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FISH AND FISHERIES OF THE FLY RIVER, PAPUA NEW GUINEA:
Population Changes Associated with Natural and Anthropogenic Factors and Lessons to be Learned

By:

Stephen Swales, Ph.D.

International Fisheries Consultant
22 Clifton Road, London, UK, N8 8JA

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Abstract

The Fly River system in Western Province, Papua New Guinea is the largest river in the country and has the most diverse freshwater fish fauna in Australasia. The river and its floodplain wetlands support local artisanal/subsistence fisheries and a limited regional commercial fishery. Monitoring of fish populations in the Fly River system has recorded over 100 fish species representing 32 families. Fish catches showed considerable temporal and spatial variability but, since the commencement of the operation of the Ok Tedi mine in the early 1980's and the input of mine-derived waste material into the headwaters of the system, long-term monitoring has revealed significant reductions in fish catches at most riverine sites in the Ok Tedi, upper and middle Fly River. However, over the same period no significant declines in fish catches have been recorded in the lower Fly or delta areas and fish catches in the artisanal subsistence fisheries have increased as more nets and other resources have been made available to the village communities along the river. Although catches in some floodplain off-river water-bodies have declined, these changes are thought to be associated mostly with the effects of natural climatic phenomena, particularly recent severe El Niño droughts, introduced species and increased commercial and artisanal fishing. Possible mechanisms accounting for the declines in fish catches in the Ok Tedi and middle Fly River are discussed. The loss and degradation of fish habitat due to river bed aggradation is likely to be the major cause of the declines in fish catches, but quantitative information is lacking. Reductions in water quality, particularly through elevated levels of total suspended solids, may also be implicated in declining fish catches. Other mine-related environmental changes, such as elevated levels of dissolved and particulate copper, may also be involved, but the available evidence suggests that most copper in the system is not bio-available due to the large amount of organic matter in the system. This case-study clearly illustrates how many environmental factors, both natural and anthropogenic, may affect inland fisheries in a developing country and the major problems faced by fishery managers in the 21'st century to sustain fish biodiversity under the many environmental pressures of major resource development works.

The Fishery Resource and its Exploitation

The Fly River system in Western Province, Papua New Guinea, is the largest river, in terms of water flow, in Australasia. With a mean annual discharge of approximately 6,000 cumecs the Fly is similar in size to the Niger and Zambesi Rivers in Africa and the Danube in Europe (Welcomme, 1985). However, with a catchment area of only 76,000 km^2 the Fly outranks all the world's major rivers in terms of runoff per unit catchment area. This is due to the very high rainfall in the region, ranging from 10,000 mm per annum in the upper catchment near the mine to around 3,000 mm per annum near the coast. The Fly River and its major tributary the Strickland River flow for over 1200 km from their source in the Western Highlands of Papua New Guinea down to the Gulf of Papua (Figure 1). In its meandering course to the coast the Fly falls only 20 metres over the 800 km river length between the town of Kiunga and its estuary. Much of the Fly catchment, particularly in the middle and upper reaches, consists of dense, primary tropical rainforest. In the middle Fly area, tropical swamp forest thrives in the floodplain wetlands while further downstream the drier climate gives rise to open savanna forest and grasslands.

The first systematic survey of the fish populations of the Fly River was carried out in the mid 1970's by T.R. Roberts, who discovered that the fish populations in the Fly are characterized by the large size of some species, the abundance of endemic species and the dominance by groups that are poorly represented in other parts of the world (including 17 species of catfish in the families Plotosidae and Ariidae) (Roberts, 1978). The Fly River system was found to support the most diverse fish fauna in the Australasian region, with 128 recorded native freshwater species representing 33 families. Seventeen species are known only from the Fly basin, and thirty or more are known only from the Fly River and one or more of the large rivers in central-southern New Guinea (Roberts op.cit.).

The inland and marine fisheries of Papua New Guinea are under the jurisdiction of the P.N.G. Department of Fisheries, which manages and regulates the fisheries. The Community Relations Department of Ok Tedi Mining Ltd. (OTML) liases with local villagers along the river and provides nets and other equipment to improve local fisheries. Fish freezers are provided at stations along the river to store catches of barramundi, *Lates calcarifer,* much of which is sold to supply the mining community in the region. The only other commercially important species is the Papuan black bass, *Lutjanus goldiei*, which is generally much less abundant than barramundi. Minimum size restrictions are imposed on the commercial catches, but illegal poaching of barramundi by villagers, particularly in the lower river and coastal areas, is widespread and difficult to control.

The Fly River system supports both artisanal/subsistence fisheries and a limited regional commercial fishery, mainly for barramundi, *Lates calcarifer,* in the river and estuary. Barramundi is a large anadromous species that is prized for its flesh throughout the Australasian region and in PNG occurs along the southern coast in estuarine and mangrove-fringed rivers west of Port Moresby. The majority of the population lives in the Fly River system and adjacent coastal waters. It is protandrous and has a complex life cycle. Fish are born as males in coastal waters, migrate into freshwater, and migrate back to coastal waters to breed – initially as males (2-6 years old) and subsequently as females (>6 years of age). The only known spawning ground is found near the village of Sigabaduru, approximately 160 km west of the mouth of the Fly River (Moore, 1982). Most adults are believed to migrate from their non-breeding habitats in the Fly River to the spawning ground at the onset of the summer monsoon season and most of the juveniles migrate back as 1-year olds (Moore & Reynolds, 1982).

In Papua New Guinea in the late 1980's, barramundi was ranked fourth in terms of both total fish production and foreign-exchange earnings (Opnai & Tenakanai, 1987). In 1995, the barramundi catch represented ~80% of the total weight of commercial seafood sold in Daru, a village near the mouth of the Fly. The fishery is important to coastal communities in Western Province because it involves many local fishers and generates cash for people in areas with few alternative sources of income. For the economy of the region it is thus vital to maintain the long-term sustainability of barramundi populations (Milton *et al*., 1998). The commercial fishery for barramundi in Western Province began after the establishment of processing and distribution centres in the province in the early 1960's. By 1969 commercial gill-net operations were established on the coast near the mouth of the Fly River at Daru and in the middle Fly River around Lake Murray (Opnai & Tenakanai, 1987). The fishery comprised commercial fishing vessels operating gill-nets and artisanal fishers in both regions.

The total catch from both areas reached 330 t year $^{-1}$ in the early 1970's, but the commercial fishery on the coast ceased operation in 1990 because of declining catch rates (Milton *et al*., 1998). An artisanal fishery for large adult barramundi developed alongside the commercial fishery during the 1970's. These fishers sold their catch to village co-operative freezer plants or commercial buyers. There are currently only two freezer plants operating, both in the middle Fly River. In addition to the fishery for adult barramundi there are subsistence and artisanal fisheries. Artisanal and subsistence fisheries exist at most villages along the length of the Fly and also in coastal areas, where the fisheries mostly target juvenile fish (Milton *et al*., 1998). Kare (1995) estimated the maximum sustainable yield (MSY) for the commercial fishery as 120 t year $^{-1}$ on the basis of commercial catch data from 1980-85. The annual catch since that period has been half that estimated MSY, and Milton *et al.* (op.cit.) suggest that the estimate is too high for the present population. Although several management measures have been introduced since 1983 to reduce the catch of juvenile and immature fish in Western Province, none appears to have succeeded, probably because of a lack of will to enforce them (Kare, 1995). The latest management and fishery plan passed by Parliament introduces measures such as minimum size-limits, and fishing area and mesh-size restrictions. The commercial catches of barramundi migrating to the coastal spawning ground are now only about 2% of those obtained in the early history of the fishery. Moreover, catches are now so low that additional measures may be needed in order to increase the potential for the population to reach levels that can sustain any commercial fishing (Milton *et al*., op. cit). The results of the study by Milton *et al* (op.cit.) also confirm the suggestion from previous studies that populations of protogynous fishes are highly susceptible to recruitment overfishing and that the dramatic decline in catch levels of barramundi in Western Province of PNG is also evidence of recruitment overfishing. Recent studies suggest that barramundi in the western coastal areas of PNG consist of just one genetic stock. It is therefore possible that movements of fish from other river systems into the Fly River system may have compensated for the overfishing of barramundi stocks in the Fly River (Milton, personal communication).

The primary human use in the aquatic ecosystem is the subsistence fishery, which forms part of the traditional way of life of villagers living along the river. Most fish are consumed by the villagers, with catfish being the preferred species, compared to barramundi and black bass in the commercial fishery. Swales (1998) estimated a current use of 416 tons/year, assuming a weekly fish intake of 2 kg/person and a population size of 4,000 people. Based on new data released in March 1999, there are now estimated to be 5,000 people living along the middle Fly River, resulting in a new fish yield estimate of 520 tons/year. These estimates do not account for by-catch that is not used or the commercial barramundi and bass fishery. Assuming that by-catch equals 10 percent of the fish consumed and that the commercial barramundi and bass fishery is responsible for approximately 36 tons/year, the estimated yield based on the combined artisanal and commercial fishery is approximately 600 tons/year. Therefore, assuming the theoretical fish yield of 7,400 tons/year, the artisanal and commercial fisheries account for approximately 10 percent of the yield.

