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A restoration plan for the Fly River, Papua New Guinea

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Abstract

The Fly River Catchment drains about 3,300 km^2 of southwester Papua New Guinea. The Fly River and its largest tributary, the Strickland river, are both subject to sediment discharges from mines in their headwaters. However, because of a naturally large sediment load, the increased loading on the Strickland and on the Lower fly below the confluence of the two rivers is not problematic. However, the discharge form the Ok Tedi mine into a tributaries of the Fly bythe same name has choked portions of the river, caused meters of aggradation of the floodplain and severely diminished the ecological health of the system. Some efforts to mitigate the effects of the mine, but these have either failed completely or only have a small impact on the problem. The design of a tailings pipeline and impoundment area to eliminate input of highly contaminated sediments to the river is presented.

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Introduction

The Fly River system in Papua New Guinea is mostly undeveloped, excepting mines in the headwaters of the two main stems of the river (the Fly and Strickland Rivers) and logging in the basin. However, geomorphic changes as a result of the increased sediment load discharged from the mines and the contamination of the floodplain by these metal laden sediments pose a potential threat to the ecosystem and the indigenous people living there, particularly on the middle Fly River. The restoration of rivers inundated with waste from mining processes is particularly difficult because of the drastic changes in channel form caused by the increased sediment load and the spread of waste downstream and across the floodplain. Restoration and mitigation efforts proposed for the river system are reviewed and the design for one of these efforts is presented in detail.

The Fly and Strickland River Basins

The Fly river, which is joined by the Strickland river from the east on the tectonically active southern side of Papua New Guinea drains 220 billion m^3 of water from its 75,000 km^2 basin each year (Figure 1, Dietrich at al., 1999). Located in the headwaters of the Fly branch of the river since 1991, the Ok Tedi Copper mine operated by Ok Tedi Mining Ltd. (OTML) discharges 62,000,000 tonnes of material into the Ok Tedi River each year. This doubles the amount of sediment carried by the Fly river that reaches the confluence of the Fly and Strickland Rivers to 1,000,000 tonnes/year (Figure 2, 3). Before mining began approximately 3% of the 5 million tonnes of sediment that were carried down the river each year were deposited on the floodplain (Higgins, 1990), but in recent years 2-3m of deposition has been observed on the natural levees alongside the river (Figure 4) which coincides with more recent estimates of 30-40% capture of sediment by the floodplains (Dietrich, University of California, Berkeley, personal communication 2003). Contaminants form the mine can be found tens of kilometers from the main channel where distributary channels such as blocked-valley lakes and connected oxbow lakes are present, but are generally limited to be within 1 km of these source areas (Day, 2000). About 1000 km^2 of floodplain on the middle Fly River has been impacted by these wastes (Apte, CSIRO Sydney, Australia personal communication). Copper concentrations in the deposited sediment in the basin were measured from 30-820 μg/g by Geoff Day in 2000, with the highest concentrations on the floodplain and in distributary oxbow lakes. Among different sediment types, the deposits composed of particles less than 63μm in diameter showed the highest concentration of metals.

The Strickland branch of the river is twice as large and has seven times the sediment load, in addition to being five times as steep as the Fly at the confluence of the two branches. It is home to the Porgera gold mine, which has little impact on the magnitude of sediment loading in the basin because a larger proportion of the basin is in the rapidly eroding headlands (Dietrich, 1999, Figure 2). As a result, the increased sediment load of the Fly river below the confluence with the Strickland is negligible when compared to the large natural load of the river at this point. The floodplain trapping efficiency on the Strickland is lower than on the Fly because of this consistently higher sediment load, so aggradation caused by deposition of mining waste is probably negligible (Dietrich, 2001). Elevated metal concentrations in the sediment from the mine waste are detectable up to 1 km from the channel in this reach as well, leaving a potential for approximately 600 km^2 of contaminated floodplain, or about 2% of the drainage basin (Apte, 2003). Lead and silver contamination of the mine sediments has been noted near hazardous levels, but the only possible human health concern detected thus far has been the accumulation of mercury in Lake Murray, which can not be isolated as an effect of the mine-derived sediment (Apte, CSIRO Sydney, Australia, personal communication).

