SEDIMENT TRANSPORT AND DEPOSITION IN THE OK TEDI-FLY RIVER SYSTEM, PAPUA NEW GUINEA: THE MODELING OF 1998 - 1999

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1. INTRODUCTION

The Ok Tedi-Fly river system is located in the country of Papua New Guinea. The Ok Tedi copper mine is presently disposing both tailings and rock waste into the river system near the headwaters of the Ok Tedi. This sediment flows from the Ok Tedi to the Fly River, eventually reaching the Gulf of Papua.

This document provides a brief report concerning the results of the modeling effort of 1998 – 1999, which were obtained as part of an overall risk assessment of mine activities. The results themselves are included in a set of two Zip discs which are described later in this report.

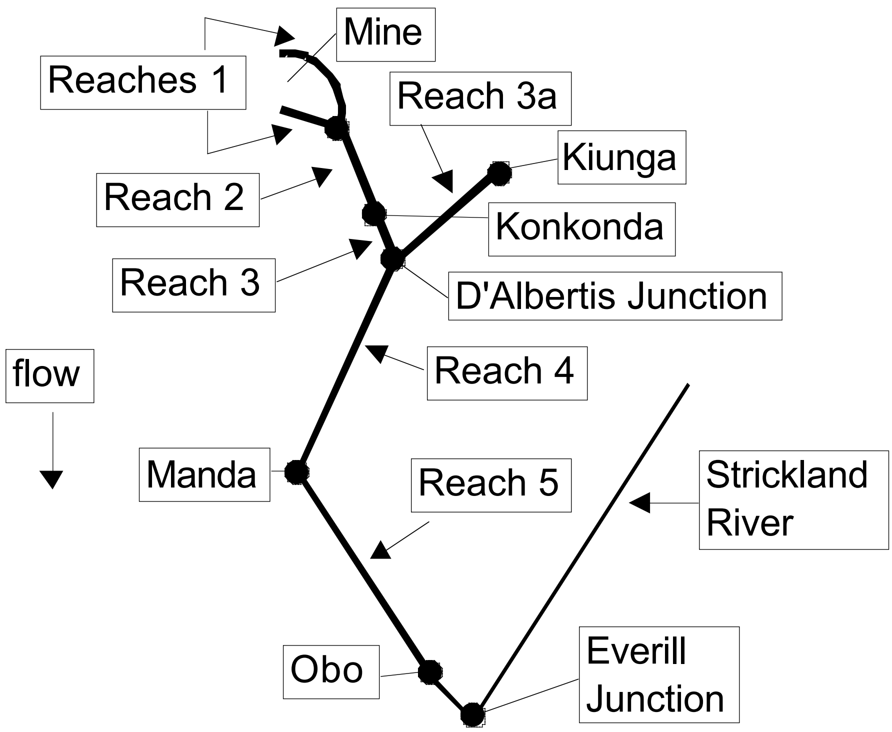

Figure 1: Definition of reaches.

It is useful to begin by defining the relevant reaches of the river itself, as shown in Figure 1. They are defined as follows for the purpose of this report:

- Reach 1: the Ok Mani, Ok Tedi, Ok Mabiong etc. upstream of the Ok Tedi and the Ok Mani near Tabubil;
- Reach 2: the coarse-bed Ok Tedi from the confluence with the Ok Mani to Konkonda, i.e. the point of transition from gravel-bed to sand-bed stream;

- Reach 3: the sand-bed Ok Tedi from Konkonda to D'Albertis Junction, i.e. the confluence with the Fly River;
- Reach 3a: the upper Fly River from Kiunga to D'Albertis Junction;
- Reach 4: the middle Fly River from D'Albertis Junction to Manda;
- Reach 5: the middle Fly River from Manda to Obo.

The downstream end of Reach 5 is near, but not at Everill Junction, where the Fly River joins the Strickland River.

The second author of this report has served as the sediment transport consultant for Ok Tedi Mining Ltd. since December of 1986. During this period a number of sediment transport models have been developed for the company. Only those of direct relevance to the present report are discussed here. The model *Okgrav5* was used to model sediment transport from the mine to a point near Konkonda, i.e. Reaches 1 and 2. The model *OkFly* was used to model sediment transport from the upstream points of Konkonda and Kiunga to Obo, i.e. Reaches 3, 3a, 4 and 5. *Okgrav5* is a program running from DOS written in the Pascal language. *OkFly* runs from DOS in Fortran, but has been provided with a Visual Basic interface.

2. GOALS OF THE MODELING

The primary focus of the modeling was the sand-bed Ok Tedi-Fly river system, i.e. Reaches 3, 3a, 4 and 5. The mine commenced sediment disposal in 1985, and will likely close no later than 2010. The modeling was designed to answer the following questions over the 70 year period 1985 - 2055.

a. What will be the pattern of bed aggradation, and subsequent degradation over the lifetime of the mine and beyond?
b. What will be the loadings of suspended sediment?
c. How will mine-derived sediment mix with natural sediment in the bed of the river?
d. What rates of overbank deposition will be observed?
e. What will be the provenance and size distributions of the bed and overbank sediment deposits?
f. How will flood frequency respond to the sediment loading?

The answers to these questions are to be used in turn to develop a risk assessment including such factors as dieback of riparian forest, potential for acid drainage, effect of sediment on aquatic fauna, fate of copper etc.

3. ORGANIZATION OF THE RESULTS

The modeling results are reported in two pairs of Zip discs. The first pair is dated 1/29/99; these results are referred to as the January results. The second pair is dated 5/10/99; these results are referred to as the May results. As will be seen below, the January results are more pessimistic and the May results are more optimistic. The May results are recommended as the likelier of the two to be quantitatively accurate.

Results are presented for seven options, as outlined below. These options are based on possible schemes for sediment control.

No Mine scheme: in this case it is assumed that the mine was never built. The predictions should show negligible changes over the 70 years of modeling.

Null scheme: the mine is assumed to continue until year 2010 with no sediment remediation.

Scheme *A*: dredge above Konkonda at 10 Mt/a for 1998, 1999, close mine on May 31, 2000.

Scheme *B*: dredge for three years, then tailings disposal to piped storage area for mine lifetime.

Scheme *C*: dredge for two years at 10 Mt/a and stop dredging for mine lifetime.

Scheme *DL*: dredge low (15 Mt/a) for mine lifetime.
Scheme *DH*: dredge high (19 Mt/a) for mine lifetime.

The two pairs of discs are organized according to the same structure. This organization is explained in the Word file "Readme.doc" on the root directory of the first of each pair of discs.

The data needed to approach the questions of Section 2 were generated using *OkFly.* In order to generate the input for that model, however, it was first necessary to run *Okgrav5.* With this in mind, *Okgrav5* is discussed first.

4. DESCRIPTION OF MODEL *Okgrav5*

Model geometry The model *Okgrav5* covers Reaches 1 and 2. The model has the following subreaches:

a. a debris flow runout zone from the Northern Dumps to a point on the Ok Gilor;
b. a subsequent fluvial reach extending to the Ok Tedi where it joins the Ok Mani;
c. a debris flow runout zone from the Southern Dumps to the confluence of the Ok Mani and the Ok Kumiup;
d. a fluvial zone extending down the Ok Mani from the Ok Kumiup to the confluence with the Ok Tedi; and
e. a fluvial zone extending down the Ok Tedi from the confluence with the Ok Mani to the gravel-sand transition (near Konkonda).

Subreaches a, b, c and d are in Reach 1 and subreach e constitutes Reach 2.

Flow calculation Reaches 1 and 2 are assumed to be sufficiently steep to allow for the assumption of quasinormal flow. As a result the full backwater equations are not used to predict the flow. Rather than use daily discharges as input, the flows are computed for a number of points in a flow duration curve. The flow duration curve is specified for each node along the system, but is assumed to be invariant in time. The model thus cannot distinguish between "wet" and "dry" years.

Sediment feed The model focuses on gravel transport. It assumes three sources of gravel: natural gravel, gravel derived from rock waste from the mine and gravel derived from slide material from either the walls of Harvey Creek (southern dumps) or the Vancouver Slide (northern dumps). The model also tracks mine-derived sand and silt. Sand and silt derive from rock waste, slide material and tailings. An additional source of sand and silt is abrasion, as discussed below.

Rock waste is fed in at the northern and southern dumps based on observed or projected annual dumping rates. Observed and predicted annual disposal rates are updated based on information from the mine. The rock waste is initially partitioned into gravel and coarser material, sand and silt fractions based on expected breakdown from the dump site to the base of the debris flow runout zones. Much of the gravel, and some of the sand and silt are captured in the debris flow runout zones as they aggrade with constant slope. The rest of the gravel is delivered to fluvial subreaches b and d.

Sediment is also produced indirectly in the form of slide material as a consequence of the dumping of rock waste. This material takes the form of the Vancouver slide mass of the northern dumps and erosion of the walls of upper Harvey Creek in response to the disposal of waste sediment. Observed and predicted schedules for this delivery are occasionally updated based on new information from consultants working for the mine. The initial breakdown into gravel, sand and silt fractions is assumed to be identical to that for rock waste.

Fluvial gravel transport Gravel transport is computed using the Parker (1980) surface-based transport relation. It treats sediment mixtures ranging from 2 mm to 512 mm on a fractional basis. Three layers are assumed in the model: a bedload layer, a bed surface (active) layer and a substrate layer. The average transport rate and transport grain size distribution for a year is based on calculations from the flow duration curve.

