Fish Passage and Fishways in New South Wales: A Status Report

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Cooperative Research Centre for Freshwater Ecology
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SUMMARY

Fish passage is the term describing the directed movement of fish past a point in a stream. It particularly relates to the engineering and biological aspects of restoring free passage at in-stream barriers. Fishways are structures that allow fish to pass barriers. The seven broad categories of fishways that have been used or considered in New South Wales are the pool type (including vertical-slot), Denil, lock, trap-and-transport, rock-ramp, bypass, and eel fishways.

Of the 55 species of native freshwater fish living in New South Wales, 32 are at present known to be migratory and to require free passage to sustain populations. However, it is now recognised that all freshwater fish need to move freely between the various areas of their habitat, although the scales of their movements are different. The fish-passage status of streams in New South Wales has been extensively compromised. Barriers to fish passage, of which there are known to be 4308 in New South Wales streams, can cause local extinctions or greatly reduce fish abundance and diversity. Dams, weirs and other structural barriers physically impede fish movement, whilst behavioural barriers such as cold-water pollution or acid drainage either deter fish from attempting to migrate or else inhibit their swimming ability.

The state goverment fisheries department, NSW Fisheries, is committed to restoring fish passage. The department has regulatory responsibility for protecting fisheries resources, including provisions for fish passage, and may require a fishway to be built under the requirements of the *NSW Fisheries Management Act 1994*. Since 1985 NSW Fisheries has developed extensive research knowledge about fishways technology and the migrations of inland and coastal freshwater species. Experience has shown that, to build successful fishways, the engineering expertise of agencies such as the NSW Department of Land and Water Conservation must be combined with the fish-biology expertise of NSW Fisheries in effective, closely integrated projects. In 1992 the State Fishways Program was created to increase cooperation between the two departments and other relevant agencies.

There have been many problems in the history of fishways and fish passage in south-eastern Australia, and lack of knowledge, inappropriate fishway designs, inadequate resources and poor maintenance have taken their toll in the past. Fortunately, the situation has improved greatly over recent years, but the continuing need for improved fishway designs and reduced fishway costs emphasises the requirement for ongoing research and development. Both NSW Fisheries and the State Fishways Program need to allocate significant resources specifically for this work. Better knowledge remains an urgent priority, especially in the areas of migratory fish behaviour, fishway hydraulics and design, and innovations such as prefabricated modular fishways and less-expensive fishway designs.

Acknowledgements

Most members of the NSW Fisheries' Freshwater Research group have contributed to the production of this report which summarises the results of many years' work. Much of the material relates to research by Dr Martin Mallen-Cooper during his years with the group. John Matthews and David McGill helped with formatting the report. Valuable advice on early drafts was provided by Darryl Grey, Craig Copeland, Allan Lugg, Paul O'Connor and Adam Smith from NSW Fisheries, by Peter Wem from the NSW Department of Land and Water Conservation and Tony Paull from Sydney Water.

1. INTRODUCTION

1.1 What is fish passage?

Fish passage is the process whereby fish move around within their environment. The term describes the directed movement of fish past a point in a stream and relates particularly to the engineering and biological aspects of restoring free passage at barriers. A fishway is

> essentially a water passage around or through an obstruction, designed to provide hydraulic conditions suitable for fish to pass the obstruction without undue stress, delay or injury

(modified from Clay 1995). Migration is defined as 'movements resulting in an alternation between two or more separate habitats occurring with regular periodicity and involving a large fraction of the population' (Northcote 1978). But all fish need to be able to move freely between habitat areas within their environment, although at present only the large-scale movements are popularly recognised as migrations. These movements can occur for a variety of reasons, including search for food and shelter, or simply for dispersal into available habitats. At a larger scale, the populations' optimal use of resources, and the flow of genetic material within populations through the movement of individuals, are essential for maintaining the fitness of the species and their adaptability to change.

Fifty-five species of native freshwater fish are recognised as occurring in New South Wales, and a further 15 estuarine species are known to enter freshwater occasionally (Harris & Gehrke 1997). Of the 55 freshwater species, 32 are recognised at present as having a migratory stage in their life cycle (see Appendix and Section 1.1.1) (Harris 1984a; Mallen-Cooper 1989; Mallen-Cooper & Harris 1990; Harris 1995; Mallen-Cooper 1996; McDowall 1996).

1.1.1 Types of migration

Freshwater fish migrations can take several forms and be made over differing distances. The following classification of migratory fish follows Myers (1949), Harris (1984a) and McDowall (1988):

potamodromous — fish that migrate wholly within fresh water;

diadromous — fish that migrate between fresh water and the sea.

Within the latter group there are a further three subdivisions:

- *anadromous* — diadromous fish that spend most of their life in the sea and migrate to fresh water to breed;
- *catadromous* — diadromous fish that spend most of their life in fresh water and migrate to the sea to breed;
- *amphidromous* — diadromous fish that migrate between the sea and fresh water, but not for the purpose of breeding.

Current knowledge on the migrations of freshwater fish in New South Wales is summarised in Table 1. Information on the life histories of some species is limited, so in the table their migratory requirement is listed as unknown. Those species that require fish passage only in their immediate environment are listed as requiring *local* fish passage. Fish are stimulated to migrate by a variety of cues such as seasonal or diurnal cycles and changes in water flow and temperature.

Table 1. Native freshwater fish species in NSW and their migratory needs, listed by freshwater ecological regions

Distrib.*	Scientific name	Common name	Family	Migration**
D	*Craterocephalus amniculus*	Darling River hardyhead	Atherinidae	Unknown
D	*Neosilurus hyrtlii*	Hyrtl's tandan	Plotosidae	Potamodromous
M	*Gadopsis bispinosus*	Two-spined blackfish	Gadopsidae	Local
M	*Geotria australis*	Pouched lamprey	Geotriidae	Anadromous
M	*Nannoperca australis*	Southern pygmy perch	Nannopercidae	Local
M/D	*Ambassis castelnaui*	Olive perchlet	Ambassidae	Local
M/D	*Bidyanus bidyanus*	Silver perch	Terapontidae	Potamodromous
M/D	*Craterocephalus stercusmuscarum*	Flyspecked hardyhead	Atherinidae	Unknown
M/D	*Galaxias rostratus*	Murray jollytail	Galaxiidae	Local
M/D	*Maccullochella macquariensis*	Trout cod	Percichthyidae	Unknown
M/D	*Maccullochella peelii*	Murray cod	Percichthyidae	Potamodromous
M/D	*Macquaria ambigua*	Golden perch	Percichthyidae	Potamodromous
M/D	*Melanotaenia fluviatilis*	Crimson-spotted rainbowfish	Melanotaeniidae	Local
M/D	*Nematalosa erebi*	Bony herring	Clupeidae	Potamodromous
M/D/NC	*Ambassis agassizii*	Olive perchlet	Ambassidae	Local
M/D/NC	*Craterocephalus fluviatilis*	Murray hardyhead	Atherinidae	Unknown
M/D/NC	*Leiopotherapon unicolor*	Spangled perch	Terapontidae	Potamodromous
M/D/NC	*Mogurnda adspersa*	Purple-spotted gudgeon	Eleotridae	Local
M/D/SC	*Gadopsis marmoratus*	River blackfish	Gadopsidae	Local
M/D/NC/SC	*Galaxias olidus*	Mountain galaxias	Galaxiidae	Local
M/D/NC/SC	*Hypseleotris* spp.	Carp-Gudgeon	Eleotridae	Local
M/D/NC/SC	*Philypnodon grandiceps*	Flathead gudgeon	Eleotridae	Unknown
M/D/NC/SC	*Philypnodon* sp.1	Dwarf flathead gudgeon	Eleotridae	Unknown
M/D/NC/SC	*Retropinna semoni*	Australian smelt	Retropinnidae	Potamodromous
M/D/NC/SC	*Tandanus tandanus*	Freshwater catfish	Plotosidae	Local
M/SC	*Galaxias brevipinnis*	Climbing galaxias	Galaxiidae	Amphidromous
M/SC	*Macquaria australasica*	Macquarie perch	Percichthyidae	Potamodromous
M/SC	*Mordacia mordax*	Shortheaded lamprey	Mordaciidae	Anadromous
NC	*Ambassis nigripinnis*	Olive perchlet	Ambassidae	Local
NC	*Arius graeffei*	Freshwater fork-tailed catfish	Ariidae	Anadromous
NC	*Butis butis*	Bony-snouted gudgeon	Eleotridae	Unknown
NC	*Craterocephalus marjoriae*	Marjorie's hardyhead	Atherinidae	Unknown
NC	*Glossamia aprion*	Mouth almighty	Apogonidae	Local
NC	*Maccullochella ikei*	Eastern cod	Percichthyidae	Unknown
NC	*Megalops cyprinoides*	Oxeye herring	Elopidae	Amphidromous
NC	*Melanotaenia duboulayi*	Duboulay's rainbowfish	Melanotaeniidae	Local
NC	*Nannoperca oxleyana*	Oxleyan pygmy perch	Nannopercidae	Local
NC	*Rhadinocentrus ornatus*	Softspined rainbowfish	Melanotaeniidae	Local