Restoration Efforts

The government of Papua New Guinea has required environmental monitoring and passed laws requiring the mines to limit their impact on the river systems. However, due to restoration plan failures and financial incentives for these officials, about 30% of whom are shareholders in the mine, little action has been taken to protect the Fly and Strickland Rivers. Because the sediment load on the Strickland is naturally elevated and there has not been any demonstrated environmental impact thus far, remediation and mitigation efforts are limited to the upper and middle Fly River.

An attempt to construct a sediment blocking dam at the Ok Tedi mine in the mid-1990's failed during a large landslide (Figure 5), following which several alternatives to divert tailings form entering the river were proposed (Kehdingen, 2001). Unfortunately, these plans, including the construction of a tailings pipeline and impoundment, were dismissed as being too costly. Instead, in order to reduce the effect of mine-derived sediment on the Fly River, direct discharge to the Ok Tedi has continued with a slot-dredge operation installed on the Ok Tedi just above the confluence with the Fly River (Kehdingen, 2001, Figure 6). An 800-m long and 10-m wide slot in the river bed captures sediment larger than sand, 200 μm, which is dredged from the channel and disposed of in 30-m terraced impoundments. Unfortunately, the dredging operation captures less than 40% of the mine-derived sediments and is ineffective at removing the fine particles with the highest concentration of metal-contaminants.

The only remediation plan to directly address the current channel form as a result of the increased sediment load is an 18 month pilot project involving the dredging of the middle Fly to remove mine-derived sediment (CRN, 1999). Though the U.S. Army Corps of Engineers has initiated dredging operations in rivers as a restoration measure (Kondolf, University of California-Berkeley, personal communication, 2003), dredging is generally viewed as damaging to the river both physically and biologically.

The delays in implementing complete mitigation and restoration efforts by OTML qualifies as a plan of no action that may continue for the remainder of mine operation, at least 2010. In 1917, G. K. Gilbert proposed that mine-derived sediment on the Sacramento River would move through the system in a symmetrical wave, analogous to a flood wave, growing longer and flatter as it moves and eventually, on the order of 50 years after cessation of mining on the Sacramento, would be flushed from the system. However, the sediments produced by hydraulic gold mining throughout the basin spread mercury, aggraded the river and are still present both on the floodplain and upstream of the main channel and tributaries (James, 1991). Since the sediment is stored in the system, it might also be expected for the river to equilibrate with its aggraded state and eventually non-mine derived sediment would bury the contaminated sediment. However, the metal laden sediment would still be remobilized by large flood events, posing a hazard to agriculture and other industries in the watershed (Dennis, 2002).

The only actions being taken to restore the Fly River and mitigate the effects of the mine do not effectively reduce sediment load, and are not approaches to re-establish the natural hydrologic regime. A combined plan of mitigating the effect of OTML on the middle Fly River is necessary, a plan that utilizes an ecologically responsible method for restoring the downstream form of the river, while mitigating the upstream impact on hydrologic processes by reducing the sediment load. Presently, a plan to remove the large amount of sediment on the floodplain is too costly and the necessary data to design such a plan is unavailable. The design of a tailings pipeline and impoundment areas is presented as a viable alternative to discharging directly into the river.

Pipeline and Tailings Impoundment Design

The original tailings pipeline considered by OTML was 80 cm in diameter and would carry slurry 110 km from the mine processing plant to one of the tributaries of the Ok Tedi (Kehdingen, 2001). Landsliding in the region would be a concern on the unstable mountain slopes, but building the pipeline along the ridgelines of the mountain would minimize the possibility of slope failure. Current operation of the mine produces about 170,00 tonnes of tailings each day (Dietrich, 1999), but Venton & Associates report that design operational capacity for the pipeline would need to be 45-160 thousand tonnes/day in order to export all tailings less than 0.2 mm in diameter to an impoundment area (2002).

