SECTION 4 : SEDIMENT TRANSPORT

4.1 INTRODUCTION

Probably one of the most important impacts that has been identified in this pre-feasibility study, is the fear that sediment movement in the Okavango Delta would be disrupted by the construction of a weir in the river, if an appropriate method is not found to move sediment through or around the impoundment. Much thought has therefore been given to methods that could be employed that would ensure that sediments are not trapped in the basin.

In this section, the mechanics of sediment transport are described, followed by a detailed description of the sediment movement and dynamics of the Okavango Delta. The results of sediment sampling in the Delta and at the project site are discussed in sections 5.3 and 5.4.

4.2 MECHANICS OF SEDIMENT TRANSPORT

4.2.1 INTRODUCTION

A large number of publications deal with sediment transport in rivers and reservoirs, but the most widely used in the South African context include Basson and Rooseboom (1997 and 1999)[1&2)] and Rooseboom and le Grange (2000)[10)]. These publications contain the tools that are required for mathematical modelling of sediment transport in typical South African rivers and reservoirs, as well as the design of reservoir outlets which can be used to limit sediment build-up in reservoirs.

Different sediment transport modes are encountered in rivers and reservoirs viz:

colloidal transport,

turbulent transport (laminar and turbulent boundary layers), and

density currents.

In the case of a small reservoir at Popa Falls, turbulent transport would be the predominant sediment transport mode. Colloidal transport will be responsible for only a very small fraction of the total load, made up of the smallest particles. Density currents are only generated within deep reservoirs with steep bed slopes and are not expected to play a significant role at Popa Falls.

4.2.2 TURBULENT TRANSPORT

Turbulent transport forms the dominant transporting mechanism in most rivers and reservoirs. The turbulent sediment load is often split into bedload and suspended load components. Bedload refers to sediment particles that are carried along the bed and which are not carried in suspension over long distances. Suspended load refers to that part of the load which is generally carried above the bed. In cobble bed rivers, which also carry sand, it is possible to draw a clear distinction between bedload and suspended load. In sandbed rivers it is often difficult to distinguish between suspended load and bedload, when the acting shear velocities are much greater than the critical value. Particles which are carried as bed load along one river reach may be carried in suspension at another reach where the bed slope is steeper.

As the sediment carrying capacity of a stream varies exponentially with varying flow velocity, a large proportion of the total sediment load is transported when velocities are high, i.e. under flood conditions. Conversely, when flow velocities in a river decrease e.g. when entering the still waters of an impoundment, the suspended load precipitates out and the rate of bedload transport stalls, creating a build up of sediment at the head of the impoundment. The water exiting the impoundment thus contains very little sediment. This “sediment hungry” water will be highly erosive for some distance downstream until a new dynamic equilibrium in terms of sediment load has been achieved. The potential for sediment entrapment in the weir basin and erosion downstream of the weir could have significant effects on the Okavango River and Delta. The importance of sediment as a key driver in the geomorphological development of the Okavango Delta is described in the following section.

4.3 SEDIMENT TRANSPORT IN THE OKAVANGO RIVER AND DELTA

4.3.1 PREVIOUS STUDIES

Numerous studies have been undertaken by the Department of Geology of the University of the Witwatersrand under the guidance of Prof. T. S. McCarthy since 1986 9) to examine, *inter alia*, the sedimentation dynamics of the major fluvial channel system of the Okavango Delta, with particular emphasis on the upper, permanently flooded portion. What follows hereafter is a summary of the salient aspects and results of the work carried out by McCarthy et al. in the panhandle and Delta.

The survey covered a channel length of 300 km, which is equivalent to a straight length of 150 km, in which ten sites were selected (numbered A to J) for detailed investigation. These sites were located between Shakawe, some 25 km downstream of Mohembo, and Xugana on the Maunachira channel of the Delta. Depth profiles and velocities were measured at each site and the slope of the water surface determined.

The bedload transport rate was measured using two 7,62 cm Helley-Smith bedload samplers of wall thickness of 5,5 mm fitted with 0,06 mm nylon mesh bags. The density of the sand was determined in a laboratory to be 1,77 gm/cm³ with a standard deviation of 0,03. Because of a wide variation in the sediment yields obtained with the sampler, it became necessary to take a large number of measurements, the average of which was considered to be the bedload sediment in movement at the time of sampling.