* M = River Murray, D = Darling River, NC = North coast (coastal drainages from Wyong River north), SC = South coast (coastal drainages from Hawkesbury River south).
** Current knowledge of the species' migration patterns
(From: Harris 1984a; Mallen-Cooper 1996; McDowall 1996; Stuart 1997)

Table 1 continued

Distrib.*	Scientific name	Common name	Family	Migration**
NC/SC	*Anguilla australis*	Short-finned eel	Anguillidae	Catadromous
NC/SC	*Anguilla reinhardtii*	Long-finned eel	Anguillidae	Catadromous
NC/SC	*Atherinosoma microstoma*	Smallmouthed hardyhead	Atherinidae	Unknown
NC/SC	*Galaxias maculatus*	Common jollytail	Galaxiidae	Catadromous
NC/SC	*Gobiomorphus australis*	Striped gudgeon	Eleotridae	Amphidromous
NC/SC	*Gobiomorphus coxii*	Cox's gudgeon	Eleotridae	Potamodromous
NC/SC	*Hypseleotris compressa*	Empire gudgeon	Eleotridae	Unknown
NC/SC	*Hypseleotris galii*	Firetailed gudgeon	Eleotridae	Potamodromous
NC/SC	*Macquaria novemaculeata*	Australian bass	Percichthyidae	Catadromous
NC/SC	*Mugil cephalus*	Striped mullet	Mugilidae	Amphidromous
NC/SC	*Myxus petardi*	Freshwater mullet	Mugilidae	Catadromous
NC/SC	*Notesthes robusta*	Bullrout	Scorpaenidae	Catadromous
NC/SC	*Potamalosa richmondia*	Freshwater herring	Clupeidae	Catadromous
NC/SC	*Pseudomugil signifer*	Southern blue-eye	Pseudomugilidae	Amphidromous
SC	*Mordacia praecox*	Nonparasitic lamprey	Mordaciidae	Anadromous
SC	*Prototroctes maraena*	Australian grayling	Prototroctidae	Amphidromous
SC	*Pseudaphritis urvillii*	Congolli	Bovichtidae	Amphidromous

* M = River Murray, D = Darling River, NC = North coast (coastal drainages from Wyong River north),
SC = South coast (coastal drainages from Hawkesbury River south).
** Current knowledge of the species' migration patterns
(From: Harris 1984a; Mallen-Cooper 1996; McDowall 1996; Stuart 1997)

1.1.2 Implications of obstructed fish passage

For fish that have large-scale migrations in their life cycles, particularly anadromous and catadromous species, the prevention of fish passage causes local extinctions above barriers and can greatly reduce population numbers downstream of those barriers (Faragher & Harris 1994; Marsden *et al.* 1997; Harris *et al*. 1998; Pethebridge *et al.* 1998). For all fish species, major barriers isolate and can modify previously continuous fish communities, resulting in changes in the faunal community structure in that river system (Harris & Mallen-Cooper 1994; McDowall 1996; Stuart 1997; Harris 1997; Harris *et al.* 1998). Complete barriers to upstream fish passage, such as large dams, have the most obvious effect.

Partial barriers to fish migration such as low weirs can be passable at certain stream flows, or may be removed at certain times (Mallen-Cooper & Edwards 1991; Harris *et al*. 1992; Mallen-Cooper & Thorncraft 1992; Williams *et al.* 1996; Pethebridge *et al.* 1998). Partial barriers have less immediately noticeable impact on fish populations than total barriers. If conditions allowing fish passage occur only infrequently, they may not correspond to the natural timing of fish migration each year, or suitable conditions may not extend over a long enough period to permit movement by a sufficient portion of the population. In these situations recruitment to upstream areas is reduced; mortalities increase, because of predation for example; fish congregate below the barrier; and the overall productivity of the system decreases (Harris 1984a; Harris & Mallen-Cooper 1994; Mallen-Cooper *et al.* 1995).

The locations of barriers in the catchment can also dramatically influence their impact on fish populations. At higher altitudes, even total barriers to fish passage may isolate only a relatively small proportion of the total available habitat in a catchment. In such cases, only a small proportion of fish in a population, or of species in the river catchment's total fish community, may reside above the barrier. Nevertheless, the cumulative effect of a number of these barriers can be significant.

Barriers to fish migrations in the lower reaches of a river usually cause the greatest damage to fish populations. Migratory fish, particularly diadromous species, are generally found in greater numbers at lower altitudes (McDowall 1988, 1996; Harris & Gehrke 1997). Catadromous and potamodromous life cycles are both common among Australian species, so both adult and juvenile fish commonly attempt to migrate past barriers. In coastal lowland reaches, especially at the tidal limit where larval and juvenile catadromous fish require upstream passage, even very small barriers can totally bar the weaker-swimming fish (Harris 1984a; Mallen-Cooper 1992, 1994), resulting in recruitment failure to all upstream habitats in that catchment (Harris 1984a; Stuart 1997; Harris 1988).

Fish passage is required in both upstream and downstream directions. Requirements for downstream passage generally have not been considered in Australia, though the need to protect downstream migrants has been recognised in other countries, especially for anadromous salmonid species (Clay 1995). However, the Narrandera Fisheries Centre has recently begun a study of downstream movements of larval and juvenile fish in the Murray river system, and a project on the downstream migration of adults has begun in Victoria.

1.1.3 History of fishways in Australia

The need to provide fish passage was recognised early in Australia, with 44 fishways being built in New South Wales between 1913 and 1985 (Harris 1984b; Mallen-Cooper 1989; Mallen-Cooper & Harris 1990; Mallen-Cooper 1993). Unfortunately, the majority of these fishways were poorly built or used an inappropriate design and generally were not maintained. As a result, the fishways provided limited fish passage, if any (see Section 3.1) (Eicher 1982; Harris 1984b; Mallen-Cooper 1989). The main reason for this failure was that the behaviour and swimming ability of indigenous fish species had not been considered. Fishway designs were adapted from the Northern Hemisphere where upstream migrations are dominated by the large powerful adults of anadromous salmonid species which can leap to overcome barriers. In Australian streams, upstream migrations are predominantly by small juvenile potamodromous and catadromous fish. These are generally species that neither leap nor have the swimming ability of adult salmonids.

In 1980, recognising the need to improve fishway designs and that suitable expertise was not available in Australia, NSW Fisheries engaged George J. Eicher, a prominent American fishways expert, to visit New South Wales and advise on a fish-passage facility program. The resulting report (Eicher 1982) identified some of the problems with our existing fishways, suggested suitable fishway designs and indicated future research priorities. In 1985, research into the swimming ability of native fish was undertaken in Manly Vale Hydrology Laboratory by NSW Fisheries to help improve fishway designs (Mallen-Cooper 1992, 1994). The first fishway built using this new information was a vertical-slot design at Torrumbarry Weir on the River Murray, which not only proved to be very effective but, combined with other research (see Appendix), provided substantial further insights into the behaviour of migratory fish (Mallen-Cooper *et al.* 1995). Since 1985, a further 32 fishways employing a variety of different designs have been built in New South Wales (Table 2).

1.1.4 New South Wales State Fishways Program

Experience has shown that to achieve successful fish passage it is essential that the engineering expertise within agencies such as the NSW Department of Land and Water Conservation (DLWC) is combined with the fish-biology expertise within NSW Fisheries in an effective and closely integrated program. In 1992 the State Fishways Program was created to increase cooperation

Table 2. Fishways built after 1985 and specifically designed to provide fish passage for native freshwater fish in New South Wales

Fishway No.	Weir name	Stream name	Type*	Monitoring**
Coastal streams				
1	Bulahdelah	Crawford R.	Vertical-slot	Ongoing
2	Penrith	Nepean R.	Vertical-slot	Partial
3	Cobbitty	Nepean R.	Vertical-slot	Partial
4	Sharpes	Nepean R.	Vertical-slot	None
5	Camden	Nepean R.	Vertical-slot	None
6	Liverpool	Georges R.	Vertical-slot	Proposed
7	Dalgety	Snowy R.	Vertical-slot	None
8	Bray Park	Tweed R.	Denil	Ongoing
9	Jabour	Richmond R.	Denil	Proposed
10	Deep Ck	Nambucca R.	Rock-ramp	None
11	Jerrys Plains	Hunter R.	Rock-ramp	Ongoing
12	Lower Weir	Wyong R.	Rock-ramp	Completed
13	Theresa Park	Nepean R.	Rock-ramp	Proposed
14	Mt Hunter	Nepean R.	Rock-ramp	Proposed
15	Ingleburn	Georges R.	Rock-ramp	None
16	Macdonalds	Macquarie R'let	Rock-ramp	Completed
17	Unnamed	Minnamurra R. (2)	Rock-ramp	None
Inland streams				
18	Boggabilla	Macintyre R.	Vertical-slot	Proposed
19	Barraba	Manilla R.	Vertical-slot	None
20	Torrumbarry	R. Murray	Vertical-slot	Continuing
21	Goondiwindi	Macintyre R.	Rock-ramp	Completed
22	Unnamed	Cockburn R. (3)	Rock-ramp	None
23	Unnamed	Bell R. (3)	Rock-ramp	Completed
24	Cooma	Murrumbidgee R.	Rock-ramp	Ongoing
25	Yarrawonga	R. Murray	Lock	Ongoing
26	Manilla	Namoi R. (2)	Rock-ramp	None

* See text for explanation of fishway types; number of fishways on a stream shown in parentheses after name
** Current status (June 1999) of projects to monitor fish passage or to assess the effectiveness of the fishway.

between the above agencies. Its main objective is to restore and maintain adequate fish passage throughout the rivers of New South Wales for the preservation of native fish populations, for ecosystem conservation, for human consumption and for economic reasons (Anon. 1996).