A value of 1:1 mass ratio of solids to liquid was used in the analysis and the solids have a density of 2.4 g/cm^3. The velocity through the pipeline necessary to create a pseudoheterogenous flow where the solids are held in suspension to limit wear of the pipeline was determined using the Densimetric Freude number, F_L. F_L was determined graphically to be 0.8 for particles that are 84% finer than 0.2 mm diameter, d (Liu, 2003). The velocity, V_L, in the pipe was then determined according to the relationship:

$$V_L = F_L[2gD(S-1)]^{1/2}$$

where D is pipe diameter, g is gravity, and S is the solid specific gravity. Velocities for various pipe sizes are shown in Table 2. The velocity which would minimize head loss along the pipe, Vo, thereby minimizing the pressure head gradient in the pipe is determined using the modified Durand equation (Liu, 2003):

$$Vo=3.22[g(S-1)]^{1/4}C_V^{1/3}(DV_s)^{1/2}d_s^{-1/4}$$

where C_V is the solid volume concentration and V is the settling velocity of the appropriate particle size. Values of Vo are also available in Table 2.

These velocities were then compared to the volumetric flow rates determined using the three loading rates of solids, a 1:1 mass ratio and the pipeline diameters used in the previous set of analyses. The high operational capacity is the most critical design constraint in terms of minimizing environmental impact. Also, given the relatively short expected lifespan of the pipeline (7 years) and small size of most of the particles, it is anticipated that subcritical flow and pipeline abrasion will not be major concerns. Therefore, it is suggested that parallel pipelines 60 cm in diameter would be best suited to carry the slurry to the impoundment area.

It should be noted that the sediment produced by OTML is very small and is at the limit of the analytical techniques used to produce the results above. This may explain the disparity between the pipeline proposed in 1996 and the results presented here.

The tailings pipeline would necessarily lead to an impoundment area where the tailings would be permanently stored. If the mine operated at full capacity for the remaining 7 years of planned operation, the impoundment area would require a total volume of 580 million m^3. If the tailings impoundment, constructed on the hillslope near the head of the Ok Ma, were to have a maximum height of 30 m, the height of the dredged materials, nearly 40 km^2 of impoundments would be created in 7 years. This large area is partly due to the fact that the impoundments can only be built in series (Figure 8), and not stacked because of drainage needs and stability issues (EPA, 1994). Because the impoundment areas are being constructed with engineered walls and drainage (Figure 7) it would likely be possible to increase the average height of the impoundments, decreasing the area.