In respect of suspended sediments, it “*was found to be very low and attempts to quantify this by filtration were abandoned because the long times and large water volumes required to accumulate sufficient solids for gravimetric determination*” As an alternative, it was decided to determine suspended sediment concentrations using a Hach model 16800 Turbidimeter. The results were measure in Nephelometric Turbidity Units (**NTU**) and converted to total suspended load in kg/s and kg/m³.

The results of these bedload and suspended load tests show that the bedload discharge varied from zero at Site A to 0.057 kg/m of channel width/second at Site J. Suspended sediment concentrations varied from 0.000435 kg/m³ at Site A to 0,0123 kg/m³ at Site E_N. These results convert, in the case of bedload to zero at Site A to 194.766 m³/day at Site E_N, and in the case of suspended sediments, to 0,36 m³/day at Site A and to 49.30 m³/d at Site E_N.

Although water discharge through the study area decreases gradually between Shakawe and the end of the study area at Site A, bedload movement does not show a similar pattern. Total bedload movement reduces rapidly from approximately 202,1 m³/day at Site I (30 km downstream of Mohembo) to 38,1 m³/day at Site H, which is only 50 km further downstream of Site J, indicating that there is an accumulation of approximately 118,7 m³/d in the intervening reach based on an average river width of 76 m between the two sites.

From the work carried out in the Delta by McCarthy et al., the following relationship was drawn up between bedload discharge per unit width per second (kg/m width/s) and flow velocity:

$$\boxed{\mathbf{Q_b = 0.13\, U^{3.10}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \mathbf{1}$$

where Q_b = bedload discharge per unit width per second
U = Flow Velocity (m/s)

The regression coefficient ‘R^2’ for the above relationship is 0,919 provided the outrider data for sites G_N and H are excluded. If this data is included, the regression coefficient decreases to 0,615. This clearly indicates the sensitivity of the equation to the effects of factors such as depth and gradient.

If the variables of depth and gradient are included in the multiple regression analysis, a best fit line to the data yielded the following equation which yielded a regression coefficient of 0,912:

$$\boxed{\mathbf{Q_b = 21.2\, D^{1.14}\, U^{3.47}\, G^{1.00}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \mathbf{2}$$

where Q_b = bedload discharge per unit width per second
D = Depth (m)
U = Flow Velocity (m/s)
G = Gradient (%)

It is therefore evident that there are many factors that influence bedload movement. Caution should therefore be exercised when applying equations, such as those quoted above, to other reaches of the river. The reader is referred to **Section 5.4** for discussions on the results of sediment transport measurements carried out at Divundu towards the end of April 2003 and at the beginning of June 2003 and the comparison thereof with previous tests carried out in the Delta.

4.3.2 MODES OF TRANSPORT

The entire Okavango River system is extremely unusual in global terms and especially in the context of southern Africa. Virtually the entire catchment and Okavango Delta is underlain by quartzitic Kalahari sands. This results in the river's sediment load being primarily fine sand, (0,25mm to 0,43mm in size), with little clay or silt in suspension, and low nutrient concentrations.

The upper catchment of the Okavango River in Angola has been altered very little by human activities, but in Namibia, much of the riverine forest has been destroyed for slash and burn agriculture or commercial irrigation projects, leading to some increase in turbidity in recent years. However there are currently no major impacts of human activities on the river flow or water quality. This results in extremely clear waters with an extremely low suspended sediment load.

In most southern African rivers, the catchments comprise complex geology with a diversity of land uses and thus rivers carry a range of particle sizes ranging from coarse rocks and pebbles carried as bedload (saltating and rolling) to fine colloidal particles carried in suspension, even under low flow conditions. Usually the suspended portion of the sediment load is quite high and therefore it is a major factor in the design of dams and sediment release structures. This may be contrasted with the sediment transport dynamics of the Okavango whereby a significant proportion of the sandy sediment is transported primarily as bedload, in the form of complex dune forms (see section 5.4.1.3 for discussion). This material moves by saltation. Some sand will go into suspension during above-average peak flows but this has not been quantified at this stage. However, under normal flow conditions, it is believed that the suspended material comprises organic matter, which will settle out rapidly under still water conditions.