Fish yield in any system is partially a function of the size of the catchment area. Based on data from a number of rivers around the world, Welcomme (1985) provides a relationship between fish yield and catchment size, including consideration of floodplain area given its importance in productivity. The relationship derived by Welcomme has been used in other projects in Papua New Guinea, such as the Sepik River Enhancement Project implemented recently by F.A.O., and probably provides estimates of fish yield within an order of magnitude. Using this relationship, a yield of 7,411 tons/year was estimated for the middle Fly River. It should be noted that the fishery would never realize the potential maximum yield for a variety of reasons, including population size, absence of a market, and fishing equipment. In the mid-1980s, artisanal use in the middle Fly River was estimated to be about 310 tons/year. These estimates are no longer applicable because artisanal fishing efforts have increased substantially as OTML has made more resources available to villagers, population sizes have increased, and the availability of gill nets has increased.

Apart from the local commercial and artisanal fisheries the only other significant impacts on the fish resource of the Fly River system arises through mining activities in the headwaters of the Fly and Strickland Rivers. The Ok Tedi copper and gold mine is situated in the upper catchment of the Fly River in Western Province, Papua New Guinea, close to the source of one of its largest tributaries, the Ok Tedi (Ok means water in the language of the local Yongom people). The smaller Porgera gold mine is also located in the headwaters of the Strickland River. The Ok Tedi mine is one of the largest copper producing mines in the world, with a total ore reserve in 1996 of over 400 million tons. Located on Mt. Fubilan in the headwaters of the Ok Tedi, construction for the project began in 1981 and the mine commenced operation in 1984, initially as a gold mine. Copper production started in 1987 and gold production ceased in 1988. Because of the high rainfall and geological instability of the region, construction of a tailings dam was not feasible, and the mine has been operating without waste retention. The Ok Tedi mine discharges up to 80,000 tons per day (tpd) of waste rock and 120,000 tpd of tailings from its mining operations directly into the Ok Tedi/Fly River system.

The main environmental impacts arising from mining operations arise from the introduction of large amounts of sediment into the river system, which results in elevated levels of suspended solids and increased river bed aggradation. The key water quality parameters affected by mine operations are total suspended solids (TSS), particulate copper (pCu) and dissolved copper (dCu). The level of each of these parameters varies temporally and spatially, both along the Ok Tedi/Fly River system and between years. However, it is considered that most copper in the river is largely not bio-available due to its complexation with the high levels of dissolved organic matter in the river and so would not be expected to have toxic effects on aquatic life (Stauber, 1995).

At the outset of mining operations, it was a statutory requirement from the PNG government authorities that the environmental impacts of mining activities in the Fly River system be monitored and that the effects of mine waste discharges did not lead to unacceptable damage to the fish and fisheries of the river system. As a result, environmental monitoring of mine impacts began in 1981, with permanent hydrological, chemical and biological monitoring programs being established in 1983. River monitoring sites now extend along the length of the river, from the headwaters down to the river delta and the Gulf of Papua. The extensive long-term monitoring program means that the Fly River system is one of the most intensively studied tropical river systems anywhere in the world.

Monitoring of the possible biological impacts of mine operations has been carried out throughout the Ok Tedi/Fly River system, from the headwaters down to the estuary, and includes a range of habitats, including the main river channel, tributaries and streams, floodplain off-river water-bodies and estuarine and coastal habitats. The primary biological habitats of the Fly catchment which were sampled are high gradient streams in upland regions, lowland riverine habitats with and without associated wetlands, and the lakes and oxbow cut-offs associated with the wetlands of the middle Fly and Strickland River reaches. The river channels throughout the system are generally of low biological productivity, primarily due to high water turbidity and instability of the bed material. The off-river habitats are generally confined to the middle and lower Fly and the Lower Strickland areas. These habitats are highly productive areas and are the main food source for fish in the associated river channels.

Since the early 1980's, the OTML biological monitoring program has formed the only routine sampling in the Ok Tedi, Fly River and its delta. A variety of faunal groups are routinely monitored, but the main emphasis of the monitoring program is on freshwater fish populations. This is both because of the importance of fish in the diet of the local villagers living along the Fly and the ability of fish to integrate river ecological processes and so provide a valuable indicator of 'river health' (Fausch *et al*, 1990; Harris, 1995; Simon, 1999). Catches in the artisanal subsistence fisheries have not been monitored, due to a lack of resources, and only limited catch statistics are available for the commercial fishery (Opnai & Tenakanai, 1986).

Fish monitoring in the biological monitoring program has been carried out by staff from the OTML Environment Department using standardized methodologies, including gill-netting, seining, rotenoning and electrofishing. However, a standardized gill-netting procedure forms the basis of most routine fish sampling at over 30 sites in the main river channel and floodplain off-river water-bodies (see Figure 1). A set of 13 gill-nets (stretched mesh size 1-7 inches) is set at each site for 24 hours and checked at dawn, dusk and the end of the sampling period. Fish are identified to species, measured (fork or total length) to the nearest 1 mm and weighed (to the nearest 1 gram). Sampling at most sites is conducted on a monthly or quarterly basis.

Importance of Biodiversity in the Fishery and Non-target Biodiversity Concerns

The fish fauna of the Fly River system is the most diverse in Australasia. A total of approximately 128 fish species, representing 32 families, has been recorded from the Fly River system (Roberts, 1978). Seventeen of these species are known only from the Fly basin, and thirty or more are known only from the Fly and one or more of the large rivers in central-southern New Guinea. The freshwater fish fauna is dominated by catfish of the families Ariidae (sixteen species) and Plotosidae (ten species), groups which are rare elements in the freshwater fish faunas of other regions of the world (Roberts, op.cit.). This compares to a total of just 70 species recorded from the Sepik-Ramu River, on the north coast of New Guinea (Coates, 1993).

In most ways the composition of the freshwater fish fauna is largely determined by its position in the Australasian geographical zone and, in common with the northern Australia region, lacks primary freshwater groups of the Ostariophysi (Bishop & Forbes, 1978; Roberts, 1978). The fish fauna of the Fly River is characterized by the large size of some species (e.g. anchovy *Thryssa scratchleyi*, catfish *Arius augustus,* Papuan black bass, *Lutjanus goldiei,* and barramundi, *Lates calcarifer*). The barramundi is the main predator species in the river, providing valuable commercial and artisanal fisheries. Many of the freshwater fish in the system, including barramundi, tarpon, *Megalops cyprinoides*, mangrove jack, *Lutjanus argentimaculatus*, mullet and eels, are migratory and move regularly between freshwater and estuarine areas for feeding and/or reproduction, reflecting the marine origins of many of the species (Bishop & Forbes, 1978).

The fish fauna of the Fly River system has few specialist types (i.e. species which are restricted to a single food or habitat type) so that most of the resident species are widely distributed. Overlap in diet and habitat requirements is an important mechanism for fish survival since the floodplain can dry out in years of severe drought. Fish ecology is characterized by an overlap of species resident in the two main habitat types, the main river channel and the floodplain with its numerous water-bodies. The high biological productivity of the Fly River floodplain provides valuable nutrients and food supplies. Migratory species such as barramundi depend on this productivity, feeding largely on herrings (*Nematolosa* spp.), which are often very abundant in off-river water-bodies. The most important food items for other fish are aquatic and terrestrial invertebrates, algae, plants and organic detritus. A wide range of fish feeding groups are represented in the river and off-river water-bodies, but aquatic insectivores are the predominant feeding guild in the system (Swales *et al*, 1999).

A total of 86 fish species representing 32 families was captured from riverine monitoring sites in the Ok Tedi/Fly River system. Catfish in the families Ariidae (16 spp.) and Plotosidae (9 spp.) were the most diverse groups overall, although *Nematolosa* herrings were the most numerous species, forming 37% of the total catch. The main predator species, barramundi *Lates calcarifer*, comprised over 30% of the overall catch biomass. In comparison, a total of 66 fish species, representing 33 families, was recorded from floodplain habitat monitoring sites, with Plotosid and Ariid catfish being the dominant groups. Herring species (*Nematolosa* spp.) were often very abundant, particularly in oxbow lakes, and formed 66% of the total catch in all the floodplain habitats.

The mean number of species recorded from river channel sites each year has remained relatively constant (approx. 20 species) (Figure 4). However, in the Ok Tedi the number of recorded species declined markedly over the period 1993-96, from around 15 recorded species to just 3 species in 1996. In contrast, the mean number of recorded species in the Fly River main channel sites remained relatively constant over the same period at around 20-25 species. In the floodplain sites, the number of species recorded in blocked valley lakes and oxbow lakes has also remained relatively constant over the sampling period (Figure 5), with the exception of a marked decline in the blocked valley lakes over the period 1993-94. This decline coincided with El Niño drought conditions, which caused the drying out of many of the floodplain habitats. However, several species, such as the sawfish, *Pristis microdon,* are becoming much less frequent in catches in the main channel sites on the middle and upper Fly, and this species has not been recorded in catches from the middle or upper Fly for several years.