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Figures

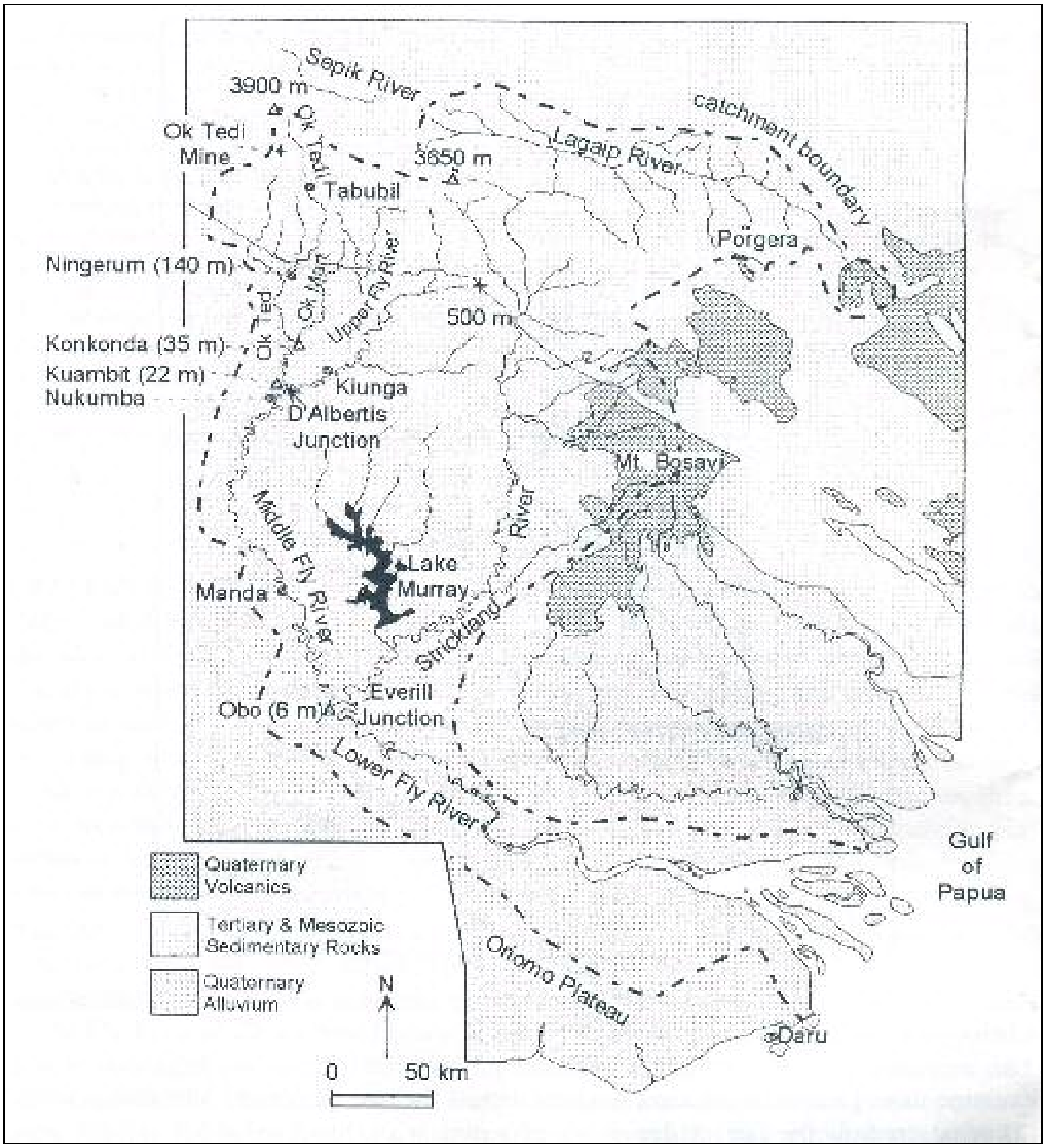

Figure 1. Map of the Fly River Basin (Dietrich, 1994).