The program has identified and prioritised key areas of work including:

- establishment of a database of artificial barriers to fish passage in New South Wales;
- creation of a model to prioritise barriers for restoring fish passage;
- the physical removal of non-essential barriers;
- construction of new fishways;
- continuing research into new fishway designs;
- assessment of the performance of fishways; and
- increasing public awareness of fish passage issues.

Progress in these areas of work is summarised in State Fishways Program reports (Anon. 1996).

1.2 Barriers to fish passage

1.2.1 Physical barriers

Fish passage can be physically obstructed in several ways: by blocking fish with the walls of dams and weirs, or by creating excessive water turbulence or water velocities greater than those which the fish can swim against. Various types of road crossings commonly interrupt the longitudinal continuity of the stream bed or water-surface profile and constitute physical barriers (Pethebridge *et al.* 1998). Fish use differing swimming modes including a faster burst of speed for short distances and a cruising speed for longer distances. The distance over which fish have to swim to negotiate a physical barrier is a critical variable in fish passage (Videler & Wardle 1991). At barriers with sloping downstream faces, fish may be able to ascend part-way up, only to become exhausted and be washed back downstream. Common artificial barriers in New South Wales waters include dams, weirs, regulators, farm dams, floodgates, causeways, culverts, pipes, channelised streams, bridge footings, erosion control works and other kinds of instream works. These structures inhibit the fish-distribution patterns previously influenced by natural barriers such as waterfalls.

1.2.2 Behavioural barriers

Behavioural barriers can be caused by changes to habitat structure. For instance, habitat can be interrupted by the creation of large still-water storages in flowing river systems, or by the alteration of natural stream channels to straightened shallow channels lacking cover, or by the destruction of aquatic vegetation that provides sheltered migration paths for the young of species such as Australian bass (Harris 1983). Furthermore, alteration of natural streamflow regimes in regulated rivers disrupts the environmental cues responsible for triggering fish migration (Ward & Stanford 1986; Mallen-Cooper *et al.* 1995; Mallen-Cooper 1996) and can create behavioural barriers. Behavioural barriers to fish passage can result from changes to the aquatic environment that affect fish physiology. Various forms of water pollution are important in this context, especially cold water released from thermally stratified dams, toxicants, low pH from acid sulphate soils or low levels of dissolved oxygen (Clay 1995).

1.3 Fishways for physical barriers

1.3.1 When is a fishway effective?

Fishways mitigate barriers to fish-passage. An effective fishway is defined as one that successfully transmits at least 95% of all fish species and individuals attempting to negotiate the barrier, and which operates in at least 95% of the range of flow conditions experienced at that site (Mallen-Cooper 1992). Except in high-level strucures and specially developed designs such as pump fishways, a free water surface must be maintained throughout the fishway, with no pipes, controls or other submerged structures in the fishes' pathway.

The first requirement for an effective fishway is that fish attempting to migrate can find the fishway entrance and enter without delay. The fish then need to be able to ascend through the fishway, exit in an area where they will not be swept back downstream, and be able to continue with their upstream movement. These requirements need to be met over the full daily and seasonal cycles.

Without regular maintenance all fishways are likely to become clogged with debris and their effectiveness will decline. To prevent this, fishways should be placed on a regular maintenance schedule and be inspected at least once each year. They should also be checked after every inundation by high flows because channels can become choked with sediment under these conditions. Mechanically operated fishways require specific maintenance schedules.

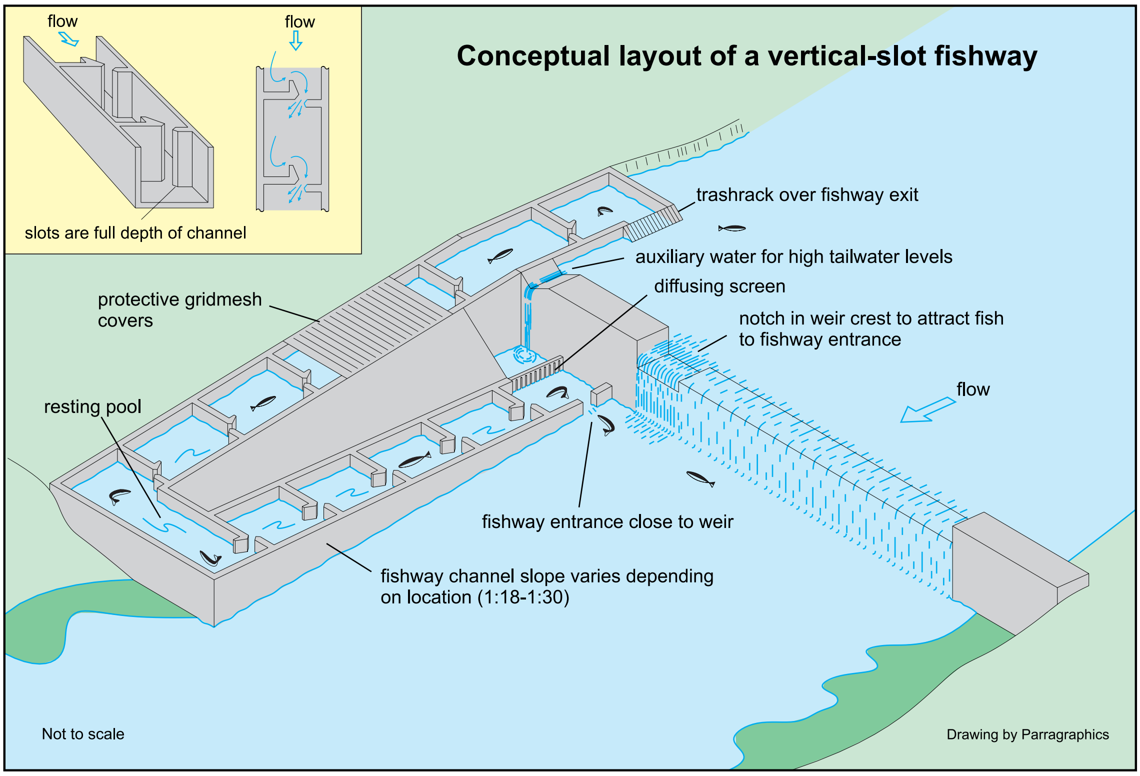


Figure 1. Conceptual layout of a vertical-slot fishway

1.3.2 Types of fishways

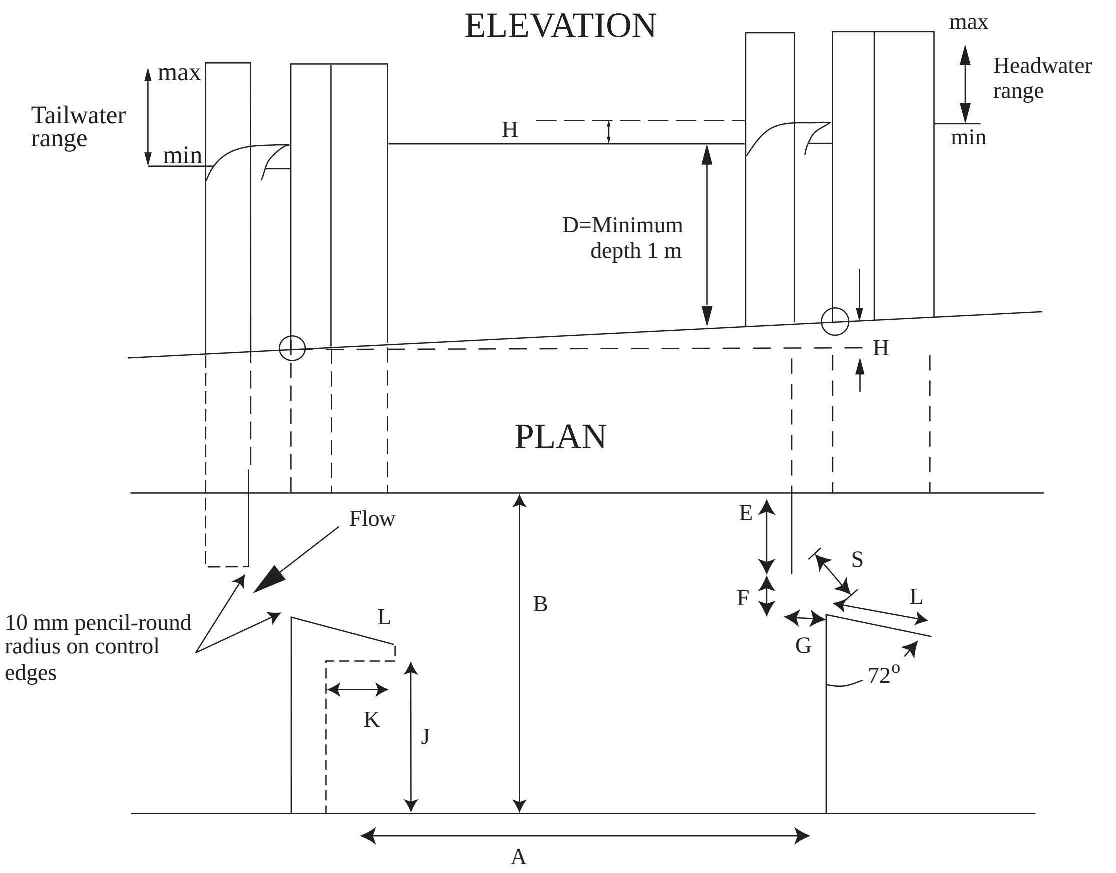
There are many types of fishways. Seven broad categories are at present in use worldwide (Clay 1995; Mallen-Cooper 1996): these are the pool-type (including especially the vertical-slot design), Denil, lock, trap-and-transport, rock-ramp, and bypass fishways, as well as fishways designed specifically for eels and their elvers.

