The depositional web on the floodplain of the Fly River, Papua New Guinea.

Geoff Day[1], William E. Dietrich[2]*, Joel C. Rowland[2], and Andrew Marshall[3]

[1] Rio Tinto plc, 6 St James's Square, London, UK, SW1Y 4LD, Geoff.Day@riotinto.com

[2] Department of Earth & Planetary Science, 307 McCone Hall, University of California – Berkeley, Berkeley, CA 94720

[3] Andrew Marshall and Associates, Sydney, Australia, amara@ozemail.com.au

* Corresponding author. bill@eps.berkeley,edu, 510 642-2633

Abstract
Floodplain deposition on lowland meandering rivers is usually distinguished as either occurring by lateral accretion during channel migration or by overbank deposition. Previous studies on the Fly River in Papua New Guinea suggest, however, that floodplain channels (consisting of tie channel and tributary channels) play an important role in conveying sediment out across the floodplain. Here we report the results of an intensive field study conducted from 1990 to 1998 that documents the discharge of mainstem water from the Fly River onto its floodplain and maps the spatial pattern of sediment deposition on the floodplain (using elevated particulate copper introduced into the system due to upstream mining as a tracer). An extensive network of water level recorders demonstrates significant hydraulic heads from the mainstem out the floodplain channels. For the monitoring period 1995 to 1998, net water discharge out the floodplain channels was about 20% of the flow. Another 20 % is estimated to spill out in wet years overbank from the mainstem. Annual floodplain coring from 1990 to 1994 acquired over 800 samples across the 3500 km^2 Middle Fly floodplain for use in documenting temporal and spatial patterns of sediment deposition. Early samples record the rapid spread of sediment up to 10 km's away from the mainstem via floodplain channels. Later, more intensive coring samples document a well defined exponential decline in sediment deposition from the nearest channel (which differed little between floodplain and mainstem channels). Deposition, averaging about 6 to 9 mm/yr, occurred in a 1 km corridor either side of the channel and effectively ceased beyond that distance. About 40% of the total sediment load was deposited on the floodplain, with half of that being conveyed by the floodplain channels. Levee topography along the mainstem and floodplain channels are similar, but cannot be explained by the observed exponential functions. Shear flow during extended periods of flooding may give rise to the localized levee deposition. Our study demonstrates that floodplain channels can inject large volumes of sediment-laden mainstem waters great distances across the floodplain where they spill overbank, forming a narrow band of deposition, and thereby creating a depositional web.

1. Introduction

Floodplain formation in lowland meandering rivers is generally described as occurring through two processes: lateral shifting (and bar accretion), and overbank deposition during flood events [e.g. Wolman and Leopold, 1957]. The relative importance of these two processes varies from river to river. Although few field studies have quantified these processes [Kesel et al., 1974; Mertes, 1994; Walling et al., 1996; Dunne et al., 1998; Allison et al.,1998; Middelkoop and Asselmann, 1998; Goodbred and Kuehl, 1998; Tornqvist and Bridge, 2002; Aalto, 2003], the evidence is clear enough. We see oxbows and the remnant traces of channel banks scattered across floodplains recording the past shifts of the channel. The common rise of the bank near the channel to form levees results from sediment outfall from floods, and once the river shifts away from the bank, the abandoned levees may take the form of scroll bar deposits. In some rivers, a walk across the floodplain downstream of the outer bank of bends after a flood reveals sandy bedforms and organic debris wrapped around vegetation, indicating substantial currents during flood flows. In some cases there is also scour around trunks of trees. Localized outpouring of sediment-rich waters through bank gaps forms distinct crevasse splay deposits. The extensive rings of scroll bar complexes left on the inside of expanding meander loops reveal that the lateral shifting and bar accretion is episodic. So too the overbank deposition will be episodic, as flood magnitude typically varies greatly year to year. Hence, floods cause episodic accretion of bar deposits and floodplain flows can have strong currents, scour and deposit and distribute sediment widely. Together the interaction of lateral shifting and overbank deposition as net aggradation of the river bed occurs gives rise to an elevated scroll bar complex across which meandering rivers shift back and forth [Ikeda, 1989]. This description, while widely accepted, is incomplete in important ways.

On many river systems, the floodplain is laced with channels which drain and, in some cases, may return to the mainstem. The size of such channels are typically a fraction of the mainstem, hence are not equivalent to anabranching channel systems. These channels introduce sediment laden flows far across the floodplain, where the sediment may either accumulate on the bed or spill overbank. This distribution of sediment creates a “depositional web”, i.e sediment is injected along narrow path lines (in and bordering channels) across the floodplain, often far from the mainstem. Such floodplain accretion causes much greater lateral dispersion of sediment (and any contaminants they may carry), contributes to net accretion of sediment due to deposition far from the common sweep of active meanders, and creates a different stratigraphic record than would be expected from the processes described above.

Dunne et al. [1998] calculate on the Amazon that floodplain channels divert and capture on their beds as much as 37% of the total annual load. Overbank deposition from the mainstem and bar storage during mainstem shifting add large quantities of sediment to the floodplain, but high bank erosion rates return much so that about only 16% of the total load is estimated to go into storage. On the Fly River in Papua New Guinea, Dietrich et al. [1999] noted two distinct types of floodplain channels that convey sediment to the floodplain. Numerous small channels, originally called “tie channels” by Blake and Ollier [1971], connect the main stem to off-river water bodies (oxbows and blocked valley lakes). These channels deposit sediment into the lakes and by so doing progressively advance into them [Rowland et al., 2005; Rowland et al, submitted]. Sediment is also conveyed overbank when the flows rise above the channel banks. The other channel type is tributary channels. During rising stage, flow reversal can occur on the tributaries and water can be pushed 10's of kms upstream, and, where flows exceed bank capacity, overbank deposition occurs. Dietrich et al. [1999] also noted that on the Fly, rain onto the floodplain lead to flooding of the plain that preceded the rise of the mainstem flows. As the mainstem flows rise, these floodwaters, free of river sediment (and typically black with organic material), effectively prevent the development of significant hydraulic heads across the floodplain, hence the width of sediment laden water is confined to a relatively narrow band bordering the channel. Mertes [1997] used remote sensing data to document this tendency of saturated floodplains to form before mainstem overflows on several large rivers. The combination of the distributary nature of the floodplain channels and the relative confinement of sediment laden flows to areas near the channel forces localized deposition along the mainstem and floodplain channels leading to the development of a depositional web.

Here we quantify for the first time the spatial pattern of flow and sediment accretion associated with a depositional web across a floodplain. We do so along the Middle Fly River, which has an extensive floodplain channel system, and, due to upstream mining, is discharging sediment with a distinct metal rich signature which allows us to document spatial patterns of deposition. Our field data show that these networks of channels may convey as much as 20 % of the total discharge of the Fly onto the floodplain, and, correspondingly, convey and deposit about 20% of the total sediment load onto the plain as well. Overbank discharge of sediment along the mainstem causes another 20% of the sediment to be deposited on the floodplain. On the lower Middle Fly because lateral migration rates during the period of monitoring were essential zero, these deposition rates record net sediment loss to the floodplain. We suggest that the depositional web process is associated with low gradient, wet floodplains with significant sediment losses.

2. Study site

The Fly River system (Figure 1) consists of steep bouldery rivers that cut through the rapidly uplifting Southern Fold Mountains of Papua New Guinea (reaching 4 km in height) that progressively join downstream into two primary mainstem channels (the Fly and the Strickland Rivers). These two primary channels drop their gravel by 900 and 730 kilometers, respectively, upstream from the delta outlet and then transform into downstream fining, meandering, sand-bedded rivers bounded by 4 to 14 km wide floodplains crossing through intensively dissected lowlands which are underlain by an extensive carbonate platform [Pigram, 1989] . The rivers join at an elevation of about 6 m, and the mainstem heads downstream into a progressively more tidally dominated flow as it enters into the Fly delta. Where the rivers join, the drainage of the Fly is 18,400 km^2 and the average annual discharge is 2244 m^3/s , while the Strickland area is 36,000 km^2 and carries an average annual discharge of 3110 m^3/s [Dietrich, et al., 1999]. The natural load of the Middle Fly is estimated to be about 10 million tonnes while that of the

Strickland is about 70 to 80 million tonnes. Only about 30% of the 75, 000 km^2 catchment area is in the steep, uplands source area.

Mining in the headwaters of the Fly (on the Ok Tedi river) led to a large inflow of mining waste into the river beginning in 1985. On the Middle Fly this caused the sediment load to increase by about 4.5 times, leading to progressive aggradation of the channel bed, increased flooding, and accelerated delivery of sediment to the floodplain. It led to the delivery of sediment across the floodplain that is elevated in copper far above background (in this initially pristine catchment), which enabled sampling to trace the spread and rate of sediment accretion. We will focus on floodplain sedimentation rates up to 1994 and floodplain hydrology to 1998. At these times, aggradation due to mine loading was concentrated near the Ok Tedi junction. Since then sweeping changes have occurred downstream. Though the basic processes described below still pertain, the relative rates have shifted. Our description of floodplain conditions is applicable up to 1998.

The focus of this paper is the Middle Fly Reach (Figure 2) bordered by the upstream junction with the Ok Tedi (D'Albertis Junction) and the downstream junction with the Strickland (Everill Junction). Through this reach the longitudinal profile along the river flattens from about 6×10^{-5} to about 1×10^{-5} approaching Obo (Figure 3) and associated with this decline the median bed grain size (pre-mining) decreased from 0.3 to approximately 0.1 mm. In response to Holocene sea level rise, river aggradation elevated the Fly River, blocking lowland tributaries and forming some 30 blocked valley lakes. The central scroll bar complex rises above surrounding back swamp areas, and contains about 47 oxbow lakes (Figure 2). All of the block valley lakes, and 29 of the oxbow lakes have distinct floodplain channels (tie channels) connecting the lakes to the mainstems (see Rowland et al. [2005] and Rowland et al. [submitted] for more details about tie channels). Eight additional oxbows receive flow directly from the mainstem at high flow. The total off-river water body area of 420 km^2 is about 12% of the total floodplain area (3500 km^2).

The channel morphology and floodplain characteristics vary downstream. The first one-third of the better drained floodplain is covered in rainforest (pre-1997) which gradually shifts downstream to predominantly swamp grass in the lower one-third. Correspondingly, the channel narrows from about 350 m to 250 m before reaching Obo, point bars disappear by Manda, and the rate of lateral channel migration declines from about 3.5 m/yr to 1 m by 200 km downstream. Where the channel enters the swamp grass reach, though oxbows are common and well-defined scroll bars emerge, the channel has ceased migrating laterally [Dietrich, et al., 1999].

Starting near the Binge River and running parallel to the Middle Fly along the eastern edge of its floodplain is the Agu River, which lies lower than the Fly and drains it through five channels (Figure 2). The Agu River returns discharge to the Fly just north of Manda and the start of the swamp grass reach. While the floodplain channels connecting the Fly to Agu consistently drain towards the Agu, we have observed sediment laden flows injected over 40 km's upstream the Agu from is junction near Manda. These flows followed small channels off the Agu and onto the floodplain as well. We estimate that there is over 500 km of tie and floodplain tributary channels (a length approximately equal to the mainstem Middle Fly) which transmit Fly River sediment laden water to the floodplain.