4.3.3 SYSTEM DYNAMICS – THE IMPORTANCE OF SEDIMENT IN THE FUNCTIONING OF THE OKAVANGO DELTA

The Delta wetland has evolved around a set of unusual environmental conditions. The long-term work by McCarthy et al. has found that sediment transported to the Delta plays a pivotal role in maintaining the biological diversity of this world famous Ramsar site. This brief review outlines the importance of sediment in maintaining the diversity and well-being of the Okavango ecosystem, and examines the possible consequences of upstream sediment impoundment.

In the Panhandle of the Okavango Delta, the river divides into a number of tributaries which distribute water across the fan surface. As the velocity slows, the bedload of fine sand accumulates on the channel beds. The channel banks are made up primarily of aquatic plants growing on a substrate of peat, which also slowly accumulates through the deposition of silt and organic material. Thus, the entire channel and its flanking wetland is slowly elevated above the surrounding wetlands. After a period of time, the channel fails, usually along hippo trails, and water diverts elsewhere to form new channels.

The failure of a major channel can produce radical shifts in wetland distribution. Former wetlands become dry. The peat catches fire and slowly burns down, releasing nutrients, organics and clays, which stimulate the growth of terrestrial plants. Nutritious grasslands result, which support high game populations. Over time though, the nutrients are dissipated, the clays become mixed into the normally sandy soils, and the nutritional quality of the grasslands declines.

Thus channel aggradation and failure results in constant change and ecosystem renewal. Vegetation communities are periodically being disturbed, and can never achieve climax status. It is this constant change which is responsible for the immense biological diversity of the Okavango Delta.

Thus the sediment load, and particularly the sand in the Okavango River system is absolutely vital to the ecological functioning and life of the Okavango Delta.

4.4 SEDIMENT SAMPLING AT DIVUNDU

In view of the importance of sediment in both the design of the hydro power project and in downstream ecosystem functioning, it was strongly recommended that a more accurate estimation of the amounts of sediment being transported in suspension and as bedload in the project area was required. Therefore sediment surveys were carried out in April and June 2003 at Divundu in the project area. These are described below.

4.4.1 SEDIMENT TRANSPORT SURVEY AT DIVUNDU – 24TH TO 27TH APRIL 2003

The sub-consultants, Eco.Plan were requested by NamPower to submit a proposal to carry out the sediment survey, to organise the sampling field trip and to assemble a team of specialists to carry out the sampling programme. The scope of work encompassed the following components:

Bedload sampling using the Helley-Smith sampler.

Suspended sediment sampling using a tube sampler, and

Side-scan sonar and high-resolution bathymetric technique to quantify bedload movement.

What follows is a summary of the sediment transport survey, which was carried out under the auspices of Eco.Plan. Co-team members included Prof. T. S. McCarthy of the Department of Geology of the University of the Witwatersrand (**WITS**), who was responsible for the bedload sampling using the Helley-Smith sampler and for suspended sediment sampling using the grab sampler; and, the Marine Geoscience Unit of the Council for Geoscience in Bellville, South Africa, who were responsible for the side-scan sonar and bathymetric survey of a section of the river bottom to assess the bedload movement by tracking sediment dune movement. Mr F. Kuchling of WTC was responsible for taking samples of suspended sediments using a pump.

4.4.1.1 Bedload Sampling using the Helley-Smith Method

Sediment transport studies thus far undertaken in the Okavango Delta have used a device known as a Helley-Smith bedload sampler (McCarthy et al., (1991)). The Helley-Smith sampler was designed by the United States Geological Survey. The device consists of a rectangular funnel fitted with a catch bag made of nylon mesh that is attached to the flared end of the sampler. It is placed on the channel bottom for a fixed time period and the amount of sediment collected in the bag is then measured. The method is very laborious, and many readings are required at a site to obtain a reasonable estimate of bedload movement through a cross-section of the channel. In the case of the proposed weir site, where channel width is in the region of 150 metres, between 100 and 150 measurements were required, arranged in a grid pattern. The reason for this is that sediment movement is not uniform across the bed. Very little sediment moves in the lee of dune faces, and most movement occurs up the backs of the dunes. An average of many sites is therefore required to obtain an overall estimate of sediment movement. A flow velocity profile is measured at the site as well.