(a) Pool-type fishways

Pool-type fishways were the first type developed and consist of a series of interconnected pools bypassing an obstruction (Clay 1995). Many of the original submerged-orifice fishways designs failed because they favoured only bottom-swimming fish and were not capable of maintaining designed water velocities because of fluctuating headwater and tailwater levels. Some were built on steep slopes, creating such excessive water velocities and turbulence that not even salmon could have ascended them. Though many of the different types of pool fishways have been built in Australia (Harris 1984b), only the vertical-slot design (Figure 1) has so far been proved effective for native fish species (Mallen-Cooper 1992, 1994, 1996; Harris & Mallen-Cooper 1994; Mallen-Cooper *et al.* 1995). Figure 2 shows the design details for vertical-slot fishways as developed, tested and refined in extensive laboratory and field experiments by NSW Fisheries and NSW Public Works and Services.

In vertical-slot fishways, maximum velocity occurs as water falls through each slot, with the downstream pool acting to dissipate hydraulic energy as well as providing resting areas for ascending fish. The slope of the channel and the intervals between the slots control the water velocity through each slot, so the fishway can be designed to suit the swimming ability of particular ascending fish. Important features of the vertical-slot design are that it can operate in varying headwater and tailwater levels, and allow fish to pass through the fishway at any depth. The vertical-slot design is suitable for weirs ranging from 1 to 6 m in height.

Design of vertical-slot fishways in south-eastern Australia



Slot width (+/– 1.5%)

S = 0.15–0.25 m in coastal streams*
= 0.25 m in tributaries of Murray–Darling rivers
= 0.30 m in Murray–Darling rivers

Maximum head drop per baffle

H = 50 mm in coastal streams at tidal influence
= 100–165 mm in coastal streams above tidal influence*
= 165 mm in Murray–Darling rivers

Cell Ratios

S	A	B	E	F	G	J	K	L
1.0	> 10.0	> 6.6	1.6	$1/\sqrt{2}$	$1/\sqrt{2}$	> 2.75	> 1.0	2.2

* Decided in consultation with NSW Fisheries

Figure 2. Design details for vertical-slot fishways developed in south-eastern Australia (© NSW Fisheries and NSW Dept of Public Works and Services, Nov. 1996)

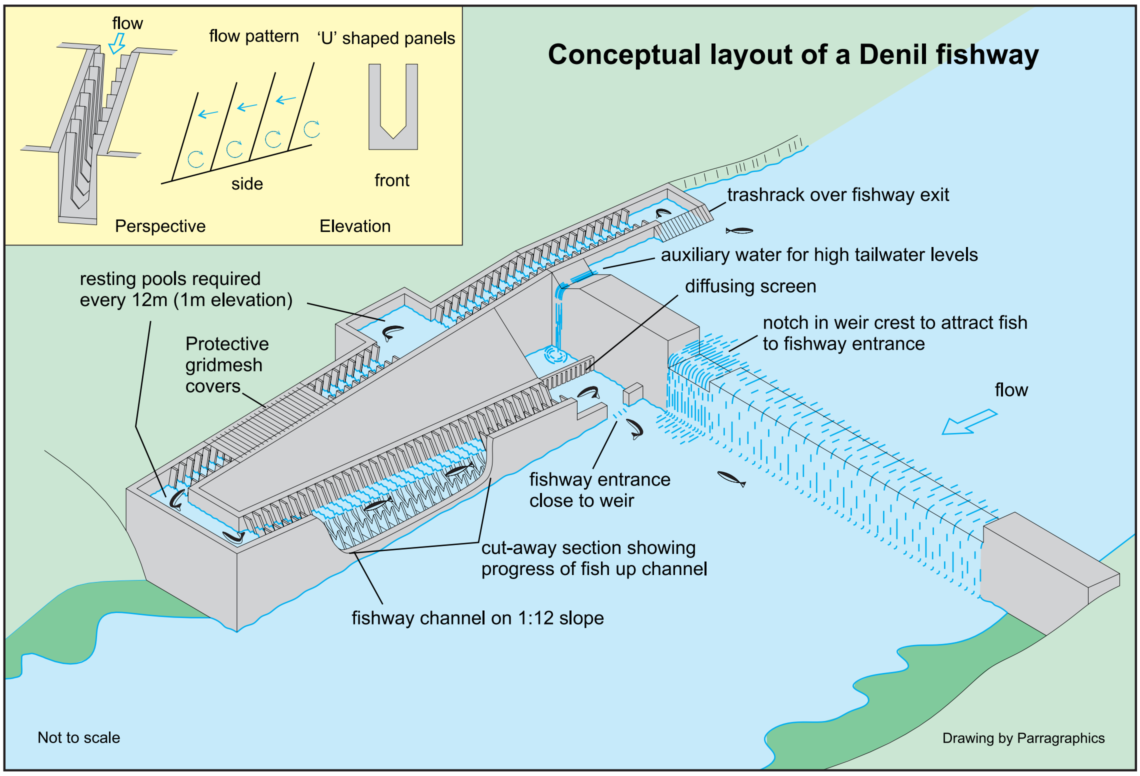


Figure 3. Conceptual layout of a Denil fishway

(b) Denil fishways

Although they use a sloping channel similar to that of pool-type designs, Denil fishways have a series of internal upstream-sloping 'U'-shaped baffles without intervening pools (Figure 3). The Denil design allows steeper channels to be used than in vertical-slot designs because they are hydraulically efficient, resulting in shorter and cheaper fishways. This feature allows for the prefabrication and installation of Denil patterns into many existing ineffective pool-type fishway channels. However, large resting pools are required for every 1 m of vertical rise. Denils are not as flexible as vertical-slot fishways because the effectiveness of the vertically asymmetrical baffles decreases with depth. This limits the operational depth range of the channel and reduces the range of headwaters and tailwaters over which it can perform effectively (Rajaratnam & Katopodis 1984).

Denil fishways have been successfully trialled at varying slopes at Euston Weir on the River Murray (Mallen-Cooper & White 1995) and their use in coastal streams is still being assessed by NSW Fisheries and the Cooperative Research Centre for Freshwater Ecology (CRCFE). However, some fish, such as young mullet, need to ascend through the fishway at the surface, and that may be of concern with this design.

(c) Lock fishways

Lock fishways operate by attracting fish through an entrance similar to that of a pool-type fishway, but instead of swimming up a channel the fish accumulate in a holding area at the base of the lock. This holding area is then sealed and filled with water to reach a level equal to the water upstream of the barrier. Fish are then able to swim out of the lock. To encourage fish to move through the various attraction and exit phases of the lock cycle, a combination of attraction flows and crowding screens can be used (Figure 4).