Rainfall in the headwaters of the Fly reaches 10 m/yr and drops progressively downstream to about 2m/yr near Obo [Dietrich et al., 1999]. Peak flows entering the Middle Fly become strongly damped downstream (Figure 4), and there were periods of over 18 months of continuous flooding in the lower Middle Fly. Often the floodplain was inundated with dark, organic rich water, and even during flood events where the flow was well above bank, the mainstem Fly would follow the mainstem channel path, hemmed in by the surrounding sediment free floodplain waters (Figure 5). As Figure 4 suggests, by the lower Middle Fly, flood pulses were largely dissipated and the primary cause of large discharge variation is drought (1997) which is driven by El Nino cycles here.

3. Hydrologic monitoring and rates of discharge to the floodplain

Sediment laden Fly River water entered the floodplain via three paths: tie channels and tributaries (during reverse flow), levee breaches and overbank flows. In order to document flow via the floodplain channels onto and from the floodplain, water level recorders were installed along 13 tie and tributary channels in order to record stage and slope. Additional recorders were installed along the mainstem and across the floodplain, such that 65 instruments were operational starting December 1995. The recorders were set for 15 minute sampling and collected data with variable success until May 1998. Battery failure, instrument fouling, bank collapse and other processes made this system very difficult to maintain. The recorders were surveyed to a common datum through differential GPS survey which had a vertical accuracy of 5 to 10 mm. The period of measurement spanned an El Nino drought that broke in 1998. Figure 6 shows station locations for a portion of the floodplain.

The Manning's relationship for velocity coupled with monitored water surface slope and measured cross-sections were used to calculate flux of water to the floodplain (following a procedure similar to that of Dunne et al. [1998]). Longitudinal profiles and cross-sectional surveys were conducted on 12 of the 13 tie and tributary channels monitored. Along the Middle Fly River, tie channels typically exhibit maximum widths on the order of 25 m and depths of 5 m but vary in width from 15 to 39 m and depth from 4.5 to 8.5 m, respectively. The two main tributaries monitored, the Binge and Agu were 74 and 100 m wide and 8.9 and 8.4 m deep, respectively. A stage- cross-sectional area relationship was calculated for each channel (when flows overtopped tie channel banks, an effective cross-sectional area was extended up into the flood based on the channel width). Surveyed mainstem stage range relative to bed height of the tie channels indicates that for 60% of the range in river stage water may flow through tie channels onto the floodplain. This agrees with visual impressions. Outflow via tie channels were commonly seen, even at relatively low stages, and at high stages, rain on the floodplain could induce outflow to the river. Measured water surface slopes ranged from -6×10^{-4} to $+8 \times 10^{-4}$ (+ is from floodplain to channel), hence the steepest slopes exceed mainstem slopes by a factor of 10. Due to equipment failure, tie channel water surface slopes were sometimes estimated by projecting the mainstem water surface slope to the month of the tie channel in order to determine the relative difference in water surface elevations between the mainstem and the floodplain. Manning's roughness term, *n*, was estimated to lie between 0.03 and 0.04. A time series of discharge was then calculated for each monitored channel. For unmonitored channels, discharge was estimated by assigning discharge rates from the most similar nearby monitored tie channel. Channels in the forested, transitional and swamp grass reaches were treated separately.

For the period of monitoring, calculated total discharge outflow to the floodplain via tie channels and tributaries was about 15 to 24 % of the mainstem flow. The relative contribution varied greatly among the channels. Figure 7 shows two cases, one near the upstream end of the floodplain where during the period of measurement, more flow exited from the floodplain to the mainstem, whereas on one of the floodplain channels connected to the Agu River, the flow was nearly always towards the low lying tributary.

Levee breaches are transient features associated with slumping which are erased by subsequent sediment infilling. During a survey in 1997, 27 levee breaches were counted in a 40 km length, and one breach dimension was surveyed with a cross-sectional area of 16 m^2. Assuming this density of levee breach along the Middle Fly, we estimate the number of such breaches to be 190. Discharge was estimated using the Manning's relationship, which was applied assuming that the water surface slope through the breach was the same as that as the nearest tie channel slope. The small size of the breaches and the relatively rare frequency of occurrence leads to a low (less than 1%) contribution to discharge to the floodplain.

Overbank flow was calculated to occur when water surface elevation exceeded bankful height. As part of a regular monitoring program conducted by Ok Tedi Mining, Ltd., 94 cross-sections have been repeatedly survey down the length of the Middle Fly (and tied into a common datum). Water level records along the river were projected between successive cross-sections and for periods when flow height exceed bank height, nearest tie channel waters surface slope was used to calculate the slope towards the floodplain. Channel bank length, overbank depth and the Manning's equation for velocity were used to estimate discharge. Attempts to measure in the field flood flow velocities failed, so estimates of Manning's n were crudely set to 0.07 to 0.1. In the drought year of 1997, these calculations correctly assess essentially no overbank flow, whereas in 1996 the estimated value was as high as 28% of mainstem discharge while in 1998 it was as low at 2.5%. Overbank flow was calculated to be highest in the forested reach where greater differences between flood height and floodplain water levels occurred.

Field observations through the drought and subsequent discharge rise showed a distinct stage-dependent pattern of injection of river water onto the floodplain. For an initially dry floodplain (most commonly developed in the forested reach), initial stage rise would drive water out through the tie channels and tributaries, filling the oxbows and blocked valley lakes. Continued stage rise causes water to spill out of the blocked valley lakes into surrounding channel networks. With further stage rise, water spills out through the levee breaches and eventually over the levee tops. In a 2 week period following the onset of rain in December 1997, the river rose rapidly in the upstream forested reach and forced water out the tie and tributary channels. But by the time the flood wave had reached the lower swamp reach, the blocked valley lakes and floodplain behind the levees were already flooded due to tie channel flows and direct rain on the floodplain. As a result of floodplain inundation in the lower reaches, there was little surface gradient outwards across the plain when the main channel stage exceeded bankfull conditions.

Although the discharge values are approximate, both quantitative assessment and visual impressions during stage rise suggests that there is significant Fly River water discharge into its adjacent floodplain. One consequence of discharge is a great dampening of the flood waves downstream (Figure 4). We suggest that at least 20% and perhaps as much as 40% of the discharge flows out onto the floodplain. Some of this water is stored in lakes and evaporates, while much of this water returns at lower stages. The returning waters are largely sediment free due to deposition and trapping of sediment in lakes and on the floodplain. These sediment-poor waters can appear as distinct inputs of black water that mix into the turbid waters of the main channel at confluences with tie and tributary channels. The sediment that does return to the Fly River commonly results from localized scour of tie channel beds due to high hyrdraulic gradients and velocities generated during return flow periods [Dietrich et al., 1999; Rowland et al, submitted].

4.0 Sediment coring and rates of floodplain sedimentation

4.1 Field and laboratory methods

A campaign to monitor the spread of mine contaminated sediment across the Middle Fly floodplain began in 1990, five years after the onset of dumping into the river. A hydrologic network and suspended sediment monitoring program had been established from the mine site to Obo [OTML,1993a]. The initial sampling followed a protocol (Applied Particulate Level or APL) established with government agreement [OTML, 1993a,b], but as it was discovered that the sediment was rapidly crossing the floodplain, a more intensive sampling effort was initiated. The sampling was done annually from 1990 until 1994.

The APL sampling program, started in 1990, consisted of 100 floodplain samples and 100 lake samples (oxbows and blocked valley lakes, referred to as off-river water bodies or ORWB). The floodplain samples were distributed across a series of zones running parallel to the river. All sampling was accomplished with a float helicopter and location was established using GPS (at this time accurate to approximately 100 m). In 1990 – 1992 shallow cores were collected and the top 5 to 10 mm sample was analyzed for particulate copper concentration ([pCu]). Starting in 1992, coring was conducted at evenly spaced points along transects (in addition to the APL samples) across the floodplain. By 1993 and continuing into 1994, 17 transects were established at approximately 10 km intervals down the floodplain and samples were collected where possible at 50 m, 100 m, 250 m, 500 m and then every 500 m to the floodplain boundary (Figure 8). Such sampling could not be conducted on the portion of the floodplain that lies Indonesia. Up to 30 cores were taken in individual transects. Additional cores were also taken in the ORWB, with typically 3 cores in each oxbow. The 17 transect sites were surveyed in with kinematic GPS by Andrew Marshall and Associates, Sydney, Australia in the same program that surveyed the water level recorders.

Cores taken in 1993 and 1994 (both transects and APL sites) were deeper, reaching in some cases 1 m. These longer cores were collected when it was realized that the depth of burial greatly exceeded initial expectations. Subsamples of these cores could then be used to obtain an inventory of elevated [pCu] with depth. The coring device was either a specifically made hand corer or a commercial gravity corer and both consisted of 50 mm diameter stainless steel buge with interchangeable polycarbonate core liners. In 1996 longer cores were obtained in seven ORWB using a pneumatically driven vibrocorer, with sample recovery up to 5 m.

Subsamples collected from cores where transferred to plastic bags and frozen at the end of each day of collection. Analyses followed OTML APL protocol [OTML, 1993b]. Once in the laboratory, samples were thawed, wet-sieved through 100 micron sieves (to focus on copper rich mine-derived sediment which was less than 100 microns). The finer sediment was dried at 104 degrees C, digested in hot acid and the [pCu] analyzed by flame atomic absorption spectroscopy. Elimination of the >100 micron sediment had little affect on the analysis. Sample analysis shows that [pCu] increases with decreasing grain size and there was little in the >100 micron size fraction.

In 1995 samples from the transects were collected for grain size analysis (of the surface deposits). Air dried samples were placed in plastic bags and crushed by hand to remove large aggregates and a subsample suspended in water and placed in in an ultrasonic bath. These samples were then analysed using a Coulter LS130 Laser Diffraction Analyzer with a size range sensitivity of 0.4 to 900 microns. If organic matter was visibly present, the sample was first combustesd at 550 C for 8 to 12 hours. In uncombusted samples, if coarse tails in the in the grain size distribution were observed, indicating the presence of organic matter, then these samples were also combusted and reanalyzed.

Suspended sediment samples were collected with Niskin samplers at four locations in 1994 and at 7 locations in 1997. During the 1997 sampling, multiple vertical profiles were conducted at each sampling cross-section and velocity measurements were made in conjucton with the Niskin sampling. The sampling effort spanned river stages at and just below bankfull, capturing both rising and falling stages. Suspended sediment samples were decanted to concentrate the sediment and run untreated in the laser analyzer to determine grain size.

Between 1990 and 1994 a total of 423 floodplain and 420 ORWB sites were cored, leading to approximately 4000 samples analyzed for [pCu] (note the APL 1994 were not analyzed correctly and not used here). In those cores in which [pCu] was mapped through the vertical, concentrations generally increase towards the surface. This could arise for three reasons: 1) increasing concentration with time arriving at the core site, 2) post deposition mobilization of copper, and 3) post-deposition vertical mixing by physical and biotic disturbance. Suspended sediment measurements indicate that from 1990 to 1994 [pCu] increased from 900 to 1300 μg/g near the Ok Tedi junction and from 700 to1200 μg/g at Obo. Earlier samples were less systematically collected but indicate a [pCu] closer to 800 μg/g near the Ok Tedi junction in the late 1980's. While these numbers do indicate an increase in time and a decrease downstream in the [pCu] delivered to the floodplain, these values are all greatly in excess of background values, which, based on deepest core samples preceding mining averaged about 31 μg/g in mineral rich samples and 15 μg/g in organic rich samples. Hence commonly measured values of between 65 and 250 μg/g (about 1/3 of all samples analyzed, for example in 1993) have [pCu] too low to be explained by a time progression of contaminated sediment signal for the river. It should be added that samples taken 1994 showed near surface values in this range, despite the well-documented high [pCu] in the source suspended load.