The precision of the method for an individual site is believed to be around 30%. However, McCarthy et al, (1992) found that there is a relationship between mean flow velocity and the movement of bedload, which can be expressed by the equation $Q = 0.13\ U^{3.1}$ (based on measurements at 10 sites in the Okavango Delta; $r^2 = 0.919$ for these data) where Q is the bedload transport (kg/m/s) and U the average flow velocity (m/s). If it is found that the data from the Divundu site (i.e. average flow velocity and bedload transport) fall on the same data array as the channels from the Okavango Delta, the measurement precision estimates of bedload transport will be considerably improved, probably to about 10% or better. Moreover, if this is the case, the movement of bedload at any time at the site can be calculated from a knowledge of the average flow velocity.

The site selected for the survey was located approximately 300 m downstream of the Divundu bridge where the channel is straight and of fairly uniform depth. The coordinates of the western stating point of the site were 18° 6’ 10”S and 21° 33’ 20”E.

A total of 134 measurements were taken at 12 sections and at between 6 and 13 points across each section. Volumes of bedload sediment varied from 1 cm³ and 1005 cm³.

Bedload samples were uniformly spread across the bed and a simple average of all measurements was used to calculate the bedload movement. Measured volumes were converted to mass units and the result converted to movement over a metre of channel width per second by the application of **Equation 1**, an equation that was derived from studies carried out in the panhandle and fan of the Delta (refer to **Section 4.3**).

The results of the survey are summarised in **Table 4.1** below.

Table 4.1 : Results of Helley-Smith Bedload Sampling

Item	Unit	Value
Active channel width	m	152
Mean channel depth	m	3.4
Width of active bedload movement	m	140
Channel cross-sectional area	m²	522
Average flow velocity	m/s	0.60
Discharge	m³/s	313

Stage (at Divundu bridge)	m	3.54
Bedload discharge	kg/m width/s	0.0267
Daily bedload discharge (mass)	t/d	323
Daily bedload discharge (volume)	m³/d	194

A "*Manual on Operational Methods for the Measurement of Sediment Transport*" by Long Yugian9) reports that problems relating to the Helley-Smith type samplers include:

When the sampler is placed into position, interference with the flow inevitably causes local scour around the entrance to the sampler,

The velocity at the entrance to the sampler is not the same as the ambient velocity as the local resistance increases due to the presence of the sampler. A small change in the local velocity has a large influence on the transport rate of sediment.

The placement of the sampler on the dune has a large influence on the quantity of sediment trapped.

Although the Helley-Smith sampler has been effectively used by McCarthy et al. in the Okavango Delta producing consistent results, because of the importance of sediment transport, it was considered prudent to assess alternative methods of sampling as well. Bedload sampling has notoriously always been difficult as the accuracy of sampling is very much dependent on where the sample is taken on the river bed, i.e. where the river bed is very even or whether on the slip face of dunes. Many methods exist for sampling bedload, each of which has its own merits but very few reliable methods are available for measuring bedload movement.