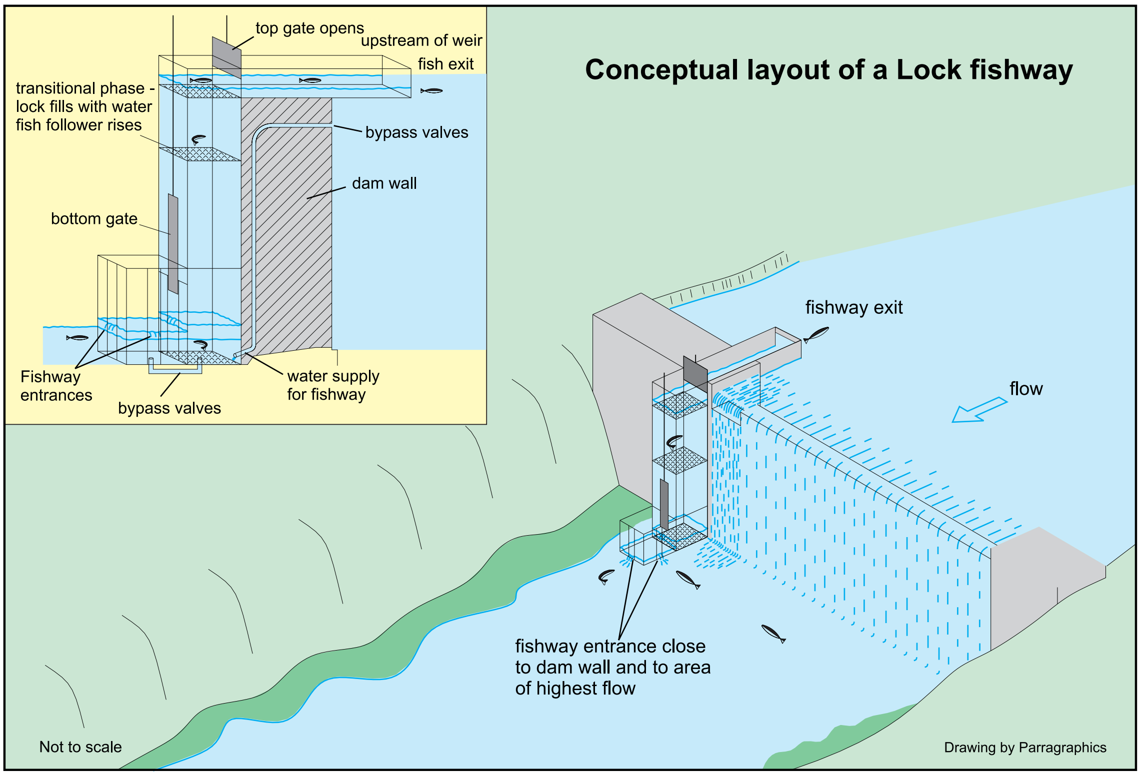


Figure 4. Conceptual layout of a lock fishway

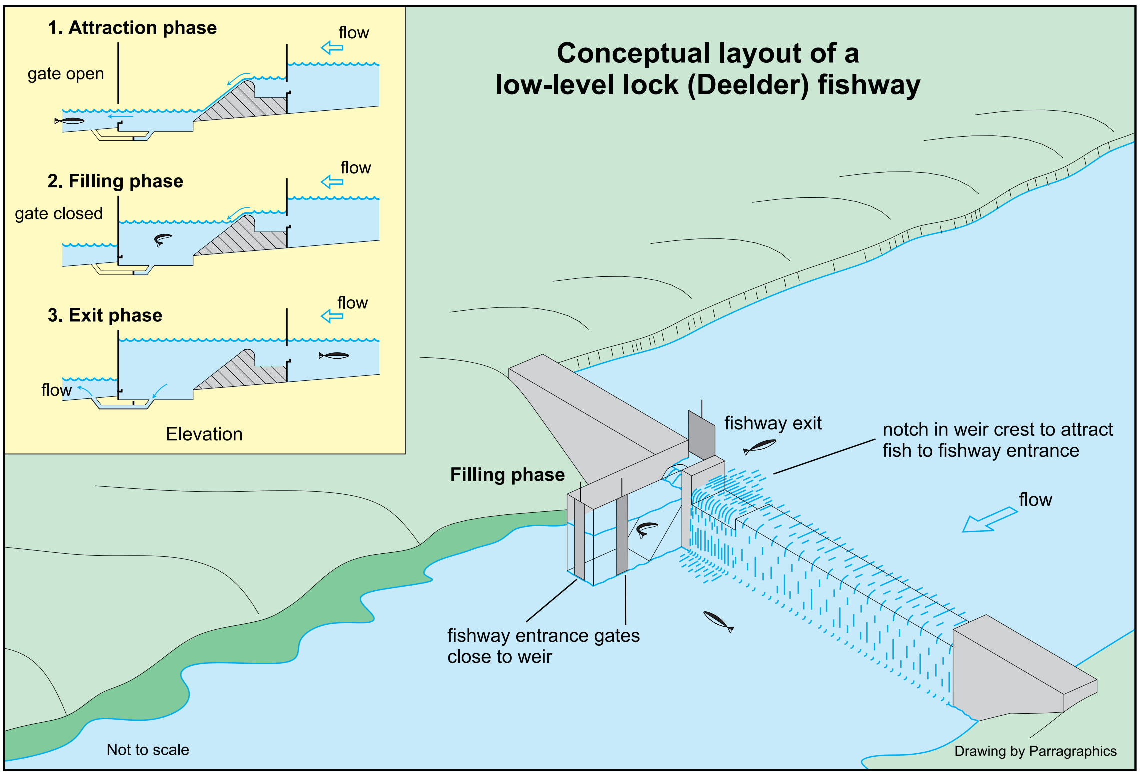


Figure 5. Conceptual layout of a Deelder fishway

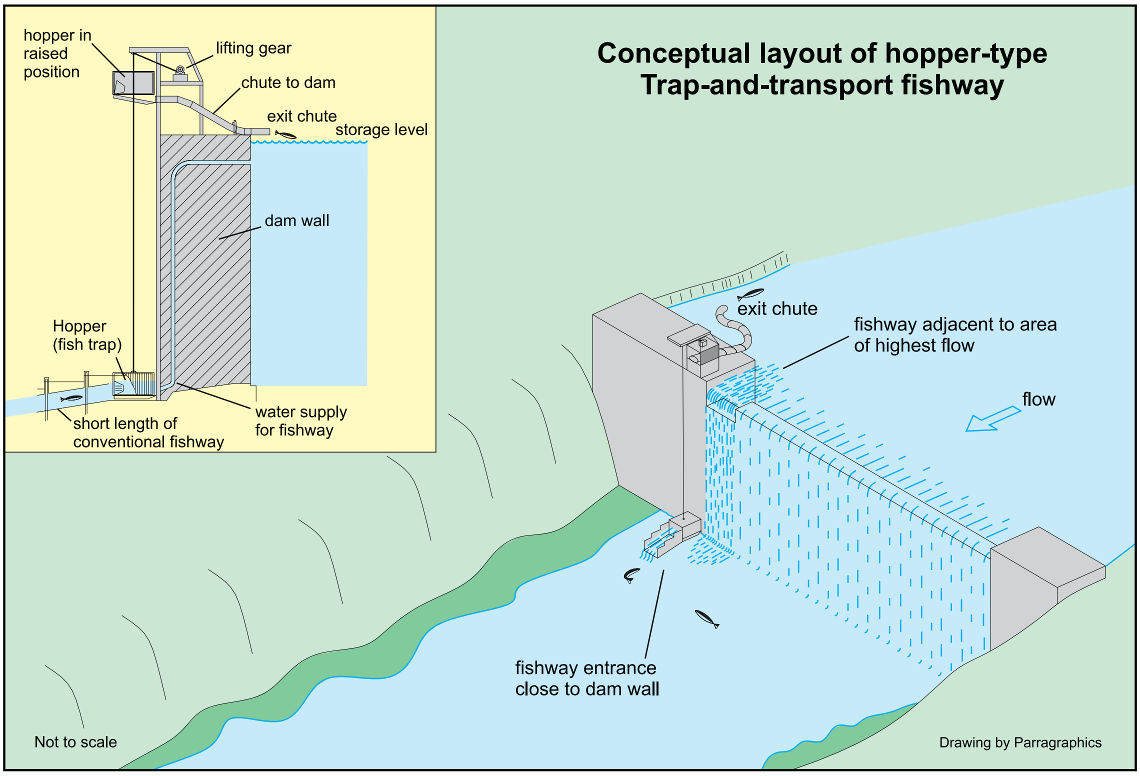


Figure 6. Conceptual layout of a trap-and-transport fishway

The only lock fishway so far built in New South Wales waters is on the River Murray at Yarrawonga Weir, and its effectiveness is currently being assessed by NSW Fisheries and the CRCFE in conjunction with the Murray-Darling Basin Commission and Goulburn-Murray Water. It has been shown to be effective in transporting fish over the 12 m-high weir, although several of the operating arrangements need modification, and problems with the fishway's exit arrangements are currently being investigated (Thorncraft & Harris 1997). In Queensland, a number of lock fishways are in use or are proposed, though recent assessment of one of these fishways also indicates that modification is needed to improve its performance (Stuart & Berghuis 1997).

The Deelder fish lock (Figure 5) is a variation of the lock fishway for use on low barriers. It is being considered for use in conversions of existing fishway channels that are too steep for pool or Denil designs but could be converted into lock fishways by the installation of automatic gates at the entrance and exit of the fishway channel.

(d) Trap-and-transport fishways

The trap-and-transport type of fishway involves attracting and trapping fish below a barrier and then physically transporting them over the barrier. The initial trapping is commonly done in a short section of pool-type fishway, with the fish usually being transported by road, rail or aerial car (Figure 6). At present no fishway of this type is operating in New South Wales, though some elver transport occurs in Tasmania (Sloane 1981). However, the potential of a pump fishway, in which fish are trapped, then pumped through a pipe over the barrier, is currently being considered by NSW Fisheries and Sydney Water for use on Tallowa Dam. A recent consultancy by NSW Public Works and Services, funded by the DLWC, has examined the pump-fishway concept and provided recommendations for the hydraulic engineering details for an installation at Audley Weir; the estimated costs compare very favourably with a vertical-slot structure.

