

**RELATIONSHIPS BETWEEN
HABITAT AVAILABILITY
AND FISH DIVERSITY: A
REVIEW**



REPORT TO

Ok Tedi Mining Limited

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Frontispiece: Tenong Dremdap surveying a section of river bank on the upper Fly River between Kiunga and D’Albertis Junction, showing high diversity of fish habitat, with good representation of riparian canopy cover, trailing riparian vegetation, large woody debris, in-stream snag habitat, trailing root mats and undercuts.

1 EXECUTIVE SUMMARY.

The principal aim of this literature review was to establish conclusively if a general relationship existed between habitat availability and fish diversity. The review was also to source and summarise literature documenting the impacts of river bed aggradation on fish habitat availability and, if available, on abundance, biomass and/or diversity of fish.

It was assumed that the field component of this study (Storey & Marshall, 2003) would determine if a relationship existed between aggradation and habitat availability. The implications for fish diversity then would be inferred using the observed effects of aggradation on fish habitat and the findings of the literature review detailing the literature-based relationship between habitat availability and fish diversity. The literature review therefore concentrated on establishing whether a relationship exists between habitat availability and fish species diversity.

In the first instance, the review documented a very strong and scientifically accepted relationship between habitat diversity and fish species diversity. Habitat could be characterised by many parameters, however, parameters consistently shown to strongly influence habitat diversity included water depth, water velocity, substrate composition (i.e. particle heterogeneity) and attributes of cover (i.e. riparian and instream vegetation, bank morphology and amount of woody debris).

The review found an extensive literature on habitat relationships, however, most dealt with small to medium sized rivers, with few studies targeting large rivers. Similarly, few studies dealt with tropical river systems, mostly concentrating on rivers from temperate climates (northern European and American systems). The review also failed to identify studies reporting habitat modification as a result of high levels of river bed aggradation as seen in the Fly River system, with most studies dealing with minor sedimentation, detailing effects of relatively low levels of siltation (i.e. where substrates were covered by a coating of silt or individual pools were infilled, but not gross aggradation of the channel). Therefore, the literature review was not able to draw direct comparisons between aggradation as seen in the lower Ok Tedi and upper Middle Fly and comparable studies on other large, tropical river systems.

The literature demonstrated that changes in depth, velocity, substrate structure or degree of cover result in concomitant changes in habitat availability/suitability, with associated declines in abundance, biomass or diversity of fish species. In most instances, water depth was seen as

a key parameter influencing fish diversity. Given the scarcity of relevant studies it was not possible to document the direct effects of aggradation on habitat. However, water depth consistently appears as a key habitat parameter, and since water depth is influenced by aggradation, this parameter was selected for a targeted review of how changes in a key parameter may affect habitat availability.

The review summarised studies reporting decreases in species diversity associated with reduced habitat diversity, particularly with respect to channelization (i.e. straightening and simplification of the channel), and studies which reported increases in fish diversity (and biomass/abundance of individual species) following remediation actions, such as streamlining and replacing large woody debris (i.e. increasing habitat diversity). Although some case studies were available, the majority of the literature involved modelling the effects of reduced habitat availability, with inferred effects on diversity.

With respect to the Fly River, it is considered that the generalities of the above-described relationships between fish species diversity, habitat diversity and the parameters used to characterise habitat diversity also apply. Therefore, it is reasonable to assume that a reduction in habitat availability would lead to a reduction in fish diversity. Generally, studies using models of the relationships between habitat availability and species diversity to manage systems (usually flows in impounded rivers) were based on detailed knowledge of the specific habitat requirements of individual species (or different life stages of individual species such as larval, juvenile, spawning, adult). Currently, we have limited detailed knowledge of the habitat requirements of the different life history stages of species in the Fly River system. Without this information, at least for some key species representative of different trophic groups and/or guilds, it seems unlikely that any quantitative relationship between a specific change in habitat availability and fish diversity is possible. Without an empirical relationship, and given the weight of evidence presented by Storey & Marshall (2003) and conclusions from this review, it must be considered that aggradation will result in a reduction in habitat availability which will result in a loss in species diversity.

2 BACKGROUND

It is generally considered that the major cause of the declines in fish catch in the Ok Tedi and upper Middle Fly River is the loss of fish habitat as a result of the input of mined waste rock and tailings causing, among other things, extensive river bed aggradation. Although it is a reasonable hypothesis that the loss of fish habitat by aggradation adversely affects diversity of fish (and other aquatic life), there are no quantitative data that show that aggradation causes loss of fish habitat. Therefore, the conclusion that loss of habitat is the critical factor is based more on circumstantial evidence, observations and biological experience.

Therefore, it was seen as a valuable addition to the biological monitoring program to quantify the extent of loss of fish habitat in impacted reaches of the lower Ok Tedi and upper Middle Fly, and to attempt to relate habitat loss both to aggradation. Establishing this relationship between aggradation and habitat availability was attempted by field sampling (see Storey & Marshall, 2003).

Assuming a relationship existed, then the next step would be to link habitat loss to changes in fish diversity. This step would be difficult to establish in the field because of the absence of adequate fish catch monitoring data, and also because of confounding effects of other pressures on fish catch, such as fishing pressure from local villagers, El Niño droughts and La Niña floods and impacts on recruitment from the middle Fly. Therefore, it was decided to conduct a detailed literature review to establish the strength of the relationship between habitat and fish diversity and determine if it was possible to conclusively state that a reduction in habitat availability would lead to a loss in fish diversity.

To this end, this document presents a review of published studies reporting relationships between habitat availability and fish diversity, and also to assess the role various parameters play in the relationship and how a change in those parameters will affect any relationships.

3 WHAT IS HABITAT?

Before reviewing available literature for relationships between fish habitat and fish diversity, it is necessary to as clearly as possible define the term habitat with respect to fish. In its simplest form, habitat may be considered as the area in which an organism is found. This definition may be adequate for totally sessile organisms. However, most organisms are mobile and may be found in different places for varying lengths of time. Preservation of one area may not guarantee protection of the organism if other places that are critical to the life history are

unprotected. Pusey (unpub.) suggested that for freshwater fish, habitat must provide suitable water quality, migration routes, spawning grounds, feeding sites, resting sites, and shelter from predators and disturbance. To assure these life history attributes, habitat therefore should encompass those areas and conditions necessary for all life requirements of an organism (food, cover, space, mates etc) (Harris & Kangas, 1988; cited Pusey unpub.). Also, for an organism to persist, it must have a viable population size, and to have a viable population, habitat must be of sufficient size or configuration. This definition of habitat as used by Pusey (unpub.) for in-stream flow management of North Queensland fishes, is appropriate when considering fishes of the Fly River.

To reinforce the dynamic nature of fish habitat, Cowx & Welcomme (1998) commented that a fish seldom spends its entire life in the same habitat, and usually requires a different habitat with suitable microhabitat conditions for each specific life stage (Figure 1). They further noted that fish in rivers depend on undamaged interactive pathways along four dimensions:

- longitudinal,
- lateral,
- vertical, and,
- temporal

The longitudinal pathway encompasses upstream and/or downstream migration routes for spawning/recruitment. These migrations may be over tens or hundreds of meters, or many hundreds or even thousands of kilometres, encompassing movement between headwaters, estuaries and open ocean. The lateral pathway comprises the lateral movement to backwaters, vegetated margins, and flooded oxbow lakes, lagoons and floodplain in search of spawning, feeding, rearing/nursery and predator avoidance areas. Lateral movement also occurs to avoid high flows, particularly for young-of-the-year fish with poor swimming abilities. The vertical pathway includes riverine/groundwater interactions for species spawning in benthic substrates whereby oxygenated water must penetrate to a sufficient depth to ensure survival of buried eggs. This involves interactions with sediment particle size and water velocity. The temporal pathway refers to seasonal changes in the availability of different microhabitats and the availability of the appropriate microhabitat at the appropriate time of year/life history stage.

The above descriptions illustrate the dynamic spatial and temporal nature of fish habitat. Assessment of the quality and quantity of a specific microhabitat in an instance in time, although an important means of considering fish habitat, may be inadequate and misleading if other spatial or temporal habitat requirements for a species are ignored. For example, habitat

for adults of a species may be managed to perfection, but if the specific habitat required by larval or juvenile stages is not available – then the species will not proliferate. Similarly, suitable habitat for adults of a catadromous species (one that migrates from freshwater to the sea to spawn) may be provided in a reach, but if access to that reach by returning sub-adults is prevented by a man-made barrier (i.e. a weir), then the species will not survive in the reach. These spatial and temporal needs always must be born in mind when assessing fish habitat availability. However, without knowing in detail the life history of the fish species in the system to be managed it is not always possible to know the habitat requirements of all life stages or to foresee the implications of all management activities.

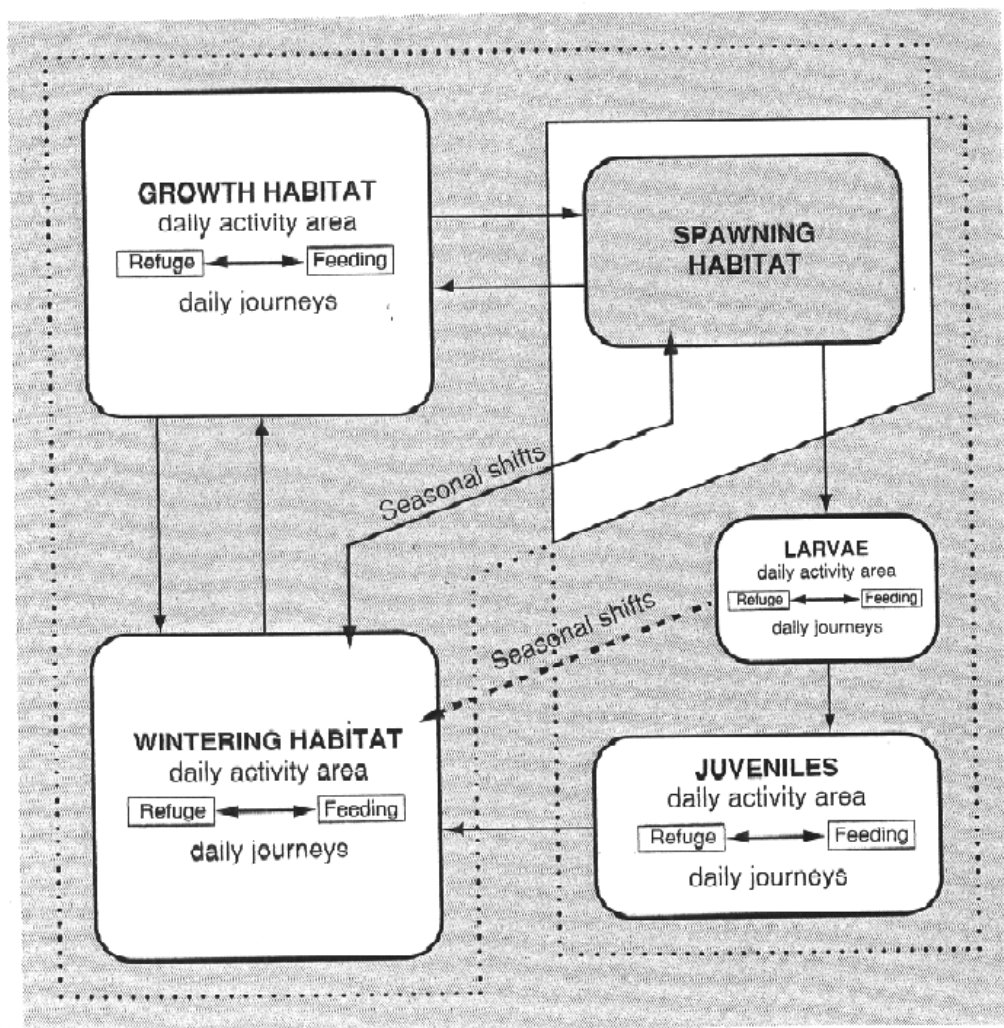


Figure 1. Functional Units in Fish Ecology (reproduced from Cowx & Welcomme, 1998; Figure 1.1)

The current study was aimed at assessing the quality of habitat at a specific location, and how changes in this habitat may affect its suitability and utilisation by fish. Therefore,

acknowledging that there are spatial and temporal considerations to fish habitat utilisation, the literature review predominantly considered reach-level changes in habitat condition and how this affected fish diversity.