4.4.1.2 Suspended Sediment Sampling

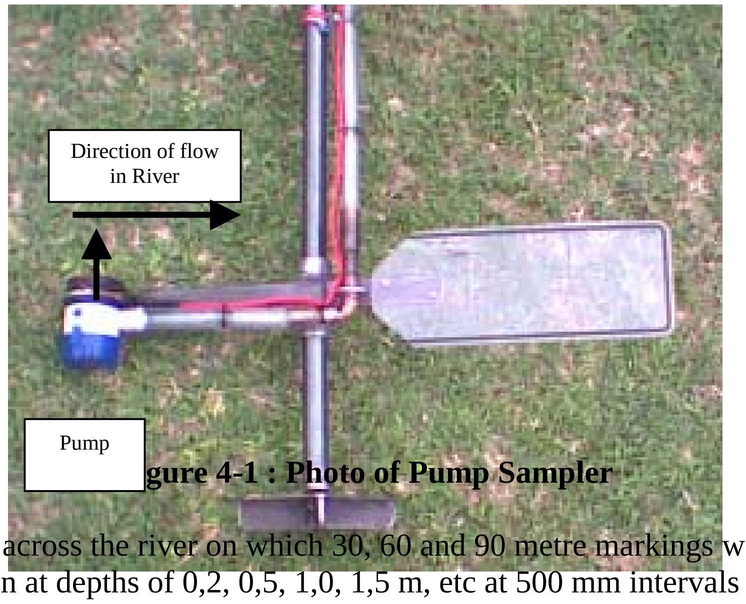
(a) Tube Sampler Method

Suspended sediment was sampled using a 2,8 litre tube sampler equipped with spring loaded doors. The sampler was lowered to the appropriate depth with the tube facing into the current. The doors were then closed and the sample brought to the surface. The water was collected in a bottle and later filtered. Samples were collected at 0,2 m, 0,5 m and 1,0 m intervals above the channel bed. Three profiles were sampled: at a quarter, half and three quarters channel width.

In addition to the above and as a means of backup information on the above method it was decided to sample suspended sediments using the pump method. Sampling using this method, was carried out by WTC.

(b) Pump Sampler

This sampler consisted of a small (discharge of 300 l/hr at 1,0 m head) 12 volt electric submersible pump attached to the end of a 20mm diameter transparent pipe, all of which is fixed to a 6 m long 25 mm diameter GMS pipe. Markings at 1 m intervals were painted onto the pipe. A 90° bend was attached to the bottom end of the plastic pipe and the pump attached to a horizontal length of pipe. A fixed vane was attached to the 25 mm diameter pipe to ensure that the pump was always located upstream of the vane. The pump was fixed 200 mm above the base plate. At each sampling point, water was pumped into 5 litre sample bottles. Details of the sampler are given in **Figure 4-1** below.



gure 4-1 : Photo of Pump Sampler

A rope was strung across the river on which 30, 60 and 90 metre markings were attached. Samples were taken at depths of 0,2, 0,5, 1,0, 1,5 m, etc at 500 mm intervals from the channel bed up to approximately 500 mm below the surface of the water. The sampler was lowered to the bottom until it rested on its base plate. The first 5 litre sample was taken at this point. Subsequent samples were taken at the intervals stated above by lifting the sampler rod by the appropriate amount. The samples were taken to the shore and filtered. Sediment retained on the filter paper was taken to Windhoek for weighing.

The results of these two different suspended sediment sampling methods proved to be inconclusive in that the size of the sample extracted (5 litres) was insufficient to obtain a meaningful result. From the analysis of the filter paper weights it is inferred that no sample exceeded a suspended load of 0,05 gm/l.

4.4.1.3 Side-Scan Sonar and Bathymetric Survey

The following is a summary from the report submitted by the Council for Geoscience entitled "*Application of Side-Scan Sonar and Bathymetric Survey Techniques to a Determination of Bedload Sediment Transport Rates in the Okavango River at Divundu, Caprivi, Namibia on Behalf of Eco.Plan/NamPower – May 2003*". The full report is given in a separate document entitled "*Pre-Feasibility Study for the Popa falls Hydro Power Project – Preliminary Environmental Assessment*".

As part of a pre-feasibility study on the proposed construction of a weir upstream of Popa Falls, near Divundu, a portion of the Okavango river was investigated using side-scan sonar and high-resolution bathymetric techniques. The geophysical survey was conducted by personnel from the Marine Geoscience Unit (**MGU**) of the Council for Geoscience (**CGS**) in order to assess bedload sediment transport rates within the river.

The principal results arising from the geophysical investigation are as follows:

- Rates of downstream migration/displacement of first order sedimentary bed forms, based on the **high-resolution bathymetric data** range between successive scans from a maximum of 8,61 m to a minimum of 1,35 m with an average value of 3,98 m (n = 28). This equates to a minimum and maximum rate of migration of 30,879 cm/hr and 4,842 cm/hr respectively with an average of 14,307 cm/hr. The potential errors associated with these measurements are very small, due to the better-than-2cm accuracy in all three principal axes of measurement (X,Y,Z) associated with these data.