Abrasion of gravel The gravel-sized rock waste is relatively easily abraded. Abrasion is included in the Exner relation for sediment continuity. The products of abrasion are computed to be silt and sand, mostly the former. The coefficient of abrasion is assumed to be relatively large near the mine and relatively smaller farther downstream, to reflect the gradual dominance of abrasion-resistant gravel as the friable material is ground out. Although the model allows for different abrasion rates for several lithologies, only two lithologies have been used; harder natural gravel and softer mine-derived gravel. The abrasion coefficients were determined based on tests performed with a Los Angeles abrasion mill with fresh rock waste from the mine.

Sediment continuity: The debris flow runout zones are assumed to aggrade at a constant slope of 8 percent, based on field measurements. The fractions of gravel, sand and silt captured in this zone are also based on field measurements. The deposits are assumed to be matrix-supported. The area of deposition is assumed to expand as the bed aggrades in accordance with the geometric expansion of the respective river valleys. The downstream ends of the debris flow runout zones are constrained by confluence with a river with sufficient discharge to move the sediment fluvially.

Within the fluvial zones b and d (Ok Gilor-Ok Mabiong-Ok Tedi and Ok Mani) the bed is allowed to aggrade or degrade between any pair of nodes according to whether or not the gravel supply exceeds the sediment delivery. The width of deposition is divided into a channel width, which is used to compute sediment transport, and a wider valley width, over which aggraded sediment is allowed to deposit uniformly. This configuration approximates the reworking of the valley flat by a braided or wandering gravel-bed stream. The channel widths were determined from aerial photography and adjusted in the “zeroing” procedure discussed below. Valley geometry was assumed to be V-shaped, so that valley width increases with bed aggradation. This was particularly important for the Ok Mani, which is now an order of magnitude wider than the pre-mine state. Valley shape was obtained from topographic maps.

Within zones b and d the deposit is assumed to be clast-supported, but sand and some silt was allowed to fill the pore space as the bed aggrades. This material is released as the bed later degrades into its own deposits.

Exactly the same algorithm is used for zone e (Reach 2, i.e. the Ok Tedi from the confluence with the Ok Mani to Konkonda), with the exception that a) valley width is not allowed to change according to bed height and b) sand and silt are not stored in the interstices of the gravel as it aggrades. Because the river later degrades into its own deposit upon mine closure, it is necessary to store in memory both the thickness of the deposit and the grain size distribution. The stored grain size distributions consist of averages of the deposit over a specified thickness.

Fluvial transport of sand and silt Sand and silt deriving directly from rock waste, slide material and tailings are allowed to deposit in or be eroded from zones a, b, c and d. They are neither deposited in nor eroded from zone e. Sand and silt is produced by abrasion in zones b, d and e. The sand and silt transport at the confluence of the Ok Tedi and the Ok Mani (upstream end of Reach 2) is delivered directly to Konkonda (downstream end of Reach 2) with no intervening storage. The sand and silt produced by abrasion along Reach 2 is also delivered directly to Konkonda with no storage. This delivery is specified in terms of a mean annual rate. The assumption of no storage of sand and silt in Reach 2 is based on estimates indicating that the error in doing so is small.

Source partitioning *Okgrav5* partitions the sand and silt arriving at Konkonda into six types: sand from rock waste, sand from slide material, sand from tailings and silt from rock waste, silt from slide material and silt from tailings. This partitioning is for the purpose of tracking copper, which is present in different amounts according to the provenance of the material.

Model zeroing Models of bed evolution are prone to wild errors if used without prudent adjustment. The model was adjusted in the following way. Assuming that no mine was ever built, gravel infeed and channel width were adjusted so as to predict a river system that changes a negligible amount over the planned lifetime of the mine. The natural gravel infeed rates were determined in this way. They are very small compared to rates of loading from the mine.

Model output The output for *Okgrav5*, along with sediment budgets determined from the output, are given in the Excel workbook *Ok99.xls* in directory *General* of the first of the two discs. In running *Okgrav5* to determine the fate of the gravel, only two schemes needed to be considered; Scheme A, according to which the mine closes in year 2000, and all the other schemes.

The workbook includes worksheets specifying production schedules, gravel budgets for all relevant reaches, and schedules for the delivery of sand and silt to Konkonda. The computed delivery schedules for sand and silt to Konkonda are given for every scheme in worksheet *SchemeResults*. The sand and silt delivery rates are broken down according to provenance. The assumed grain size distributions of the sand and silt delivered to Konkonda (and Kiunga for the case of natural sediment) are given in worksheet *GrainSizeDist*. Estimated natural loadings of sand and silt at Konkonda and Kiunga are given in worksheet *NatLoad*. How these were determined is explained in more detail below.

Worksheets *SchemeResults, NatLoad* and *GrainSizeDist* provide information concerning sediment inputs used in the model *OkFly* to model Reaches 3, 3a, 4 and 5. The flow of the models is as follows. First *Okgrav5* is run to determine the fate of the gravel in Reaches 1 and 2, and the sand and silt delivery rates from the mine at Konkonda. The output of *Okgrav5* is then manipulated with the spreadsheet *Ok99*. Then *OkFly* is run to determine the fate of the sand and silt in Reaches 3, 3a, 4 and 5.

5. DESCRIPTION OF MODEL *OkFly*

Model network Although the model was designed to be implemented for the case of Reaches 3 (lower Ok Tedi) and 3a (upper Fly River) flowing into Reaches 4 and 5 (middle Fly River), it was written for a river network of more complexity. A schematic diagram of an arbitrary set of river segments that the model could handle is illustrated in Figure 2.

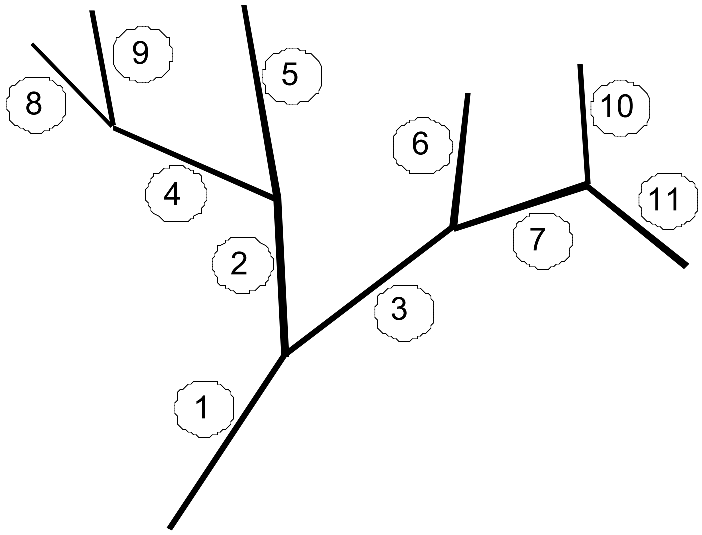

Figure 2. Illustration of the river network scheme of *OkFly*.

Note that the numbering system actually used by *OkFly* does not correspond to the numbering scheme adopted here for data presentation. Reaches 4 and 5 of the modeling exercise correspond to Reach 1 of *OkFly*, Reach 3 of the modeling exercise corresponds to Reach 2 of *OkFly* and Reach 3a of the modeling exercise corresponds to Reach 3 of *OkFly*.

Nodes and channel geometry. The locations and characteristics of all 47 nodes used in the study are specified in worksheet *Geometry* of workbook *okfly99* in directory *General* of the first of the two Zip discs. Information there includes node number, upchannel distance from Obo, channel width, floodplain width, channel area between the given node and the node just upstream and floodplain area between the given node and the node just downstream. The model also requires information concerning initial channel and floodplain elevation.

The channel and floodplain are assumed to have the simple geometries illustrated in Figure 3. The floodplain width used in the numerical model is not the width of the entire floodplain, but some “effective” width somewhat wider than the width of the meander belt. This “effective” width was used to account for the fact that much of the water in the floodplain is locally derived, and does not come from the channel. This fact is shown clearly in aerial photographs of the river in flood, showing dirty water in a band near the channel and ponded clear water away from the channel. The model also requires information concerning initial channel and floodplain elevation.

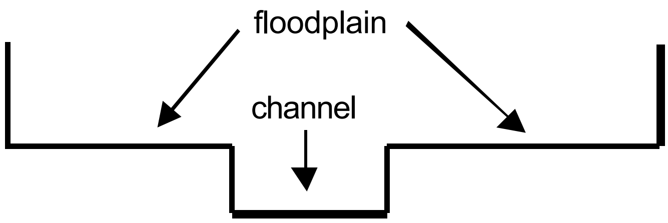

Figure 3. Simplified channel and floodplain geometry.

Discharges and flow calculation As opposed to *Okgrav5*, *OkFly* uses daily discharges based on flow records (including discharge and water surface elevation) at Konkonda, Kiunga, Kuambit, Manda and Obo. The daily discharges are based on two cycles of “dry,” “medium,” “wet” and “El Nino” years at each site. The flow records for each such year are based on a real record. The specification of flows from year to year is given in worksheet *Hydrology* of workbook *okfly99* in directory *General* of the first of the two discs. It should be noted that “dry” years, for example, are not necessarily dry everywhere. An interpolation scheme was used to determine the daily discharges at nodes for which flow records were not available.