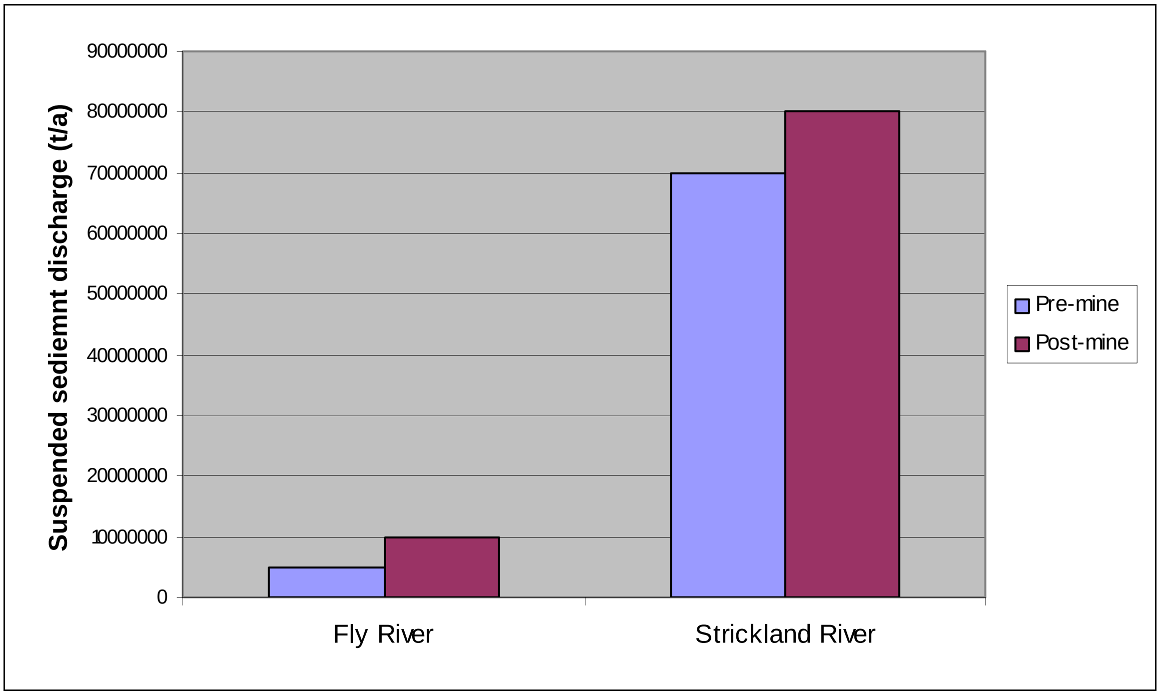

Figure 2. Pre and post mining suspended sediment loads on the Fly and Strickland Rivers.

Figure 3. Mine-derived sediment deposits choking the upper-middle Fly River

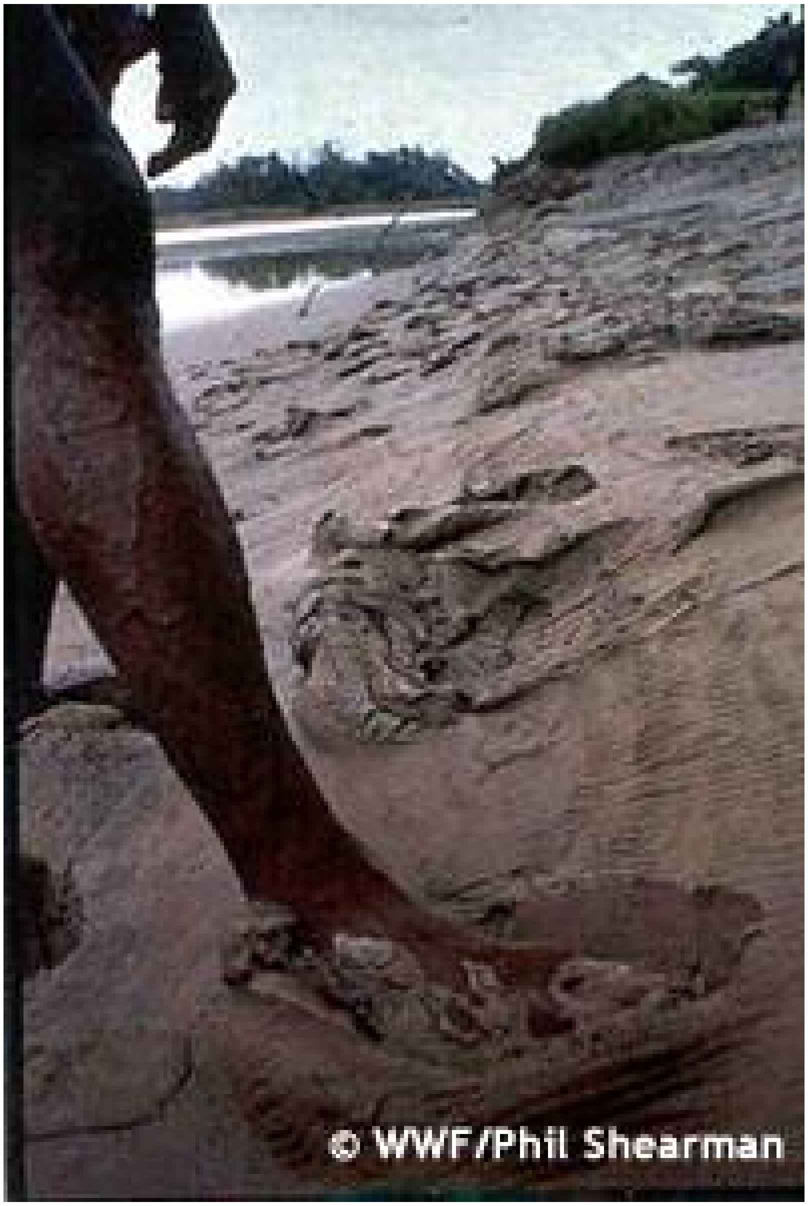

Figure 4. Fresh silt and clay deposits on the natural levees of the middle Fly River.