There are also two non-native introduced species in the Fly River system, the climbing perch, *Anabas testudineus*, and the walking catfish, *Clarias batrachus.* These species were first recorded in catches in the early 1990's and have since become widespread in the system, particularly the climbing perch. Native fish, particularly catfish species, prey on the climbing perch, often causing mortality through spines on the operculum and fins lodging in the throat of the catfish. Large numbers of dead catfish with perch lodged in their throats are a frequent occurrence in the middle Fly floodplain (Swales *et al*, 1999). Both climbing perch and walking catfish are also likely to compete with native species for both food and space. It is thought that villagers travelling from other parts of the country introduced both species into the system. Both species are valued as food fish since they can survive out of water for long periods. Villagers travel from village to village carrying fish wrapped in moist leaves, often disposing of excess fish in the nearest waterway. There are currently no management plans in force to halt the spread of either introduced species.

Management History and how Biodiversity has been Incorporated in Fisheries Management

The commercial and artisanal fisheries of the Fly River system have generally been characterized by a non-interventionist approach to management by government agencies. As a result, there is very little data available on these fisheries, although studies on the barramundi fishery are currently underway. Traditional artisanal/subsistence inland fisheries in developing countries are often managed using social and economic regulating mechanisms, rather than by fisheries authorities (Welcomme, 1979; 2000). The fisheries may be managed intuitively by the fishermen themselves, with high catches being allowed in times of plenty and lower catches when populations are reduced. Also, it is often the case that government fisheries departments in developing countries, such as PNG, simply do not have the resources to manage all their fisheries effectively. This can easily lead to over-exploitation of fisheries and their subsequent collapse.

This may be the case with the barramundi fishery in the Fly River, where the fishery is currently not being effectively regulated and illegal fishing and environmental changes due to mining and other natural causes may be having severe adverse effects on the fisheries and river ecosystem. Recently, however, the PNG Department of Fisheries commenced a three-year study, in conjunction with CSIRO Fisheries in Australia, to investigate the status and biology of barramundi stocks and fisheries in the Fly River system. The study will provide biological information on stock composition, movements, reproduction, genetics etc., which can be used to improve fisheries management. This study was prompted by concern over the declining catches of barramundi in the system and the lack of knowledge of the biology of stocks to aid management decisions. Also, the major environmental changes, including declines in fish catches, in the Ok Tedi/Fly River system recently caused the PNG government authorities to request OTML to investigate ways in which mining impacts in the river can be mitigated (see below). There is clearly a need in cases such as this, where fisheries in a major river system are declining, for other countries or agencies to assist with resource management to prevent major loss of biodiversity.

Summary of Status and Trends of Target Species

Fish catches in the Ok Tedi and Fly rivers and off-river water-bodies showed considerable temporal and spatial variation over the period of monitoring. However, since sampling first commenced in the early 1980's fish catches at many riverine sites, particularly in the Ok Tedi, have declined considerably, with reductions of up to 90% at sites in the Ok Tedi and up to 75% in the middle Fly (Figure 2). Reductions in fish catches at riverine sites downstream of the mine are partly due to decreases in catches of barramundi (Figure 3).

Statistical analyses of trends in fish catches at riverine sites were carried out using the techniques of linear regression, rank correlation and analysis of variance. The results indicated that long-term declines in fish catches at all riverine sites in the Ok Tedi were significant ($P<0.05$) (Figure 6). Catches at sampling sites in the Ok Tedi have declined overall by up to approximately 85 - 95% over the period of sampling, with the greatest long-term declines being in the lower Ok Tedi around Ningerum. Catches at sites in the middle Fly have also declined significantly over the period of sampling, with reductions ranging from 65% at Kuambit (FLY 10) to 74% at Bosset (FLY 14) and 69% at Obo (FLY 15). However, no significant changes in fish catches were recorded at sites in the lower Fly or delta areas. Figure 7 shows the mean fish catch biomass estimates recorded at each river channel site in the Ok Tedi and Fly River over the sampling period, showing the low catches in the Ok Tedi particularly.

Since fish sampling first commenced in the early 1980's, barramundi, *Lates calcarifer,* formed a high proportion of catches at many riverine sites, particularly in the middle Fly (Figure 3). The proportion of barramundi in the total catch at Kuambit (FLY 10) in the middle Fly has varied considerably since the commencement of sampling in 1983, ranging up to 67% and 87% by number and weight, respectively. However, barramundi have tended to form a much lower proportion of the total catch at this site over the more recent period of monitoring, particularly over the last few years. The numbers and biomass of barramundi in catches at this site have declined overall during the 1990's. At other sites, catches have also been variable, but with catches declining in the lower middle Fly (sites FLY14, FLY15) over recent years (Figure 3). Barramundi catches in the lower Fly at Ogwa (FLY20) have not shown the same decline over recent years and there is no evidence of a decreasing trend in catches in this area of the river.

Fish catches in many off-river water-bodies on the floodplain of the middle Fly continue to be high, but also show considerable inter and intra-annual variability. Differences in catch size and species composition were recorded between blocked valley lakes and oxbow lakes, with several of the smaller fish species being more abundant in the shallower, well-vegetated blocked valley lakes (eg. *Melanotaenia* sp.), while the deeper oxbow lakes supported more of the larger predatory species (eg. *Lates calcarifer*). Catches in the oxbow lakes were also generally higher and more diverse than the blocked valley lakes or grassed floodplain sites

(Figure 8). Although catches at many sites have shown declines in species diversity and biomass over time such changes are thought to be due largely to climate phenomena, particularly El Niño droughts, which cause large areas of the floodplain to dry out periodically, with adverse consequences for fish stocks through loss of habitats and changes in water quality. There is as yet no evidence that declines in fish stocks in any off-river water-bodies are due to the effects of upstream mining operations (Swales *et al*, op.cit). Also, in recent years two species of introduced fish, the climbing perch, *Anabas testudineus,* and the walking catfish, *Clarias batrachus*, have become widespread and abundant in floodplain areas of the Fly River system, with unknown consequences for native fish stocks (Storey et al., in prep.).

Results and Lessons Learned

The major findings of this study are that the fish populations and fisheries of the Fly River system have been influenced greatly by a range of both natural and anthropogenic factors, including the hydrological effects of recent major El Niño droughts, introduced species and, most significantly, through the recent environmental changes associated with mining operations in the catchment, specifically through the effects of the Ok Tedi copper mine situated in the headwaters of the Fly River. The results of long-term biological monitoring of the Fly River system suggests that recent major reductions in biodiversity and fish population abundance in the main channel of the Ok Tedi, upper and middle Fly are directly attributable to environmental changes associated with the input of mine waste discharges from the Ok Tedi copper mine.

In particular, significant declines in fish catches at riverine sites in the Ok Tedi and Fly River since commencement of sampling are likely to be indicative of corresponding reductions in overall fish population abundance (Swales *et al.,* 2000). Long-term monitoring of fish populations has demonstrated significant declines in fish catches at many riverine sites over the period of sampling, coinciding with the period of operation of the Ok Tedi mine and the discharge of mine wastes into the Ok Tedi/Fly River system (Smith & Hortle, 1991; Smith & Morris, 1992; Swales *et al*, op.cit.). However, changes in fish catches in floodplain sites do not appear to be mine-related and appear to be largely associated with climatic factors (Swales *et al* 1999). Also, no significant changes in fish catches were apparent at riverine sites in the lower Fly, below the junction with the Strickland River. Fish catches at sites in the upper Fly River have, however, also declined over the period of monitoring, with these changes probably being related to the lack of recruitment from the depleted fish populations in the middle Fly area (Swales *et al*, op.cit).

The decline in fish catches at sites along the Ok Tedi and Fly River, from the region of the Ok Tedi mine, shows a longitudinal gradation. The greatest reductions are seen at sites closest to the discharge of mine effluents, with a declining progression down to the lower reaches as the effects of mine discharges are reduced. The declines in fish catches downstream of the mine are suggestive of adverse environmental impacts arising from the discharge of mine-derived effluents into the headwaters of the river system. However, the evidence which is currently available is largely circumstantial and there is little information on cause and effect. Although a range of bioassay and toxicity studies have been carried out over recent years, no acute toxic effects of mine discharges on water quality and aquatic life have been detected (Smith et al., 1990). A recent study showed no evidence of toxicity of copper to algae in the Fly River system and the evidence which is available suggests that most of the copper in the system is bound to dissolved organic carbon and is not bio-available (OTML, 1999; Smith et al., 1990; Stauber, 1995).