The flow calculation is based on steady, gradually varied flow computed upstream from Obo, where water surface elevations were specified. In the event that the Froude number of the flow is in excess of 0.75 (an event that did not occur in the modeling effort reported here) the flow is treated as quasinormal. The technique does not assume constant water discharge between nodes, as this is allowed to vary according to an interpolation scheme, reflecting the interaction between channel and floodplain hydrology. The flow is partitioned between channel and floodplain in a standard way.

Hydraulic resistance *OkFly* uses the Brownlie (1981) model of hydraulic resistance to compute in-channel resistance. Expressed in terms of friction slope S_f, it takes the form

$$S_f = 0.02054 R^{1.286} F_g^{\,2.572} \left(\frac{H}{D_{50}}\right)^{-1.361} \sigma_g^{\,0.4130} \quad \text{for lower flow regime} \tag{1a}$$

$$S_f = 0.01252 R^{1.086} F_g^{\,2.172} \left(\frac{H}{D_{50}}\right)^{-1.304} \sigma_g^{\,0.2785} \quad \text{for upper flow regime} \tag{1b}$$

where H denotes in-channel depth, D_{50} denotes the median grain size of the sediment in the surface (active) layer of the bed, *R* denotes the submerged specific gravity of the sediment and σ_g denotes the geometric standard deviation of the sediment in the surface layer. In addition, F_g is a grain Froude number given by

$$F_g = \frac{Q_w}{BH\sqrt{RgD_{50}}} \tag{2}$$

where Q_w denotes in-channel water discharge, B denotes channel width and g denotes the acceleration of gravity.

Flow regime is defined as follows. If $S_f > 0.006$ then the flow is assumed to be in upper regime. For $S_f < 0.006$ the following parameters are computed;

$$F_g' = 1.74 S_f^{\,-1/3} \tag{3a}$$

$$\delta = \frac{11.6\nu}{u_*'} \tag{3b}$$

where ν denotes the kinematic viscosity of water and

$$u_*' = \sqrt{gHS_f} \tag{4}$$

where S_f is computed from (1b).

The lower limit of upper regime flow is given by the criterion

$$\ell g\left(\frac{F_g}{F_g'}\right)=\begin{cases}-0.02469+0.1517\ell g\left(\frac{D_{50}}{\delta}\right)+0.8381\ell g^2\left(\frac{D_{50}}{\delta}\right), \text{ for } \frac{D_{50}}{\delta}<2\\ \ell g(1.25) \quad \text{for } \frac{D_{50}}{\delta}\geq 2\end{cases}$$

(5a)

where ℓg is shorthand for the logarithm to the base 10. If the value of $\ell g(F_g/F_g')$ is grreater than that given in (5a), the flow is in upper regime. The upper limit of lower regime flow is given by the criterion

$$\ell g\left(\frac{F_g}{F_g'}\right)=\begin{cases}-0.2026+0.07026\ell g\left(\frac{D_{50}}{\delta}\right)+0.9330\ell g^2\left(\frac{D_{50}}{\delta}\right), \text{ for } \frac{D_{50}}{\delta}<2\\ \ell g(0.8) \quad \text{for } \frac{D_{50}}{\delta}\geq 2\end{cases} \tag{5b}$$

If the value of $\ell g(F_g/F_g')$ is less than that given by (5b) the flow is in lower regime.

If the value of $\ell g(F_g/F_g')$ is less than that given by (5a) but greater than that given by (5b), the flow is in transition, and the flow regime is decided depending on whether or not the flow is rising (in which case it is assumed to be in lower regime) or falling (in which case it is assumed to be in upper regime).

In point of fact the model calculations never entered upper regime. This is characteristic of sand-bed rivers with slopes below 0.0005.

Floodplain resistance was computed using a Manning formulation, such that

$$Q_{wf}=\frac{H_f^{5/3}S_{ff}^{1/2}B_f}{n} \tag{6}$$

where H_f denotes floodplain depth, S_{ff} denotes floodplain friction slope, B_f denotes floodplain width and n denotes the Manning coefficient of resistance. The value of n was inferred by means of calibration. The relation between floodplain friction slope S_{ff} and in-channel friction slope S_f is as follows;

$$S_{ff}\Delta x_f = S_f\Delta x \tag{7}$$

where Δx denotes along-channel distance between nodes, and Δxf denotes the corresponding along-valley distance.

There is reason to believe that floodplain discharge does not exceed 10% of total discharge. In *OkFly* a maximum of 30% of flow is allowed on the floodplain.

Computation of sediment transport In order to compute the sediment transport rate, the sediment in motion is first divided into wash load and bed material load. In the calculations of January, 1999, bed material load was considered to be material in excess of 20 mμ and wash load was considered to be material finer than 20 mμ. In the calculations of May, 1999 the cutoff size was raised to 43 mμ after a perusal of available data on river bed grain size distributions.

Wash load was assumed to continue downstream with no storage in the bed of the river. As such, no sediment transport equation was used to treat wash load. Deposition of wash load on the floodplain was, however, allowed, as described below. For this reason wash load was non-conservative, such that the transport rate of wash load decreases down the channel due to loss to the floodplain during floods.

The basis for the calculation of bed material load was the Brownlie (1981) formulation. This relation computes total bed material load Q_s as a function of a single grain size D_{50}, here taken to be the median size of the sediment in the active layer of the bed. The relation takes the following form:

$$Q_s = 7.115 \times 10^{-3} \frac{c_F}{R+1} Q_w \left(F_g - F_{go}\right)^{1.978} S_f^{\,0.6601} \left(\frac{H}{D_{50}}\right)^{-0.3301} \tag{8}$$

where

$$\begin{cases} c_F = 1 \text{ for laboratory data} \\ c_F = 1.268 \text{ for field data} \end{cases} \tag{9}$$

In equation (8), the parameter F_{go} is given as

$$F_{go} = 4.596 \tau_{*o}^{\,0.5293} S_f^{\,-0.1405} \sigma_g^{\,-0.1606} \tag{10}$$

where

$$\tau_{*o} = 0.22Y + 0.06e^{-17.73Y} \tag{11}$$

and

$$Y = \left(\sqrt{R} R_g\right)^{-0.6} \tag{12}$$

where grain Reynolds number R_g is defined as

$$R_g = \frac{\sqrt{g D_{50}^{\,3}}}{\nu} \tag{13}$$

An important aspect of the present analysis is an accounting for differential transport of grain sizes in a sand mixture. Under pre-mine conditions, for example, the bed of the Fly River showed a consistent tendency for downstream fining, from about 0.3 mm near D'Albertis Junction to about 0.1 mm near Obo. The mine-derived sand likewise shows a wide range in grain sizes. A review of the literature revealed no transport relations for sand that specifically address the issue of differential transport of sand in mixtures. It was thus necessary to devise a new technique for the case at hand.

A first attempt to treat the problem was based on an adjustment of the parameter F_{go} in (6) so that it varied as a function of grain size in a mixture. This corresponds to the introduction of a "hiding function" into the condition defining the threshold of motion. This procedure was used in the January calculations. It became apparent, however, that most of the bed material transport takes place under conditions that are so far above the threshold of motion that the adjustment produced very little differential transport.

With this in mind, the following procedure was implemented in the May calculations. For simplicity all of the bed material load was assumed to be in suspension. While this statement is unlikely to be completely accurate, under the high flow conditions that transport the bulk of bed material load it can be expected that suspended load dominates bedload by a factor of 3:1 or more. The material of the surface (active) layer was divided into a number of grain size ranges, each with a characteristic grain size D_j. A near-bed volume concentration of suspended sediment c_{bj} was assumed for this range, and the vertical distribution of suspended load in this range was computed from the Rousean distribution as

$$c_j = c_{bj}\left(\frac{(1-\zeta)/\zeta}{(1-\zeta_b)/\zeta_b}\right)^{\frac{v_{sj}}{\kappa u_*}} \tag{14}$$

where c_j denotes the volume concentration of the jth fraction a distance z above the bed, ζ = z/H, ζ_b = z_b/H where the near-bed elevation z_b is here chosen as 5% of the depth, v_{sj} = the fall velocity associated with size D_j, κ is the Karman constant and u_* is the shear velocity of the flow.

Assuming the vertical distribution of streamwise flow velocity to follow a 1/6 power law, it can be shown after some work that the volume transport rate of the jth grain size range Q_{sj} is given by

$$Q_{sj} = \alpha_r c_{bj} UHB \int_{\zeta_b}^{1}\left(\frac{(1-\zeta)/\zeta}{(1-\zeta_b)/\zeta_b}\right)^{\frac{v_{sj}}{\kappa u_*}} \zeta^{1/6} d\zeta \tag{15}$$

where U is the average flow velocity and α_r is a coefficient associated with in-channel resistance. As long as bedforms keep the surface layer well mixed, it is reasonable to assume a simple linear relationship between the fraction F_j of the jth grain size in the active layer and c_{bj}, such that

$$c_{bj} = \alpha_s F_j \tag{16}$$

where α_s is another constant. Substituting (16) into (15), it is found that

$$Q_{sj} = \alpha_r \alpha_s UHBF_j \int_{\zeta_b}^{1}\left(\frac{(1-\zeta)/\zeta}{(1-\zeta_b)/\zeta_b}\right)^{\frac{v_{sj}}{\kappa u_*}} \zeta^{1/6} d\zeta \tag{17}$$

The constant $\alpha_r\alpha_s$ can be evaluated by summing (17) and equating the result to that predicted by (8). Further reducing, the fraction p_j of bed material load in the jth size range is found to be given by the relation

$$p_j = \frac{Q_{sj}}{Q_s} = \frac{F_j \int_{\varsigma_b}^{1} \left(\frac{(1-\zeta)/\zeta}{(1-\zeta_b)/\zeta_b} \right)^{\frac{v_{sj}}{\kappa u_*}} \zeta^{1/6} d\zeta}{\sum_j F_j \int_{\varsigma_b}^{1} \left(\frac{(1-\zeta)/\zeta}{(1-\zeta_b)/\zeta_b} \right)^{\frac{v_{sj}}{\kappa u_*}} \zeta^{1/6} d\zeta} \quad (18)$$

Thus in the present formulation the total transport rate of bed material load is given by (8) and the size distribution of the bed material load is given by (18). Sorting is associated with the variation of fall velocity v_s with grain size D; finer grains have a lower fall velocity, a more uniform concentration distribution in the vertical and thus a higher transport rate relative to content in the surface (active) layer.