The concern about post-deposition remobilization of copper and led to a field study of porewaters at several locations across the floodplain in 1993. Porewaters were found to be highly reducing below the ground surface with minor dissolved copper in the water. This favors formation of insoluble copper sulfides and limited mobilization. Mobilization has become a central issue on the aggraded, seasonally drained levees since this study [OTML, 2006]. For the period of this study, we can conclude that post-depostional movement of copper was minor

Because of the rapid dominance of the Fly sediment load with mine-derived sediment and the high particulate copper of that load, we argue that core samples with [pCu] values well below the incoming contaminated values record the effects of mixing between the contaminated and pre-mine sediments on the floodplain. Field evidence of such mixing was plentiful. During seasonal drying of the floodplain, the surface would deeply crack, allowing contaminated surface material to tumble deep into the pre-mine sediment deposit below. Vigorous vegetation growth (relative to the relatively modest rates of sedimentation) would tend to stir and allow downward passage of elevated [pCu]. Given the large disparity between background and mine derived sediment, relatively minor vertical mixing can greatly increase the signal at depth. This suggests that to calculate sedimentation rate, we need to get an inventory of elevated [pCu] with depth and calculate the equivalent thickness of deposit at the concentration of the incoming sediment.

Figure 9 shows a schematic representation of a core sub-sample of length L_s (for example, the top 10 mm of a 1990 to 1992 core) with an average [pCu] concentration ($\overline{\varepsilon_s}$) and an average bulk density of ($\overline{\rho_s}$) through the sample. The thickness of deposited copper-rich (unmixed) sediment in the sub-sample (L_c; Figure 9) can then be determined based on the mass balance:

$$L_s \cdot \overline{\varepsilon_s} \cdot \overline{\rho_s} \cdot A = L_c \cdot \varepsilon_c \cdot \rho_c \cdot A + (L_s - L_c) \cdot \varepsilon_b \cdot \rho_b \cdot A \qquad (1)$$

where: L_s is the length of the sub-sample analyzed; $\overline{\varepsilon_s}$ and $\overline{\rho_s}$ represent the average [pCu] and bulk density of the core sub-sample throughout L_s respectively; A is the cross-sectional area of the core; L_c is the length or thickness of deposited copper-rich sediment; ε_b and ρ_b are the background [pCu] and bulk density of pre-mine floodplain sediment; and ε_c and ρ_c are the average [pCu] and bulk density of deposited copper-rich sediment.

$\overline{\rho_s}$ varies according to the relative contributions of ρ_c and ρ_b by:

$$\overline{\rho_s} = \frac{\rho_c \cdot L_c + \rho_b \cdot (L_s - L_c)}{L_s} \qquad (2)$$

Rearrangement of equation (2) into (1) allows calculation of the copper-rich sediment thickness (L_c) via:

$$L_c = \frac{L_s \cdot \rho_b (\overline{\varepsilon_s} - \varepsilon_b)}{(\rho_c (\varepsilon_c - \overline{\varepsilon_s}) - \rho_b (\varepsilon_b - \overline{\varepsilon_s})} \qquad (3)$$

The calculated value of L_c, the date the core was collected, and the time the mine had been in operation was then used to determine the rate of sediment deposition over that interval. This procedure is incomplete, however, if the contamination is spread down the core with varying concentrations.

The above method can be modified to calculate the thickness of copper-rich sediment in a core with elevated [pCu] over several depth horizons. Each horizon sub-sample of length L_{s_i} has an average [pCu] of $\overline{\varepsilon_{s_i}}$. Assuming that each value of $\overline{\varepsilon_{s_i}}$ represents the mean [pCu] averaged over half the core length between each of the immediate upper and lower horizon sub-samples (z_i), we used equation (4) to estimate the total thickness of copper-rich sediment (L_{Cu}) throughout the entire core by summing the individual L_{c_i} values for each z_i to lowest sampled horizon, *n*,

$$L_{Cu} = \sum_{i=1}^{n} \frac{z_i \cdot \rho_b (\overline{\varepsilon_{s_i}} - \varepsilon_b)}{(\rho_c (\varepsilon_{c_i} - \overline{\varepsilon_{s_i}}) - \rho_b (\varepsilon_b - \overline{\varepsilon_{s_i}})} \qquad (4)$$

If $\overline{\varepsilon_{s_n}} > \varepsilon_b$ (i.e. the core had not sampled all the way through the copper-rich sediment) a value of z_i for this particular horizon sub-sample was rounded up generally to the next 50 or 100 mm based on a review of the [pCu] through the core profile. The average background bulk density, ρ_b, was either 1.1 gm/cm^3 for mineral rich deposits or 0.5 gm/cm^3 for organic-rich deposits. Similarly, the background [pCu] (ε_b) varied between these two sediment types. As mentioned above, based on deep and distant samples, for mineral rich samples ε_b is approximately 31 μg g^{-1} and for organic rich samples it is 15 μg g^{-1}.

As mentioned above monitoring results reported by OTML reveal that the [pCu] of Fly River suspended sediment (ε_c) was not constant, varying both temporally (increasing concentration between years) and spatially (decreasing downstream). The increase between years was likely due to increased ore and waste rock throughput from the mine and the gradual saturation of background sediment in the bed of the river with copper-rich sediment. The decrease along the length of the Fly possibly reflects a combination of deposition of fine-grained sediment (generally higher in [pCu]; discussed below) in the upstream reaches, and from dilution by natural sediment delivered from the tributaries and bank erosion along the Middle Fly. Table 1 lists the [pCu] used for ε_c for each sampling year. These data were obtained from OTML reports [OTML 1990a, 1991, 1992, 1993] and re-sampled to coincide with the years between the coring program rather than the calendar year averages reported by OTML. The mean suspended sediment [pCu] data from Nukumba as used for ε_c for all cores within the forest reach and the data for Obo was used for cores from the transition and swamp reaches.

Given the spatial and temporal dependency of ε_{c_i} shown in Table 1 a consistent reach and time dependent scheme was adopted for assigning which value of ε_{c_i} to use for each depth interval (z_i). We assigned 1994 values to the surface samples in the cores and then progressively earlier incoming values for incremental samples at depth. For most samples from 1993 and 1994, analyses were performed at depth intervals below the surface of 0- 5 mm, 20 – 25 mm, 60 – 65 mm, (and if cores went deeper) at 100-105 mm, 205-210 mm or the deepest part of the core. In such a sequence we assigned 1994 to the first layer, 1993 to the second, 1992 to the third, and so forth with the lowest value having an ε_{c_i} set equal to that of 1990. If the incoming concentrations preceding 1990 were lower, then our deposition rates are an underestimate.

In about 20 of the samples, the [pCu] concentration of the surface sample was greater than the average value incoming ε_{c_1} Table 1. In these 20 cases the value of L_{c_i} was set equal to L_{s_i} in Equation 4. Possible explanations for $\overline{\varepsilon_{s_i}} > \varepsilon_{c_i}$ may include a greater percentage of fine grained sediment in the sample ([pCu] increases with decreasing grain size; discussed above), or variation (above the annual ε_c mean) of the

[pCu] in the main channel as a result of specific flow conditions during a flood event, or short term operating fluctuations at the mine.

Equation (4) was used to calculate sediment deposition since start of mine from the [pCu] profile data from 1993 and 1994 at all floodplain zone-band, transect and blocked valley coring sites. The blocked valley lake deposits were included in the floodplain data set because they tended to seasonally dry up, acting more like floodplain surfaces both in depositional patterns and mechanics (wetting, drying and mixing). Oxbow lakes remain partially inundated throughout the year and were treated separately from the floodplain data. Application of equation (4) to the oxbow samples was problematic because the majority (71 %) of oxbow cores sampled did not penetrate the entire depth of copper-rich sediment. For those oxbow cores the value of Z_n was rounded up to the next 50 mm increment. This procedure was repeated for all cores not sampling the entire depth of copper-rich sediment and the value of L_{Cu} calculated using equation (4). Hence the calculations of deposition thickness for the majority of oxbow samples represent a minimum estimate of deposition thickness.

For the majority of oxbows sampled, cores were collected from between 1 and 9 locations. To determine the total amount of sediment deposited in each oxbow the mean value of L_{Cu} from all cores in each oxbow was calculated and applied across the area of each particular oxbow. Not all oxbows were cored, such as those on the Indonesian side of the border. An estimate of the total deposition across all oxbows was calculated by using the total amount of deposition calculated in those oxbows that were cored and multiplying that value by the ratio of total oxbow area to cored oxbow area. The total area of cored oxbows was 24.9 km^2 and the total of all oxbows was 34.3 km^2, which required the total deposition volume from the cored oxbows to be multiplied by 1.4 (34.3 km^2/24.9 km^2) to estimate the total deposition in all oxbows. The computed inflow from tie channels discussed above was also used in combination with estimated suspended sediment concentrations to compare with sediment core based estimates of oxbow infilling.

4.2 Sedimentation patterns

The floodplain sampling reveals significant gradients in the spatial and temporal patterns of deposition. Figure 10 are histograms of the 200 APL [pCu] values from 1990 to 1993 (shallow cores only). Even though significant mine waste release didn't begin until 1987, by 1990 nearly one-half of all the floodplain samples and two-thirds of the ORWB samples had elevated [pCu] above background values of 15 to 31 μg/g. Figure 11 shows the difference between 1990 and 1993 for surface samples of all cores collected in the lower Middle Fly. These data reveal a downstream advance of the contaminants, a large increase in [pCu] with time, but at values below suspended sediment source concentrations, and a rapid lateral transport across the entire floodplain (over 10 km in just 4 years). The latter observation was most surprising and careful inspection of the sample sites shows that this rapid spread was associated with dispersion out floodplain channels (tie and tributary channels).

The total sediment flux to oxbow lakes is poorly constrained because of the shallow cores collected which consistently failed to reach uncontaminated sediment after the first few years. Using the 420 shallow cores collected as part of the APL program and estimating rates in unmonitored lakes, we estimate the minimum deposition to be about 8.5 million tonnes. As a separate analysis, we used the discharge calculated into the oxbow lakes and estimated the suspended sediment concentration entering the lakes to arrive at a value of about 19 million tonnes. These deposition values represent 2.4 to 4.2 % of the total sediment load that entered the Middle Fly River between 1985 and 1994. In an independant analysis examining the volume of sediments deposited in two dated oxbow lakes (350 and 900 years old), Rowland et al. [submitted] estimate that oxbow lakes captured approximately 1.5% of the pre-mine sediment load of the river.