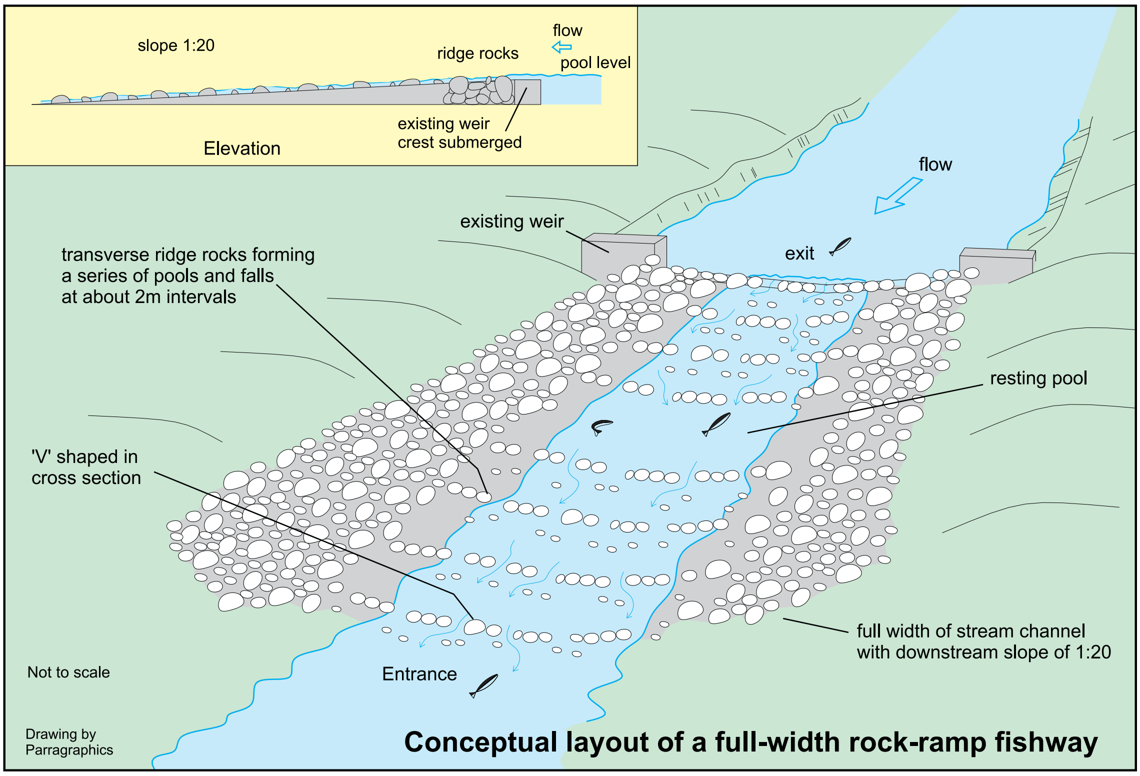


Figure 7. Conceptual layout of a full-width rock-ramp fishway

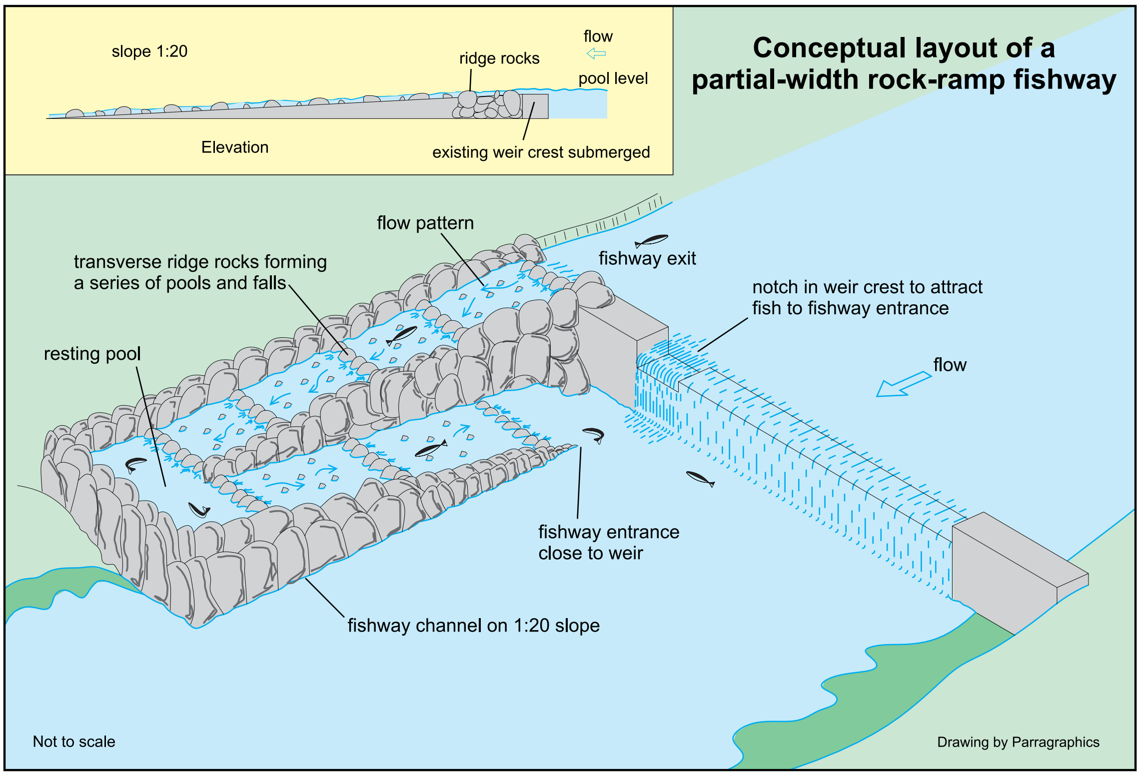


Figure 8. Conceptual layout of a partial-width rock-ramp fishway

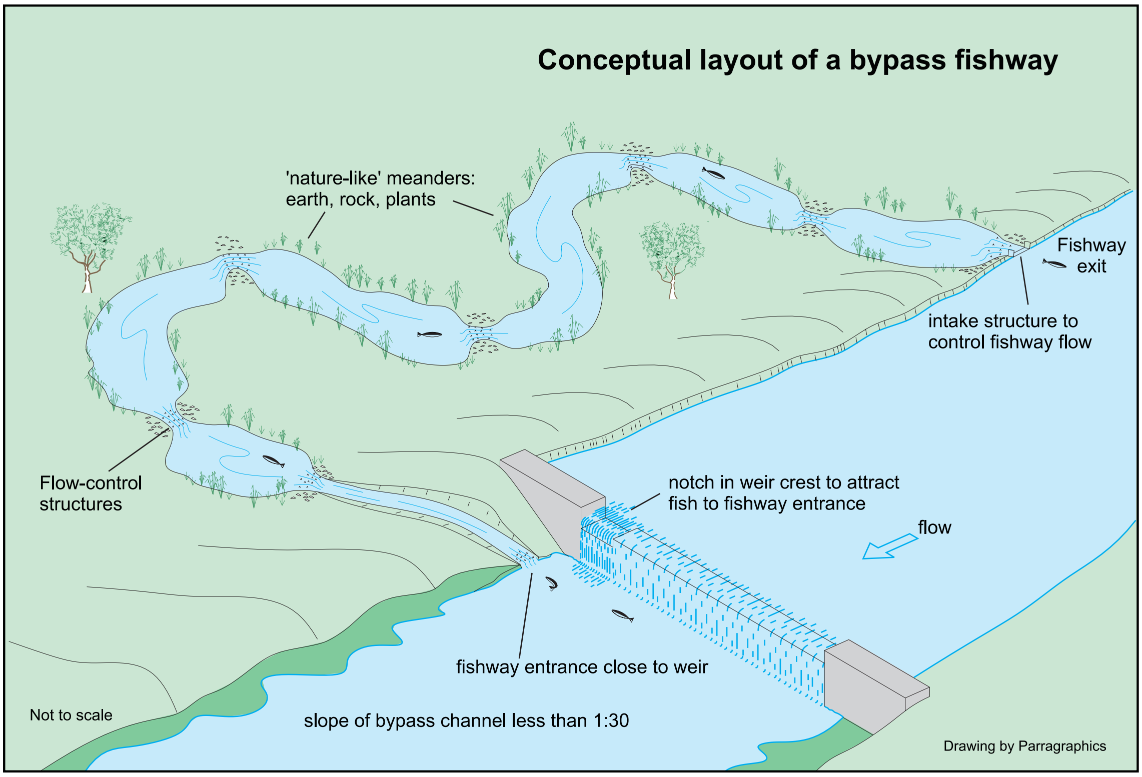


Figure 9. Conceptual layout of a bypass fishway

(e) Rock-ramp fishways

Rock-ramp fishways were developed as a simple and relatively low-cost adjunct to more-formally engineered fishway designs, particularly for overcoming low barriers and in association with stream erosion-control works (Harris *et al.* 1998; Newbury & Gaboury 1988). They are built on a slope of 20:1 and large rocks are placed to form a series of transverse small pools and falls at about 2 m intervals (Figure 7). Rock-ramp fishways have also been built over only part of the width of a barrier, generally with a return leg to bring the entrance close to the weir wall (Figure 8). Assessment of rock-ramp fishways in New South Wales has shown that small and juvenile migrating fish species can ascend during low flows, although larger fish may require higher flows to provide passage (Thorncraft & Harris 1996; Harris *et al.* 1998). Therefore, this type of fishway is particularly suited for providing fish passage on low weirs such as tidal barriers that obstruct small fish, but it may need a relatively high drown-out frequency to allow effective passage of larger fish.