Sediment continuity The Exner formulation for sediment continuity for sediment mixtures can be decomposed into the following two relations.

$$B\frac{\partial \eta}{\partial t} + \frac{1}{1-\lambda_p}\frac{\partial Q_S}{\partial x} = -q_\ell$$

(19a)

$$B\frac{\partial (L_a F_j)}{\partial t} + f_{Ij} B \frac{\partial (\eta - L_a)}{\partial t} + \frac{1}{1-\lambda_p}\frac{\partial Q_s p_j}{\partial x} = -q_\ell p_{\ell j}$$

(19b)

In the above relations x denotes in-channel distance downstream, t denotes time, η denotes bed height, L_a denotes the thickness of the active layer, λ_p denotes the porosity of the surface (active) layer of the bed, q_ℓ denotes the volume loss of sediment per unit distance downstream per unit time to the floodplain and $p_{\ell j}$ denotes the fraction in the jth size range of sediment lost to the floodplain. The parameter f_{Ij} denotes the grain size fractions that transfer across the interface as the bed aggrades or degrades. When the bed degrades, fractions f_{Ij} are set equal to the corresponding fractions in the substrate stored immediately below the surface layer. When the bed aggrades, the fractions f_{Ij} are set equal to a weighted average of the surface and load fractions. The following relation based on the work of Toro-Escobar et al (1996) has been used for this purpose;

$$f_{Ij} = 0.7 p_j + 0.3 F_j \quad (20)$$

Equations (18a) and (18b) are solved as follows for the evolution of the bed. A solution to the shallow water equations allows for an evaluation of the parameters necessary to compute both the transport rate Q_s and grain size fractions of the load p_j everywhere. Equation (19a) is then solved to determine the change in bed elevation at each node. Then (19b) is solved to determine the change in the composition of the surface (active) layer. The model used to compute the deposition of sediment on the floodplain is given below.

Floodplain deposition It was incumbent upon the authors to devise a simple but useful model for floodplain deposition, in so far as nothing else seems available in the literature. According to the convective model of Parker et al. (1996), the rate of loss to the floodplain q_ℓ is specified as

$$\frac{q_{\ell}}{B_f} = \frac{\partial \eta_f}{\partial t} = \alpha_f \frac{Q_{sf}}{B_f^2} \tag{21}$$

where Q_{sf} denotes the portion of the total in-channel sediment transport rate that rides above the level of the floodplain, η_f denotes floodplain elevation and α_f is a dimensionless order-one coefficient that must be obtained by calibration. Here Q_{sf} is taken to include both wash load and bed material load that reside in the water column above the level of the floodplain during floods, as illustrated in Figure 4. The above calculation is applied at each time: when the river is not in flood Q_{sf} vanishes and there is no deposition on the floodplain.

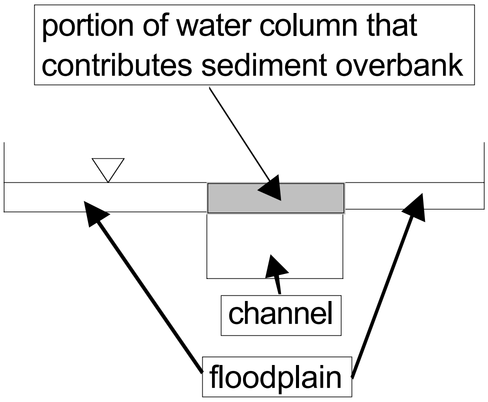

Figure 4. Illustration of the model for floodplain deposition.

The grain size distribution of the sediment deposited overbank is taken to be that of the grain size distribution of that portion of the suspended sediment above the channel bed that is also above the elevation of the floodplain. That is,

$$p_{\ell j} = \frac{c_{bj} \int_{\zeta_f}^{1} \left(\frac{(1-\zeta)/\zeta}{(1-\zeta_b)/\zeta_b} \right)^{\frac{v_{sj}}{\kappa u_*}} \zeta^{1/6} d\zeta}{\sum_j c_{bj} \int_{\zeta_f}^{1} \left(\frac{(1-\zeta)/\zeta}{(1-\zeta_b)/\zeta_b} \right)^{\frac{v_{sj}}{\kappa u_*}} \zeta^{1/6} d\zeta} \tag{22}$$

where $\zeta_f = H_b/H$ and H_b denotes bankfull depth. Note that H_b must be less than H, i.e. the river must be in flood, in order to render the calculation meaningful.

In evaluating (22) the wash load is included in the calculations. That is, for range j within the range of washload, the Rousean distribution of suspended sediment that when integrated yields the total washload transport rate is computed, and that portion residing above the floodplain is used as the basis for the grain size distribution of sediment transferred to the floodplain. In this way both bed material load and wash load contribute to floodplain deposition. Although wash load does not interact with the bed, it is not entirely conservative due to loss to the floodplain.

The coefficient α_f in (21) was obtained by calibration. For Reach 3, calibration was performed so as to yield a set amount of sediment deposited overbank by 1992, for which rough observations were available. For Reaches 4 and 5, calibration was performed so as to yield a loss of total load of about 3 – 4% to overbank deposition between Kuambit and Everill Junction under pre-mine conditions (Dietrich et al, 1999).

Spatial distribution of overbank sediment The model outlined above provides an estimate of the rate of deposition and grain size distribution of overbank sediment, and also provides an indication as to how this rate and distribution varies downstream. It is not adequate, however, to determine how the thickness of the deposit varies away from the channel. The results of the calculation were thus further analyzed assuming that the thickness of the deposit declines exponentially away from the channel. The coefficient in this relation was provided by W. Dietrich (personal communication). As a result, the model provides a gross indication of the spatial variation of thickness of overbank deposits in both the streamwise and normal coordinates.

Flood frequencies in the absence of the mine Minor adjustments in local initial floodplain and bed elevation were made in order to calibrate the model to "observed" pre-mine flood frequencies at several key sites down the river. In several cases the "observed" value was based on consensus rather than hard data. There is, however, general agreement that even under pre-mine conditions the frequency of flooding in Reaches 3, 3a, 4 and 5, i.e. those under consideration in the model, was rather high. Some calibrated values are presented below.

Site	Percent of time the river is in flood (pre-mine)	
	January model	May model
Konkonda	12	9
Kiunga	16	26
Kuambit	29	42
Wygerin	51	67
Manda	53	78
Obo	53	59

Treatment of Reach 3a The sediment from the Ok Tedi depositing at D'Albertis Junction has raised the bed sufficiently so as to create substantial backwater in the upper Fly River (Reach 3a). This backwater has not only exacerbated flooding and dieback, but also as created a long zone of deposition of naturally derived sediment in the upper Fly. It proved impossible to model the observed bed aggradation at Kiunga with a model terminating at Kiunga. With this in mind an extra reach has been artificially added upstream of Kiunga. This reach has the same bed slope and cross-sectional shape as the reach in the vicinity of Kiunga. The length of the reach was adjusted so as to provide reasonable results for bed aggradation at Kiunga.

Model zeroing As in the case of *Okgrav5*, the model was zeroed so as to produce minimal change in bed elevation, flooding frequency and rate of overbank deposition over the 70 year calculation period in the absence of the mine. The zeroing was performed successfully except for one feature. It proved impossible to predict the observed pre-mine rate of fining of characteristic bed grain size between D'Albertis Junction and Everill Junction. Although the zeroed May model does predict substantial downstream fining between these sites, further development would have been required to reproduce the pre-mine data.

Testing of the model The model has been calibrated for a) floodplain Manning's n, b) frequency of floodplain inundation under pre-mine conditions and c) rate of overbank deposition of sediment. The model has not been calibrated for bed aggradation rate. The values predicted by the model at Konkonda, Kuambit and Kiunga, however, agree reasonably well with available data.

6. OUTPUT OF MODEL *OkFly*

The model predicts a pulse of sediment slowly migrating down the Ok Tedi-fly River system, with increased river bed elevation, flooding and overbank deposition of sediment persisting throughout the 70-year period (from 1985 to 2055) modeled. The height of the leading edge of the pulse of aggrading bed sediment is in excess of 3 m in the January model, but about 1 m in the May model. There are two main reasons for the decrease in the height of the pulse: a) the change in the cutoff size for bed material load from 20 mµ to 43 mµ and b) the adoption of a more effective sorting routine for suspended sediment. Both of these features tend to increase the throughput of finer sediment from the system and reduce the adverse effects of the mine as predicted by the May model in comparison with the January model.

The January model thus may be described as "pessimistic" and the May model as "optimistic." The authors of this report believe the May model to be more likely to be closer to reality. It should be pointed out, however, that even the "optimistic" calculations predict a continuing very strong signal of the mine in terms of bed aggradation, increased flooding and overbank sediment deposition.