A range of possible impact mechanisms may be associated with the declines in fish catches in the system. Although there is no evidence that changes in water quality through the input of mine wastes are directly toxic to aquatic life, monitoring of metal levels in fish tissues from samples taken from a range of sites in the Ok Tedi and Fly River has demonstrated elevated levels of copper, lead, zinc and cadmium in fish flesh, liver and kidney. However, there is currently no evidence that the metal levels recorded in these samples are indicative of lethal or sub-lethal effects of mine wastes on fish survival (Smith *et at* 1990; Swales *et al*, 1998).

Other possible causes for the declines in fish catches in the system include the increased suspended sediment concentration and increased rate of river bed aggradation. Although TSS concentrations have increased several fold over pre-mine levels, there is no evidence that these levels are toxic to fish and other aquatic life. Most rivers in New Guinea are naturally turbid due to the high rainfall and land instability and it is thought that fish and other aquatic life are adapted to the high sediment loads. The dominance of Ariid and Plotosid catfish in the fish fauna of many rivers is thought to be indicative of the natural adaptation of the fish fauna to high sediment loads. However, since levels of TSS have increased several fold over pre-mine levels there is clearly potential for adverse effects on fish stocks and significant adverse effects on fish are likely in many areas of the river.

The greatly increased rate of river bed aggradation due to the input of mine wastes into the system is perhaps of more significance to aquatic fauna than increases in TSS. The extent of bed aggradation from pre-mine levels varies from over 6 metres in parts of the Ok Tedi to around 2-4 metres in the middle Fly. Although there is no direct evidence for adverse effects on fish and other aquatic fauna, it is very likely that such high levels of sedimentation would result in considerable loss and damage to fish habitats and the elimination of other aquatic life. Consequently, it is most likely that in severely impacted areas, such as the Ok Tedi, physical loss and damage to habitats is probably the main reason for the declines in fish catches which have been observed. In other areas, such as the middle Fly, the role of river bed aggradation in declines in fish catches is less clear, largely due to a lack of quantitative information relating levels of habitat loss and degradation to river bed aggradation in the system.

It is well established that fish populations in tropical river systems exhibit large natural variations in abundance associated with natural environmental factors such as climatic changes associated with El Niño droughts, which have major effects on the extent of floodplain inundation in the Fly River (see Swales *et al*, 1999; Winemiller, 1996). Since the life cycle of many riverine fish is closely associated with the annual cycle of flooding, variations in river flow may have major consequences for fish population dynamics. There is evidence of this from the Fly River. There has been a succession of El Niño droughts in the region in 1982, 1986, 1992 and most recently in 1997. During these droughts the majority of the floodplain, except for deeper floodplain lakes, dries out, and in response, fish move off the floodplain and into the main river channel. At this time, as fish become concentrated in the main channel, fish catches may increase, as occurred at Kuambit, Bosset and Obo following the 1992 drought. The increased dominance of barramundi in catches at riverine sites in 1990-91 was also thought to be due to natural climatic factors as more fish migrated up the river from coastal spawning areas, following a period of very good recruitment (Swales *et al*, 2000).

Off-river water-bodies on the Middle Fly floodplain provide important habitats for fish spawning and recruitment and provide both adult and juvenile fish with valuable feeding and refuge areas. It is known that river bed aggradation in the lower Ok Tedi and middle Fly areas has caused die-back of floodplain forest over large areas (currently approx. 500 km^2), due to increased frequency and duration of floodplain inundation, with the likelihood of further significant increases in the extent of die-back (OTML, 1999). Although fish catches at floodplain sites have remained relatively high over recent years, losses of large areas of floodplain forest in the middle Fly area clearly may be adversely impacting the floodplain ecosystem and hence fish ecology. Also, these effects may be being partially masked by the large fluctuations in the fish populations in the off-river water-bodies, which are associated with the effects of the El Niño droughts.

In addition, other anthropogenic and natural environmental factors may also be involved in the recorded declines in fish catches in the system. For example, the extent of artisanal and subsistence fishing in the middle Fly River has increased over recent years as more resources have become available. It is likely that these fisheries may have a substantial impact on fish stocks, particularly in species such as barramundi, although there is little available information. However, the artisanal and commercial fisheries in the middle and lower Fly have been estimated to be relatively low, in the range of 600 tons/year. This figure has been estimated to be approximately 10% of the potential yield of the fishery in this part of the river (Swales, 1998). However, there is clearly potential for major reductions in fish catches in both commercial and artisanal fisheries if populations continue to decline in the middle Fly and if these reductions spread to downstream areas of the river. However, there are currently no restrictions on catch size or fishing effort to limit the artisanal subsistence fisheries. Although legal size-limits are imposed on catches in the commercial fishery for barramundi, in practice these are not monitored due to a shortage of resources, consequently leading to the over-exploitation of juvenile fish, particularly in coastal areas, with potentially serious effects for the fishery (Swales, 1998).

This case-study has shown clearly how a single resource development operation in a developing country has had devastating environmental effects on a major world river system, with severe consequences for fisheries biodiversity. Perhaps the most important single lesson to be learned from this experience is the urgent need for more international cooperation amongst environment, conservation and fisheries agencies and the need to be more pro-actively involved in the protection and management of a country's resources. There is also an urgent need to implement legislation which would not allow major resource developments such as this to proceed without adequate protective measures and other safeguards in place to protect the environment.

Guidelines, Policies or Legislation that have Resulted from this Experience

The main approach to fish and fishery restoration in the Fly River system is currently one of investigating environmental management through mitigation of mining impacts rather than through active management of the fishery itself. In 1996, Ok Tedi Mining Limited commenced studies to undertake a Human and Ecological Risk Assessment (HERA) to provide management advice on the environmental risks posed by the operations of the mine. The overall purpose of the HERA was to provide a comparative assessment of the ecological risks associated with five different mine waste mitigation options. A Peer Review Group (PRG) was also formed from international experts in the field of environmental science to provide advice, recommendations and peer review related to the human and ecological risk assessment of the terrestrial and aquatic ecosystems of the Ok Tedi/Fly River systems downstream of the mine. The HERA was based on the state of knowledge to July 1999.

As a result of these and previous studies (OTML, 1996), Ok Tedi Mining Ltd. recently commenced a program of works aimed at mitigating the impacts of mine waste discharge on the Ok Tedi/Fly River system. A number of possible mitigation schemes were evaluated and a trial scheme was selected which involved the dredging of a selected area in the lower Ok Tedi to remove mine-derived sediments from the water column. A further possible option, which awaits full evaluation, is the piping of tailings waste to storage areas in the lower Ok Tedi. It is hoped that the dredging scheme will reduce the rate of river bed aggradation and so reduce the adverse environmental effects associated with mine operations. However, other mitigation options are also currently being assessed by Ok Tedi Mining Ltd., ranging from immediate mine closure to dredging and storage of tailings.

The HERA provided Ok Tedi Mining Ltd. with a comparative assessment of the relative risks associated with five different mine waste mitigation options (OTML, 1999);

- Mine closure in FY2000 (Option A – Early Closure Option);
- Dredge to FY2001 and store tailings to FY2010 (Option B – Tailings Option);
- Dredge through FY1999 (Option C – No-Dredge Option);
- Dredge 15 million tons per annum (Mt/a) to FY2010 (Option DL – Dredge Low Option);
- Dredge 19 Mt/a to FY2010 (Option DH – Dredge High Option).

The conclusions from the study point out that there exist a number of uncertainties regarding the possible environmental effects of continued mine operation and waste discharge on the hydrological, chemical and biological properties of the aquatic environment of the Ok Tedi/Fly River system. In particular, a lack of clear understanding of the precise mechanisms underlying the recent declines in fish populations in the river system causes serious difficulties in making recommendations for adequate mitigative measures.

Also, a lack of previous studies of mining impacts and suitable techniques for habitat restoration in large tropical river systems means that there are few, if any, previous studies which could assist in management decisions. Although there is a growing amount of experience and information on fisheries and watershed rehabilitation in temperate river systems (see Cowx & Welcomme, 1998; Lucas & Marmulla, 2000; Swales, 1994a, 1994b), little of this is directly applicable to the restoration of large, complex tropical rivers, such as the Fly River system. Most efforts at river and fishery rehabilitation have been carried out in temperate river systems supporting commercially or recreationally valuable fisheries (Bayley *et al*., 2000). In many ways, the Fly River system, its fish communities and the environmental changes produced through mining activities and the methods required for its mitigation are probably unique in the world.

It is likely that the recovery of Fly River fish populations to pre-mine levels will necessarily depend largely on the rate at which suitable habitat conditions are restored in the river. It is anticipated that mine closure and the cessation of waste input into the system would provide the greatest effect in mitigating risks to aquatic life. This option would result in a rapid reduction in TSS to pre-mine levels, thereby reducing TSS risks to aquatic life. Riverbed aggradation relative to other mitigation options would be substantially reduced, although still elevated several metres relative to pre-mine levels. The impact of this on risks to aquatic life is unknown.