4 DOES HABITAT DIVERSITY INFLUENCE FISH DIVERSITY?

There is an assumption that the greater the diversity of habitats within a system, then the greater the number of species of fish a system will support. This is also one of the three basic underlying principals that predetermine fish diversity in large, floodplain rivers of the world (Welcomme, 1985). Establishing the strength of the relationship between habitat diversity and fish diversity is important if a change in fish diversity as a result of a change in habitat is to be inferred. Although habitat diversity may be measured in different ways, there is a wealth of literature that supports the relationship. Gorman & Karr (1978) specifically examined the relationship between habitat complexity (diversity) and fish diversity in a number of streams in tropical Central America (Panama) and temperate North America. They found significant positive correlations between fish diversity and habitat diversity measured along three dimensions; water depth, water velocity and substrate type (Figure 2).

Following the methodology used by Gorman & Karr (1978), Schlosser (1982a) found significant positive relationships between habitat diversity and species diversity in a temperate North American stream (Figure 3). It was observed that predictable qualitative changes in fish community structure occurred along habitat gradients, however, random variations in flow played a critical role in regulating community structure and this precluded quantitative predictions. They noted that because of temporal variation, community attributes in shallow habitats seemed particularly variable.

In tropical northern Australia, Bishop & Forbes (1991), based on work by Bishop & Harland (1982), found a significant positive correlation between habitat diversity (measured in four dimensions; water depth, substrate type, aquatic vegetation and bank cover) and fish diversity (Figure 4).

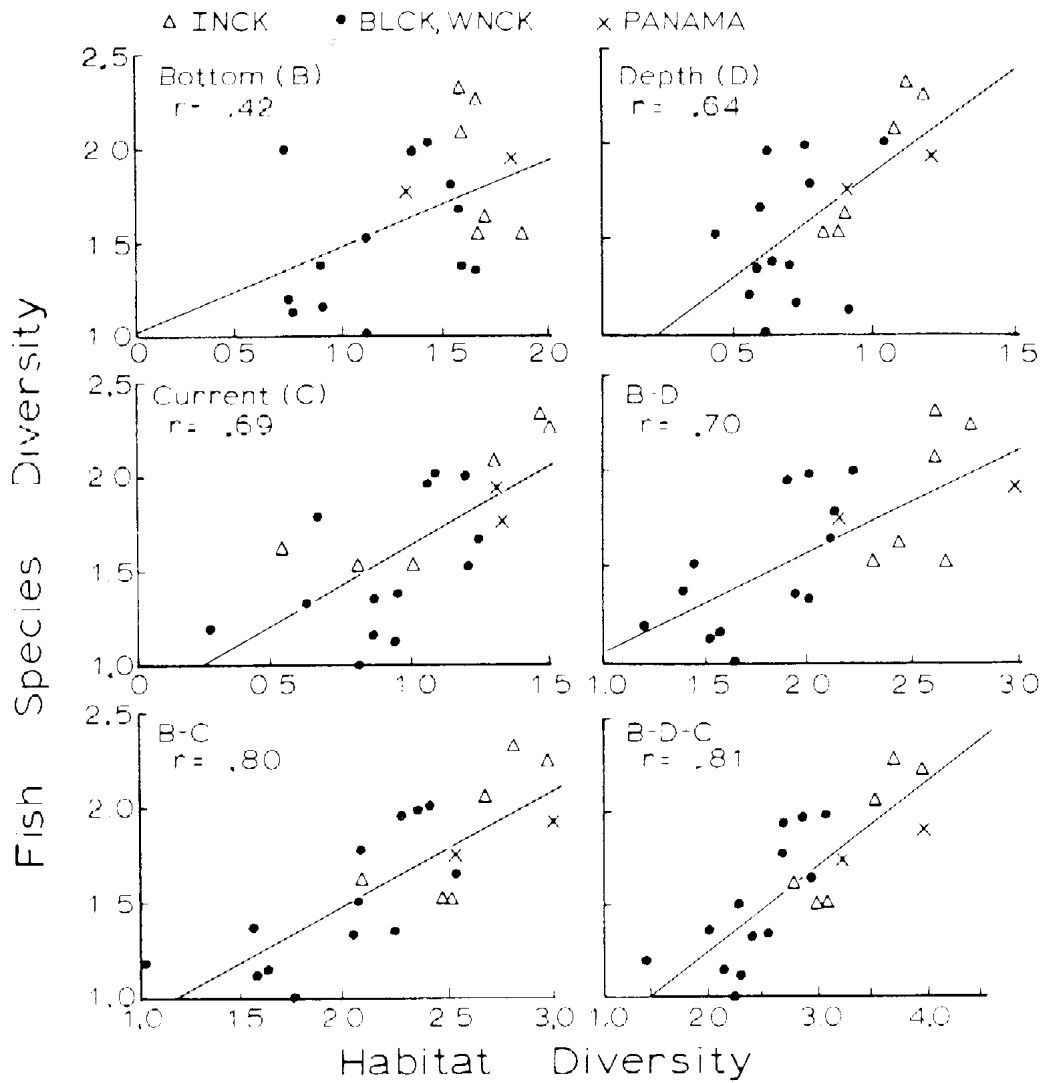


Figure 2. Regressions of fish diversity against habitat diversity for streams in Indiana and Panama (reproduced from Gorman & Karr, 1978; Figure 2).

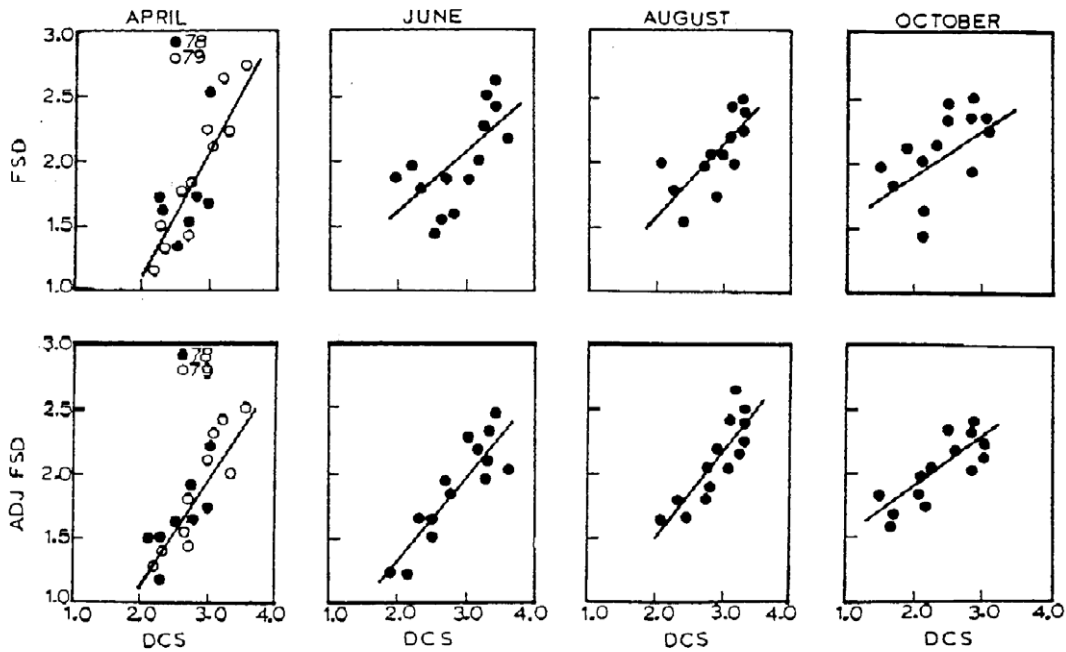


Figure 3. Relationship between habitat diversity (DCS) and fish diversity (FSD & Adj FSD) (reproduced from Schlosser, 1982a; Figure 9).

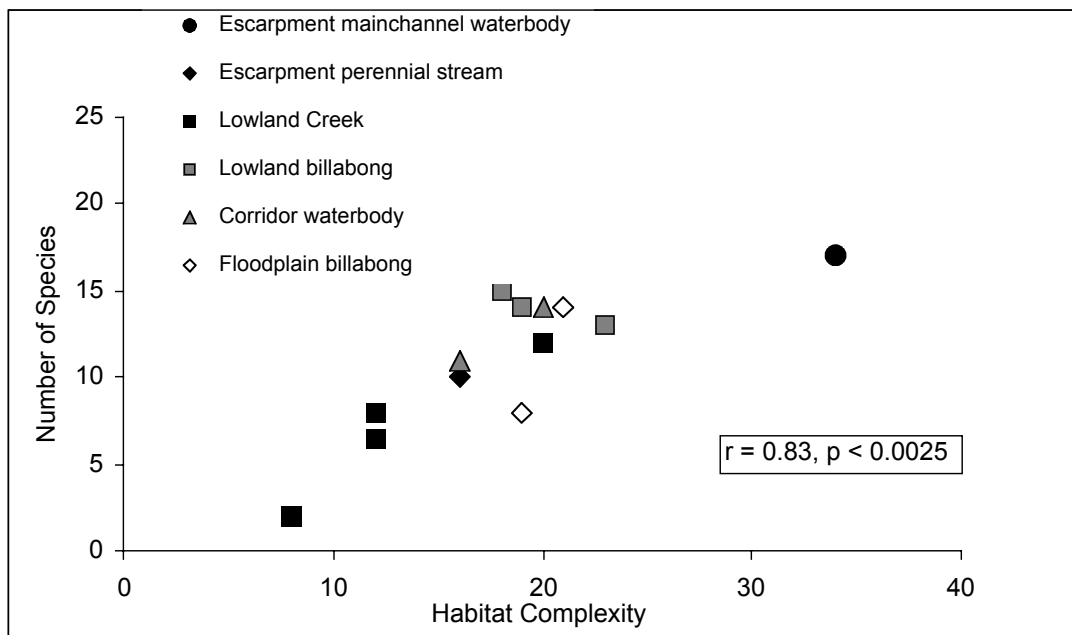


Figure 4. Relationship between habitat complexity and fish diversity (reproduced from Bishop & Forbes, 1991).

Cowx & Welcomme (1998) similarly reported a strong correlation between fish species diversity and habitat diversity, as calculated from a combination of substrate, depth and current (Figure 5). They commented that in lowland sections of rivers, the potential capacity of the reach to support a rich fish community depended on habitat complexity.