Figure 12 shows sediment deposition (derived from equation (4)) as a function distance from the nearest channel for the sample year 1993. Although the transects were designed to sample at intervals from the channel bank of the Fly, we found that often our cores would be closer to a floodplain channel, and, correspondingly the sedimentation would be higher. Therefore, in Figure 12 we use the shortest distance to any channel as a measure of travel distance across the floodplain. Two striking features standout in Figure 12**.** First there is a well-defined exponential decline in sedimentation with distance from channel bank, and, second, the sedimentation abruptly declines at 1 km from the channel and remains roughly constant farther out. Similar expontential patterns with an abrupt transition in overbank deposition rates have been reported by Middelkoop and Asselmann [1998] and Tornqvist and Bridge [2002]. Regression analysis was done separately for the forested, transitional and swamp grass reaches and for deposition from the mainstem versus the floodplain channels and ORWB (these lakes, connected by tie channels to the mainstem also became sources of sediment when the lakes filled with water) (Table 2). Regressions for 1993 showed significant differences in deposition between the three floodplain reaches, but only in the swamp reach did the tie channel exponential and the mainstem exponential function give a significant difference. In 1994, no significant differences were found between floodplain channel types (perhaps due to reduced data density as a consequence of flaws in the 200 APL laboratory analyses). The range of 2 to 3.8 in the value of the exponential decay constant (-b, Table 2) reported here is greater than that used by Mackey and Bridge [1995] (0.35 – 1.4), and on the low end of values cited by Middelkoop and Asselmann [1998] for studies on the Rhine-Meuse system (3 – 10). No correlation was found with relative elevation on the floodplain unlike that proposed by Howard [1992] and Middelkoop and Asselmann [1998]).

Integration of the exponential function out to 1 km for each distinct channel and floodplain type and division by the depositional length (1 km) gives the average deposition amount for the active portion of the floodplain (Table 3). By 1994, the deposition ranged from 77 mm in the forested reach to 48 mm in the swamp reach. Dividing by the period of significant mine waste addition to the river (7 and 8 years for 1993 and 1994), the average deposition rate across the 1 km active zone of the floodplain ranged from 9.6 mm/yr in the forested reach to 6.0 mm/yr in the swamp reach.

We took advantage of a GIS coverage of the Middle Fly to use the exponential relations listed in Table 2 and 3 to calculate the total overbank deposition onto the floodplain. The GIS model used 20 m by 20 m grid cells within the floodplain boundary, and excluded channels, oxbows and elevated areas deemed above the common floodplain inundation level. The locally appropriate exponential function was applied along the mainstem and actively transmitting floodplain channels throughout the Middle Fly floodplain. Deposition beyond 1 km was set equal to the observed 1993 amount (0.5 mm) and 1994 amount (0.7 mm) as appropriate. Where channel curvature causes 1 km strips to overlap, only one rate was permitted (no double dipping) and deposition was eliminated if the 1 km strip crossed into an adjacent channel. The cumulative load by 1993 is calculated to be 110 million m^3 or 133 million tonnes (for a surface bulk density of 1.2 t m^{-3}) and in 1994 it is 137 million m^3 or 164 million tonnes. We checked these calculations by computing the mean deposition and multiplying by the estimated channel length (Table 3). This manual method gives about 25% higher amounts because it does not consider the affects of channel curvature on deposition rate calculation, nor does it exclude elevated areas or oxbows.

Figure 13 shows the resulting predicted pattern of deposition from the GIS model of the exponential functions (1993) for a portion of the Middle Fly at the upper end of the swamp reach where the Agu drains into the Fly. Sample points are shown as well. Most of the floodplain sedimentation occurs along a relatively narrow corridor on either side of the mainstem and floodplain channels with the rest of the floodplain receiving very little sediment. The Agu River which runs parallel to the Fly and drains it in 5 places is a major pathway for sediment dispersion across the floodplain. This demonstrates that tie and tributary channels act as distributary systems forming a distinct depositional web.

Table 4 summarizes data derived from OTML reports that define the introduction of sediment by mining to the Fly system and the load entering the Middle Fly. Comparison with the GIS derived sedimentation rates indicates that 164/455 or 36% of the total load entering the Middle Fly was deposited onto the floodplain as overbank deposits, accouting for loss into the ORWB and that the mine derived tracers probably didn't show up until 1987 (thus lowering the total sediment) would raise this value to at least 40%. The difference between the sediment load onto the floodplain between 1994 and 1993, 31 Mt, is the net deposition for the year 1994. The suspended sediment load entering the Middle Fly in 1994 was estimated from monitoring data to be 62 Mt, which is a trap efficiency of 50%. This higher value may reflect the effects of aggradation which by 1994 had caused the bed at Kuambit to rise about 2 to 3 m, leading to more frequent and longer duration flooding.

5. Discussion

The approximately 40% loss of sediment to the floodplain matches the independently estimated discharges of water to the floodplain. There are large uncertainties in the sediment flux and discharge determination but it seems safe to say the number is at least 20% and could well exceed 40%. An earlier reported loss rate (3%) by Dietrich et al., 1999 was based on the early APL results before it was realized that the cores were too shallow, hence this rate is clearly wrong. Such rates of overbank deposition are similar or even less than that reported elsewhere in large rivers [Goodbred and Kuehl, 1999; Kesel et al., 1992; Dunne et al. 1998; Middelkoop and Asselmann 1998). In fact Dunne et al. [1998] estimate that overbank deposition on the Amazon was 1.7 times the load that arrived at the downstream gauging station of their study reach, but that a similar amount was swept back into the channel during lateral migration. Unlike the Amazon, however, the Fly has very modest lateral migration rates. Dietrich et al. [1999] estimate that for the active 250 km long reach downstream of D'Albertis junction the mean bank erosion rate for the entire channel length (not just the bends) is about 1 m/yr. This erosion rate would cause about one-half the natural load (about 10 Mt/yr) to be exchanged with the banks and would return some of the overbank deposits. In the lower Middle Fly no migration was occurring, hence overbank deposits were not being returned to the channel. The extensive transport of sediment away from the mainstem via floodplain channels on the Fly causes much of the overbank deposits to go into net storage (Figure 13).

We can obtain another estimate of floodplain deposition rate by calculating from our observations what the natural sedimentation rate would have been and comparing that with other, longer term values. By the time of the last sediment survey for this project (1994) river bed aggradation was still modest and significant changes in flooding regimes were not evident down much of the Middle Fly. We can therefore reason that the main change in sedimentation was due to higher suspended load concentrations rather than high flood frequencies (this is distinctly not true in more recent years). Based on the sediment budget given in Table 3, the total load for ten years entering the Fly was about 455 M tonnes. Dietrich et al., 1999 estimate the natural load to be about 10 Mt/a at D'Albertis junction on the Fly, hence over ten years the total load would have been 100 Mt. This indicates an increase of about 4.6 in suspended sediment over background, a number that is roughly similar to the concentration change from before and after mining. This suggests that a reasonable estimate of natural floodplain sedimentation rates would be to divide the observed rate by 4.6. According to Table 2 this would give a vertical accretion rate which declines from about 2 mm/yr in the forested reach to about 1.3 mm/yr in the swamp reach for the 1 km of active deposition on either side of the network of channels.

As summarized by Dietrich et al., 1999, various previous estimates based on a few dated deposits and exposed sediments suggest that the average Holocene sedimentation rate was about 1mm/yr, with the rate probably declining downstream (see Pickup [1984] and Pickup and Warner [1984]). Recent seismic surveys on the Fly (B. Bolton, personal communication), indicate that Holocene sediments are about 5 to 15 m thick, again pointing to average accretion rate of about 1mm/yr. The natural rates reported here are not corrected for post deposition consolidation that would happen with deeper burial.

Both the hydrologic monitoring and the sediment deposition mapping indicate high rates of water and sediment discharge to the floodplain via tie and tributary channels. About one-half of the outflow to the floodplain occurs via these channels. There is approximately equal channel length along the mainstem and floodplain channels, and correspondingly, roughly half of the overbank deposition occurs along the floodplain channels. Surprisingly, the exponential functions defining deposition away from the channels with distance is similar on the floodplain channels and mainstem. Given that the ultimate sediment source is the mainstem, it would seem reasonable to expect that overbank deposition should be less on distal tie and tributary borders, but this is not evident in the data. Cross-sectional surveys of both the Fly and floodplain channels reveals that each have well-defined, relatively small levees that differ little in dimensions. On the Fly the mean height for the three reach types (forest, transition, and swamp) ranged from 1.2 to 1.9 m on the mainstem and about 1.4 m on the floodplain channels. The levee widths varied from 56 to 93 m on the mainstem, and 43 to 58 m on the floodplain channels. These topographic similarities and the absence of another sediment source for the construction of these active depositional features support the observations that the floodplain channels are significant conveyors of sediment from the main channel to the floodplain.

Although there is clear evidence of lateral transport out to about 1 km from any channel on the floodplain, the mechanisms responsible for this are not clear. During field work on the floodplain no detectable currents were documented. In the forested reach, we did see evidence (deflected vegetation and sand deposits) of overbank flows in the outside of bends. We did not witness currents across the swamp grass floodplain, but presumably under the right stage history, overbank currents will develop. More puzzling are two observations. First, we note that the exponential function predicts a rapid decline over a distance of a kilometer, but the levees bordering the channels are less than 100 m wide, and are commonly separated from the rest of the floodplain by a shallow trough. Such troughs have also been observed along the Mississippi River and attributed to local subsidence due to the loading of the levee deposits [Russell, 1939]. Second, as shown in Figure 14, the grain size of floodplain sediments shows only the levees to contain more than 5% sand, and yet some sand is found out to 1 km. After the levees there is no systematic fining across the floodplain, if anything, the data suggest a slight coarsening away from the bank. We confirmed the presence of sand in the distal samples by making thin sections of the sediment.

The localized nature of the levee, which can not be predicted from a single exponential function, suggests that the mechanism of levee formation differs from that which distributes sediment farther out. The common occurrence of the Fly rising up against floodplain waters (formed from direct rain and floodplain channel spillage) means that the lateral hydraulic head is often low to zero even during high floods. This leads to clearly observable shear zones between the sediment laden main channel flows that track the channel and the stationary organic rich flood waters (Figure 5). At this shear zone sediment laden waters will tend to rain loose sediment along a corridor that defines the levee. This is a mechanism similar to that described by Leighly [1934], modeled experimentally by Sellin [1964] and numerically by James [1985], and incorporated into Adams et al.'s [2004] conceptual model of levee formation. Levee formation during extended periods of flooding with limited to no hydraulic head out of the channel may explain why there are no crevasse splay deposits on the Fly. Dispersion farther across the floodplain may occur as eddies are shed outward from the channel [Adams et al, 2004], though such a processes has not been directly observed along the Middle Fly. The lack of cross –stream fining has been observed by others (e.g. Marriott [1992], Simm [1993] and Nicholas and Walling [1996]). As these authors have suggested, perhaps the presence of high dissolved organic carbon have contributed to particle aggregation which leads to higher fine sediment deposition near the bank.

Finally, it should be asked why there is a depositional web on the Fly River, i.e. what circumstances seems to favor its existence. We suggest that it is result of a combination of a overall low gradient of the valley, sea-level rise, modest sediment load, and very wet conditions. Low gradients favor low channel migration rate, large floodplain channel head gradients relative to downstream slopes, poor drainage of the floodplain, and frequent flow reversals on the floodplain channels. Sea level rise has forced a slope change and the modest sediment load, relative to the large accommodation space created by sea level rise, means that the channel is still responding to the sea level rise. The wet conditions cause extended periods of flooding on the floodplain that is not due to advective transport over the banks. The overall low gradient of the Fly valley is, to some degree also set by the carbonate platform over which the Fly is slowly aggrading.

6. Conclusion

Independent data on floodplain hydrology and sedimentation rates demonstrate that floodplain channels (tie and tributary channels) cause injections of large quantities of water and sediment onto the floodplain of the Middle Fly River. The length of the floodplain channels is about equal to that of the mainstem, and, with that about half the river discharge and sediment load is conveyed through them. Sediment that is carried overbank from these channels rapidly deposits, reaching less than 1 km either side of the channels. This leads to the formation of a distinct depositional web across the floodplain. Because the floodplain channels disperse sediment far from the mainstem, much of the sediment deposited is going into long-term net storage. Perhaps as much as 40 % of the Fly River load is lost to the floodplain.

