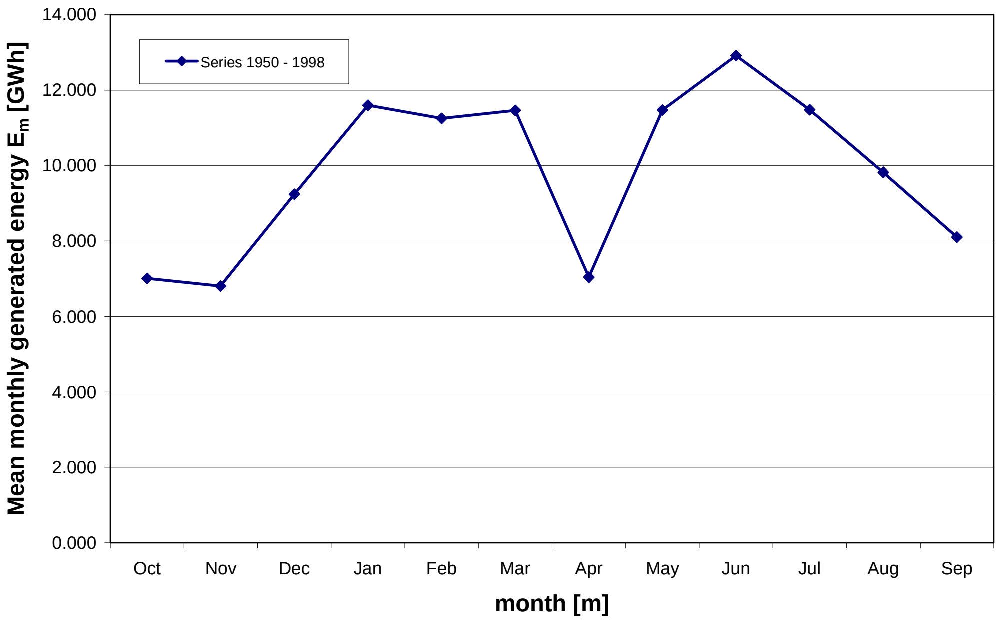

Figure 8-3 : Mean Monthly Energy Production with Hydromatrix Turbines at Site 5

and 4 Weeks Sediment Sluicing at a FSL of 1010.00 m.a.m.s.l.

8.2.2 ENVIRONMENTAL IMPACTS

Flushing (hydraulic scouring of deposited sediments) and sluicing (passing through of incoming sediment) operations) have been practised successfully to limit sediment accumulation in reservoirs (Basson and Rooseboom 1997)[2)]. Provided that large enough gates are installed, it should be possible to limit sediment build-up. In practice it is envisaged that sluicing would take place over a period of between four and six weeks during the peak flow season. It has been shown by Prof. G. Basson of the University of Stellenbosch that sluicing will only be effective if the storage capacity of the dam (in this case the weir) is less than 2% of the MAR. This guideline has been accepted by ICOLD (International Committee on Large Dams) and the World Bank for planning purposes. In the case of the sites identified and the maximum weir heights selected, the storage capacities lie below 0.3 % of the MAR, which is well below the minimum of 2% recommended for efficient sluicing.

These guidelines are based on the fact that most rivers transport much of their load in suspension. In the Okavango River, however, it is believed that the silt and clay-sized particles that are normal in most rivers, are present only in smaller quantities. The fine sand that comprises a substantial proportion of the river's load is transported as bedload in the form of migrating dunes. Furthermore, the very low gradients on the Okavango River result in fairly low flow velocities. While some sand will become truly suspended (as opposed to saltating) for periods during extreme flood events, this has not yet been quantified. Therefore, for a number of reasons, it is important to undertake model tests to verify how sluicing can be adequately effective in this case.

From tests undertaken to date, the rate of advance of dunes was measured by means of sonar bathymetry in April 2003. Under the flow conditions at that time, the rate of advance of dunes averaged about 3,4m/day. If sluicing were practised for 45 days under such conditions, a dune would advance by only 153 metres. These measurements were made a month after a fairly low annual peak. However, considerably greater rates of dune movement would be required to get all the sand through the weir during one sluicing operation because the impoundments would all be over 8km in length and much of the sediment will be deposited at the head of impoundment.