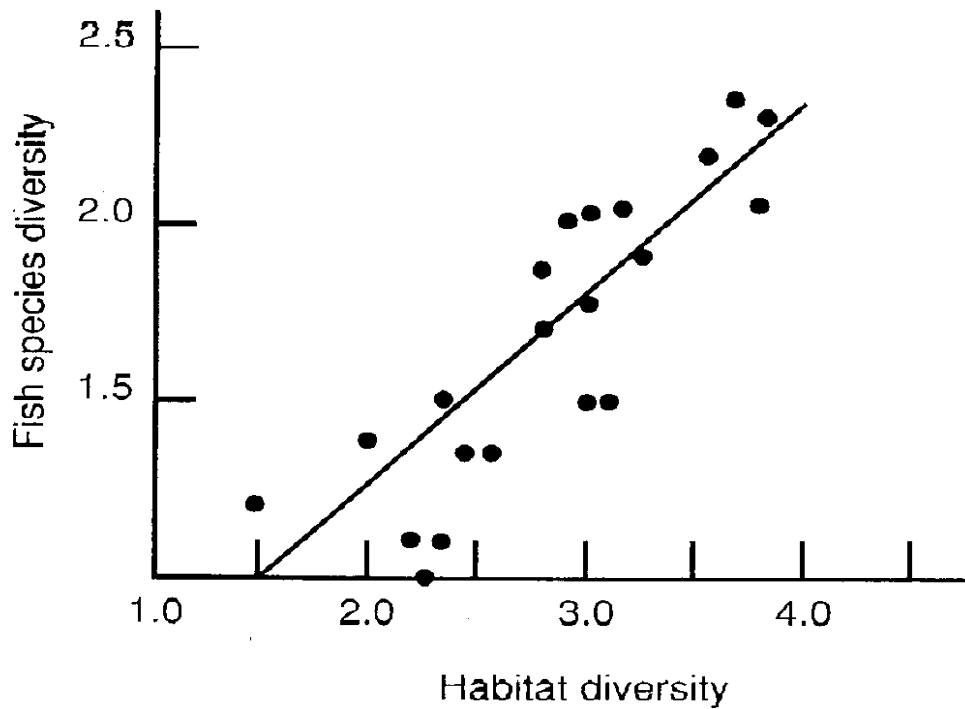


Figure 5. Relationship between habitat diversity and fish species diversity (reproduced from Cowx & Welcomme, 1998; Figure 1.5)

The literature therefore, demonstrates a strong relationship between habitat diversity and fish species diversity, which is well established and accepted in fish ecology. This acknowledged association between habitat diversity and fauna diversity has in recent years lead to the development of the ‘Functional Habitat Concept’ for river management, particularly in relation to the determination of environmental flows (Harper *et al.* 1995, Harper & Everard, 1998).

The Functional Habitat Concept treats the river as being composed of distinct habitat units, recognisable and classifiable both on the basis of their physical and their biological attributes (i.e. pools, backwaters, macrophyte beds, emergent vegetation, gravel runs etc) (Buffagni *et al.* 2000). It is assumed that it is possible to manage habitats in rivers far more easily than it is to manage species (Harper *et al.*, 1995, cited Buffagni *et al.* 2000), especially in species-rich systems, for which there may be little information on the biology of the individual species. Therefore, by having easily recognisable habitats, which support distinct communities, managing the river to maintain habitats is assumed to be an indirect way of maintaining the communities. This approach has been used in studies by Armitage & Pardo (1995), Buffagni *et al.* (2000), Harper *et al.* (1992; cited Harper & Everard, 1998), (Harper *et al.*, 1997; cited Harper & Everard, 1998), Harper & Everard (1998) (Harper *et al.*, 1998, cited Harper & Everard, 1998), Kemp *et al.* (1999) and Pardo & Armitage (1997).

5 WHAT PARAMETERS CONSTITUTE HABITAT DIVERSITY?

The above studies and others (i.e. Sheldon & Meffe, 1995; Capone & Kushlan, 1991) repeatedly demonstrated positive relationships between habitat diversity and fish species diversity. Review of the literature reveals that studies showing significant relationships between fish species diversity and habitat diversity consistently utilised the same suite of parameters to quantify habitat diversity. Cowx & Welcomme (1998) noted that depth, substrate and current all appear to be important in the use of microhabitat by stream fishes. They also noted that the presence of coarse woody debris in lowland rivers was regarded as being important in providing a major source of fish cover.

Sheldon & Meffe (1995) found depth (and covariates) and velocity (and covariates) were the primary correlates of biomass, richness, mean fish size and density in temperate rivers in North America. Bishop & Forbes (1991) and Bishop & Harland (1982) correlated species diversity to habitat diversity measured in four dimensions; water depth, substrate type, aquatic vegetation and bank cover. Gorman & Karr (1978) and Schlosser (1982a) assessed habitat diversity along three dimensions using measurements of water depth, water velocity and substrate type. The latter study also included features that could provide cover, such as tree roots and bank undercuts. Bain *et al.* (1988) used measures of water depth, current velocity, substrate coarseness and substrate heterogeneity (measures of diversity in particle size) to assess habitat diversity and found water depth and current velocity to be the most important variables affecting fish distribution. Sheldon (1968) and Moyle & Vondracek (1985) also found depth and velocity to be important habitat variables affecting fishes.

Koehn (1992) noted that depth and velocity were the major determinants of fish habitat. Grossman *et al* (1987a & b) noted that fishes in a Spanish river occupied statistically distinct microhabitats, with patterns reflecting responses to depth, velocity, substrate composition and cover. They suggested that water depth was the primary parameter influencing microhabitat use. Rabeni & Jacobsen (1993) note that fish distribution and abundance are affected by depth, current velocity, substrate particle size and cover characteristics, but that fish probably do not respond to these variables independently, but rather to combinations of variables in some hierarchical manner.

Schlosser (1987b; cited Shields *et al.* 1994) proposed a conceptual model based on previous studies that predicted increasing fish species diversity with increasing water depth and temporal physical stability. Newcombe (1981) considered that water depth and water velocity

were sufficient to estimate the relative capacity of a stream to support fish at any discharge, and Jowett & Richardson (1995) measured water depth, velocity and substrate size in assessing habitat use/preferences in eight native fish species in New Zealand streams.

These studies consistently utilised measures of water depth, water velocity, substrate composition and degree of cover (aquatic/emergent/riparian vegetation and woody debris) to characterise habitat diversity. Water depth was more often than not the main correlate with fish diversity. The exact attributes of these parameters that provide fish habitat have not been directly quantified, and these parameters likely will not function independently as Rabeni & Jacobsen (1993) noted.

6 EFFECTS OF ALTERED HABITAT DIVERSITY ON FISH DIVERSITY

As well as showing strong relationships between habitat diversity and fish diversity, the literature reveals many instances where a reduction in habitat diversity has led to a loss of fish diversity, and where rehabilitation projects have restored habitat diversity, leading to a recovery in fish diversity.

Channelization (the straightening of streams and removal of instream structures such as pool-riffle sequences and large woody debris) is one of the major reasons for loss of fish habitat. Cowx & Welcomme (1998) note that dramatic decreases in fish abundance and biomass, shifts in the species spectrum and complete loss of valuable species occur when the bed structure is made uniform during river engineering works. "On average, fish species diversity is 60% lower in channelized sections of rivers compared to natural conditions". Similarly, they noted the importance of large woody debris in rivers in providing habitat diversity, noting that fish density has declined more than eight-fold when LWD was removed (Cowx & Welcomme, 1998).

Dredging of 9.5 km of the River Stour in England, to reduce flooding, caused fish biomass to decline from 390 kg ha⁻¹ immediately before to 96 kg ha⁻¹ immediately after dredging, and the reach remained devoid of large fish for five years. Removal of pool-riffle sequence and bank-side vegetation was considered responsible (Mann, 1988).

Hortle & Lake (1983) reported lower abundance and lower species richness in a channelized compared to an unchannelised reach of a Victorian River. It was concluded that the absence

of suitable habitat (*viz.* area of snags, areas of slack water and length of bank fringed with vegetation) was responsible.

Scarnecchia (1988) recorded lower biomass and fewer species and families of fish in channelized compared with unchannelized reaches in a northwestern Iowa prairie stream. Less heterogeneity in width, velocity and substrate type was deemed responsible.

One example of where river bed aggradation is occurring is in the Lower Ord River in the Kimberley region of north-western Australia. This system has been subjected to flow regulation since 1972, and WRC (2000) consider that because of decreased river power, but continuing sediment delivery to the system, the main channel will aggrade with fine silt, and this will promote the build-up of in-stream and riparian vegetation. This process ultimately will lead to the simplification of channel topography. According to Cowx & Welcomme (1998), this leads to a reduction in habitat diversity, and in conjunction with high flow events, causes young fish to be swept from the system, with consequent loss of species. Dramatic decreases in fish abundance, shifts in the species spectrum, and complete loss of species occurs when the bed structure is simplified.

In the Fly River, rather than discharge being reduced, leading to the build-up of sediment, the delivery of sediment to the system has been increased, exceeding the carrying capacity of the system. The end result is comparable, being aggradation.

7 INFLUENCE OF WATER DEPTH

As indicated above, there is an extensive literature on relationships between water depth and fish diversity. One of the observed effects of river bed aggradation in the Fly system is a change in water depth, and a change in water depth will result in changes in other fundamental hydrological parameters, in particular velocity and discharge. Changes in depth, velocity and discharge result in changes in flow-related processes/parameters, such as erosional and depositional processes, sediment carrying capacity and turbidity. These in turn influence the quantity and quality of different types of fish microhabitat. As Bain *et al.* (1988) comment, for a specific location in a stream, a change in stream flow (total stream discharge) translates into a change in water depth and velocity. Also, as discharge changes, stream substrate and cover objects become associated with different combinations of water depth and velocity. Consequently, changes in stream flow lead to the modification of the physical composition of the aquatic habitat.

Thus, it can be seen that a change in one parameter (water depth) *per se* concomitantly involves changes in other hydrological/morphological processes and it is not possible to always clearly isolate the effects of one from the other on fish habitat and this interdependency always must be born in mind. Because no specific examples were found of the effects of extensive river bed aggradation on fish habitat, and given the effects of aggradation on water depth (& related parameters), a targeted review of the effects of changes in water depth was undertaken. This has direct relevance to the Fly River system because river bed aggradation, although it does not influence total discharge *per se*, affects depth and associated parameters such as velocity, sediment carrying characteristics etc which determine habitat availability.

In general terms, water depth is an important controlling parameter of habitat availability. It determines the amount of a particular habitat (e.g. woody debris) that is available in the water column, it determines the vertical space in the water column available to mid-water schooling species and it is an important factor in facilitating avoidance of terrestrial predators. Depth can provide relatively stable, sheltered areas whereas shallow areas are particularly sensitive to reductions in water level, and with increasing depth, light penetration decreases and hence visibility is reduced, again providing protection from predators.