The overbank deposition along the mainstem and floodplain channels follows a distinct exponential decline in rate with distance from the bank. The specific cause of this decline is not clear. Levees are narrow, often separated by a shallow trough from the rest of the floodplain, contain coarser sediment and cannot be explained by the general exponential deposition function. We suggest that levees emerge from localized shear during periods of extended flooding. The dispersion of sediment across the floodplain, its lack of fining laterally, and its rather sudden decline in sedimentation at about 1 km require further explanation.

We suggest that the depositional web found on the Fly would be favored by low gradient channels, carrying modest sediment load (relative to accommodation space), and experiencing relatively high runoff and wet floodplains.

7. Acknowledgements

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Figure Captions

Figure 1: Fly River catchment showing very generalized geology (modified from Bureau of Mineral Resources, Geology and Geophysics, Canberra, ACT, 1976). Numbers in parentheses next to site names are elevations of the bank.

Figure 2: Generalized depositional environments of the Fly River and lower Strickland area (modified from Blake and Ollier [1971]).

Figure 3: Long profile of the Middle Fly River showing bank elevations (right and left) and bed elevations (mean and minimum) based on differential GPS surveys. Values on plot show progressive decrease in river slope from the D'Albertis Junction (confluence of Fly River and the Ok Tedi) to Everill Junction (confluence of Middle Fly and Strickland Rivers).

Figure 4: Middle Fly River hydrographs recorded at Kuambit (located just downstream of the confluence with the Ok Tedi) and Obo (just upstream of the confluence with Strickland River). The hydrographs show the strong damping of peak flows as the river flows from forested reaches into the lower gradient swamp reaches. The hydrological effects of El Nino induced droughts on river discharge are visible in the late 1997 measurements presented in the figure.

Figure 5: Photograph depicting sharp boundary between sediment laden river water and sediment free, organic rich waters of the inundated floodplain at the downstream confluence of the Middle Fly and Agu rivers. Despite river stages above bankfull, distribution of sediment laden water on the floodplain is limited to a narrow band focused over the levees. The width of the Middle Fly downstream of the confluence is approximately 250 m.

Figure 6: A map of a portion of the Middle Fly River (see inset) showing the network of water level recorders established to monitor flow to and from the main channel and the floodplain. Dark areas are blocked valley lakes, the last two letters in the station location names indicate whether the station monitored tie channel (TC) or floodplain (FP) water levels.

Figure 7: Plots showing magnitude and duration of flow to (+ discharge) and away from (- discharge) the Middle Fly River. The upper plot (T0102TC) connects to an ORWB and inflows and outflows are nearly balanced. The other location (T0701TC) records flow through a channel connected to the Agu River. At this location flow is predominantly away from the Fly to the Agu.

Figure 8: Map of Middle Fly River showing floodplain sampling and transect locations. Labels (T1, T2, …) indicate transect identification numbers.

Figure 9: Schematic diagram of a sediment core with mixing between incoming Cu-rich (black) and pre-mine, Cu-poor (white) floodplain sediments. The diagram on the left

shows graphically the effect of mixing on measured [pCu] (areas of gray). The diagram on the right provides definitions of the components of the mass balance calculations used to determine floodplain deposition rates based on the Cu inventory of the core as described in the text.

Figure 10: Histograms of [pCu] in shallow floodplain cores between 1990 and 1993. The data show a progressive increase in floodplain [pCu] with time. In 1990, only three years after significant release of mine waste half the floodplain samples exhibited elevated [pCu]. The rapid dispersal of copper across the floodplain illustrates the effectiveness of the depositional web to widely distribute sediment 10s kms from the main channel.

Figure 11: Distribution and magnitude of [pCu] in floodplain surface samples along the Middle Fly River in 1990 and 1993. Comparison of the two maps highlights both the downstream progression of Cu distribution along the Middle Fly and the increase in [pCu] across the entire floodplain system. The junction of the Middle Fly and Strickland rivers is located in the bottom right of each image.

Figure 12: Cumulative deposition of seven years of mine derived sediment from all channel types. The plot highlights the exponential decrease in deposition rate within 1 km of the channel and the constant, minimal deposition at distance greater than 1 km.

Figure 13: Predicted pattern of deposition from the GIS model of the exponential functions (1993) for a portion of the Middle Fly at the upper end of the swamp reach where the Agu (along the eastern margin of the floodplain) drains into the Fly. The magnitude of deposition decreases from dark red to pink with distance from the channel, white areas are regions of the floodplain outside the influence of the depositional web. Sample locations are shown as dark dots. Yellow green colors highlight the main channel, tributary and tie channels are shown in bright yellow. The margins of ORWB are outlined in gray.

Figure 14: Plots of grain size distributions of floodplain deposits with distance from channels. Measured grain sizes are plotted in five bin classes from < 8 μm to sand size. The first panel presents data for all channel types and presents a representative size distribution of the suspended sediment load of the Middle Fly River. The other two panels present data separated by whether samples bordered the Fly River or tie channels and ORWBs. The greatest percentage of sands are found closest to the channel (0-0.01 km), though sand is present at all distance from the channel. There is surprisingly little change in the size distribution with distance from the channel and the data suggest a slight coarsening of the distribution may occur away from the channel.

	1990	**1991**	**1992**	**1993**	**1994**
Nukumba	900	900	1000	1100	1300
Obo	700	700	800	1000	1200

Table 1. Particulate copper concentration in the suspended sediment load of the Middle Fly River in μg/g.

	A (mm)			-b (1/km)			R^2		
	Forest	*Trans.*	*Swamp*	*Forest*	*Trans.*	*Swamp*	*Forest*	*Trans.*	*Swamp*
1993 Data									
All channels	243	165	139	3.79	3.69	3.23	0.96	0.97	0.85
Fly R. only	243	169	128	3.78	3.66	2.92	0.95	0.96	0.81
TC/ORWB only	245	159	179	3.82	3.60	3.77	0.94	0.98	0.89
1994 Data									
All channels	288	169	122	3.64	3.18	2.45	0.92	0.90	0.75
Fly R. only	307	187	113	3.62	3.20	2.04	0.91	0.87	0.70
TC/ORWB only	204	119	187	3.36	2.70	3.59	0.94	0.93	0.93

Table 2. Regression results of fits of exponential function (d = a*exp(-bx)) for all samples collected in 1993 and 1994 distinguished by floodplain type (forest, transition, swamp) and closest channel (mainstem Fly or floodplain channel/ ORWB).

Reach	Channel	Exp. constants (a)	(-b)	$\overline{D_{Cu}}$ (mm)	Depostion rate (mm/yr)	Channel length (km)	Deposition (m x 10^6)
1993 Data							
Forest	Closest	243	3.79	63	9.0	1,120	70
Transition	Closest	165	3.69	44	6.3	1,150	51
Swamp	Fly River	128	2.92	42	6.0	320	13
Swamp	TC & OB	179	3.77	46	6.6	410	19
Total							**153**
1994 Data							
Forest	Closest	288	3.64	77	9.6	1,120	86
Transition	Closest	169	3.18	51	6.4	1,150	59
Swamp	Fly River	113	2.04	48	6.0	320	15
Swamp	TC & OB	187	3.59	51	6.4	410	21
Total							**181**

Table 3. Floodplain sedimentation based on exponential function applied to 1 km adjacent to corresponding channel type.

Year	Tailing (t x 10^6)	Waste Rock (t x 10^6)	Wall Erosion (t x 10^6)	Sediment Load (1) (t x 10^6)	Sediment Load (2) (t x 10^6)
1985	2.38	3.80	0	17	7
1986	3.10	9.50	0	22	12
1987	9.72	11.80	0	32	22
1988	14.93	23.40	0	51	41
1989	23.60	29.70	0	53	43
1990	27.42	27.80	1	62	52
1991	27.01	27.80	19	49	39
1992	26.74	21.96	24	51	41
1993	28.62	14.03	16	56	46
1994	29.71	27.47	22	62	52
Total	**193**	**197**	**82**	**455**	**355**

Table 4. Sediment budget of the Fly River. Tailings, Waste Rock and Wall Erosion (erosion due to waste dumping) define the input to the Ok Tedi River. (1) the total suspended sediment load entering the Middle Fly at D'Albertis Junction from the Ok Tedi and Upper Fly; (2) the total mine derived sediment input to the Middle Fly (assuming an annual background load to the middle Fly of 5 x10^6 t each from the Ok Tedi and Upper Fly). Data supplied by OTML.