(f) Bypass fishways

In Europe, bypass fishways have been successfully used to provide passage past barriers for a wide range of fish species and sizes (Harris 1997). They are low-gradient earthen or rocky channels that mimic the structure of natural streams (Figure 9), and are often described as ‘nature-like’ fishways. Some flood bypass channels have been built or occur naturally, but no bypass fishways have yet been built in Australia. Their use is being considered by NSW Fisheries because they may provide a cheaper alternative to the more technical fishway designs.

(g) Eel and elver fishways

A number of other fishway types have been developed to provide fish passage in situations where the above fishways are inappropriate. These include the elver pass: generally a small-diameter pipe or channel lined with materials such as coarse brushes that provide migrating juvenile eels with a damp, complex surface over which to wriggle (Mitchell 1990; Clay 1995). An elver pass is presently being designed for Warragamba Dam.

1.4 Avoiding behavioural barriers

1.4.1 Maintaining migration corridors

It is generally not feasible to provide bypass mechanisms such as fishways around larger-scale disturbances to migration corridors. For example, if siltation or in-stream devegetation interrupts migration pathways, the distances to be bypassed could be considerable (Ward & Stanford 1986). It is therefore important to maintain existing migration corridors, and the potential impact on migratory fish must be considered when any of the following is likely to occur: changes to river geomorphology, loss of or alterations to riparian or aquatic vegetation, and any alterations to water quality. The *NSW Fisheries Management Act 1994*, the *Rivers and Foreshores Improvement Act*, the *NSW Clean Waters Act* and the *NSW Water Act 1912* include a series of regulatory controls over such activities (NSW Fisheries 1998).

1.4.2 Maintaining environmental cues

The loss of the environmental cues that stimulate fish migration is another important factor to consider when assessing impacts on fish passage. For example, if migratory cues such as increasing water temperatures in summer, or daily and seasonal flow variations, are suppressed by releases from a reservoir, fish may fail to migrate. Similarly, many species require natural daylight patterns to sustain their migration, and darkened areas such as tunnels, low culverts and pipes create behavioural barriers. It is important to maintain migration cues, and to consider the potential effect on migratory fish when changes to seasonal water temperatures and stream flows are likely to occur.

2. RIVER CATCHMENTS IN NEW SOUTH WALES AND THE BARRIERS IN EACH

The numbers and types of barriers in each major river catchment in New South Wales are listed in Tables 3a and 3b for western- and eastern-flowing streams (DLWC Weirs Inventory, unpublished data; Williams *et al.* 1996; Pethebridge *et al.* 1998). Knowledge of the types of structure is important for determining the extent to which fish passage is restricted and to indicate the species and life-cycle stages that are affected.

Dams have the greatest impact, because they virtually eliminate fish passage except for a small number of climbing species such as eels and climbing galaxias, at a few sites. At weirs, passage is only possible when the structure is 'drowned out'. Drown-out occurs when the river level is high enough to completely submerge a barrier and little or no headloss (i.e. the difference between upstream and downstream water levels) persists. Fish passage can occur when the headloss across a structure along a stream length of 50 m is approximately 0.1 to 0.3 m, depending on whether the weir crest is smooth or rough (Harris *et al.* 1992; Mallen-Cooper & Thorncraft 1992). Gated weirs and regulators can allow fish passage, regardless of river levels, if the gates or drop-boards can be raised completely clear of the water and the structure does not unduly confine stream-channel width. Tidal barriers, regardless of design, can have the greatest impact because even a small headloss can block the weakly swimming juvenile catadromous fish species. A number of other structures, such as road crossings, culverts, bridge footings and water supply pipes, can block fish passage. Fish passage needs to be protected or restored in these cases (Cotterell 1998; NSW Fisheries 1998).

Table 3a. Classes of in-stream barriers in inland catchments of New South Wales (western flowing)

Catchment name	Weir or dam	Gated weir or regulator	Tidal barrier	Other*	Total no. of barriers
Upper Murray	19	0	–	0	19
R. Murray (Riverina)	109	26	–	15	150
Murrumbidgee R.	371	40	–	22	433
Lake George	2	0	–	0	2
Lachlan R.	298	31	–	21	350
Benanee Basin	2	8	–	0	10
Border Rivers	66	2	–	9	77
Moonie R.	7	0	–	0	7
Gwydir R.	55	19	–	9	83
Namoi R.	108	6	–	2	116
Castlereagh R.	40	0	–	1	41
Macquarie R.	289	25	–	28	342
Bokhara/Culgoa R.	28	1	–	2	31
Warrego R.	41	3	–	12	56
Paroo R.	7	0	–	9	16
Darling R.	25	7	–	4	36
Total	**1467**	**168**	**–**	**134**	**1769**

* 'Other' refers to barriers such as road-crossings and culverts, many of which have not yet been identified as problems for fish passage

Table 3b. Classes of in-stream barriers in major coastal catchments of New South Wales (eastern flowing)

Catchment name	Weir or dam	Gated weir or regulator	Tidal barrier	Other*	Total no. of barriers
Tweed R.	29	0	257	0	286
Brunswick R.	19	0	12	0	31
Richmond R.	202	2	257	1	462
Clarence R.	118	0	167	3	288
Bellinger R.	68	0	31	1	100
Macleay R.	52	0	82	0	134
Hastings R.	56	0	73	0	129
Manning R.	23	0	35	4	62
Karuah R.	11	0	31	1	43
Hunter R.	126	3	189	5	323
Macquarie-Tuggerah Lakes	44	0	25	2	71
Hawkesbury	66	1	54	26	147
Sydney Coast-Georges River	48	0	40	3	91
Wollongong Coast	28	0	22	7	57
Shoalhaven	52	0	47	7	106
Clyde River-Jervis Bay	16	0	36	1	53
Moruya R.	4	0	4	1	9
Tuross R.	8	1	24	1	34
Bega R.	69	0	7	2	78
Towamba R.	6	0	5	0	11
Snowy R.	21	0	–	3	24
Total	**1066**	**7**	**1398**	**68**	**2539**

* 'Other' refers to barriers such as road-crossings and culverts, many of which have not yet been identified as problems for fish passage

3. PROTECTING AND RESTORING FISH PASSAGE

3.1 Rehabilitating ineffective fishways

The majority of fishways built before 1985 in New South Wales were poorly designed and maintained, and provided little or no fish passage (Harris 1984b). These fishways need to be rehabilitated either by modifying the existing structure — perhaps even removing the barrier — or in some cases by the addition of a new fishway (Tables 4a, 4b). Work to test the Denil design as a prefabricated insert (Mallen-Cooper & White 1995) has proceeded successfully at Theresa Park Weir (Nepean River), Euston Weir (River Murray), Jabour Weir (Richmond River) and Brays Park Weir (Tweed River). Other options, such as conversion of ineffective pool-type fishways to operate as Deelder locks, are being considered in a new study by NSW Fisheries, funded by the MDB 2001 FISHREHAB Program.

3.2 Monitoring fish-community responses to improved fish passage

Currently, NSW Fisheries is working on two projects to document the recovery of migratory fish communities after fish passage has been restored. In the Crawford River, the Great Lakes Shire Council has replaced an ineffective submerged-orifice fishway on the tidal barrier at Bulahdelah Weir with a vertical-slot fishway. A study by NSW Fisheries is comparing the recovering fish community with that in the Myall River which does not have a tidal barrier. A similar study is also under way at Bomaderry Creek, where a notch has been cut through Bomaderry Weir to restore fish passage.