For 46 – 48 weeks of the year, sand will be accumulating in the impoundment. To move this through the entire length of the impoundment in only the remaining 4 – 6 weeks of the year, without increasing the flow velocity above the natural level, would need to be model tested.

To turn now from the effectiveness of sluicing, assuming that a very high proportion of the sediment could be removed by sluicing, the environmental impacts thereof would need to be considered.

The following impacts have been identified as part of the PEA. To determine the magnitude and significance of these impacts, further investigation would be required.

- Assuming sluicing is effective, this would mean that most of the years' supply of sediment would be moved through the weir in 4 – 6 weeks. However, once through the weir, the flow velocity will be similar to normal high flow river conditions and it would need to be determined where the sluiced sediment would be deposited below the weir;

- The sand on the natural river bed is inhabited by a variety of invertebrates, bacteria etc. which fulfil a variety of ecological functions. It is possible that these benthic fauna may be smothered by the release of sediment from the impoundment.
- During the rest of the year, sediment- deprived water will be released over the weir and erosion can be expected to occur as the river regains its dynamic equilibrium with respect to its sediment load. Thus, sand banks some distance below the weir or Popa Falls can be expected to be eroded. These sandbanks are known to be the breeding grounds of the African Skimmer.
- While the concentrations of clay-sized particles are very low by world standards, it is likely that some of this material will settle in the impoundment. During sluicing the fine particles will therefore be released into the water at higher concentrations than normal – with negative impacts on water quality, particularly on water clarity.
- To the extent that sluicing would affect the hydrograph there may be negative ecological impacts. For example, many biological processes, such as fish breeding, are triggered by hydrological factors, changes in water temperature or chemistry. These factors are not well understood, or at best are only understood for certain species. Therefore, sluicing could involve significant ecological risks in river ecosystems that are not adapted to rapid changes.
- Rapid draw down of water level in the weir basin is expected to cause erosion around the perimeter of the impoundment.
- Sluicing would have to be continued after decommissioning of the power plant, unless the weir was to be removed.

8.3 BYPASS PUMPING

8.3.1 THEORY AND MECHANISMS

A sediment bypass system was considered as an alternative to sluicing. The removal of sediment from a reservoir basin, or the trapping of incoming sediment before it settles in the reservoir basin, and then pumping these sediments to a point downstream of the weir or dam, has been practised successfully in a number of countries, notably in Japan.

In the case of the Popa Falls project, it is proposed that a sand trap be constructed at a point close to the head of the basin, but sufficiently far into the basin such that velocities have reduced sufficiently to allow the suspended sediments to be caught in the trap. This may result in bedload sediments having settled out in the portion of the basin upstream of the trap. The quantities will, however, be minimal, as the trap is not expected to be located more than possibly 500 m into the basin. Bedload sediment transport will return to its equilibrium within a short space of time, whereafter all bedload and suspended sediments will be trapped in the proposed sand trap.

Sediment Trap

Details of the proposed sediment trap are given in **Figure B8-1** of **Appendix B** in **Volume 2.** The dimension and layouts given in the Figure must be considered to be preliminary, as model tests will have to be carried out to determine the size of the trap and the required cross fall to ensure that the trap functions efficiently. Apparently a system of pumping sand that has accumulated at the entrance of Coega harbour in South Africa, is being considered to keep the entrance channel free of longshore drift. This will be followed up during the detailed feasibility study phase, as research that has already been, or is being carried out may be of value to the Popa Falls application.

It is envisaged that the sediment trap will consist of a 2,5 m wide concrete channel to be constructed across the complete width of the river. The channel depth will vary from possibly 1,0 m at the left bank to 2,0 m at the right bank. Model tests will have to show whether this cross fall is adequate to move the sediment into a suction well of the pump station. The floor of the channel will slope towards the centre from both sides of the channel where it will end in a 400 mm diameter semicircular collector.

Pump Station

The sediment trap will discharge its load into a pump sump, or suction well, located under a pump station, which in turn will be located on the right bank. A suitable sludge pump will be housed in a dry pumpwell located next to the suction well. A sluice gate will be provided at the entrance to the suction well to allow cleaning and maintenance.

A preliminary analysis has shown that a 45 kW single stage sludge pump of the Weir-Envirotech type 8,10 RGM-AB, would be required.

Backup equipment would need to include, apart from a standby pump and motor, a small generator, which will start automatically when there is power failure, to supply power to the pump. This is essential as the flow in the pipeline may not stop for more than a few hours, failing which sediments will settle out in the pipeline and may cause a blockage, which will be difficult to clear.