- Rates of downstream migration/displacement of first order sedimentary bed forms, based on results of the analysis of **side-scan sonar** data range between successive scans from a maximum of 6,9 m to a minimum of 1,46 m with an average value of 3,94 m (n = 35). The potential errors associated with side-scan sonar data-derived measurements are inherently high, due to the difficulty of the determination of absolute positions of trough points in the acoustic shadow formed behind bed form brinkpoints (“crests”). In isolated cases, the inaccuracy in the interpretation of the trough point positions may reach a maximum value of 1 m. However, all of the values obtained by this method still fall comfortably within the total range of displacements as observed from the highly accurate (to within 2 cm), bathymetric data obtained.

- The principal dimensions of sedimentary bed forms observed from the data, indicate a maximum chord (length) of 31,87 m (height = 0,8 m) and a maximum height of 1,07 m (chord = 25,21 m). The minimum values observed are a chord of 7,67 m (height = 0,40 m) and, a minimum height of 0,11 m (chord =10,52 m). The observed range in dimensions for the dunes appears to be consistent with the expected range of dimensions for bed forms/dunes formed under a low current flow regime in a fluvial environment.

- Sediment transport rates appear to vary widely and indicate both sediment accretion and erosion. Based on Triangular Irregular Network (**TIN**) modelling of the data, the volume of sediment transported, associated with the four, individually defined sedimentary bed forms, in the detailed study area, ranges from a minimum of 7,52 m³ to a maximum of 38,97 m³ over the ~28 hour study period (average = 17,86 m³, n = 4). This equates to a minimum and maximum volumetric rate of change of bedload sediment, associated with the four sedimentary bed forms, in the detailed study area, over the time period, of 662,4 cm³/m²/hr and 3 862,60 cm³/m²/hr, respectively with an average value of 1 845,2 cm³/m²/hr (n = 4).

A range of the bedload sediment transported per day (24hrs) of 0,2935 m³/m width/day (minimum) and 1,5049 m³/m width/day (maximum) was obtained over the ~22 m wide dune fronts with an average value of 0,6869 m³/m/day which equates to volumes transported across four sets of different dune widths ranging from of 19,71 m³/day to 105,03 m³/day with an average of 46,94 m³/day.

The detailed study area yielding the above results is considered to be the most “active” or main portion of the river channel (thalweg) where the bulk of the bedload sediment transport occurs. It is therefore expected that these results may be used to assess the maximum sediment volumes transported on a daily basis, with a high degree of confidence, for the river at this location.

The total active channel width in the section of the river, where the side-scan sonar method was applied, was measured from the side-scan sonar records and ranges from 54,77 m to 60,87 m. Assuming a river width of 140 m, and an average width of 57,82 m with an average sediment transport volume of 46,94 m³/day, the total bedload sediment transport across the entire river would therefore equate to 113,66 m³/day.

- The portion of the river that was chosen to constitute the regional survey area was chosen based on the following criteria:
    - ◊ Proximity to one of the proposed weir sites and the position of the Water Affairs cable across the river (for which existing hydrological data are available);
    - ◊ Ease of navigability and therefore ease of “repeatability” for the survey operation;
    - ◊ Orientation with respect to observed current flow;
    - ◊ Evidence for significantly-sized and representative bed forms occurring on the river bed;
    - ◊ Ability to conduct the proposed successive surveys (or synoptic river bed “snapshots”) in a reasonably short (~ 1 hour) time frame;
    - ◊ Due to the perceived representivity of this portion of the riverbed with regard to the river as a whole.
- Based on the surveys conducted, and subsequent results obtained, it is recommended that a further series of investigations be conducted. These additional assessments of bedload sediment transport rates, should be timed to coincide with different stages of the flow regime, in order to obtain data which could be used to quantify any seasonal changes in rates, thereby allowing for annual bedload sediment transport volumes to be more accurately assessed.