As noted earlier, all the predictions of the model are provided on, Zip discs, one pair for the January modeling and one for the May modeling. Complete documentation of the contents of the discs can be found in the file *Readme.doc* in the root directory of the first disc. The following Excel files, however, which can be found under directory *General* of the first disc may be of particular interest to the user.

Inundate.xls This file provides numerical information about inundation frequencies for all schemes for the entire 70-year calculation.

Okfly99.xls This file provides numerical information on node geometry, the assumed hydrological input and the following information for a variety of sites along the river, for all 70 years of the simulation and for each scheme: incremental bed elevation; incremental mean floodplain elevation, cumulative sediment delivery, percent natural sediment in delivery, cumulative floodplain deposit mass, percent natural sediment in the floodplain, and cumulative floodplain mass as a percent of incoming sediment to a given reach. In most cases the sediment is fractionated according to size.

Okfly99a.xls This file is a computational tool to allow the computation of the fraction of a specified part of the floodplain which receives an accumulation depth of x mm of sediment over y years, where x and y are user-specified.

Okfly99b.xls This file presents the output in graphical form.

Okfly99c.xls This file presents the incremental bed elevations at every node for every year of the calculation for every scheme.

7. SOME EXAMPLES OF MODEL OUTPUT FROM *OkFly*

All but one of the examples of model output shown here are from the May model. The output from the January model is generally similar. Some of the differences are noted below.

Figures 5a-c show model predictions for incremental bed elevation above the pre-mine level as a function of time for eight sites. The up-channel distance of each site from Obo is shown in the table below.

Site	River	Distance u/s Obo in km
Konkonda	Lower Ok Tedi	459
13 km u/s D'Albertis Jn.	Lower Ok Tedi	424
Kiunga	Upper Fly	449
8 km u/s D'Albertis Jn.	Upper Fly	419
Kuambit	Middle Fly	411
Wygerin	Middle Fly	353
Manda	Middle Fly	151
Obo	Middle Fly	0

Figure 5a refers to the Null Scheme, i.e. continued mine operation with no sediment amelioration. Figure 5b refers Scheme A, i.e. to closure of the mine in year 2000. Figure 5c refers to the Dredge High option. The model predicts as much as 8 m of aggradation at Konkonda for the Null Scheme, most of which has been realized at the time of writing of this report. It is seen that the response of the mine is predicted to be more delayed in time, and the amplitude more reduced the farther down the river.

The model indicates that sediment input from the mine will be in the Fly River for many decades to come. While recovery at the upstream end (Konkonda) is relatively rapid, complete recovery in the lower Middle Fly (Reach 5) is not predicted to during the modeling period (up to year 2055).

It is seen from Figure 5b that Scheme A allows for a significant amelioration of bed aggradation. Scheme DH also offers significant benefits in this regard, as shown in Figure 5c.

The mine-derived sediment appears as a migrating front in the long profiles of bed elevation presented in Figures 6a-c, each of which corresponds to the schemes described in Figures 5a-c respectively. The height of the migrating front of mine-derived sediment is about 1.2 m for the Null Scheme, 0.7 m for Scheme A and about 0.75 m for Scheme DH. Both Schemes A and DH show a faster recovery of bed elevations after the mine stops than the Null Case.

Figure 7 shows the migrating front of the Null Case as predicted by the January model. It is seen to be 3 – 4 m high. Otherwise the predicted behavior is quite analogous to that of the May model shown in Figure 6a. it is suggested here that the migrating front predicted by the May model is somewhat optimistic, and that predicted by the January model is quite pessimistic. The model is failing to predict a layer of sediment that is presently being observed to deposit downstream of the front, however. This issue is discussed in the next section of this report.

Figures 8a-c show the cumulative masses of sediment predicted to deposit overbank in Reach 4 (D'Albertis Junction to Manda) as a result of the Null Scheme, Scheme A and Scheme DH, respectively. Scheme A provides a very considerable reduction in overbank deposition as compared to the Null Case. Scheme DH also offers some benefit, but not as much as in the case of bed aggradation. This is because dredging removes sand but very little silt, which is the size range most easily deposited overbank.

Figure 9 shows the annual frequency of flooding at Kuambit as a function of time. Four schemes are shown; the No Mine Scheme, the Null Scheme, Scheme A and Scheme DH. Again, Scheme A offers the most rapid reduction in flooding frequency. Scheme DH also offers substantial benefits.

Figure 10 show the predicted bed elevations relative to their predicted values in 1999 at as functions of time for all schemes. The site in question is Kuambit. Again mine closure (Scheme A) is seen to provide the fastest recovery, with Scheme DH performing second best.

Figure 11 shows predictions of annually averaged total suspended sediment (TSS) concentration in mg/l at Kuambit for the No Mine Scheme, Null Scheme, Scheme A and Scheme DH. The calculations are based solely on material finer than 62.5 microns. Note that suspended sediment concentrations drop off very quickly to background values after mine closure in 2010 (Null Scheme) or 2000 (Schemes A and DH). Scheme A is thus effective in bringing back background values of TSS ten years earlier than the Null Scheme. Calculations for Scheme DH indicate slightly elevated values of TSS as compared to the Null Case during the period 2000 – 2010. This is because dredging reduces bed elevation without reducing the silt load. This prevents silt from being lost overbank, resulting in slightly higher TSS values.

In summary, the model *OkFly* predicts that the effect of mine sediment on the Lower Ok Tedi and the Middle Fly River will be substantial. The effect should persist for decades, even were the mine to be closed in 2000. The strongest persistence is observed farthest downstream, where the amplitude of mine-induced perturbation is smallest.

The model predicts that the recovery of bed elevation, flood frequency, rate of overbank deposition of sediment and TSS concentrations would be most rapid in the case of Scheme A, i.e. mine closure in 2000. Scheme DH, i.e. dredging, also offers substantial improvement over the Null Scheme in the case of bed elevation and flood frequency. Scheme DH provides some improvement in overbank deposition of sediment. It provides virtually no benefit in terms of TSS concentrations, but rather slightly elevates them during the period 2000 – 2010. In all schemes TSS concentrations are expected to recover very rapidly after mine closure, however.

8. VERIFICATION OF THE MODEL: ITS LIMITATIONS

The model *OkFly* is useful but far from perfect. It is important to note that the model was calibrated for flood frequencies, but has not been calibrated for bed aggradation. Model output for bed elevation in 1998 is plotted against observed data in Figure 12. The observed data are from Marshall and Rau (1999). The predicted and observed aggradation in meters is measured relative to a pre-mine average. The observed data are plotted in two different ways. “Meas 1” refers to aggradation averaged over river width excluding banks. “Meas 2” refers to aggradation over a bed width (excluding banks) that has been further reduced by 10 – 20 percent. Predicted results are shown for both the January and May models. They extend from Konkonda on the lower Ok Tedi to Obo on the lower middle Fly River.

Both the measurements and the data show a wedge of sediment extending downstream from Konkonda. The model values are in reasonably good agreement with the predicted values with the exception of about 1.5 m of aggradation observed from Obo to about 250 km upstream.

The reason for the bed aggradation in the lower half of the Middle Fly River is not known. It appears, however, to be a deposit associated with the backwater of the much larger Strickland River, which enters downstream of Obo at Everill Junction. The mean bed elevation at Ogwa, just downstream of Obo, has fluctuated as much as 2 m from 1990 to the present. The natural load of the Strickland River has been estimated to be 60 – 80 Mt/year, and is rather larger than what is expected in the lower Middle Fly River due to the effect of the mine. In addition, the grain size distribution at Ogwa has remained near 250 μm, i.e. much coarser than that of the Fly River just upstream and near pre-mine values. It thus seems unlikely that the bed level fluctuations at Ogwa are due to mine-derived sediment.

If the above hypothesis is correct, the model must be extended downstream at least as far as Ogwa in order to capture the backwater deposits in the lower Middle Fly River evident in Figure 12. At present the data to do this are not available. They would have to be synthesized based on relatively scanty records. If the aggradation in question is indeed a backwater deposit, however, it is likely that the aggradation would not increase substantially in time until the main wave of sediment from the mine shown in Figurs 6a-c and 7 progrades into the lower Middle Fly River.

Other areas where the model could be improved are related to a) the computation of grain size sorting in sand-bed streams, b) the formulation of channel flooding on a floodplain which has its own hydrology due to direct rainfall, c) overbank sediment contribution to off-river water bodies and d) estimates of sediment production by abrasion on the Ok Mani and upper Ok Tedi.