As highlighted by Gorman & Karr (1978), fish have evolved to exploit specific habitats often defined by depth. Examples include highly adapted body form and mouth structure, vertical segregation of sympatric species in pools based on morphological and behavioural adaptations, and species subdividing riffles horizontally based on current and substrate. Similar specialisation was noted by Welcomme (1985), whereby tropical stream fishes in African and Asian streams separated vertically, based on morphology and feeding habit. The different communities included; a pelagic community consisting of small species with upward facing mouths, a mid-water community of streamlined fishes with terminal mouths, a bottom community of drab coloured species with dorsally-humped profiles and ventrally-positioned mouths, and a marginal community in rocky and vegetated areas consisting of elongate species with a sinuous habit (Figure 6). A reduction in depth will ultimately force species to alter their optimum habitat utilisation, and force together species which are normally segregated.

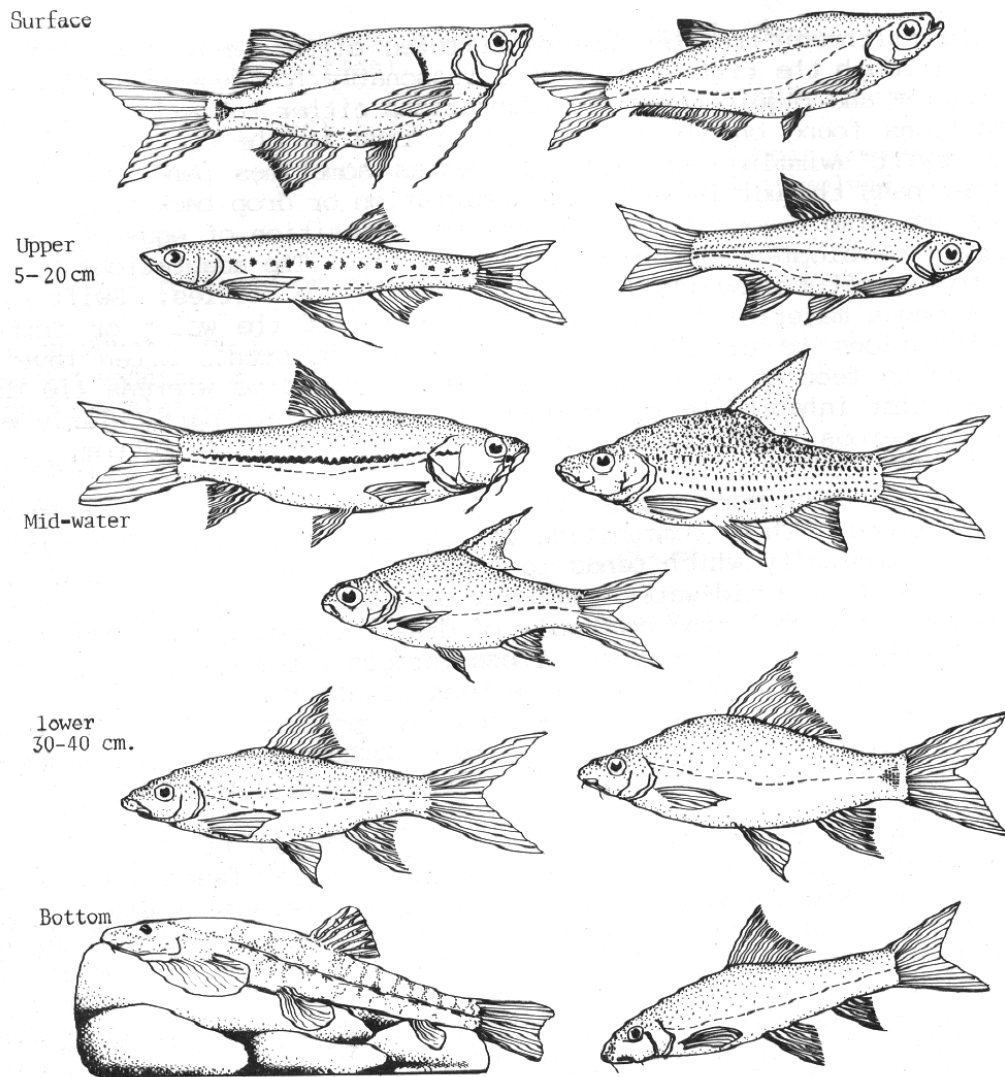


Figure 6. Segregation by depth of cyprinid species in a Borneo stream (reproduced from Welcomme, 1985; from data in Inger & Chin, 1962; cited Welcomme, 1985).

Grossman *et al.* (1987a) in a study of microhabitat use in the upper Matarraña River in Spain classified species as occupying one of three statistically distinguishable depth-determined microhabitat types; high velocity upper water column, low velocity lower water column and shelter-orientated benthic habitat. In a similar study, but of the lower Matarraña River, Grossman *et al.* (1987b) again noted that fish species occupied statistically distinct depth-determined microhabitats and the species could be classified into four assemblages; upper water column, mid-water column, lower water column and benthic habitat. They hypothesised that the observed vertical segregation of fishes was produced by a combination of predator avoidance and evolutionary adaptation. They cited other studies which also had observed vertical segregation in fish species (Sheldon, 1968; Mendelson, 1975; Baker & Ross, 1981; Moyle & Senanayake, 1984; Moyle & Vondracek, 1985). Segregation seemed to be related to a range of factors, including trophic adaptation (i.e. feeding mode), whereby benthic feeders

are near the bottom, surface feeders near the top and planktivores in mid-column. Predatory pressure was also a factor, whereby small fish and young of large species are found near the bottom or in shallow areas. Predatory pressure was observed by Power (1984) in a study of microhabitat use by Panamanian stream-dwelling catfishes, and Power *et al* (1985) and Schlosser (1987a; cited Bain *et al.* 1988) documented vertical segregation whereby large piscivorous fish force small fish into shallow refugia. Bain *et al.* (1988) observed that shallow and slow-flowing areas were used by small, young fish of several species, and deep areas were primarily inhabited by larger, older fish. Schlosser (1982a, b), Finger (1982) and Moyle & Baltz (1985) similarly observed these relationships. Scheidegger & Bain (1995) recorded lower densities of larval fish in a highly flow-regulated river compared to unregulated sites. This was attributed to loss of nursery habitat, with the current velocity in these shallow marginal areas increasing above the sustained swimming speed of larvae.

These studies demonstrate the importance of a range of water depths in providing suitable microhabitat for fish assemblages, and some of the processes and functions by which vertical segregation of species occurs. Reduction in water depth may reduce the number of depth-related microhabitats, which may either force a species from a system due to the absence of a critical microhabitat, or bring species that are normally spatially segregated into direct contact, and potentially into competition (i.e. predatory pressure), which also may lead to the loss of a species from a system.

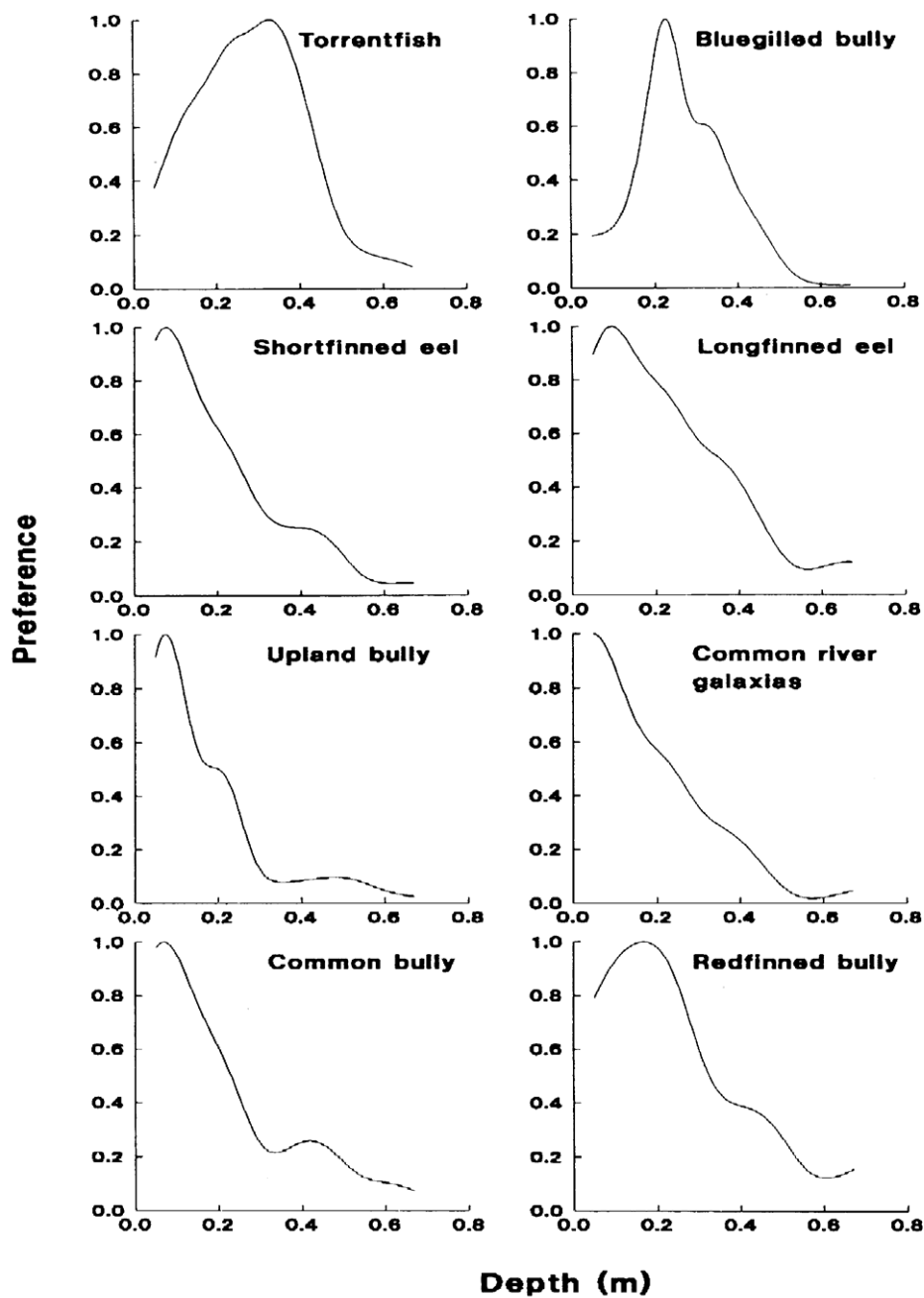


Figure 7. Depth preferences of eight native New Zealand fish species (reproduced from Jowett & Richardson, 1995).

In many studies, the assessment of changes in habitat suitability is achieved by examining discharge-related changes in **Weighted Usable Area (WUA)**. WUA is most often taken to represent a measure of the amount of habitat within a study reach that is suitable for use by a target species and is derived by application of the depth, velocity and substrate preference indices to the simulated conditions at each discharge (Pusey, 1998). Jowett & Richardson (1995) calculated WUA for eight native species of New Zealand fish using preferences for depth (Figure 7), substrate size and velocity, to be used in future flow management of New

Zealand streams. Other examples of WUA calculated for individual species and life stages of species are presented by Glova & Duncan (1985) and Newcombe (1981) (Figures 8 & 9 respectively).