Figure 5. Tailings pipeline beginning and terminal points from 1996 proposal (Kehdingen, 2001).

Figure 6. Slot dredger on the Ok Tedi River (Kehdingen, 2001).

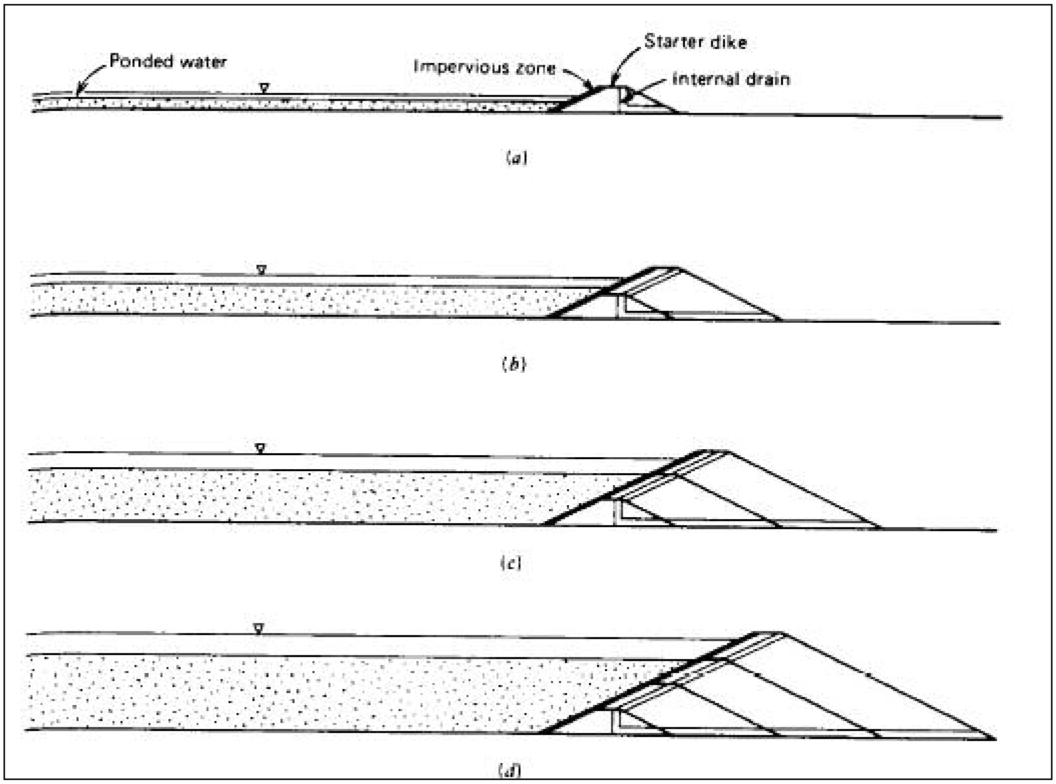

Figure 7. Tailings dam construction over time (EPA 1994).