4.4.1.4 Discussion

The section of the river in which the side-scan sonar method was applied contained several rock outcrops which prevented the scanning of the complete river width. The Marine Geoscience Unit’s report also mentions that the reason for the selection of the ≈22 m wide section was that this contained the most prominent dunes. It was assumed that average bedload transport of 46,94 m³/day applied to the estimated average total active channel width of 57,82 m. The total bedload movement of 113,66 m³/day across the full channel width of 140 m was consequently determined by linear extrapolation.

Aerial observations during the low flow period have shown that dune fronts meander across the river which indicates that bedload transport is not uniform across the full width of the river, particularly in sections that contain rock outcrops. The results obtained by the side-scan

sonar method have shown in the Divundu case, whilst the method is probably the most accurate to determine bedload movement, that the results should be treated with caution on account of the rock outcrops. It is therefore considered essential that further side-scan sonar surveys should be conducted during the next phase of the project if sluicing remains an option, and that these be conducted over the full width in section of the river that is uniform and where there are no rock outcrops.
The results of the various bedload sampling investigations that were carried out, with the exception of those carried out in the Delta, must be considered as being applicable to a point in time only and consequently should not be used to determine bedload movement in general terms in the Okavango River.

The results obtained from the various methods used to sample bedload vary from 114 m³/d (bathymetry and side-scan sonar method) to 194 m³/d based on the Helley-Smith method (both of which took place in the period 24th to 27th April 2003 at Divundu) and between 202 m³/d and 38 m³/d in the Delta (Stanistreet, McCarthy and Cairncross, 1991[12)]). The latter samples were taken in the period December 1987 to January 1988. It is therefore evident that there are significant variations, not only in time, but also in the methods used. For example in the case of the Divundu investigations, the bedload estimations varied between 114 m³/d and 194 m³/d.

4.4.2 SUSPENDED SEDIMENT SAMPLING AT RUNDU BETWEEN 1973 AND 1991

Suspended sediment sampling was carried out by the Department of Water Affairs of the Ministry of Agriculture, Water and Rural Development, at Rundu from 1973 to 1991. Three samples were taken during 1973, 35 during 1976, 45 during 1977, 46 during 1978, 32 during 1979. 5 during 1980, 2 during 1990 and 2 during 1991. The samples taken in 1973, 1980, 1990 and 1991 are too few to be considered representative. The results of the samples taken between 1976 and 1979 are summarised in **Table 4-2** below.

Table 4-2 : Summary of Suspended Sediment Sampling Carried out at Rundu.

Year	**No. of Samples**	**Sediment Concentration [mg/l]**		
		Minimum	Maximum	Average
1976	35	1	59	30
1977	45	2	37	19.5
1978	46	1	39	20
1979	32	2	32	17

For an average mean annual flow of 170.5 m³/s between 1976 and 1980, the average volume of sediments transported down the river at Rundu amounted to 8,87 m³/day based on a density of the sediment of 1,66 tons/m³. This is considerably less than that measured at Divundu during May and June 2003. Some of the reasons for the difference are the following

- The sampling method used.

The river flow at Rundu is significantly less than that at Divundu.

- The bulk of the sediment is transported by the Cuito River.

The accuracy of the sampling process (e.g. high concentrations (59 mg/l) measured in low flow period, as in the case of October 1976, indicate inconsistencies in sampling).

With due consideration being given to the above reasons for the low sample concentration, and to the extrapolation of these results to Divundu, showed that there is very little difference between the Rundu results and those obtained during the June 2003 sampling at Divundu.

4.4.3 SUSPENDED SEDIMENT SAMPLING AT DIVUNDU – 3RD TO 6TH JUNE 2003

Due to the fact that the results of the earlier suspended sediment sampling produced poor results on account of the fact that water samples extracted were too small (5 litres), it was decided to revisit the site and take 100 litre samples. The gauge plate reading on the western pier of the Divundu bridge was 3,32 m at the time of the visit, which is equivalent to a flow of 290 m^3/s. The flow was down from the 313 m^3/s measured on the previous visit.

Hundred litre samples were taken at 15 different locations and depths. Water was continuously pumped until twenty 5 litre sample bottles were filled. The 20 bottles were taken to shore and allowed to settle. After a time the excess water was decanted until the total volume was reduced to about 1-2 litres. This process was followed for all 15 samples. The reduced samples were taken back to Windhoek for drying and weighing at the NamWater laboratory.