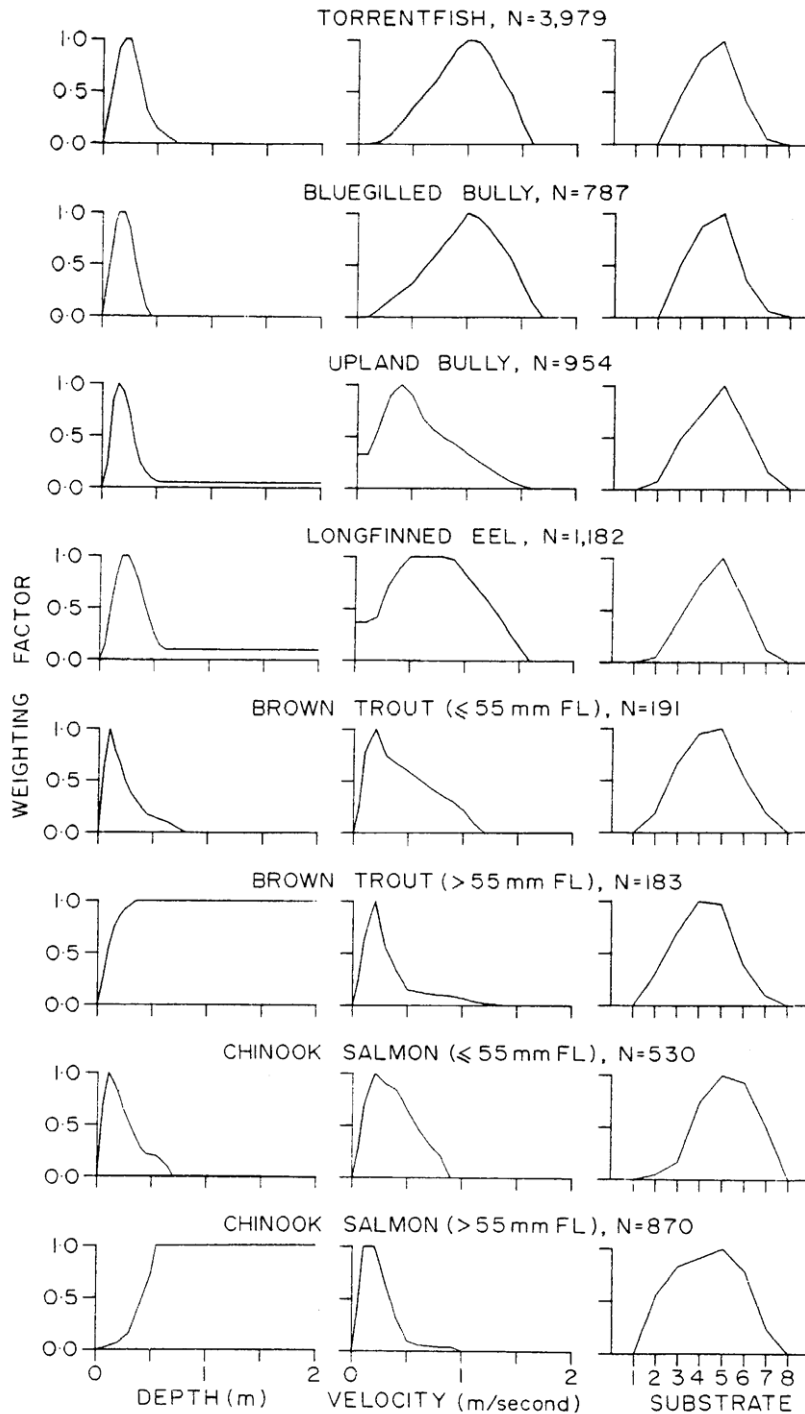


Figure 8. Habitat suitability weighting curves in relation to water depth, water velocity and substrate type for six species of fish (reproduced from Glova & Duncan, 1985, Figure 7).

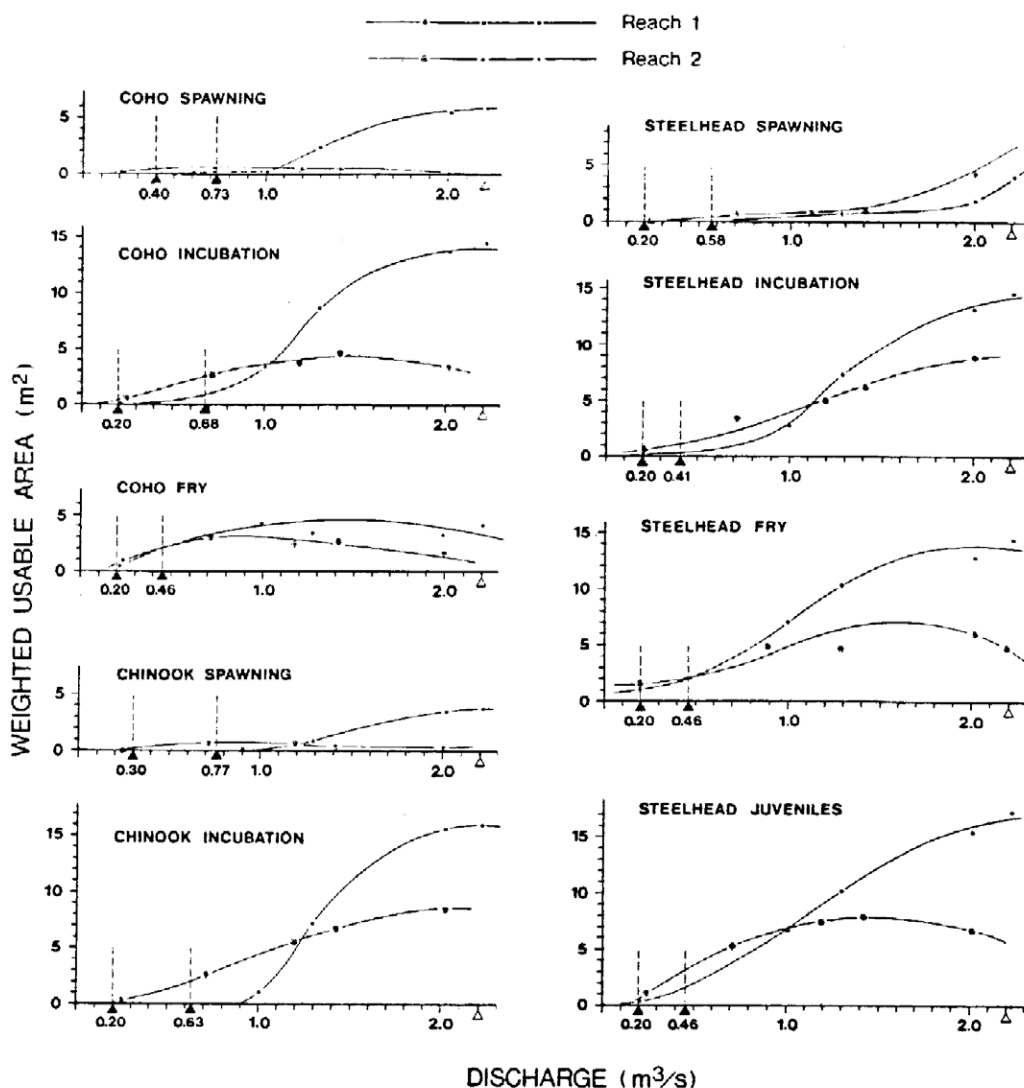


Figure 9. Changes in WUA for life-history stages of three species as a function of discharge. Vertical bars show mean and minimum monthly discharge occurring during each life stage (reproduced from Newcombe, 1981, Figure 1).

These studies all indicate changes in habitat availability under different flow regimes, usually with a decline in habitat suitability/availability with declining discharge and depth. As can be seen from the plots, the optimum habitat often occupies a narrow range of flow conditions. Other examples of the importance of depth to fish include Thomas & Bovee (1993) who derived habitat suitability criteria for rainbow trout using frequency of occurrence at different depths (Figure 10) for use in flow management, indicating depth preferences by the species. Cowx & Welcomme (1998) also noted that depth, as well as substrate and current appear to be important in the use of microhabitat by stream fishes. They further reported that the heterogeneity of the river bed, described by the variability in maximum depth measured in

different transects is indicative of habitat complexity which in turn determines species richness (Figure 11).

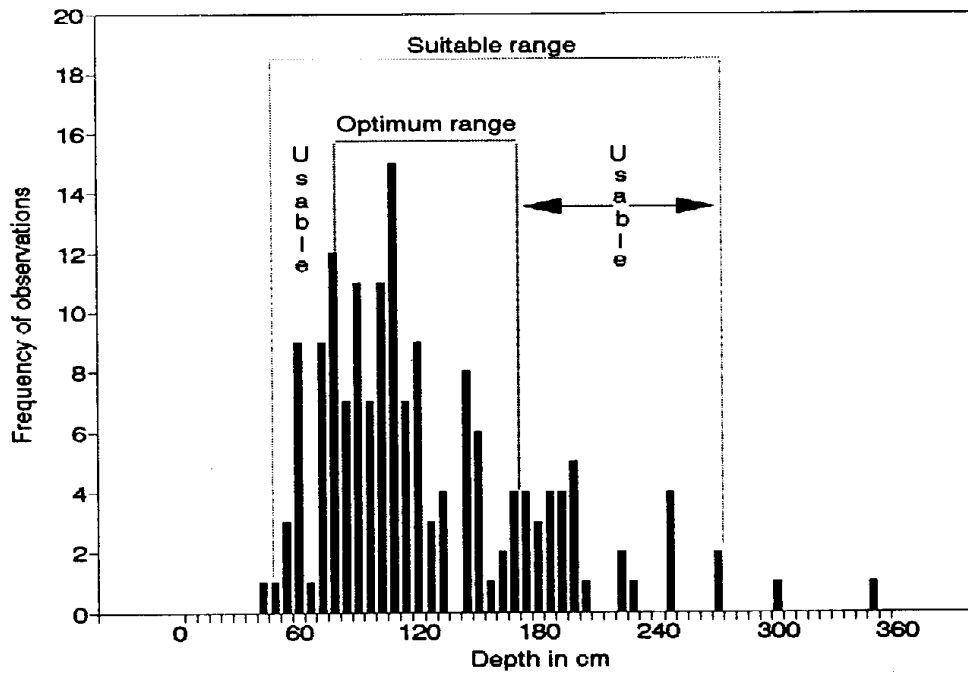


Figure 10. Frequency distribution of depths utilized by adult rainbow trout, indicating habitat suitability criteria (Reproduced from Thomas & Bovee, 1993; Figure 1)

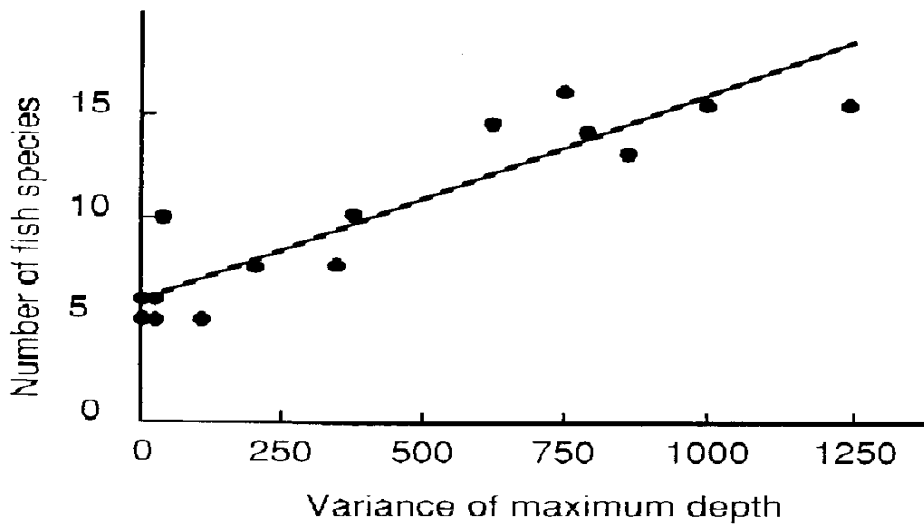


Figure 11. Number of fish species related to maximum depth (reproduced from Cowx & Welcomme, 1998; Figure 1.6)

Based on the above-described relationship between variability in maximum depth and fish population size (Cowx & Welcomme, 1998; Figure 11), inference may be made that a reduction in depth will lead to a reduction in species diversity.