The waste discharges from the Ok Tedi mine are currently the only major human disturbance affecting the aquatic ecosystem of the Fly River system. The river catchment consists predominantly of primary tropical rainforest and open Savannah grasslands, while the river itself is completely unregulated by dams, water diversions or other abstractions (the Western Province area of PNG is sparsely populated, with an average human density of less than two persons per square kilometer). The river system also has a large, intact floodplain system of lakes and other wetlands, with a network of channels linking the river to its floodplain. There are few such river systems remaining intact in the world, particularly in western, temperate countries, where most have been grossly modified by land clearance, river engineering and water pollution (Welcomme, 1995). The adverse environmental effects of current mining operations, the proposed mitigation of mine impacts and the restoration of the Fly River system to its former condition must therefore be considered as issues of major national and international importance.

This case-study showed clearly that fish populations in this major tropical river system exhibited significant declines in abundance and diversity, almost to the point of extinction in some areas, associated with the long-term discharge into the river system of large amounts of mine-waste materials from the Ok Tedi copper mine. Although the Fly River system is by world standards a major river system, in terms of water discharge, this has not prevented mine-waste pollution from a single point source from having devastating environmental effects over large stretches of river. The ability of the river system to assimilate the waste materials has clearly been exceeded, causing major changes to the aquatic and terrestrial environments and large reductions in fish population abundance and diversity in the system.

Also, this case-study clearly illustrates the essential need for adequate waste treatment and storage measures when mining and exploiting mineral resources within a watershed. Mining operations in both temperate and tropical regions may have major environmental consequences, for both terrestrial and aquatic ecosystems (Sengupta, 1993). In the case of the Ok Tedi mine, seemingly intractable problems for waste storage - related to the geological instability and high rainfall in the area - meant a tailings storage dam could not be constructed in the early stages of the project. As a result, with the full agreement of the PNG government authorities, the only available option was the disposal of waste rock and tailings directly into the Ok Tedi River, with the likely environmental degradation, which would ensue.

One of the major findings from this case-history is the vital importance when assessing the aquatic environmental impacts of resource development projects of a detailed, long-term biological monitoring program and the use of fish populations as the main indicator organisms for assessing environmental degradation (see Fausch, 1990; Simon, 1999). The inherent dynamic diversity in fish assemblages of tropical rivers (Winemiller, 1996) means that long-term monitoring of populations is required to detect population changes due to both natural and anthropogenic causes. Large tropical rivers are complex ecosystems, with many factors affecting biotic communities and an extensive dataset is required to begin to assess environmental change due to anthropogenic disturbance. The results of this study also illustrate how major climate-change events, in this case El Niño droughts, can have marked effects on fish population dynamics in tropical rivers. However, many factors, both natural and anthropogenic, were shown to exert important influences on fish populations in the Fly River system.

Although there is considerable circumstantial evidence linking declining fish catches in the Ok Tedi and Fly Rivers with the discharge of waste materials from the Ok Tedi mine, there are considerable uncertainties over the precise causal mechanisms underlying the declines in fish catches in the system and also the likely environmental effects of the different mine waste mitigation options. This reflects both our lack of understanding about how large tropical river ecosystems function and also the practical and logistic difficulties of studying a large, remote tropical river system. The main emphasis in most studies in freshwater ecology has, until recently, been on small streams and rivers in temperate regions and relatively few studies have been carried out on large tropical river systems (Bayley *et al.*, 2000).

This case-study also shows the importance of undertaking not only a detailed long-term fish population monitoring program, but also of carrying out adequate research studies to link changing fish catches with the underlying environmental mechanisms. In addition to demonstrating declining fish catches through a well designed fish monitoring program, it is also essential to be able to elucidate the ecological mechanisms underlying the declines. Research investigations should also be carried out concurrently with the monitoring program, rather than at a later date when an impact has been demonstrated. The lack of such information in this case-study has clearly impaired the ability to implement suitable mitigative measures to restore fish population abundance in the Fly River system.

The practical and logistical difficulties in carrying out fishery studies in a large tropical river system should also be borne in mind and should not be underrated. Similarly, the lack of understanding about how such ecosystems function has hindered developments in effective river management. As already stated, most ecological studies on fish communities have been carried out in temperate streams and rivers and relatively few have been undertaken in tropical regions of the world, particularly on large river systems. There may be considerable differences in the ecological dynamics of fisheries in tropical river ecosystems, which are connected with hydrological and climate differences between temperate and tropical regions (Talling and Lemoalle, 1998; Welcomme, 1979,1985).

This case-study also clearly illustrates the difficulties facing the sustainable development of mineral resources in a third-world country. The need to develop resources to provide economic benefits to a developing country should not outweigh the need to conserve the environment and protect its flora and fauna. In hindsight, the question of whether to proceed with a resource development project such as this without adequate measures to protect the environment should perhaps have been considered more seriously before mining operations were allowed to proceed. In the long-term, the environmental costs of proceeding with such a venture may outweigh the economic and community benefits. As such, the major benefit of this case-study may ultimately lie in demonstrating the difficulties involved in the sustainable development of mineral resources within the watershed boundaries of a tropical river system in a developing country and the wide range of both natural and anthropogenic factors which may impact upon a tropical river fishery.

Conclusions

1) Monitoring of fish populations in the Fly River system in the Western Province of Papua New Guinea has indicated major declines in fish catches in the Ok Tedi, middle and upper Fly areas which seem to be related to both natural and anthropogenic factors.

2) Declines in fish catches and biodiversity in main channel sites in the Ok Tedi, upper and middle Fly appear to be directly related to the environmental changes associated with waste discharges from the Ok Tedi copper mine. In contrast, changes in fish catches at floodplain sites in the middle Fly area appear to be related to hydrological changes associated with recent El Niño droughts.

3) Circumstantial evidence suggests that river bed aggradation due to the deposition of mine-derived sediment and the subsequent loss and damage to fish habitat is the most likely cause of the decline in fish populations. However, other factors, such as reductions in water quality and the toxic effects of waste metals, may also be involved.

4) However, fish catches in floodplain lakes generally remained high, although population reductions were associated with the effects of recent El Niño droughts. Similarly, fish catches at sites in the lower Fly area remain high.

5) Fish catches in the Ok Tedi were the most badly affected, with catch reductions of up to 95% and the elimination of most fish species. Fish catches at sites in the middle Fly were also markedly reduced over the period of monitoring. Catches of barramundi, an important commercial fish species, also declined considerably during the 1990’s.

6) The case-study illustrates both the necessity for long-term monitoring of riverine fish populations in detecting the adverse effects of human impacts associated with resource development and the difficulties in complex tropical ecosystems of isolating causal mechanisms associated with declines in fish catches.

7) Mitigation of the adverse effects on fish populations requires adequate information on the environmental effects of mining activities. Research investigations should be carried out concurrently with environmental monitoring.

8) The sustainable development of resources in developing countries is only achievable when the economic gains are not jeopardized by the environmental costs.

References

Bayley, P. B., K. O'Hara, and R. Steel. 2000. Defining and Achieving Fish Habitat Rehabilitation in Large, Low Gradient Rivers. Pages 279-290, *in* I. G. Cowx, (Ed.). Management and Ecology of River Fisheries. Fishing News Books.

Bishop, K. A., and Forbes, M. A. 1991. The Freshwater Fishes of Northern Australia. Pages 79-107, *in* C. D. Haynes, M. G. Ridpath, and M. A. J. Williams, (Eds.). Monsoonal Australia, Landscape, Ecology and Man in the Northern Lowlands. A. A. Balkema, Rotterdam.

Coates, D. 1993. Fish Ecology and Management of the Sepik-Ramu, New Guinea, a Large Contemporary Tropical River Basin. Environmental Biology of Fishes 38:345-368.

Cowx, I. G., and R. L. Welcomme. 1998. Rehabilitation of Rivers for Fish. Fishing News Books. 260 p.

Fausch, K. D., J. Lyons, J. R. Karr, and P. L. Angermeier. 1990. Fish Communities as Indicators of Environmental Degradation. American Fisheries Society Symposium 8:123-144.

Harris, J. H. 1995. The Use of Fish in Ecological Assessments. Australian Journal of Ecology 20:65-80.

Kare, B. 1995. A Review of Research on Barramundi, Reef Fish, Dugong, Turtles and Spanish Mackerel and Their Fisheries in the Torres Strait Adjacent to Papua New Guinea. Science in New Guinea 21:43-56.

Lucas, M. C., and G. Marmulla. 2000. An Assessment of Anthropogenic Activities on and Rehabilitation of River Fisheries: Current State and Future Direction. Pages 261-279, *in* I. G. Cowx, (Ed.). Management and Ecology of River Fisheries. Fishing News Books.

Milton, D. A., D. Die, C. D. Tenakanai, and S. Swales. 1998. Selectivity for Barramundi (*Lates calcarifer*) in the Fly River, Papua New Guinea: Implications for Managing Gill-net Fisheries on Protandrous Fishes. Marine and Freshwater Research 49:499-506.