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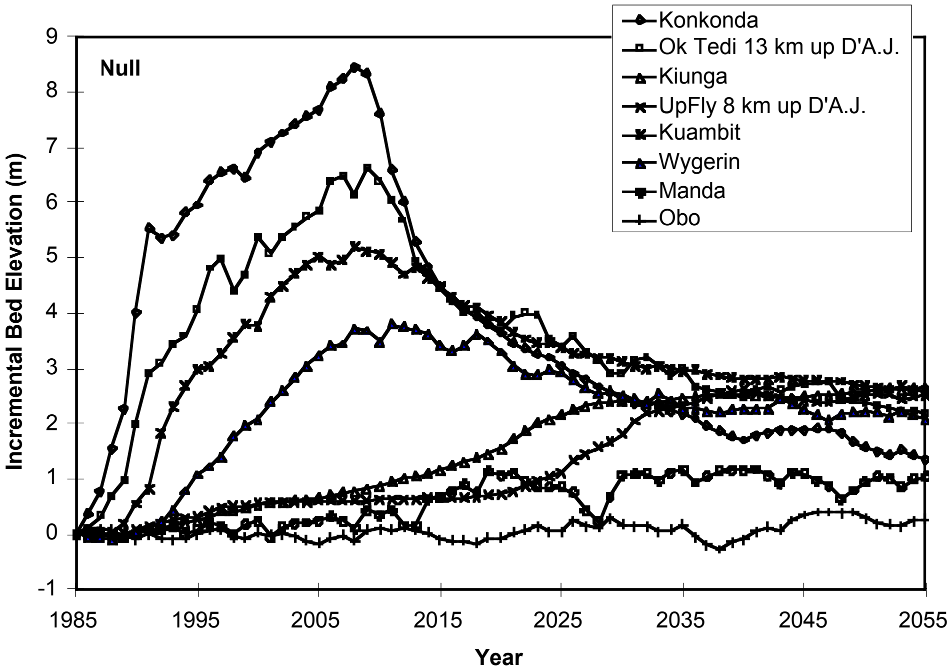


a)Figure 5a. Incremental bed elevations, May model, Null Scheme

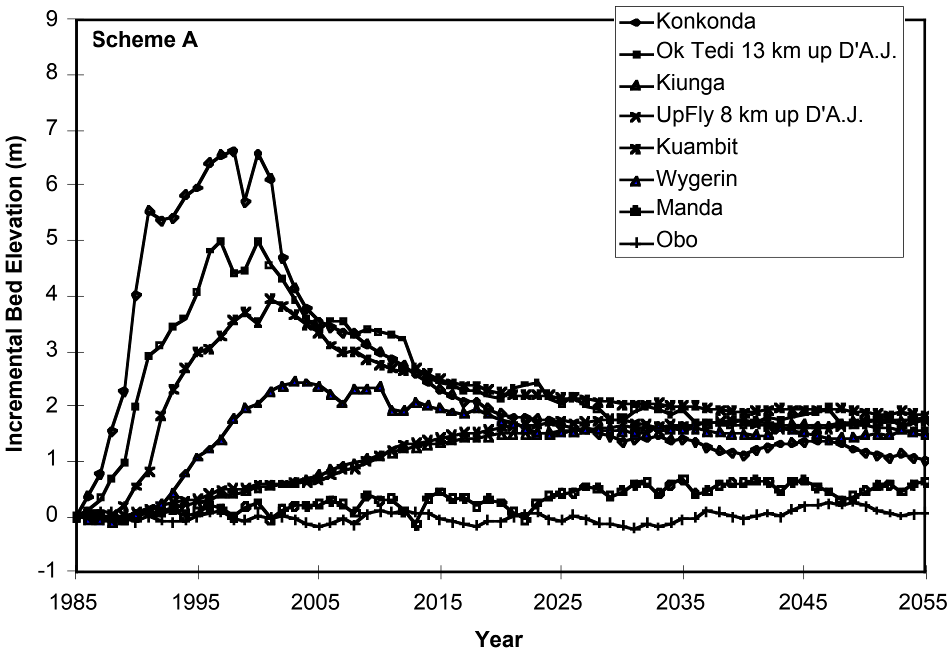


Figure 5b. Incremental bed elevations, May model, Scheme A

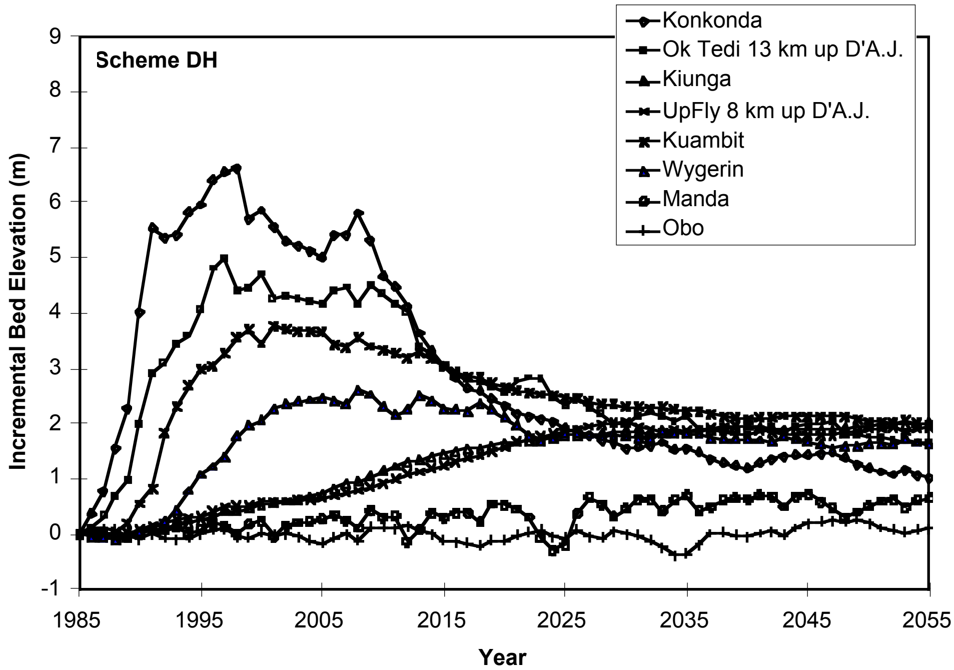


Figure 5c. Incremental bed elevations, May model, Scheme DH.

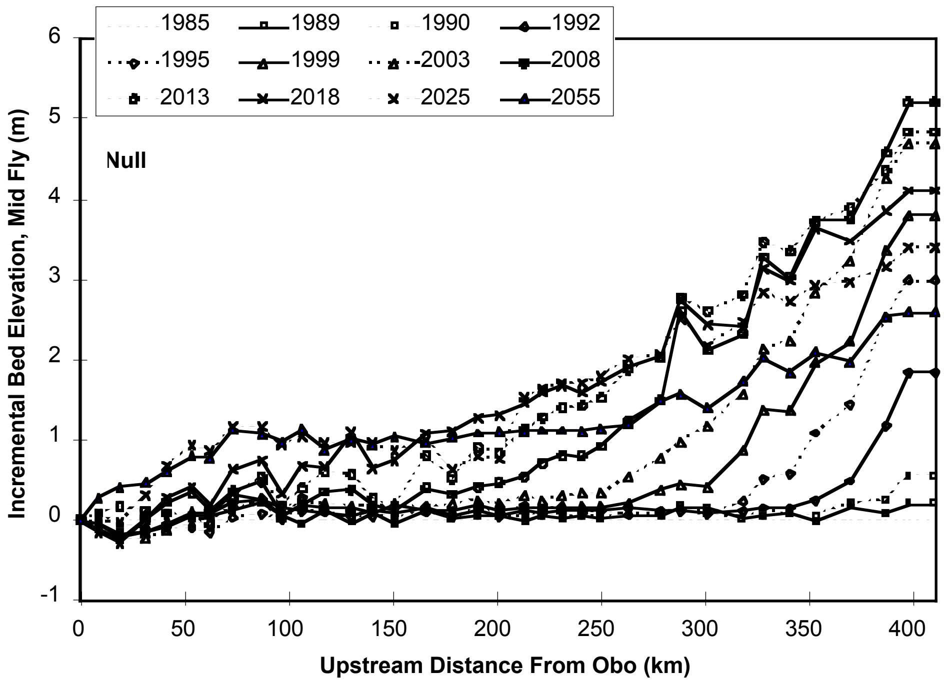


Figure 6a. Bed long profiles, May model, Null Scheme.

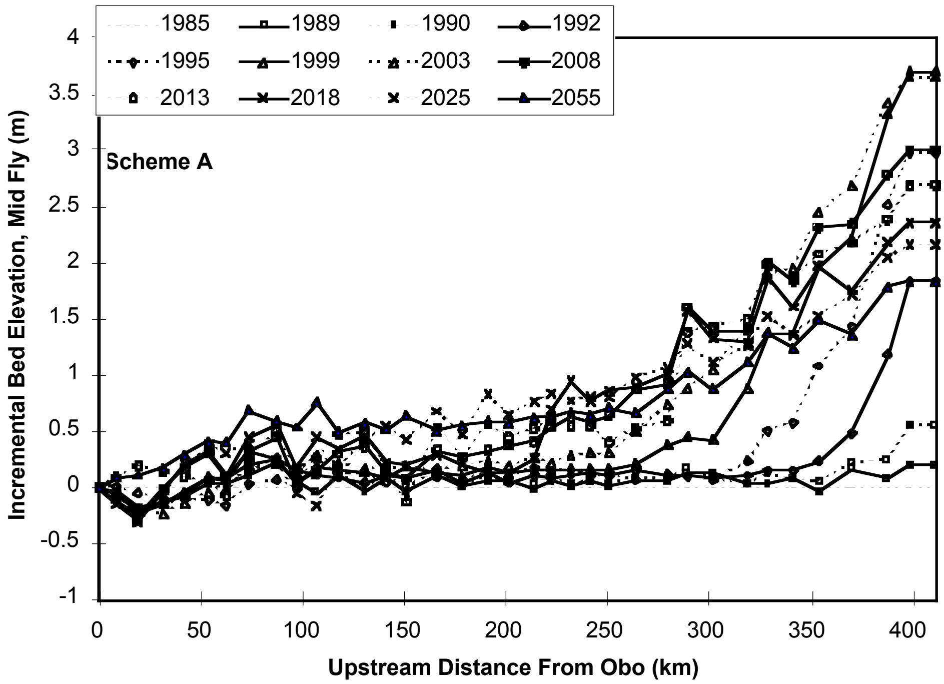


Figure 6b. Bed long profiles, May model, Scheme A.