A number of studies have observed changes in fish assemblages due to actual changes in depth. For example, Mann (1988) reported that reduced water levels resulted in low flows and shallow water which in turn led to the formation of dense populations of the small cyprinid *Phoxinus phoxinus* in place of larger cyprinids, trout, pike and perch.

Other examples of effects of depth reductions on fish assemblages include Newcombe (1981) and Orth & Maughan (1982) (cited Glova & Duncan, 1985) who noted that usable habitat tends to drop off markedly when flows are reduced below base levels. Rabeni & Jacobson (1993) predicted that a decrease in average and maximum channel depth would be accompanied by a decrease in intra- and interspecific segregation, and therefore a reduction in fish diversity.

Bain *et al.* (1988) noted that shallow and slow-water fishes, an abundant and diverse group of exclusively small fish (comprising > 90% of the fish in an unregulated control river), were adversely affected (reduced abundance and diversity) by artificially high variability in flow in a regulated river. Decreases in flow displaced the shallow shoreline zone, forcing fish restricted to these areas to relocate. Bain *et al.* (1988) and Kroger (1973; cited Bain *et al.*, 1988) observed fish stranded and isolated in pools by rapid reductions in discharge.

Bain *et al.* (1988) noted that changes in water level expose the shallow and slow-water fishes to increased predatory pressure. Power *et al.* (1985) and Schlosser (1987a; cited Bain *et al.*, 1988) have documented that large piscivores force small fish into shallow refugia. If variable flows either force the small fish out of this habitat or allow access by the piscivores then the functional value of the habitat is lost and a reduction in the shallow and slow-water fish guild will result (Bain *et al.*, 1988).

Cowx & Welcomme (1998) noted that lateral habitat, often characterized by low-velocity areas ($< 4 \text{ cm sec}^{-1}$) at the margins of the stream channel are important for young-of-the-year fish. Increase in lateral habitat area has resulted in major improvement in the density of age-0 fish, with flow-on effects to population size. Conversely, reduction in lateral habitat has been correlated with elimination of young-of-the-year fish. Depending upon channel shape, small increases or decreases in depth may substantially alter the area of lateral habitat. Similarly, in a constrained channel, an increase in discharge and associated increase in velocity may reduce the areas of low velocity, flushing young-of-the-year fish from the system.

Rabeni & Jacobson (1993) commented that for a North American river, the entire fish assemblage would benefit from a restoration of the overall hydraulic diversity. They predicted that a decrease in the quality and diversity of habitat will reduce fish community diversity and abundance of individual species. They further predicted that a decrease in average and maximum channel depth would be accompanied by a decrease in intra- and interspecific segregation and therefore a reduction in fish diversity.

Reduced water levels may have indirect adverse effects other than loss of habitat. Mann (1988) noted that reducing flows in an English river allowed the establishment of extensive growths of aquatic macrophytes. When they died and decomposed, high mortalities of fish resulted because of oxygen depletion.

Patton & Hubert (1993) sampled an impounded river in southeastern Wyoming. Low-velocity backwaters and shallow side-channel habitats were declining due to channel incision associated with reduced flows. Fish diversity was greatest in backwaters, and shallow side-channel and deep main-channel habitats contained substantially different fish assemblages. It was considered that continued loss of backwater and side-channel habitats as a result of reduced flows would ultimately lead to loss of species from the system.

Shields *et al.* (1994) observed for northwest Mississippi rivers that habitat quality was inferior in incised channels compared to reference channels. Incised channels were dominated by shallow, sandy habitats, moderate to high mean local Froude numbers and contained relatively little organic debris. This compared to reference channels which had greater mean depths, contained more woody debris and provided more deep pool habitat. Fish assemblages in incised channels were composed of smaller fishes, representing fewer species. Species richness was directly proportional to the mean local Froude number, an indicator of the availability of pool habitat.

Koehn (1992) noted that the amount of water determines the area of the streambed which is covered (as measured by wetted area or wetted perimeter) and hence the amount of aquatic habitat available. Changes in water depth normally influence wetted perimeter. However, he also noted that the amount of habitat does not necessarily increase proportionally with flow, and a combination of particular habitat variables which may be deemed as important for a species may even decrease as higher flows increase water velocities (Figures 12).

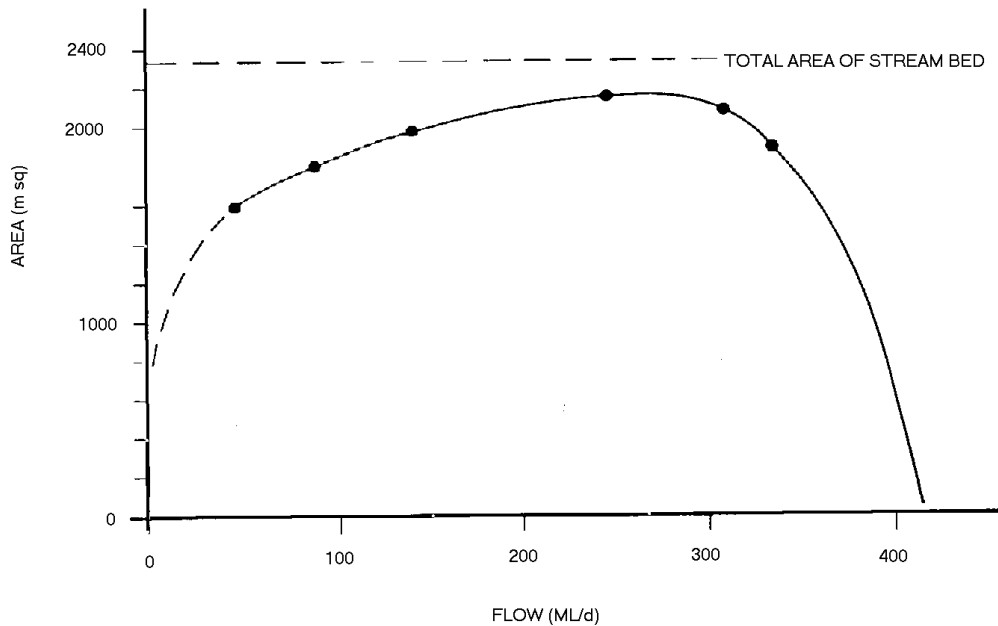


Figure 12. Rearing habitat for freshwater blackfish *Gadopsis marmoratus* (defined as water with a depth > 45 cm and velocity < 30 cms/sec) at a range of flows at the Mt McKenzie section of the Gellibrand River (reproduced from Koehn, 1992; Figure 2).

The above studies have repeatedly established strong relationships between depth and fish species diversity. As an indication of the importance of these relationships they have been extensively utilised in the management of fish populations in regulated rivers, and specifically in modeling the effects of changes in flow on depth and thus on species diversity and suitability of regulated systems to individual species. Examples are here given to further emphasis the strength of the relationships between fish habitat and diversity.

The predominant approach for modeling fish species habitat requirements, the Instream Flow Incremental Methodology (IFIM), essentially looks at Weighted Usable Area (WUA) and how this is affected by discharge and depth. Reduced discharge leads to reduced WUA and so a lowered carrying capacity. Species abundances also reduce and species may even be lost if usable habitat drops below a critical level to maintain a viable population size.

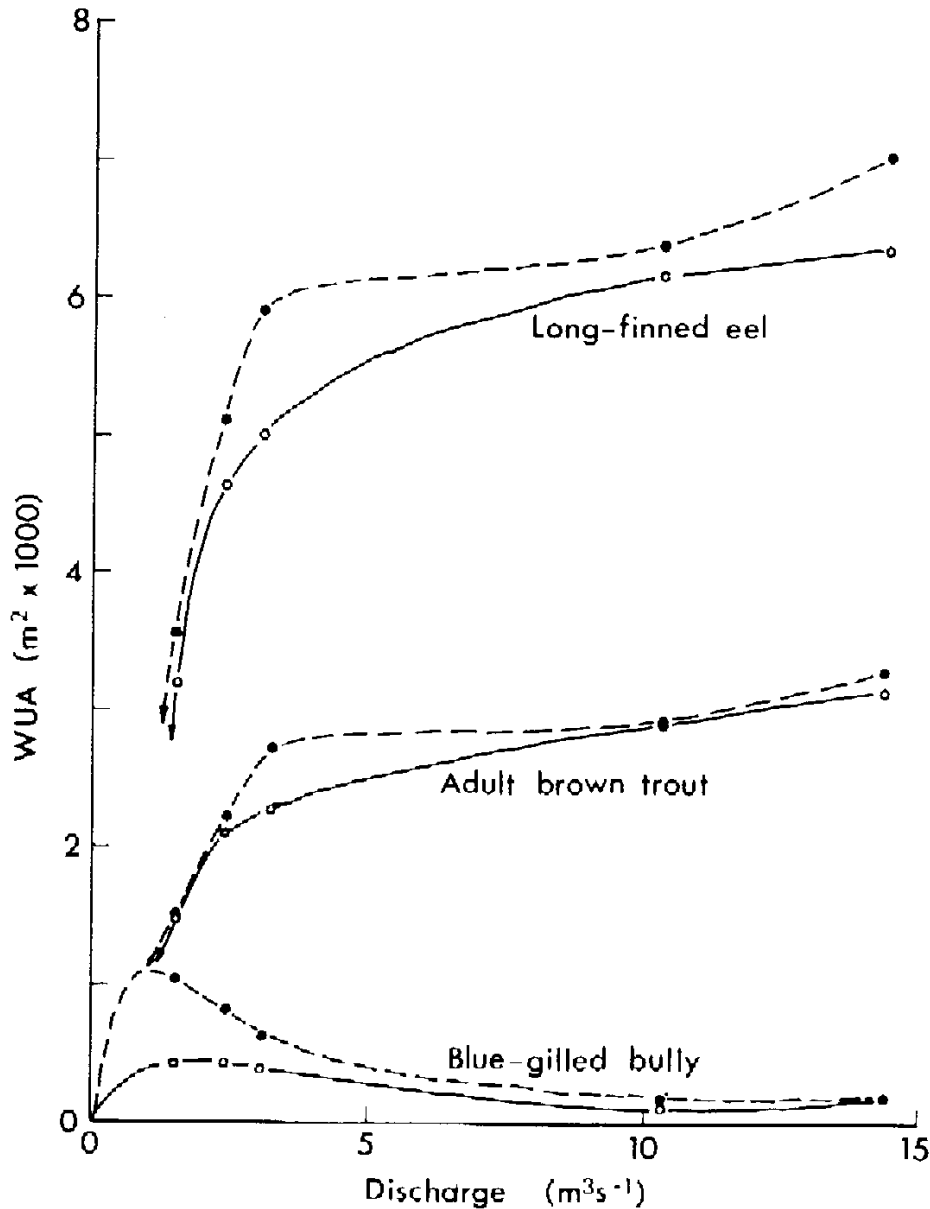


Figure 13. Simulated and measured WUA (dashed and solid lines respectively) for selected species as a function of discharge (Reproduced from Mosley & Jowett, 1985; Figure 6).