Moore, R. 1982. Spawning and Early Life History of Barramundi (*Lates calcarifer*) in Papua New Guinea. Australian Journal of Marine and Freshwater Research 30:647-61.

Moore, R., and L. F. Reynolds. 1982. Migration Patterns of Barramundi (*Lates calcarifer*) in Papua New Guinea. Australian Journal of Marine and Freshwater Research 33:671-82.

Opnai, J., and C. D. Tenakanai. 1987. A Review of Barramundi Fisheries in Papua New Guinea. Pages 50-55, *in* Management of Wild and Cultured Sea Bass/Barramundi (*Lates calcarifer*). Proceedings of an International Workshop, 24-30 June, 1986. Darwin, N.T., Australia.

OTML. 1999. Assessment of Human Health and Ecological Risks for Proposed Mine Waste Mitigation Options at the Ok Tedi Mine, Papua New Guinea. Detailed Level Risk Assessment. Final Report. Ok Tedi Mining Ltd. 210 p.

Roberts, T. R. 1978. An Ichthyological Survey of the Fly River in Papua New Guinea with Descriptions of New Species. Smithsonian Contributions to Zoology 281:72.

Sengupta, M. 1993. Environmental Impacts of Mining - Monitoring, Restoration and Control. Lewis Publishers, London. 494 p.

Simon, T. P. (Ed.). 1999. Assessing the Sustainability and Biological Integrity of Water Resources using Fish Communities. C RC Press, Boca Raton. 671 p.

Smith, R. E. W., and K. G. Hortle. 1991. Assessment and Prediction of the Impacts of the Ok Tedi Copper Mine on Fish Catches in the Fly River System, Papua New Guinea. Environmental Monitoring and Assessment 18:41-68.

Smith, R. E. W., and T. F. Morris. 1992. The Impacts of Changing Geochemistry on the Fish Assemblages of the Lower Ok Tedi and Middle Fly River, Papua New Guinea. The Science of the Total Environment 125:321-344.

Smith, R. E. W., M. Ahsanullah, and G. E. Batley. 1990. Investigations of the Impact of Effluent from the Ok Tedi Copper Mine on the Fisheries Resource in the Fly River, Papua New Guinea. Environmental Monitoring and Assessment 14:315-331.

Stauber, J. L. 1995. Toxicity Testing Using Marine and Freshwater Unicellular Algae. Australian Journal of Ecotoxicology 1:15-24.

Swales, S. 1998. Theoretical Yields and Current Status of Commercial and Artisanal Fisheries in the Middle Fly River. Unpublished report to Ok Tedi Mining Ltd. 15 p.

--------- 1994a. Strategies for the Conservation of Stream Fish Populations. Pages 34-48, *in* I. G. Cowx (Ed.). Rehabilitation of Freshwater Fisheries. Fishing News Books.

--------- 1994b. Habitat Restoration Methods – a Synthesis. Pages 133-138, *in* I. G. Cowx, (Ed.). Rehabilitation of Freshwater Fisheries. Fishing News Books. 486 p.

---------. Storey, A. W., I. D. Roderick, B. S. Figa, K. A. Bakowa, and C. D. Tenakanai. 1998. Biological Monitoring of the Impacts of the Ok Tedi Copper Mine on Fish Populations in the Fly River System, Papua New Guinea. The Science of the Total Environment 214:99-111.

----------, Storey, A. W., I. D. Roderick, and B. S. Figa. 1999. Fishes of Floodplain Habitats of the Fly River System, Papua New Guinea, and Changes Associated with El Niño Droughts and Algal Blooms. Environmental Biology of Fishes 54:389-404.

-----------, Storey, A. W., and K. A. Bakowa. 2000. Temporal and Spatial Variations in Fish Catches in the Fly River System in Papua New Guinea and the Possible Effects of the Ok Tedi Copper Mine. Environmental Biology of Fishes 57:75-95.

Talling, J. F., and J. Lemoalle. 1998. Ecological Dynamics of Tropical Inland Waters. Cambridge University Press. 441 p.

Welcomme. 1979. Fisheries Ecology of Floodplain Rivers. Longman, London

Welcomme, R. L. 1985. River Fisheries. FAO Fisheries Technical Paper 262. 330 p.

Welcomme, R. L. 2000. Principles and Approaches for River Fisheries Management. Pages 331-345, *in* I. G. Cowx, (Ed.). Management and Ecology of River Fisheries. Fishing News Books.

Winemiller, K. O. 1996. Dynamic Diversity in Fish Assemblages of Tropical Rivers. Pages 99-134, *in* M. L. Cody, and J. A. Smallwood, (Eds.). Long-Term Studies of Vertebrate Communities. Acadamic Press, San Diego.

Figures and Tables

Figure. 1. Location of study sites in the Ok Tedi/Fly River system

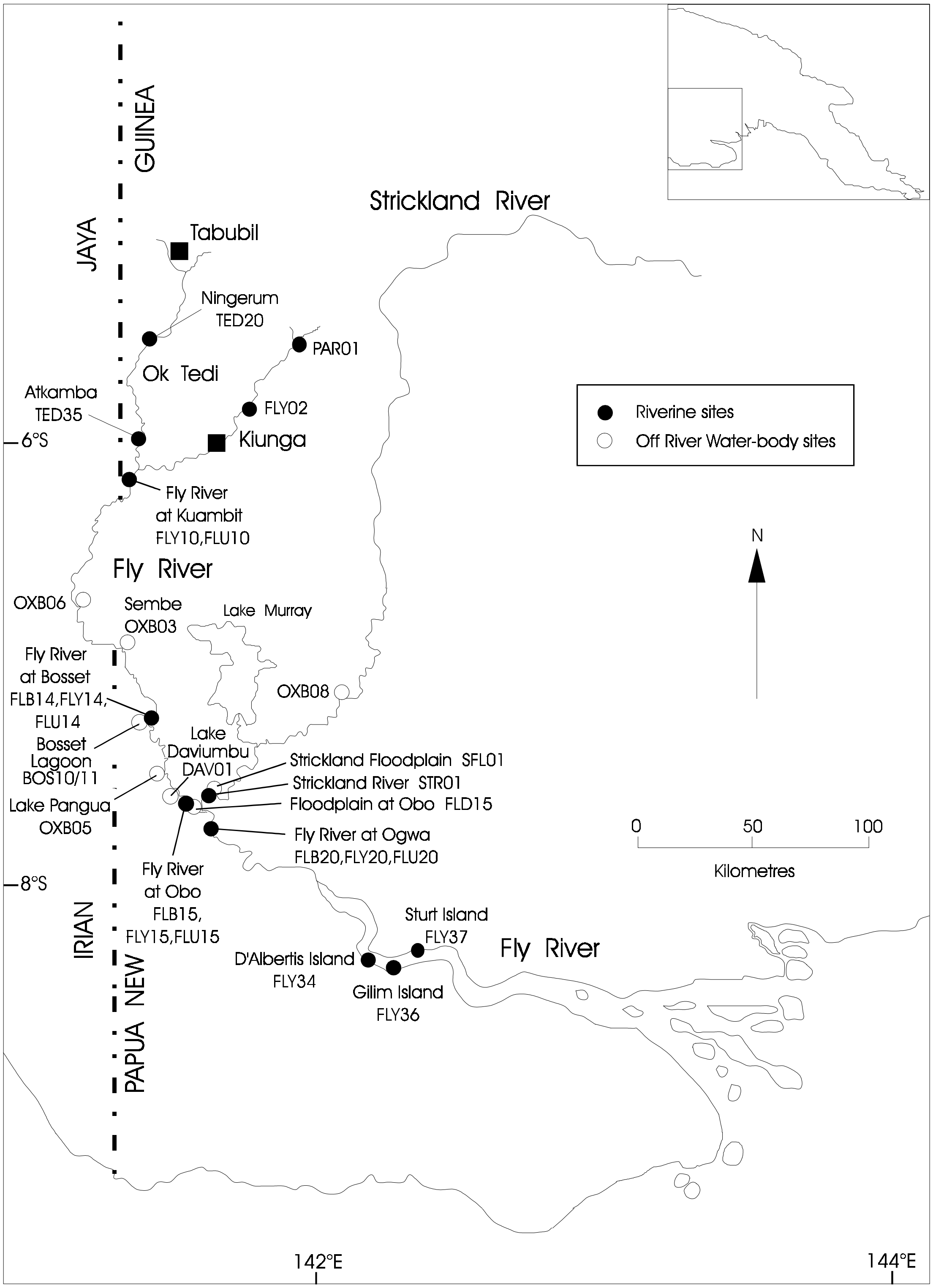

Figure 2. Percentage change in fish catches at study sites over the monitoring period. Figures in parentheses indicate significant (P<0.05) reductions.