Auxiliary equipment will include aerators to keep sediments in suspension in the suction well and a small high pressure pump to circulate water from the suction well into the far end of the sediment trap, back into the suction well. The purpose is to create a strong cross flow in the sediment trap to ensure that sediments do not settle in the trap but are transported into the suction well.

Pipeline

The approximate length of the pipeline is 10 km. The elevation difference between the pump station and the end of the pipeline is approximately -2.5 m. If Site 5 is selected, a ±10 m high ridge is located approximately 4 km downstream of the pump station at the Frans Dimbare Youth Centre. Present indications are that it will not be possible to by-pass this ridge. This ridge not only increases the pumping head, but unfortunately also prevents the pipeline from being designed as a pumping main with a continuous downward gradient, which would be beneficial to the movement of sediments in the pipe and would be less likely to cause blockages in the pipeline. A detailed survey of a pipeline route during the next phase of the study will show if it is possible to find a way around the ridge.

The sediment loaded water will be pumped to a point immediately downstream of the weir. When designing the pumping main, consideration must be given to the type of pipe to be used on account of the accelerated wear, which must be expected due to the sediment laden water, and to the flow velocity in the pipeline.

Preliminary calculations have shown that a 250 mm diameter, Class 12, pipe would be the most economical, based on a pumping head of 35 m, a lifespan of 20 years and a discount rate of 16% p.a.

Tests were carried out in 1985 on Durapenta uPVC pipes on behalf of the mines, to establish the wear characteristics of the pipe when transporting slurry. These tests have shown that the average mass loss over a period of 1200 hours was 0,0206 gm/m/hr. Over a life span of 20 years, the total mass loss would amount to 3,61 kg/m. The residual mass after 20 years in the case of a Class 12 pipe, is therefore approximately 13,9 kg/m. A 250 mm diameter Class 16 pipe, with a mass of 17,5 kg/m, is therefore required to allow for abrasion losses.

The minimum flow velocity in the pipe should be between 0,8 and 1,2 m/s to ensure that the sediments do not settle out in the pipeline. The abrasion would increase significantly if the velocity is greater than 1,2 m/s.

Cost Estimate

Preliminary cost estimates were prepared, based on the preliminary layout and assumptions described in the previous sections. It is estimated that the sediment by-pass installation will cost N$ 6.84 million. Details of the estimate are given in **Table A13-8** of **Appendix B** in **Volume 2**.

The consequence of this alternative on the predicted average annual energy production is discussed in detail in **Section 8.3.2**.

8.3.2 IMPACT ON POWER GENERATION

The loss of energy production through sediment sluicing during the flood season can be avoided with the installation a bypass pumping system. **Figure 8-4** shows the mean monthly energy production if a sediment bypass system is provided, which can be compared with **Figure 8-3** for sluicing. The mean annual energy, as well as the detailed costs, were calculated for Site 5 for a FSL of 1010,0 m.a.m.s.l. and with a sediment bypass system in place. The mean annual energy production increases for the bypass solution from 118,2 GWh (4 weeks sediment sluicing) to 131,8 GWh, which is an increase of approximately 10%. The costs for the sediment bypass structures are described in detail in **Section 14**.

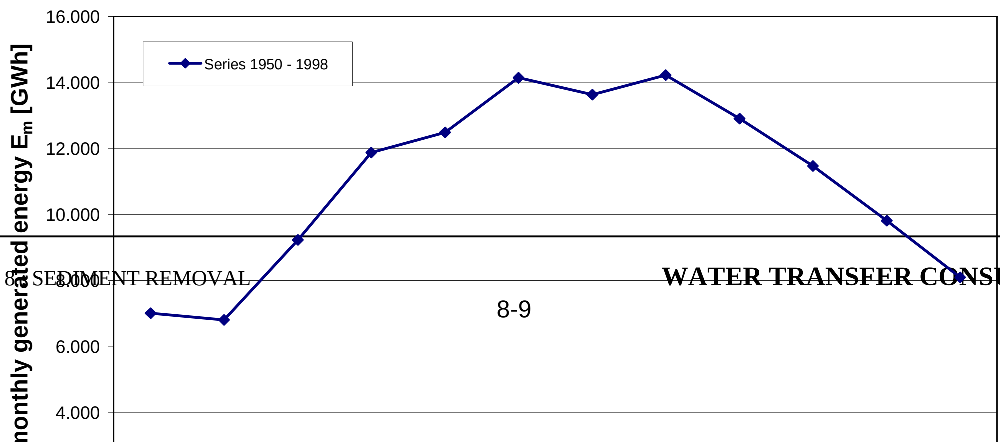

Figure 8-4 : Mean Monthly Energy Production with Hydromatrix Turbines at Site 5 with Sediment Bypass Option and a FSL of 1010.00 m.a.m.s.l.