Specific examples of actual relationships between WUA and species include Mosley & Jowett (1985) who modelled and measured changes in WUA for three species under varying discharge (Figure 13), Stalnaker (1979) who modelled available spawning habitat for steelhead trout under different flow regimes and reported reductions in habitat with reduced flow (Figure 14), and Glova & Duncan (1985) who calculated WUA averaged across six species of New Zealand fish, demonstrating decreases in WUA under decreasing channel width and discharge (Figure 15).

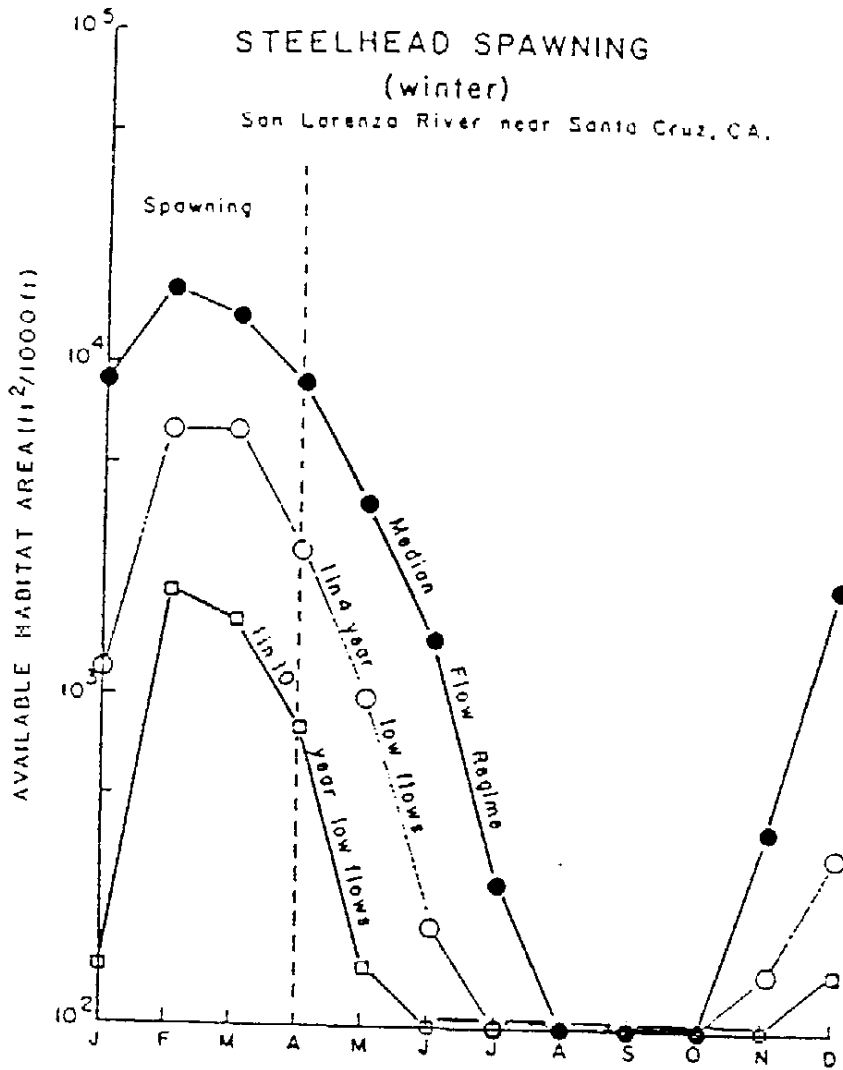


Figure 14. Availability of Steelhead trout spawning habitat under different flows (Reproduced from Stalnaker, 1979; Figure 8)

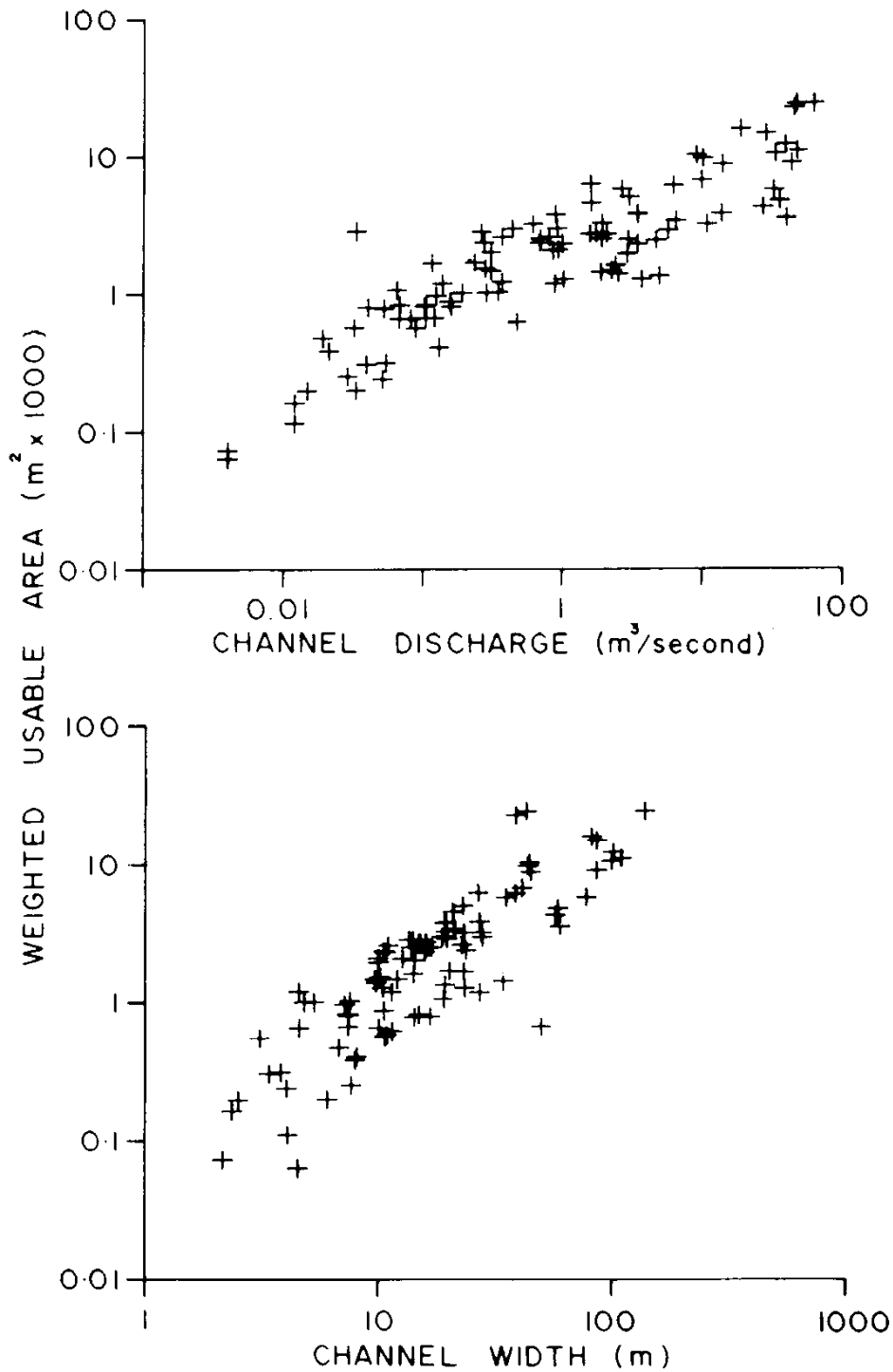


Figure 15. Changes in WUA and channel width and channel discharge for six species of New Zealand fish (Reproduced from Glova & Duncan, 1985; Figure 9)

Most IFIM have been developed for smaller streams, with few applied to large lowland rivers, principally because of the difficulties of modelling habitat availability in these systems. However, Mathews & Bao (1991) report a modified version of the IFIM, the Macrohabitat

Assessment Technique (MAT) developed for the Colorado River, a low-gradient, warm-water river in Texas. The approach was still based on assessment of habitats potentially usable by fish, but attempted to include modules to simulate circulation patterns such as backwaters and eddy currents. They commented that reductions in flow rate will generally result in less habitat available to fish. Also, at lower flows fish are crowded in to less space and forced to alter their optimal microhabitat use of physical structures. As part of this technique Mathews & Bao (1991) modelled declines in snag habitat availability under decreasing flows (Figure 16).

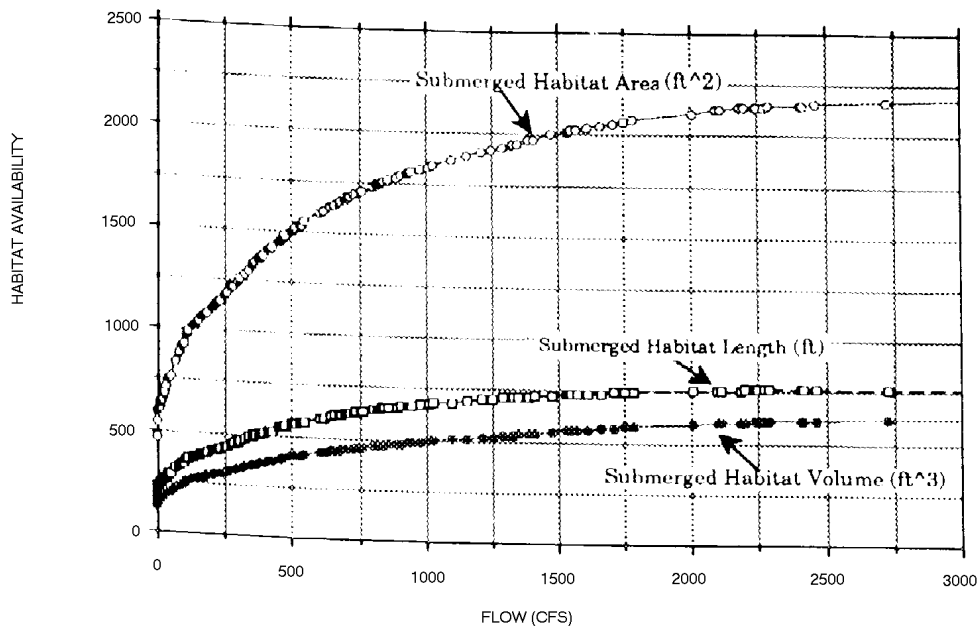


Figure 16. Changes in snag habitat availability in the Colorado River under different flows (Reproduced from Mathews & Bao (1991); Figure 3)

The above studies cite examples of potential, observed and modelled effects of changing water depth and associated parameters on fish diversity and serve to illustrate the strength of the underlying relationship between fish diversity, habitat diversity and water depth and how this relationship is affected by changes in flow regime.