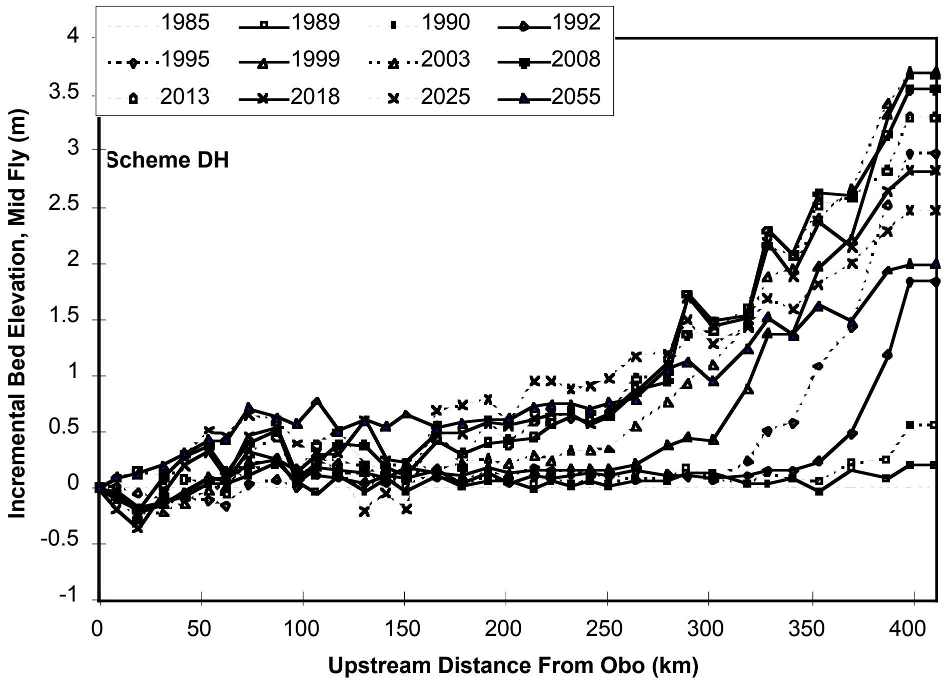


Figure 6c. Bed long profiles, May model, Scheme DH.

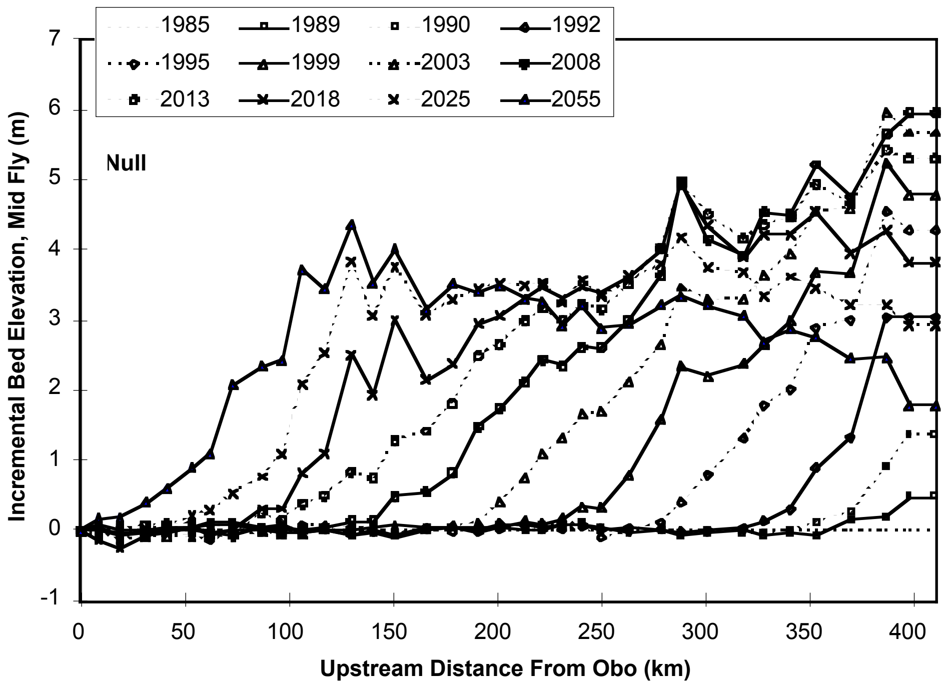


Figure 7. Bed long profiles, January model, Null Scheme.

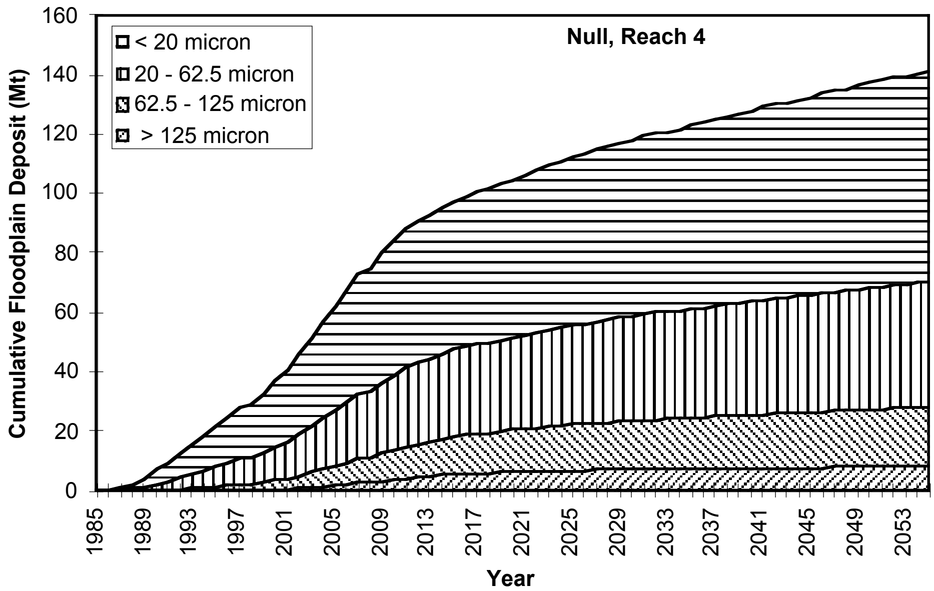


Figure 8a. Cumulative floodplain deposit in Mt, May model, Reach 4, Null Scheme.

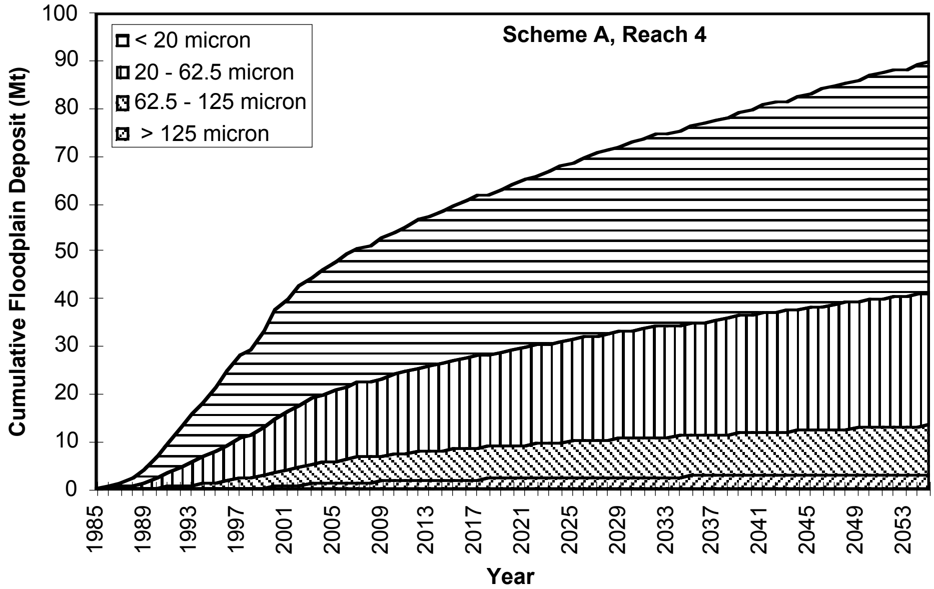


Figure 8b. Cumulative floodplain deposit in Mt, May model, Reach 4, Scheme A.