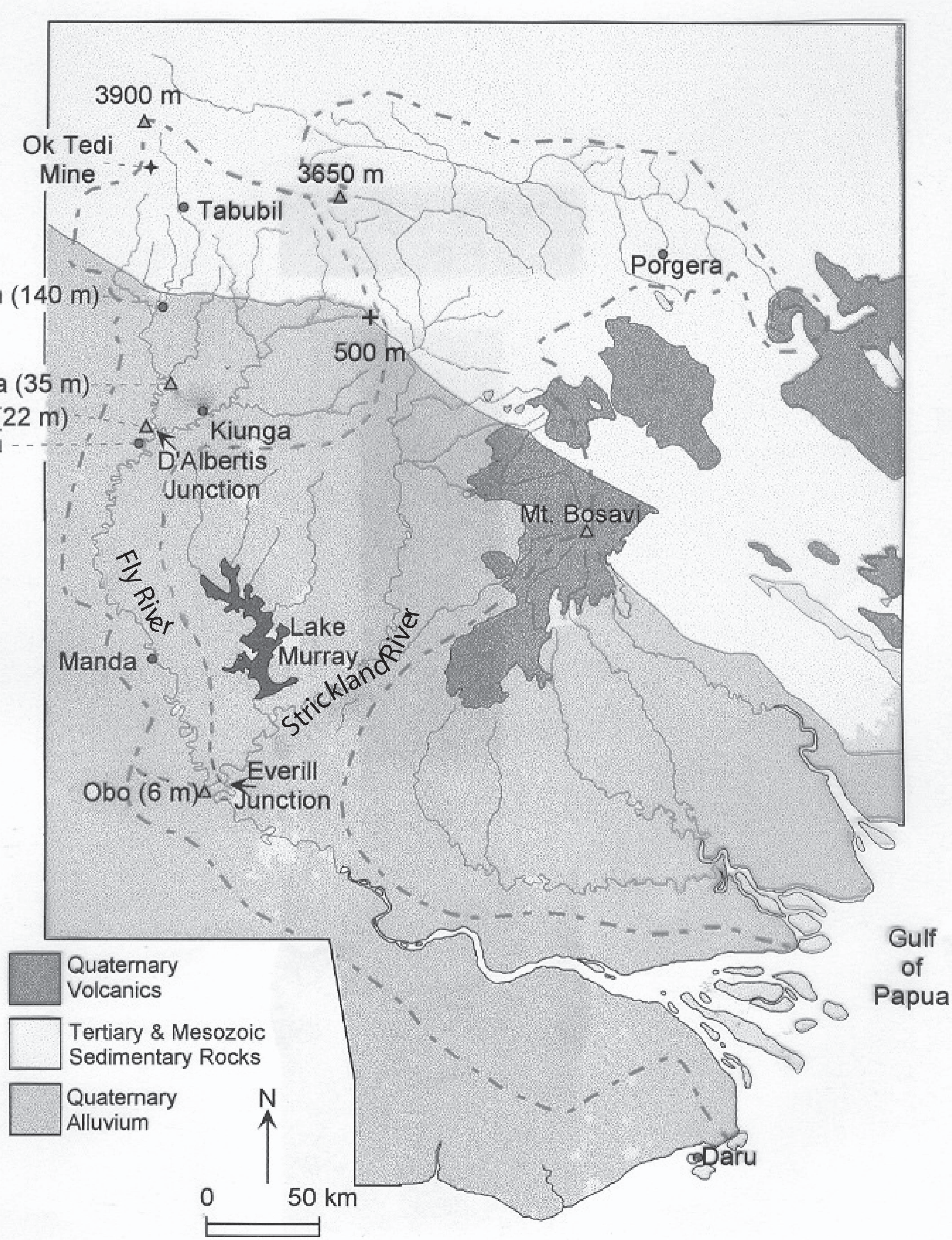
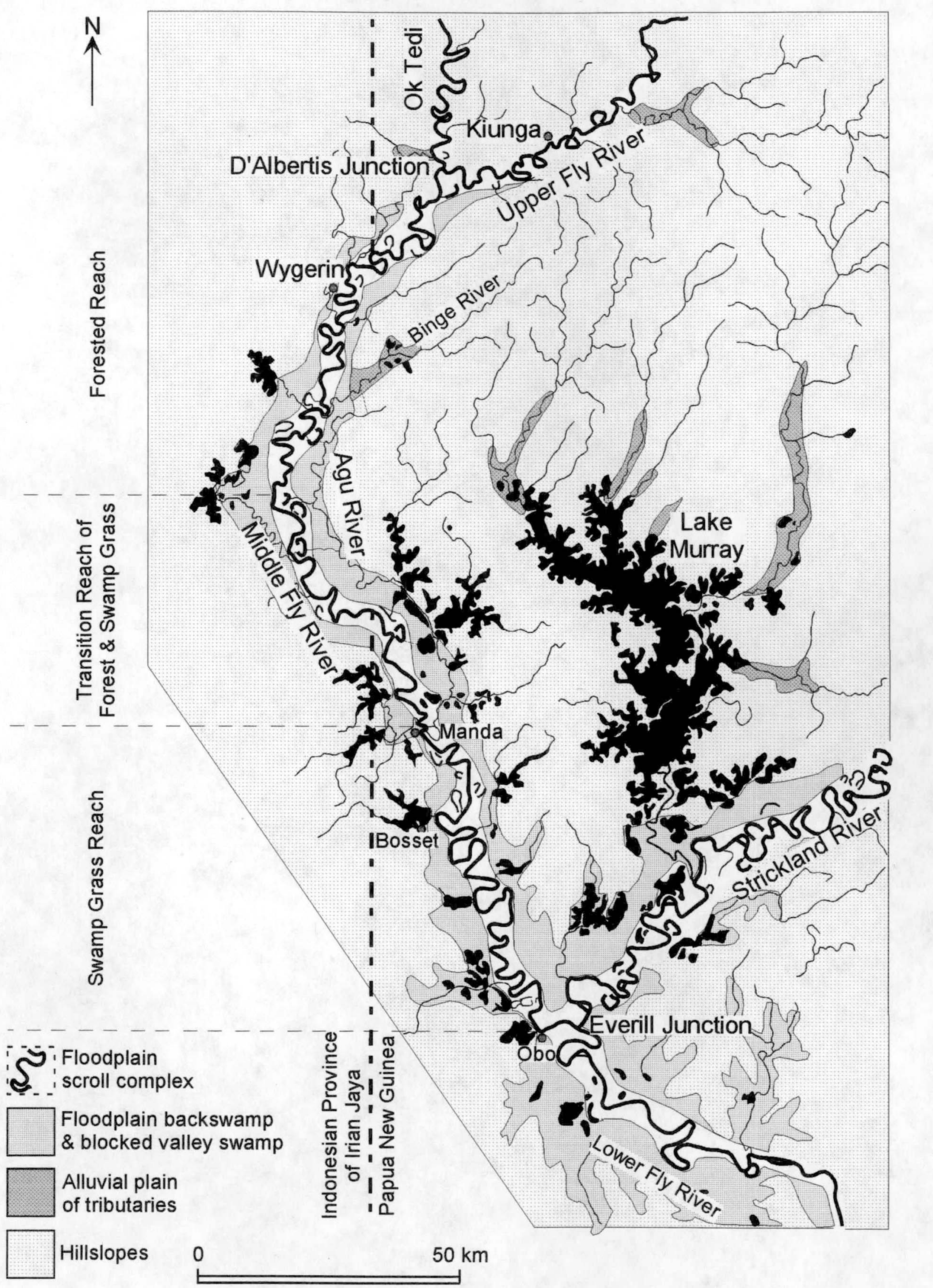
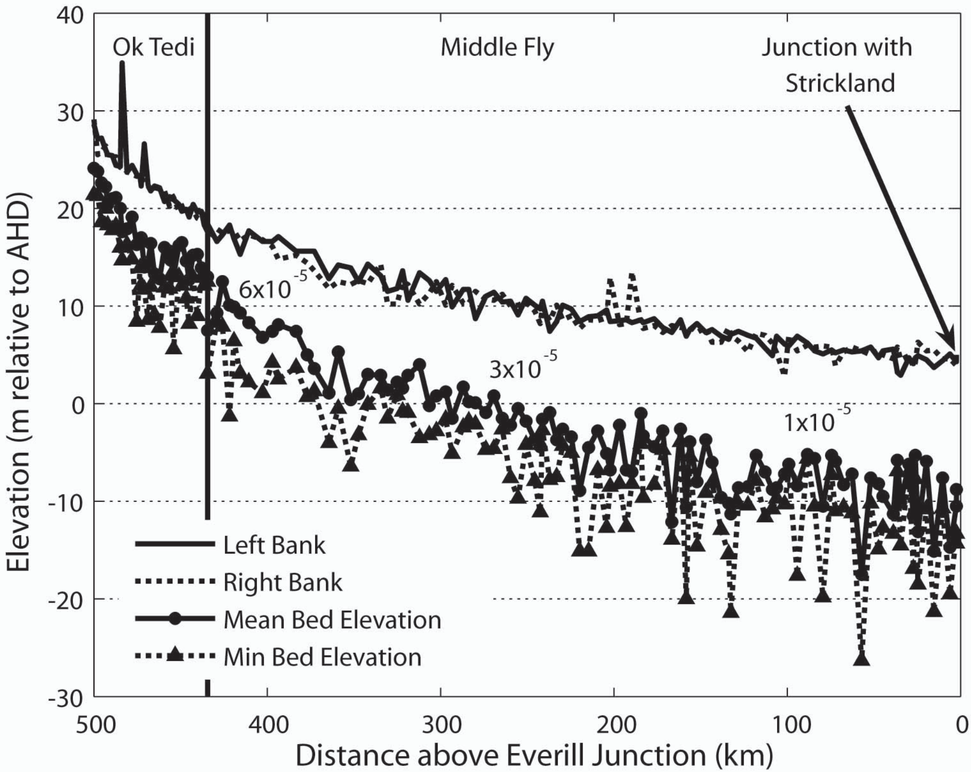
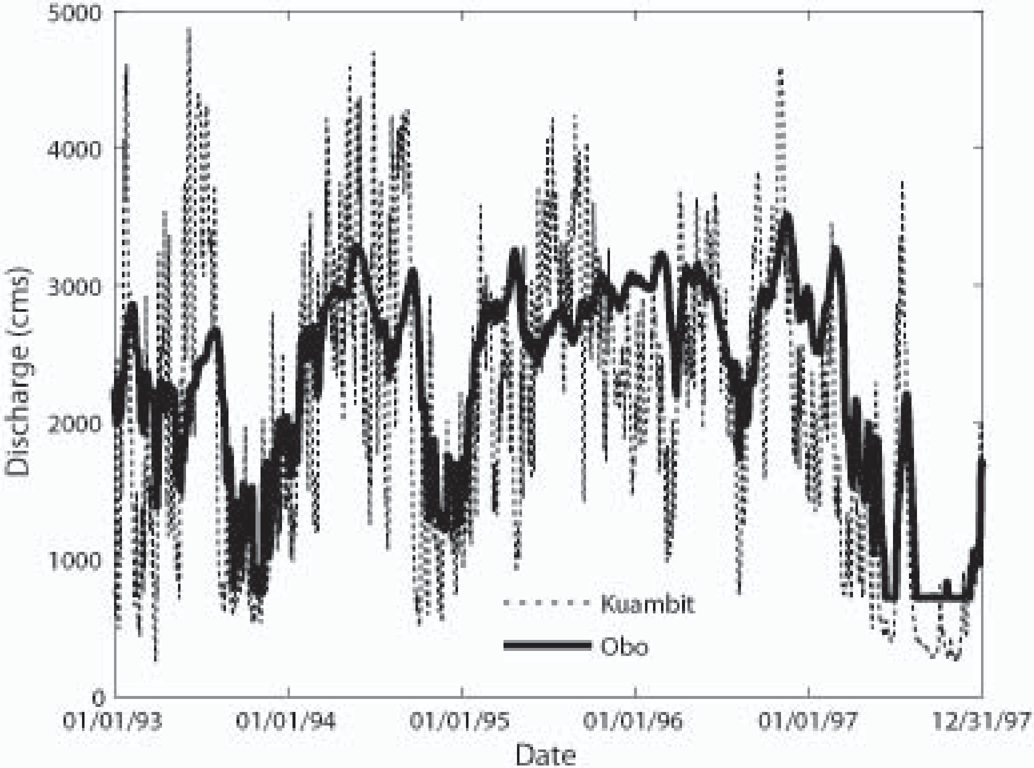
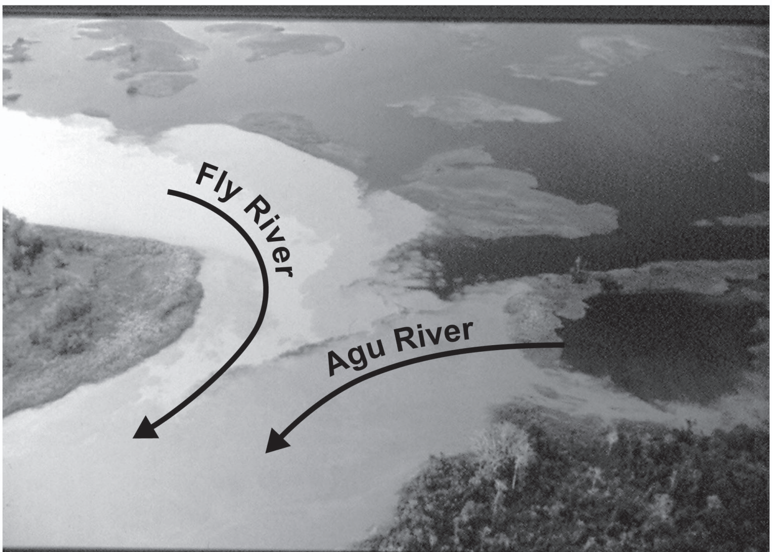

3900 m
Ok Tedi
Mine
3650 m
Tabubil
Porgera
Ningerum (140 m)
500 m
Konkonda (35 m)
Kuambit (22 m)
Nukumba
Kiunga
D'Albertis
Junction
Mt. Bosavi
Fly River
Lake
Murray
Strickland River
Manda
Everill
Junction
Obo (6 m)
Gulf
of
Papua
Daru
Quaternary
Volcanics
Tertiary & Mesozoic
Sedimentary Rocks
Quaternary
Alluvium
N
0
50 km