With respect to the Fly River, it is considered that the generalities of the above-described relationships between fish species diversity, habitat diversity and the parameters used to characterise habitat diversity also apply. The above studies reporting relationships between

stage height and fish habitat availability are based on detailed knowledge of the specific habitat requirements of individual species (or different life stages of individual species such as larval, juvenile, spawning, adult). Currently, we have limited knowledge of the habitat requirements of the different life history stages of fish species in the Fly River. Without this information, at least for some key species representative of different trophic groups and/or guilds, it seems unlikely that any quantitative relationship between a specific change in habitat availability and individual fish species is possible. Without an empirical relationship for fish in the Fly River, and given the weight of evidence above, it must be considered that river bed aggradation will likely cause a reduction in habitat availability and that this will result in a loss in species diversity.

8 LITERATURE CITED

- Armitage, P.D. & Pardo, I. (1995) Impact assessment of regulation at the reach level using macroinvertebrate information from mesohabitats. *Regulated Rivers: Research & Management* 10:147-158
- Bain, M.B., Finn, J.T. & Booke, H.E. 1988. Streamflow regulation and fish community structure. *Ecology* 69:382-392.
- Baker J.A. & Ross, S.T. 1981. Spatial and temporal resource utilisation by southeastern cyprinids. *Copeia* 1981:178-189
- Bishop, K.A. & Forbes, M.A. 1991. The freshwater fishes of northern Australia [In] Haynes, C.D., Ridpath, M.G. & Williams, M.A.J. (eds) *Monsoonal Australia, Landscape, Ecology and Man in the Northern Lowlands*. A. A. Balkema, Rotterdam & Brookfield, pp 79 – 107
- Bishop, K.A. & Harland, W.G. 1982. Further ecological studies on the freshwater fishes of the Alligator Rivers region (final report). Open File No. OFR34, Supervising Scientist for the Alligator Rivers Region.
- Buffagni, A., Crosa, G.A., Harper, D.M. & Kemp, J.L. (2000) Using macroinvertebrate species assemblages to identify river channel habitat units: an application of the functional habitats concept to a large, unpolluted Italian river (River Ticino, northern Italy). *Hydrobiologia* 435:213-225.
- Capone, T.A. & Kushland, J.A. 1991. Fish community structure in dry-season stream pools. *Ecology* 72:983-992.
- Cowx, I.G. & Welcomme, R.L. 1998. *Rehabilitation of Rivers for Fish*. FAO, Fishing News Books, Oxford, UK & Malden, MA.
- Finger, T.R. 1982. Fish community-habitat relations in a central New York stream. *J. Freshwater Ecology* 1:343-352

- Glova, G.J. & Duncan, M.J. 1985. Potential effects of reduced flows on fish habitats in a large braided river, New Zealand. *Transactions of the American Fisheries Society*, 114:165-181.
- Gorman, O.T. and Karr, J.R. 1978. Habitat structure and stream fish communities. *Ecology* 59: 507-515.
- Grossman, G.D., de Sosta, A., Freeman, M.C. & Lobon-Cervia, J. 1987a. Microhabitat use in a mediterranean riverine fish assemblage: fishes of the upper Matarraña. *Oecologia* 73: 501-512
- Grossman, G.D., de Sosta, A., Freeman, M.C. & Lobon-Cervia, J. 1987b. Microhabitat use in a mediterranean riverine fish assemblage: fishes of the lower Matarraña. *Oecologia* 73:490-500
- Harper, D & Everard, M (1998) Why should the habitat-level approach underpin holistic river survey and management. *Aquatic Conservation* 8:395-413.
- Harper, D.M. Ebrahimnezhad, M. & Climent, F. (1998) River restoration: setting the goals and measuring the successes. *Aquatic conservation: marine and Freshwater Ecosystems* 8: 5-16.
- Harper, D.M. Smith, C.D. & Barham, P.J. (1992) Habitats as the building blocks for river conservation assessment [In] Boon, P.J., Calow, P. & Petts, G.E (eds) *River Conservation and management*, John Wiley, Chichester, UK
- Harper, D.M., Smith, C.D., Barham, P.J. & Howell, R. (1995) The ecological basis for the management of the natural river environment. [In] Harper, D.M. & Ferguson, A.J.D (eds) *The Ecological Basis for River Management*. John Wiley & Sons Ltd, Chichester, UK 219-238.
- Harper, D.M., Smith, C.D., Kemp, J. & Crosa, G. (1997) The use of functional habitats in conservation management and rehabilitation of rivers [In] Brettsko, G & Helesic, J (eds) *The Ecological Basis for River Management*, John Wiley, Chichester, UK
- Harris, L.D. & Kangas, P. 1988. Reconsideration of the habitat concept. *Transactions of the 53rd North American Wildlife and Natural Resources Conference* 137-144.
- Hortle, K.G. & Lake, P.S. 1983. Fish of Channelized and unchannelized sections of the Bunyip River, Victoria. *Aust. J. Mar. Freshw. Res.* 34:441-450.
- Inger, R.F. & Chin, P.K. 1962. The freshwater fishes of North Borneo. *Fieldiana (Zoology)* 45:1-268.
- Jowett, I.G. & Richardson, J. 1995. Habitat preferences of common, riverine New Zealand native fishes and implications for flow management. *New Zealand Journal of Marine and Freshwater Research* 29:13-13.
- Kemp, J.L., Harper, D.M. & Crosa, G.A. (1999) Use of functional habitats to link ecology with morphology and hydrology in river rehabilitation. *Aquatic Conserv: Mar. Frshwater. Ecosyst.* 9: 159-178.

- Koehn, J.D. 1992. Freshwater fish habitats: key factors and methods to determine them. [In] Hancock, D.A. (ed) Sustainable fisheries through sustaining fish habitat. Proceedings of the Aust. Soc. Fish Biol. Workshop held at Victor Harbor, S.A., 77-83.
- Kroger, R.L. 1973. Biological effects of fluctuating water levels in the Snake River, Grand Teton National Park, Wyoming. *Am. Midland Naturalist* 89:478-481.
- Mann, R.H.K. 1988. Fish and fisheries of regulated rivers in the UK. *Regulated Rivers: Research & management* 2:411-424
- Mathews, R.C. & Bao, Y. 1991. Alternative instream flow assessment methodologies for warmwater river systems. USDA Forest Service General Technical Report RM-207, pp 189-196.
- Mathews, R.C. & Bao, Y. 1991. Alternative instream flow assessment methodologies for warmwater river systems. [In] Warmwater Fisheries Symposium, June 4 – 8th, 1991, Scottsdale, Arizona, (eds) Copper, J.L. & Hamre, R.H., USDA Forest Service General Technical Report RM-207.
- Mendelson, J. 1975. Feeding relationships among species of *Notropis* (Pisces: Cyprinidae) in a Wisconsin stream. *Ecol. Monogr.* 45:199-230
- Mosley, M.P. & Jowett, I.G. 1985. Fish habitat analysis using river flow simulation. *New Zealand Journal of Marine and Freshwater Research* 19:293-309.
- Moyle, P.B. & Baltz, D.M. 1985. Microhabitat use by an assemblage of California stream fishes: developing criteria for instream flow determinations. *Transactions of the American Fisheries Society* 114:695-704
- Moyle, P.B. & Senanayake R. 1984. Resource partitioning among the fishes of a rainforest stream in Sri Lanka *J. Zool.* 202:195-223
- Moyle, P.B. & Vondracek, B. 1985. Persistence and structure of the fish assemblage in a small Californian stream. *Ecology* 66:1-13
- Newcombe, C. 1981. A procedure to estimate changes in fish populations caused by changes in stream discharge. *Transactions of the American Fisheries Society* 110:382-390.
- Orth, D.J. and Maughan, O.E. 1982. Evaluation of the incremental methodology for recommending instream flows for fishes. *Transactions of the American Fisheries Society* 111: 413-445.
- Pardo, I & Armitage, P.D. (1997) Species assemblages as descriptors of mesohabitats. *Hydrobiologia* 344:111-128
- Patton, T.M. & Hubert, W.A. 1993. Reservoirs on a Great Plains stream affect downstream habitat and fish assemblages. *J. Freshwat. Ecol.* 8: 279-286.
- Power, M.E. 1984. Depth distributions of armored catfishes: predator-induced resource avoidance. *Ecology* 65: 529-537
- Power, M.E., Matthews, W.J. & Stewart, A.J. 1985. Grazing minnows, piscivorous bass and stream algae: dynamics of a strong interaction. *Ecology* 66:1448-1456.

- Pusey, B.J. 1998. Methods addressing the flow requirements of fish [In] Arthington, A.H. & Zalucki, J.M. (eds) Comparative Evaluation of Environmental Flow Assessment Techniques: Review of Methods. LWRRDC Occasional Paper 27/98, pp 141.
- Rabeni, C.F. & Jacobson, R.B. 1993. The importance of fluvial hydraulics to fish-habitat restoration in low-gradient alluvial streams. *Freshwater Biology* 29:211-220.
- Scarnecchia, D.L. 1988. The importance of streamlining in influencing fish community structure in channelized and unchannelized reaches of a prairie stream. *Regulated Rivers: Research & Management* 2:155-166
- Scheidegger, K.J. & Bain, M.B. 1995. Larval fish distribution and microhabitat use in free-flowing and regulated rivers. *Copeia* 1995(1):125-135
- Schlosser, I.J. 1982a. Fish community structure and function along two habitat gradients in a headwater stream. *Ecol. Mon.* 52:395-414.
- Schlosser, I.J. 1982b. Trophic structure, reproductive success and growth rates of fishes in natural and modified headwater streams. *Canadian Journal of Fisheries and Aquatic Sciences* 39:968-978
- Schlosser, I.J. 1987a. A conceptual framework for fish communities in small warmwater streams [In] W.J. Matthews & D.C. Heins (eds), Community and evolutionary ecology of north American stream fishes. University of Oklahoma, Norman, Oklahoma.
- Schlosser, I.J. 1987b. The role of predation in age- and size-related habitat use by stream fishes. *Ecology* 68:651-659
- Sheldon, A.L. 1968. Species diversity and longitudinal succession in stream fishes. *Ecology* 49:193-198
- Sheldon, A.L. and Meffe, G.K. 1995. Path analysis of collective properties and habitat relationships of fish assemblages in coastal plain streams. *Canadian Journal of Fisheries and Aquatic Sciences* 52: 22-33.
- Shields, F.D., Knight, S.S. & Cooper, C.M. 1994. Effects of channel incision on flow stream habitats and fishes. *Environ. Management* 18:43-57
- Stalkner, C.B. 1979. Effects on fisheries of abstractions and perturbations in streamflow. pp. 366-383
- Storey, A.W. & Marshall, A. (2003) Effects of river bed aggradation on fish habitat of the Fly River. Unpublished report to Ok Tedi Mining Ltd by Wetland Research & Management and Andrew Marshall Pty Ltd, 51 pp.
- Thomas, J.A. & Bovee, K.D. 1993. Application and testing of a procedure to evaluate transferability of habitat suitability criteria. *Regulated Rivers: Research & Management* 8:285-294.
- Welcomme, R.L. 1985 River Fisheries. FAO Fisheries Technical Paper No. 262. 330 p

WRC 2000. Recommendations for Estimation of Interim Ecological Water Requirements for the Ord River. Unpublished report by the Ord River Scientific Panel to the Water and Rivers Commission, pp 115.