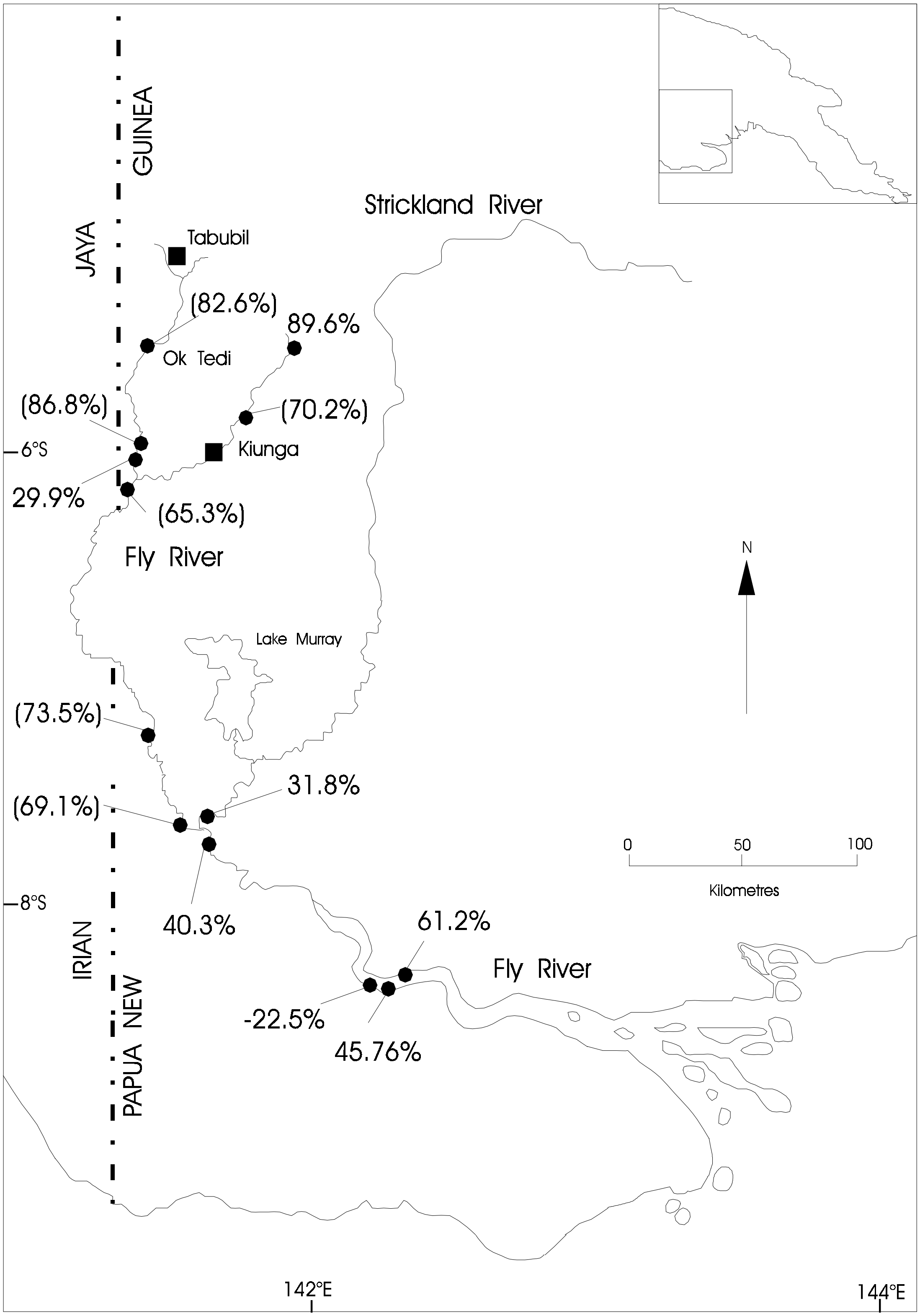

Figure 3. Temporal changes in catches of barramundi (mean ± 95 % CI) at sites in the Fly River.

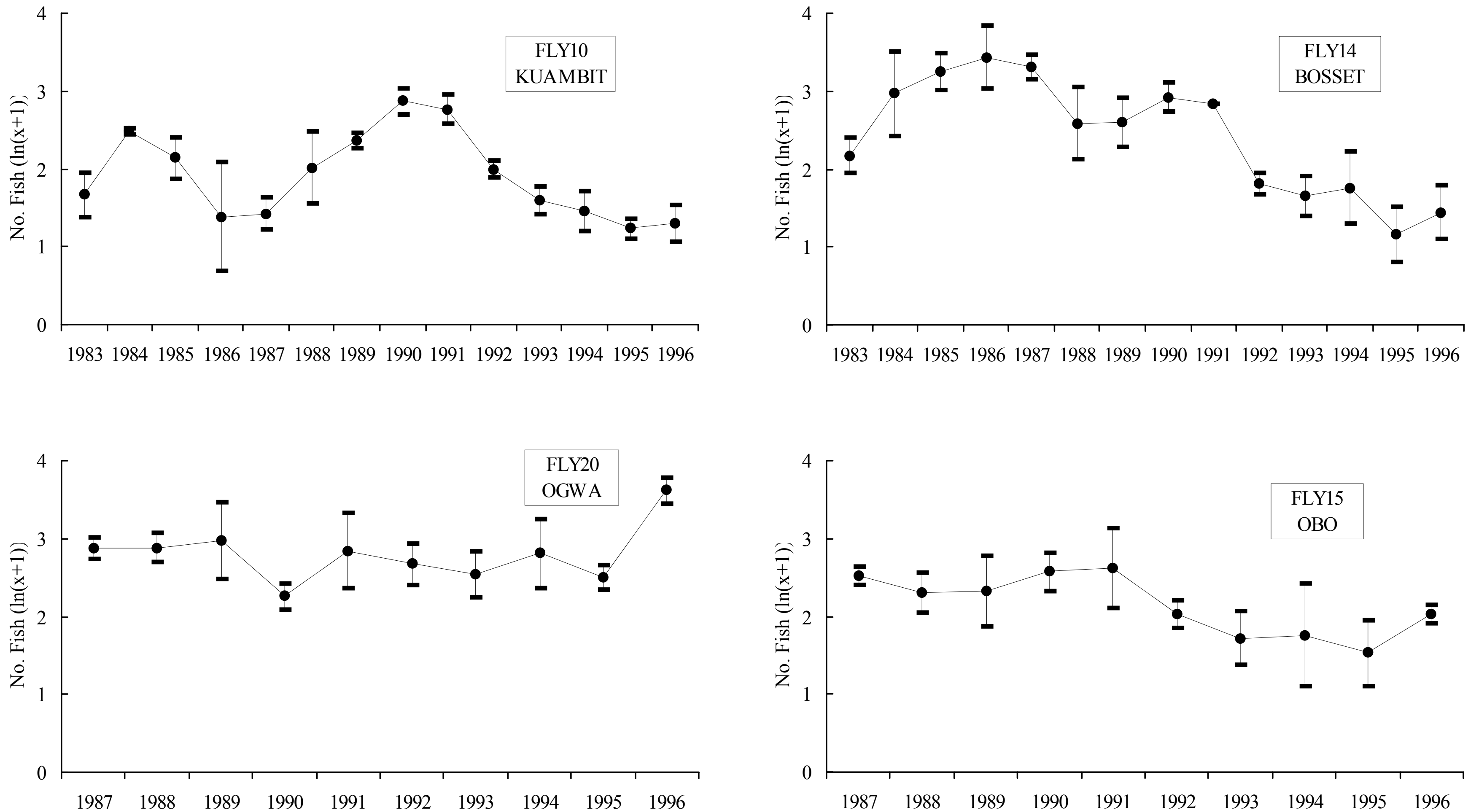

Figure 4. Mean number of fish species recorded at river channel sites since the commencement of sampling (♦ all riverine sites; □ Ok Tedi sites only; ο all sites except Ok Tedi).