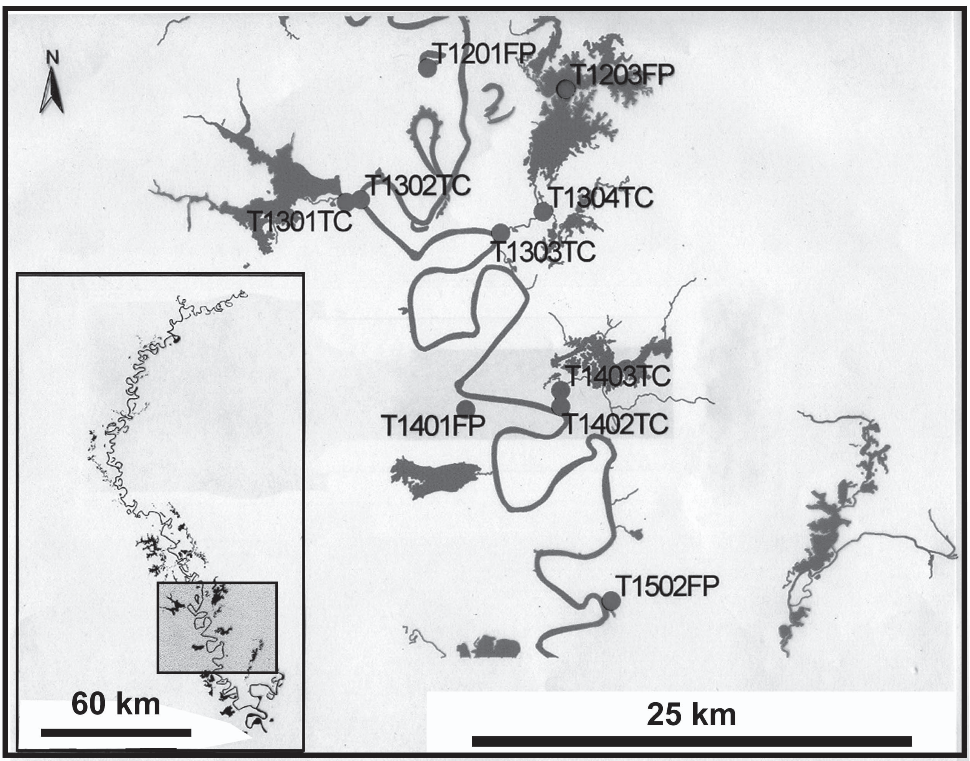
Figure 2 **Day et al.**

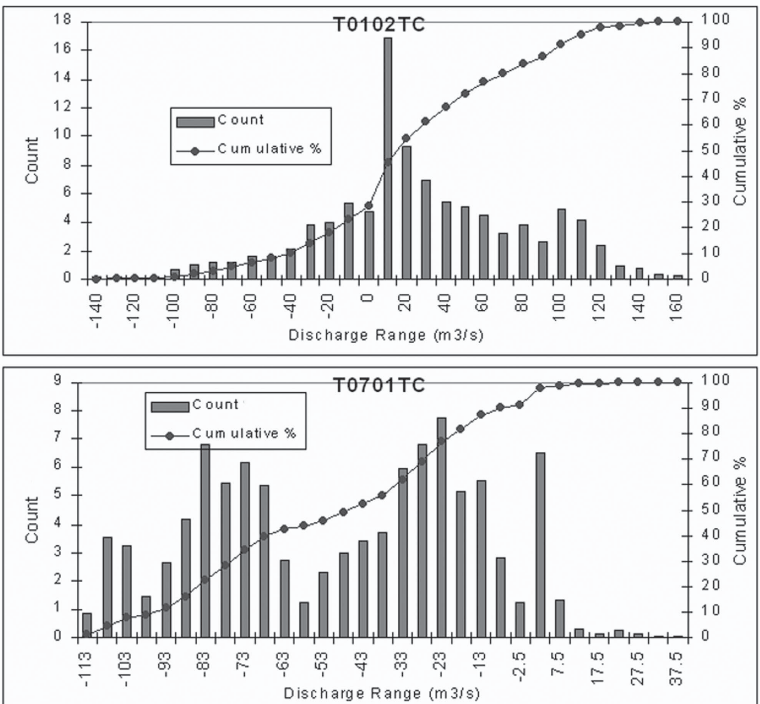



Ok Tedi
Middle Fly
Junction with Strickland
6x10^-5
3x10^-5
1x10^-5
Left Bank
Right Bank
Mean Bed Elevation
Min Bed Elevation
Elevation (m relative to AHD)
Distance above Everill Junction (km)
40
30
20
10
0
-10
-20
-30
500
400
300
200
100
0

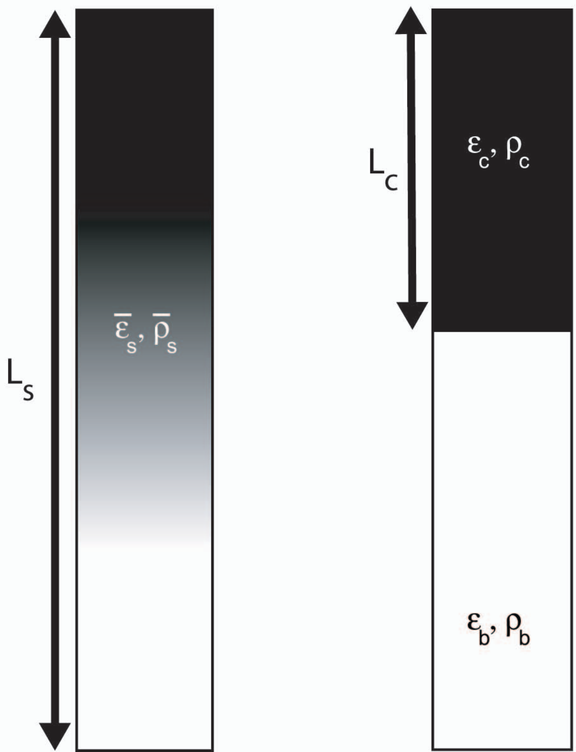

5000
4000
3000
2000
1000
0
Discharge (cms)
01/01/93
01/01/94
01/01/95
01/01/96
01/01/97
12/31/97
Date
Kuambit
Obo

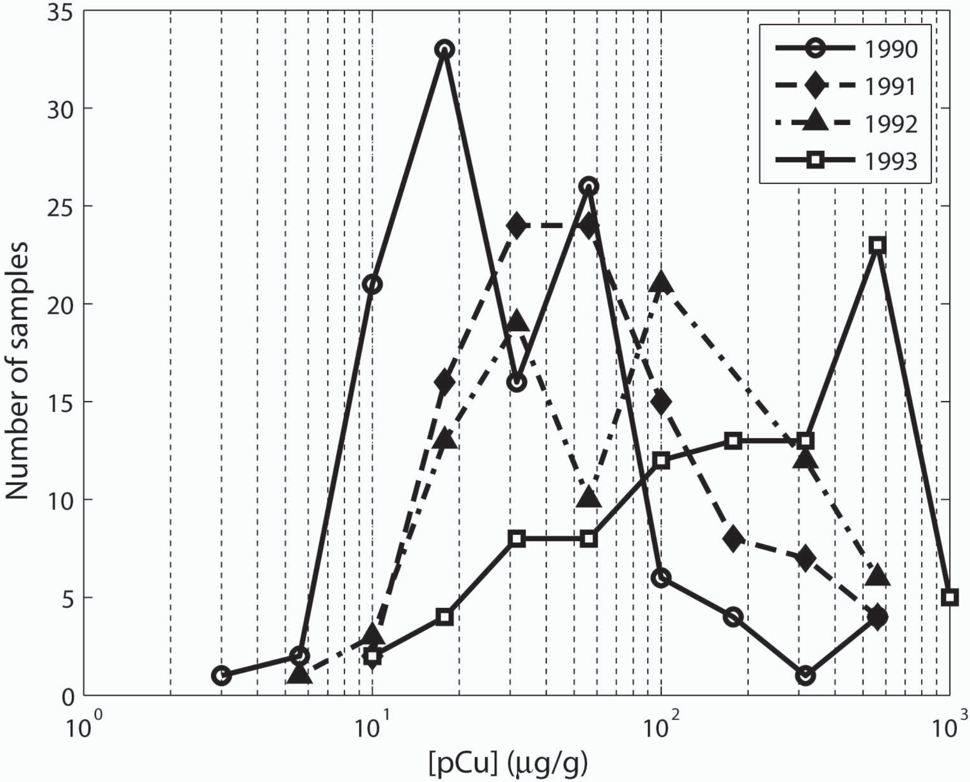

Fly River
Agu River

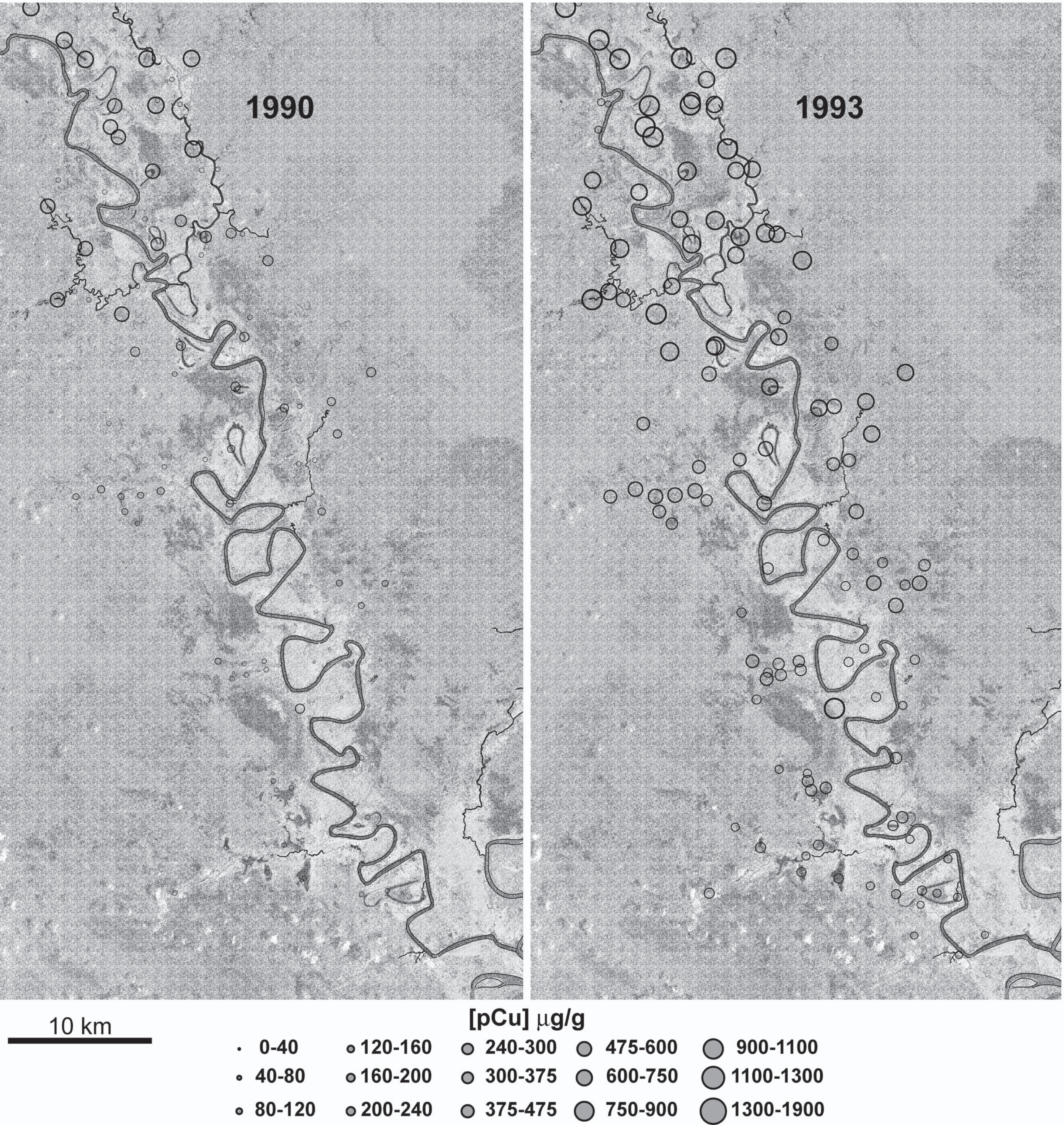

N
T1201FP
T1203FP
T1302TC
T1301TC
T1304TC
T1303TC
T1403TC
T1401FP
T1402TC
T1502FP
60 km
25 km


T0102TC
Count
Cumulative %
Count
Cumulative %
Discharge Range (m3/s)
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160
T0701TC
Count
Cumulative %
Count
Cumulative %
Discharge Range (m3/s)
-113
-103
-93
-83
-73
-63
-53
-43
-33
-23
-13
-2.5
7.5
17.5
27.5
37.5