8.3.3 ENVIRONMENTAL IMPACTS

Assuming that it is possible to capture and pump almost all of the sediment reaching the impoundment, this method would have a number of advantages: -

- The need for sluicing would be eliminated, which would reduce or eliminate the negative impacts of sluicing as follows: -
  - ◊ reduce the risk of erosion around the perimeter of the impoundment due to rapid draw-down during sluicing,
  - ◊ eliminate the issue of deposition below the weir and the subsequent problem of redistribution of the sediment downstream,
  - ◊ reduce the risk of eroding sandbanks where the African Skimmers breed,
  - ◊ reduce the ecological impacts on benthic fauna associated with sluicing of sediment,
  - ◊ reduce the potential impacts on water quality that could result from the sluicing of sediments that are enriched with clay and organic matter,
  - ◊ reduce the impact on turbidity.
- Sand, with its low content of organic matter would be pumped past the weir on a continuous basis,
- Pumping should be the most reliable way to get sediment through the weir,
- Power could be generated throughout the year with no "down time" - so the economics and continuity of electricity supply would improve,
- There should be less wear on the turbines as there would be far less sand passing through them.

The disadvantages of the pumping option are: -

- There would be a heavy onus on the power station operator to ensure faultless management to avoid any interruption in the sediment pumping system. A back-up system for pumping would therefore be required,
- Sediment pumping would need to continue forever after decommissioning the power station, unless the weir was removed.

8.4 EVALUATION OF SEDIMENT REMOVAL OPTIONS (TECHNICAL/FINANCIAL, SOCIAL AND ENVIRONMENTAL)

Table 8-3 provides a summary of the technical, financial, environmental and social implications of the various options available to deal with the accumulation of sediment in the weir basin.

Table 8-3 : Evaluation of Different Sediment Removal Options

Criteria	Sluicing	Bypass pumping	Do nothing
TECHNICAL			
Minimise maintenance requirements	2	1	3
Maximise effectiveness of sediment removal	1	3	1
Sub-total (Rank)	**3(3)**	**4(1)**	**4(1)**
FINANCIAL			
Minimise capital cost of installation	1	2	3
Minimise operating costs	2	1	3
Maximise electricity production	1	3	3
Sub-total (Rank)	**6 (2)**	**5 (3)**	**9 (1)**
ENVIRONMENTAL			
Minimise impact on the hydrograph	1	3	3
Minimise impacts on water quality	1	2	1
Minimise impacts on benthic fauna	1	3	1
Minimise downstream erosion	1	3	1
Minimise erosion in the weir basin	1	3	3
Minimise impact on geomorphology of the Delta	2	3	1
Sub-total (Rank)	**7 (3)**	**17 (1)**	**10 (2)**
SOCIAL			
Minimise impact on tourist industry in the Delta	2	3	1
Sub-total (Rank)	**2**	**3**	**1**
TOTAL (RANK)	**18(3)**	**26(1)**	**23(2)**

A score of 1 means that the objective is not, or poorly achieved, 2 = fair and a score of 3 means that the objective can be achieved. Criteria in red indicate fatal flaws.

It is clear from **Table 9-3** that while the 'do nothing' option is the cheapest and least technically challenging option, it is fatally flawed in that there is a high probability that interrupting the sediment movement in the Okavango River would have long-term serious negative impacts on the geomorphology of the Delta, with a related impact on the tourism potential of this area.

Of the remaining two options, it is clear that sluicing is the least costly, both in terms of capital expenditure and operating costs compared to bypass pumping, but there are potential high risks for the environment. These could be mitigated to a large extent by the bypass pumping option. However, both systems have inherent risks attached to them, both in terms of the many unknowns that exist at present and in terms of the reliance of both systems on human intervention.