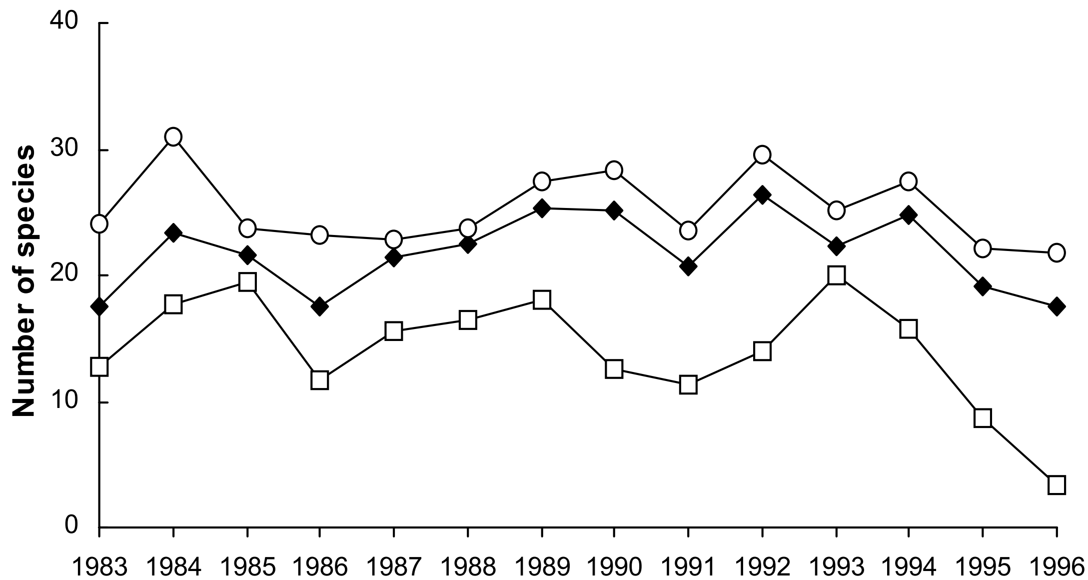

Figure 5. Annual number of fish species recorded in blocked valley lakes (•) and oxbow lakes (□) on Fly River floodplain.

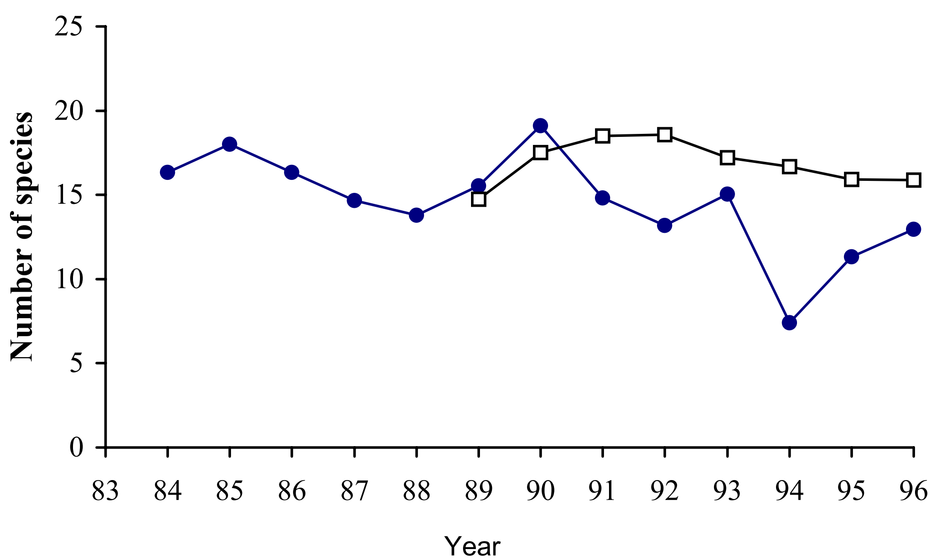

Figure 6. Temporal changes in Gill-net catches at sites in the Ok Tedi and Fly Rivers.

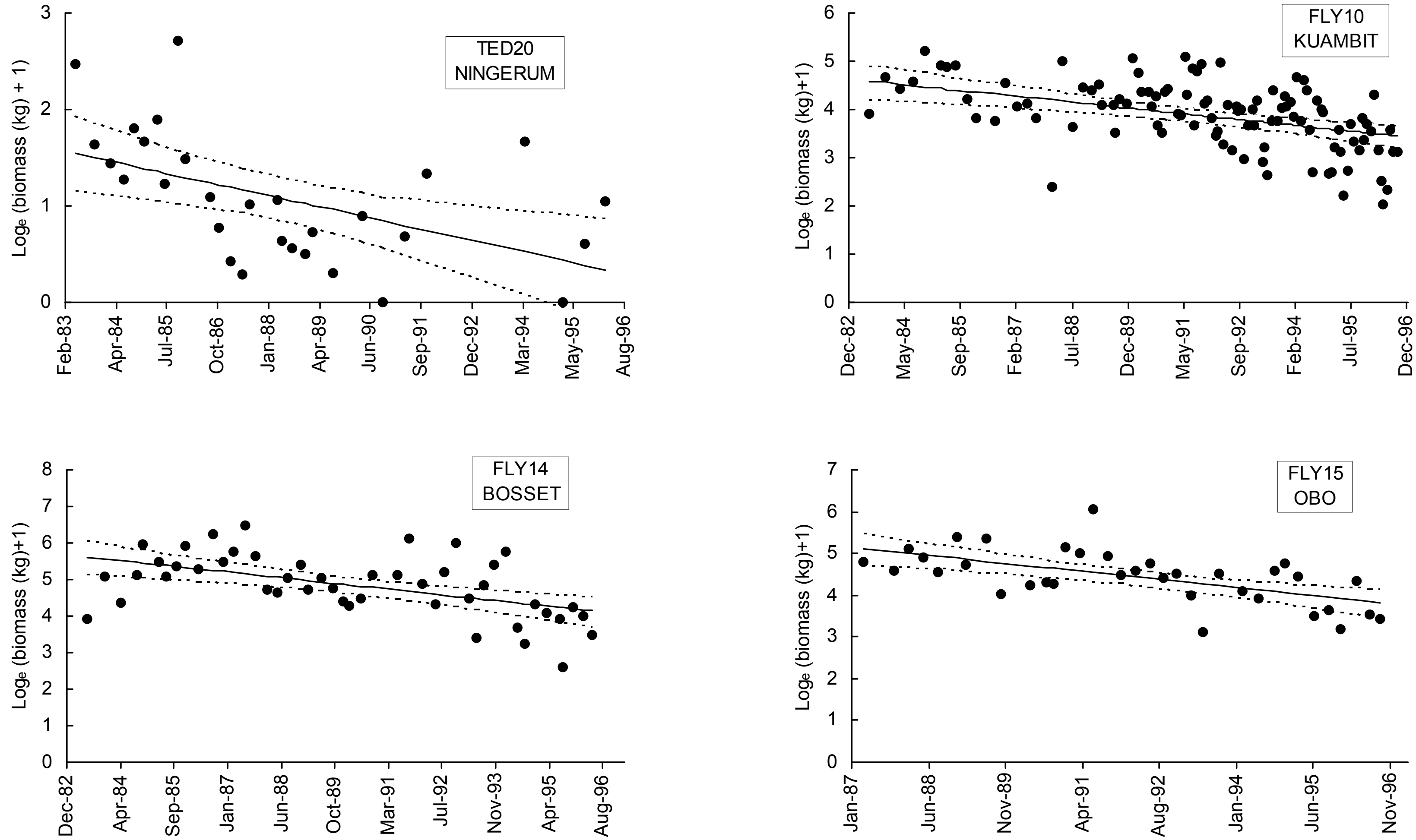

Figure 7. Mean estimates of fish catch biomass (open bars) and species number (shaded bars) (+/- 95% confidence limits) at each river channel site since the commencement of monitoring.

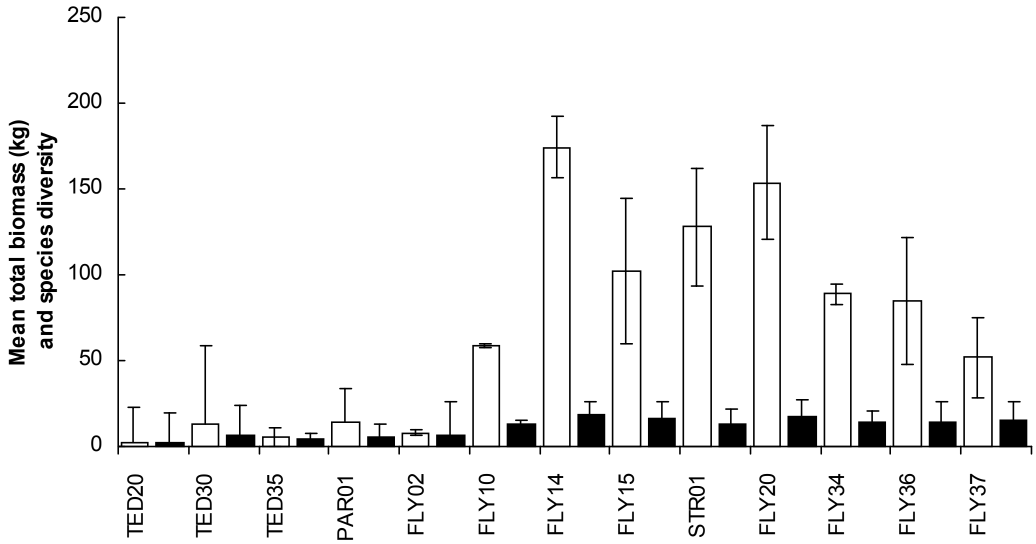

Figure 8. Mean fish biomass (open bars) and species diversity (shaded bars) estimates (+/- 95% confidence limits) recorded at each floodplain site.