The samples were filtered and washed with deionised water through a pre-dried (103°C) and washed Whatman GF/C glass microfibre filter. This filter has a particle size retention of 1,2µm. The filter and the residue were dried in the oven at a temperature of 103°C for one hour.

After igniting, cooling, dessicating and weighing, the total suspended solids were determined on the filter. This step was included to confirm that the weight of the organic material was still part of the weight of the filter. The residue on the filter was then ignited to constant weight at 550°C to burn off all the volatile solids. The results of these tests are given in **Table 4-3** below.

Table 4-3 : Results of Suspended Sediment Sampling between 3rd and 6th June 2003

Position Across River	Chainage [m]	Concentration of Suspended Sediment [g/100l] at Stated Depths from Riverbed Level				
		0.2 m	**0.5 m**	**1.0 m**	**1.5 m**	**2.0 m**
1	35	0.2871	0.0996	0.0739	0.0648	0.0368
2	70	0.4389	0.0727	0.0266	0.0238	0.0302
3	105	0.9469	0.1915	0.0673	0.0284	0.0175
Average		**0.5576**	**0.1213**	**0.0559**	**0.0390**	**0.0282**
Average in g /l		**0.0056**	**0.0012**	**0.0006**	**0.004**	**0.0003**
Sediment Load -m^3/day		**16.84**	**3.66**	**1.69**	**1.17**	**0.85**

The above analysis has shown that concentrations varied from .0056 g/l at a point 200 mm above the riverbed to 0.0003 g/l at a point 2 m above the riverbed. These concentrations convert to sediment transport amounting to 16.84 m^3/day 200 mm above the bed to 0.85 m^3/day 2 m above the riverbed. The average transport of suspended sediments over the full river depth, as measured on the day of sampling, therefore amounts to 24.21 m^3/day.

The results from this sediment sampling survey demonstrate that suspended sediment loads should not be ignored. It must, however, be remembered that these rates apply to a single point in time and that concentrations of suspended sediments will vary according with the flow. Maximum concentrations can be expected to occur at the peak of the annual flood hydrograph and, equally, the minimum at the lowest point of the flood hydrograph. In order to be able to assess the average total suspended sediment load per annum, it will be necessary to carry out a comprehensive sediment sampling programme covering a period of 5 years with sediment concentrations sampled every day. As this will be a very costly exercise, it is recommended that sampling be carried out for, at the very least, once every two weeks during the detailed feasibility study phase particularly during the high flow period in the river.

4.5 CONCLUSIONS

If the results of the various methods employed to determine the bedload movement are compared with one another, it is evident that the bedload sediment transport can amount to anything between 114 m^3/day (side-scan sonar method), 194 m^3/day (Helley-Smith method at Divundu at an average flow velocity of 0,60 m/s), 197 m^3/day (Helley-Smith method in the Delta) and 302,9 m^3/day (based on Prof. McCarthy's bedload transport/velocity relationship using a velocity of 0,67 m/s at Divundu), depending on the method of sampling/survey, the location of the sampling site and the time of the year. The accuracy of the extrapolation of the results of the side- scan sonar method from 22 m wide sections of the dune fronts to the full river width of 140 m, is also questionable and requires confirmation. Equally, figures quoted for suspended sediment transport range from negligible to 86,8 m^3/day. It is therefore quite apparent that more extensive sampling is required before it is possible to predict what the sediment movement, be it bedload or suspended load, is likely to be at any particular reach in the river, and at any particular time of the year.

It is therefore recommended that additional bedload sediment sampling be conducted in the following phase of the project and that this be carried out every three months over a period of twelve months. In this manner it will be possible to determine the variation of the bedload and suspended sediment load movement over a full season. It is further recommended that bedload sediment movement be carried out using the side-scan sonar method and that suspended sediments be sampled using the pump method with 100 litres being collected per sample. A suitable site should be selected in which no rock outcrops occur and the river has a uniform cross section. Both bedload and suspended sediment load should be sampled at the same location and at the same time.