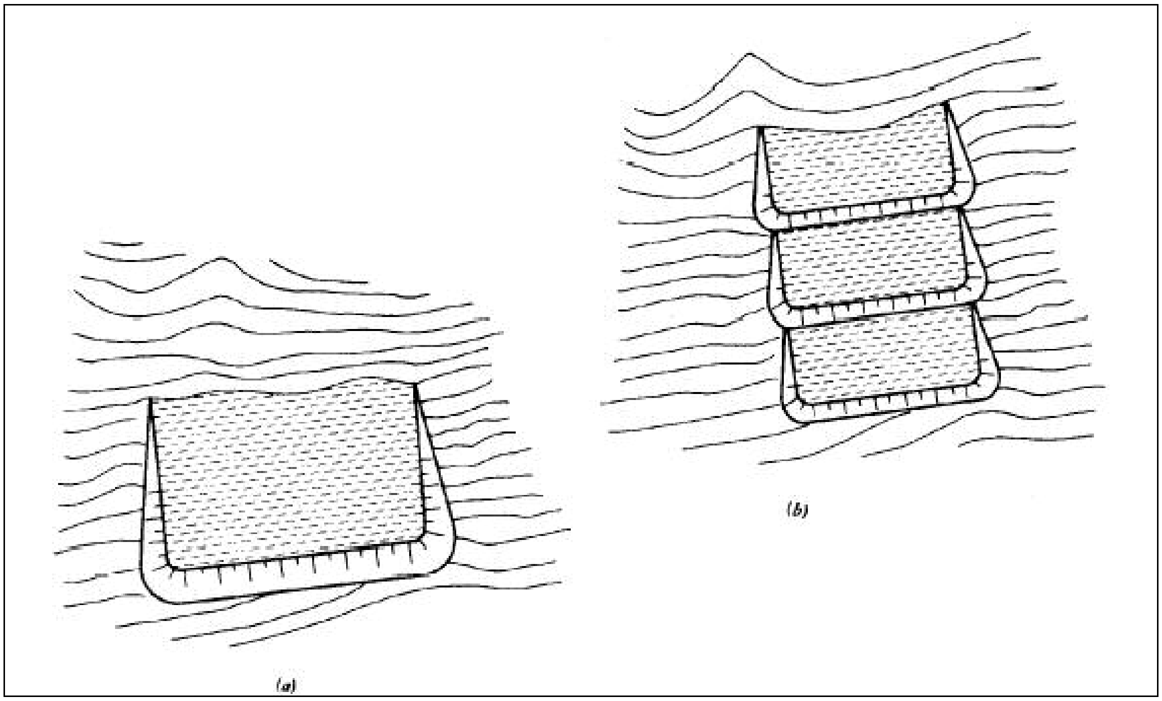

Figure 8. Single and multiple hillside tailings dam configurations (EPA 1994).

Tables

River	Area (km^2)	Contaminated Area (km^2)	% Basin Area Contaminated	Flow Rate (m^3/s)	Annual Flow (m^3)	Floodplain Aggradation (m)	Pre-mine Sediment Discharge (t/a)	Current Discharge (t/a)
Fly	18400	1200	7	2244	7.08E+10	2-3	5000000	10000000
Strickland	36740	600	2	3110	9.81E+10	small	70000000	80000000

Table 1. Relevant data about the Fly and Strickland Rivers.

Pipeline design								
D (m)	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45
Vs (m/s)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
V_L (m/s)	4.25	4.63	4.47	4.31	4.14	3.97	3.78	3.59
Vo (m/s)	4.70	4.55	4.40	4.24	4.07	3.90	3.72	3.53

Table 2. Pipeline design velocities for various pipe sizes where D is pipe diameter, Vs is settling velocity, V_L is the velocity necessary for suspension to be maintained and Vo is the velocity where the pressure loss along the pipe is minimized.

Volumetric velocity determination								
D (m)	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45
Vavg (m/s)	2.53	2.88	3.31	3.84	4.51	5.36	6.49	8.01
Vlow (m/s)	1.38	1.57	1.81	2.09	2.46	2.92	3.54	4.37
Vhigh(m/s)	4.99	5.68	6.52	7.56	8.87	10.56	12.78	15.78

Table 3. Flow velocity for average, low and high tailings discharges defined as 3300, 1800 and 6500 t/h respectively (Venton and Associates, 2002).

Impoundment area design	
High Tailings Rate (t/h)	6500
Mass Solid/liguid ratio	2
Volume Solid/liquid ratio	0.29
Life of mine (y)	7
Total tailings (m3)	5.81E+08

Table 4. Maximum design capacity of tailings impoundment for life of mine.

Figure and Table Captions

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