N
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12
T13
T14
T15
T16
T17
20 10 0 20 Kilometers


L_s
$\bar{\varepsilon}_s, \bar{\rho}_s$
L_c
ε_c, ρ_c
ε_b, ρ_b


35
30
25
20
15
10
5
0
Number of samples
10^0
10^1
10^2
10^3
[pCu] (μg/g)
1990
1991
1992
1993


1990
1993
10 km
[pCu] μg/g
0-40
40-80
80-120
120-160
160-200
200-240
240-300
300-375
375-475
475-600
600-750
750-900
900-1100
1100-1300
1300-1900

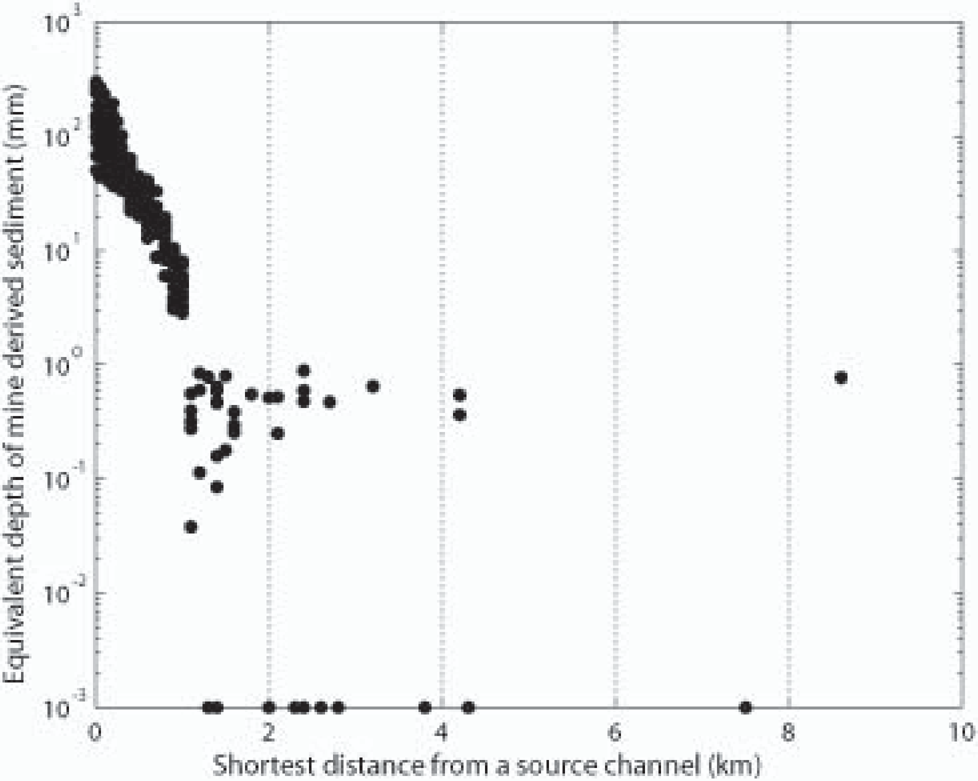
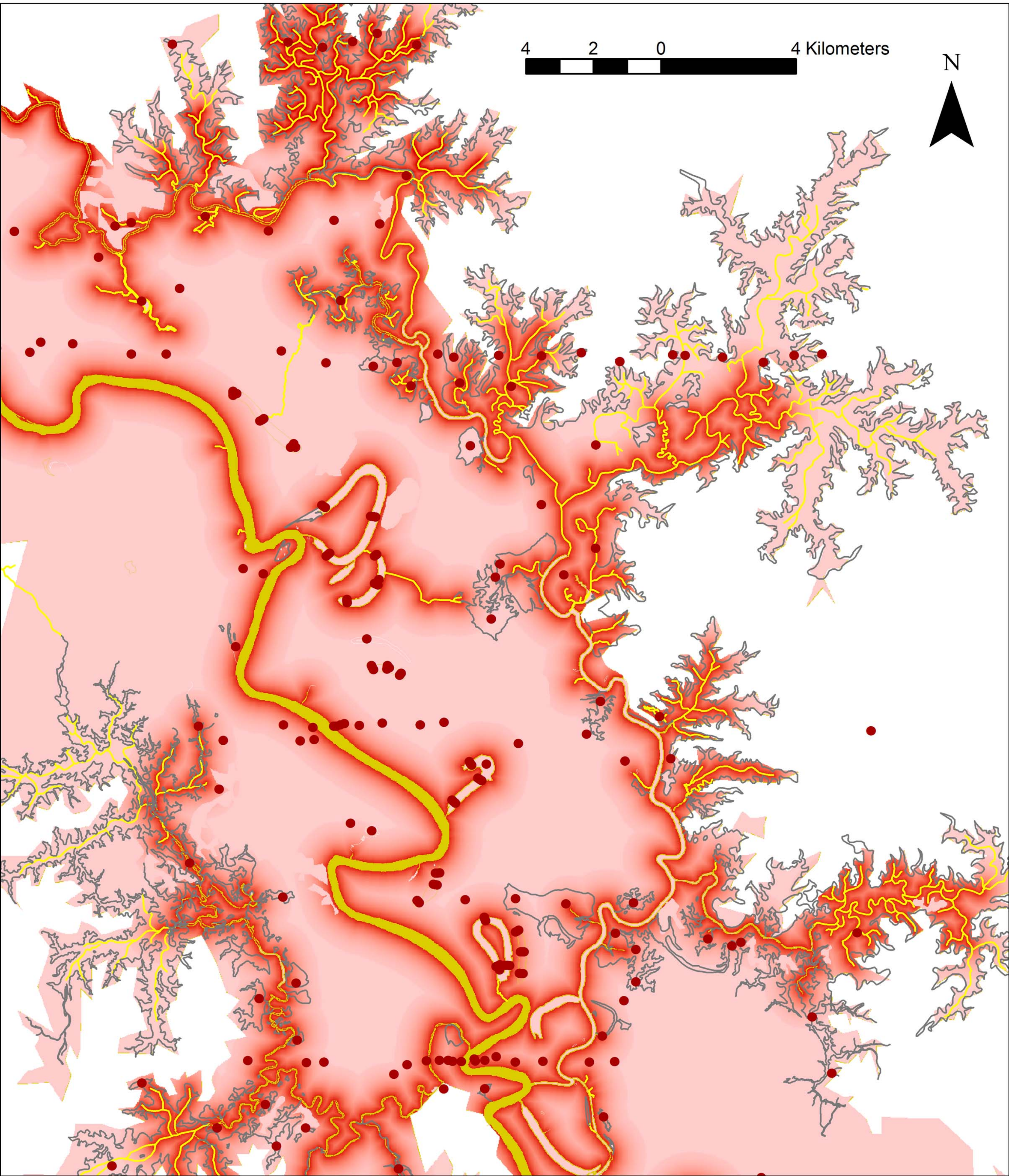
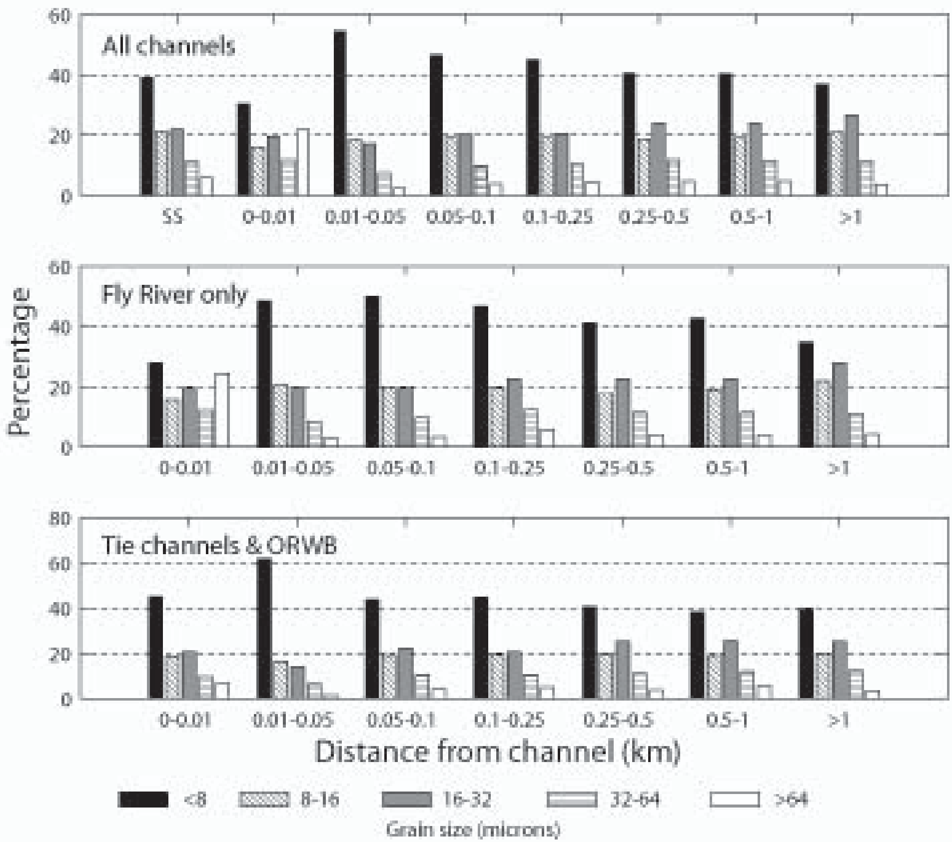

Equivalent depth of mine derived sediment (mm)
Shortest distance from a source channel (km)
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
0
2
4
6
8
10

Figure 13

Day et al.




All channels
Fly River only
Tie channels & ORWB
Percentage
SS
0-0.01
0.01-0.05
0.05-0.1
0.1-0.25
0.25-0.5
0.5-1
>1
Distance from channel (km)
<8
8-16
16-32
32-64
>64
Grain size (microns)