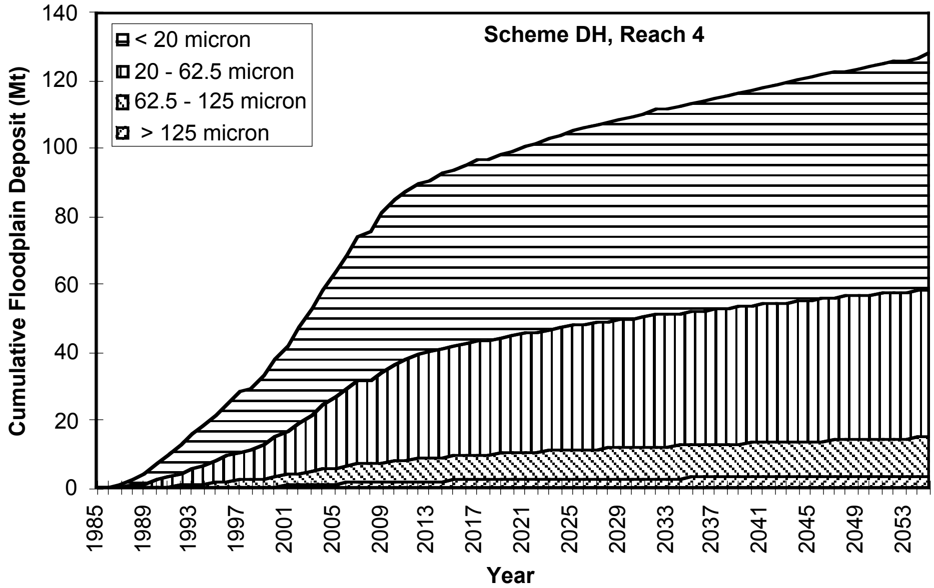


Figure 8c. Cumulative floodplain deposit in Mt, May model, Reach 4, Scheme DH.

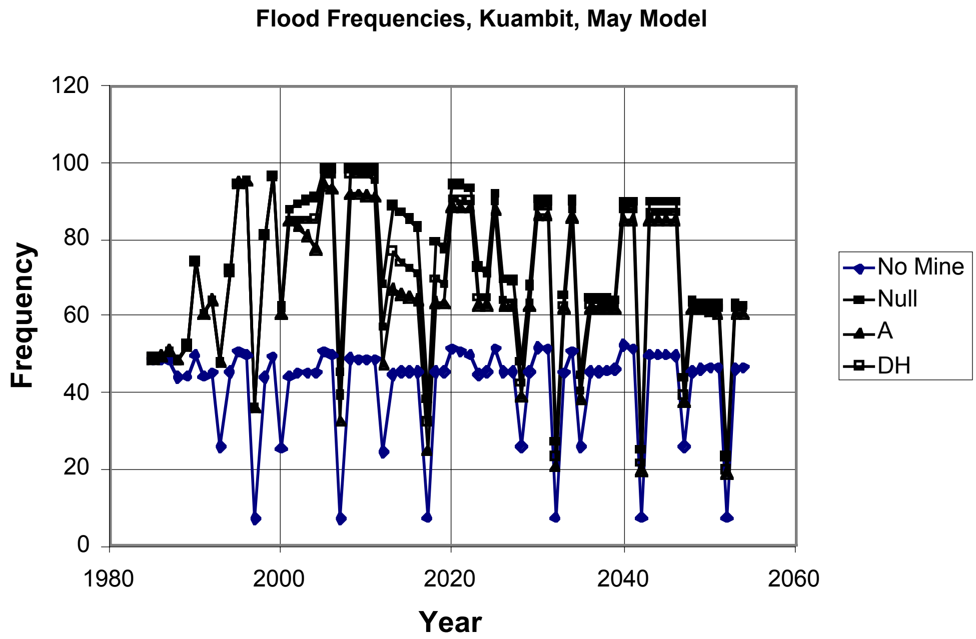


Figure 9. Flood frequencies at Kuambit, May model.

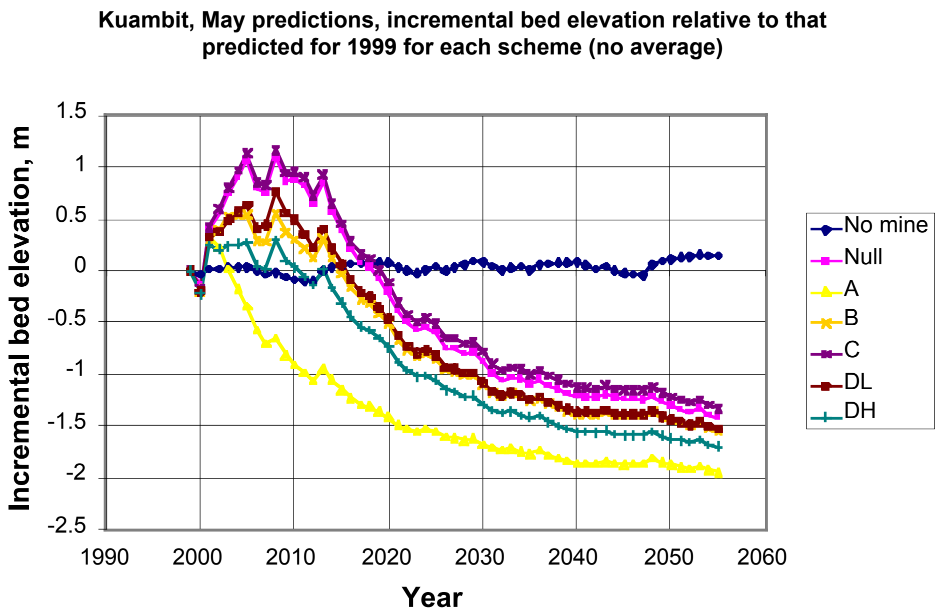


Figure 10. Incremental bed elevation above the predicted 1999 level for all schemes, May model, Kuambit.

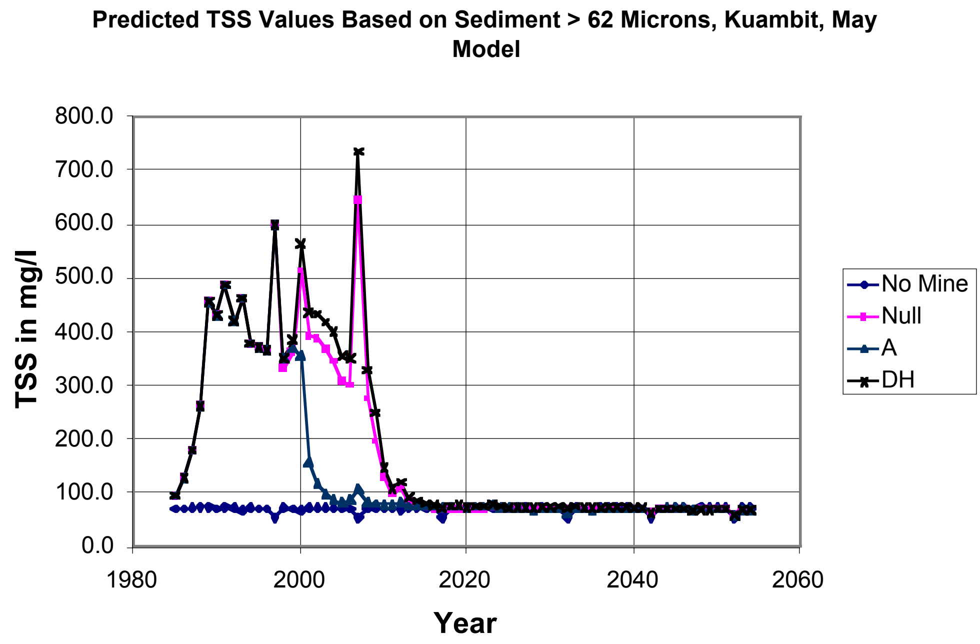
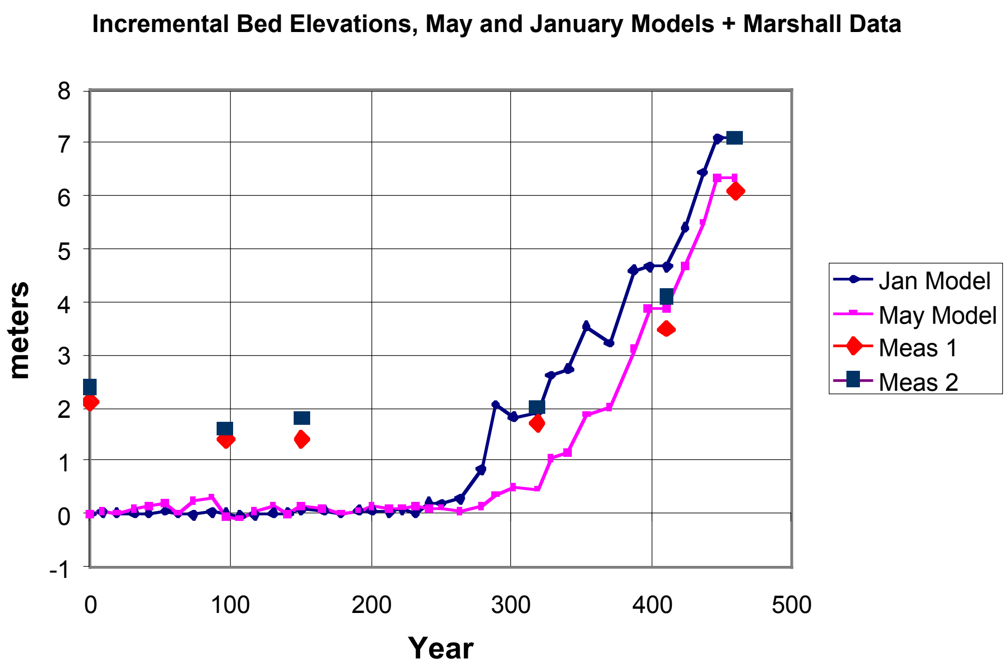


Figure 11. Predicted total suspended sediment (TSS) concentrations based on material finer than 62.5 microns, Kuambit, May model.

Figure 12. Comparison of measured and predicted bed profiles in terms of incremental



elevations along the Ok Tedi-Fly River system from Konkonda (far right) to Obo (far left) in 1998. Both the predictions of the January and May models are shown.