Table 4a. Pre-1985 fishways in New South Wales requiring refurbishment on western-flowing streams

Fishway no.	Location/stream name	Type	Possible remedies
1	Combadello/Mehi R.	Submerged orifice	Denil insert
2	Tareelaroi/Mehi R.	Submerged orifice	Denil insert
3	Mollee/Namoi R.	Submerged orifice	Denil insert
4	Gunidgera/Namoi R.	Submerged orifice	Denil insert
5	Weeta/Namoi R.	Submerged orifice	Denil insert
6	Collarenebri/Barwon R.	Submerged orifice	Denil insert
7	Weir No. 8/Barwon R.	Submerged orifice	Denil insert
8	Walgett/Barwon R.	Submerged orifice	Denil insert
9	Brewarrina No. 15/Darling R.	Submerged orifice	Denil insert
10	Louth No. 20A/Darling R.	Submerged orifice	Denil insert
11	Louth No. 21/Darling R.	Submerged orifice	Denil insert
12	Tilpa No. 24/Darling R.	Submerged orifice	Denil insert
13	Marebone/Macquarie R.	Dual vertical slot	Deelder lock or new fishway
14	Berembed/Murrumbidgee R.	Submerged orifice	Deelder lock or Denil insert
15	Yanco/Murrumbidgee R.	Submerged orifice	Deelder lock or Denil insert
16	Hay/Murrumbidgee R.	Submerged orifice	Deelder lock
17	Balranald/Murrumbidgee R.	Submerged orifice	Deelder lock or Denil insert
18	Lock 6/R. Murray	Submerged orifice	Deelder lock or Denil insert
19	Lock 15 (Euston)/R. Murray	Submerged orifice	Denil insert

Table 4b. Pre-1985 fishways in New South Wales requiring refurbishment on eastern-flowing streams

Fishway no.	Location/stream name	Type	Possible remedies
1	Sextonville/Richmond R.	Submerged orifice	Denil insert
2	Doubtful Ck	Submerged orifice	Denil insert
3	Casino/Deep Ck	Submerged orifice	Denil insert
4	Weir No. 8/Mungay Ck	Overfall pool	Denil insert
5	Weir No. 8/Mungay Ck	Submerged orifice	Denil insert
6	Cedar Party Ck	Submerged orifice	Denil insert
7	Glennies Creek Causeway	Denil	Rock-ramp
8	Muswellbrook/Hunter R.	Destroyed	None needed
9	Seaham/Williams R.	Uncertain	Denil insert
10	Ourimbah Ck	Submerged orifice	Rock-ramp & Denil insert
11	Bottom Dam/Jenolan R.	Overfall pool	Denil insert
12	Gauging Station/Cowmung R.	Overfall pool	Denil insert
13	Wallacia/Nepean R.	Overfall pool	Denil insert
14	Audley/Hacking R.	Destroyed	New fishway
15	Brownlows Hill/Nepean R.	Overfall pool	Denil insert
16	Tapitallee Ck	Submerged orifice	Denil insert
17	Buckenbowra R.	Submerged orifice	Denil insert
18	Anglers Reach/Long Plain Ck	Overfall pool	Denil insert
19	McLaughlin R.	Overfall pool	Denil insert

3.3 Changing management practices to enhance fish passage

The potential for using the navigation locks on the River Murray to enhance fish passage has also been investigated by NSW Fisheries. Mallen-Cooper *et al.* (1992) showed that by making simple modifications to the standard operation cycle of the Euston Weir Lock, fish passage was increased from an average of 4.3 fish per cycle to 200 fish per cycle. Ninety percent were native fish. Whilst this enhanced fish passage was a valuable improvement, it was noted that, because of their entrance limitations, modified locks could not be considered adequate substitutes for new fishways.

The management of gated or drop-board weirs is another area where changes to operational procedures can enhance fish passage. This type of weir is generally installed to regulate stream levels, particularly for irrigation offtakes, and the weir is removed when not needed. Managers of these weirs need to be aware that only partial removal or any delay in removing the weir can adversely affect fish-passage opportunities.

3.4 Determining priorities in restoring fish passage

Fish passage must now be considered during the construction of any new in-stream barrier (*NSW Fisheries Management Act 1994* Part 7 (3, 4, 5 and 8)), and when an existing barrier is being modified, but sometimes it may not be required or justified. If the barrier effect is minimal — e.g. because well-designed culverts have been incorporated, or because the site is in a small, high-altitude headwater where fish passage needs do not justify the expense of a fishway, or because the site is in a minor headwater where there is little or no long-term fish habitat upstream of the barrier — fish passage may not be essential. However, the cumulative effect of multiple barriers is an important consideration.

Because of the large number of barriers already existing in New South Wales and requiring fish passage, an objective method is required for assigning a strategic order of priority to fish-passage restoration projects. The criteria that need to be considered when assessing the relative priority of

Figure 10. Scheme for ranking the priority of individual sites for provision of fish passage; see text for details of scheme's application

Priority Factor A	Criterion	Priority Factor B: 5	Priority Factor B: 3	Priority Factor B: 1	SCORE
2	1. river size	large	medium	small	_____
2	2. location in system	tidal/core habitat	non-tidal/non-core habitat	montane	_____
2	3. threatened species	endangered	threatened	none	_____
2	4. upstream habitat	abundant	moderate	limited	_____
2	5. downstream obstructions	none	rare	many	_____
2	6. proportion obstructed	>66%	33–66%	<33%	_____
2	7. drownout passage	rare	occasional	frequent	_____
2	8. barrier type	crested weir	piped	culvert	_____
1	9. fishway	ineffective fishway	no fishway	no fishway	_____
1	10. fishway cost	low	medium	high	_____
1	11. independent support	strong	moderate	none	_____
				TOTAL	_____

individual structures include the following:

1) *river size* — the relative size of the whole catchment of the particular river or stream;

2) *location in system* — tidal sites in coastal rivers are critical for migration of juveniles of many fish species. Similarly 'core habitats' in inland rivers are areas in lowland regions believed critical for large-scale recruitment; they are generally downstream of Echuca, Wilcannia, Narrandera and Condobolin. Montane habitats above 700 m in altitude have generally less need for fish passage because of the low abundance of native migratory fish there.

3) *threatened species* — this refers to the presence, in any particular river reach, of species nationally classified as endangered or threatened. Consideration should also be given to threatened populations and ecological communities at risk.

4) *upstream habitat* — the amount of upstream habitat which should become accessible when a fishway is installed;

5) *downstream obstructions* — this refers to the occurrence and severity of other artificial and natural barriers downstream of the site;

6) *proportion obstructed* — the proportion of the whole catchment of the particular stream which lies upstream of the site;

7) *drownout passage* — the frequency with which high flows create effective drownout condition at the site, so that head-loss and velocity are minimal and fish can swim over the barrier;

8) *barrier type* — this refers to the basic structure of the barrier, which influences the ability of migrating fish to pass upstream;

9) *fishway* — this indicates the presence or absence of an effective fishway on the barrier; it may be simpler and cheaper to restore an ineffective structure than to build a new one;

10) *fishway cost* — the likely cost of building a fishway;

11) *independent support* — this refers to the level of financial and other support for a fishway from local government, landholders, industry, community groups, etc.

These criteria are arranged into a priority-ranking scheme for assessing individual structures in Figure 10. The 11 criteria (rows) are grouped in the scheme in declining order of importance, with two broad groups having priority-weighting multipliers (Priority Factor A) of 1 or 2. Priority Factor B is allocated to the three descriptor columns, with weighting levels of 5, 3 and 1. To apply the scheme for any given site, a score is produced for each of the 11 criteria by multiplying the two relevant priority factors for the particular row, recording the result in the 'Score' column, then summing over all 11 criteria. The total score is then used as the measure of the overall priority of any particular site against other sites on a local, regional or statewide basis. The scheme's operation has been successfully tested using a limited series of sites whose characteristics are well known (Pethebridge *et al.* 1998). It is now believed to be suitable for general application in fish-passage management.

3.5 Regulatory authorities and legislation

NSW Fisheries has a legislative responsibility for protecting fisheries resources under the *NSW Fisheries Management Act 1994* (NSW Fisheries 1998). In the present context this responsibility relates to structures and activities that may impede fish passage. In addition, there are other government agencies with related responsibilities in managing freshwater resources, including:

- NSW Government
  - NSW Department of Land and Water Conservation (DLWC),
  - Department of Urban Affairs and Planning,
  - NSW Environment Protection Authority,
  - Roads and Traffic Authority,
  - State Rail Authority,
  - Waterways Authority,
  - NSW National Parks and Wildlife Service;
- other important NSW agencies
  - water corporations,
  - local government councils,
  - total catchment management groups,
  - catchment management trusts,
  - river management committees;
- Commonwealth and interstate
  - Murray-Darling Basin Commission,
  - Border Rivers Commission.

4. FUTURE DIRECTIONS

4.1 Quality control: ensuring new fishways are effective

Sufficient biological and engineering expertise is now available to build and operate successful fishways for native fish. Nevertheless, fishways often suffer initial problems in their operation that have to be addressed before fully effective fish passage is provided. These problems fall into two broad categories.

1. There can be unforeseen 'layout' problems and design difficulties: an example was the extended exit channel on the Boggabilla Weir vertical-slot fishway that led to peak water velocities extending over an excessive distance, preventing many fish from exiting the fishway. This problem was corrected by reducing the cross-sectional area of each downstream slot with a sill at the bottom of the slot, thus reducing fishway discharge and water velocity at the exit. This type of problem could have been identified before construction and could be prevented in future by a technical review committee, whose task would be to scrutinise plans before completion.
2. The second problem arises from the need to build fishways as cheaply as possible; many aspects of fishways are built to minimum design criteria. This assumes that the behaviour of both the fish and the fishway are predictable under all conditions. Using the Boggabilla Weir vertical-slot fishway as an example again, the original design for the fishway was based on the storage levels designed to be maintained during spring and summer, the peak fish migration period. As this was to be at the 50% storage level, the fishway only needed to surmount the barrier to that height. Unfortunately, the storage level has been managed at an *average* of 50%, and frequently fluctuates to well over the 50% level, resulting in the fishway providing effective passage for only about half the required time. Further negotiations are addressing this problem. A similar cost-minimisation issue relates to the use of rock-ramp fishways that occupy part of the width, rather than the full width of stream channels. This approach has provided substantial cost savings but poses additional issues of fishway capacity and performance in higher flows.

While there is a continuing need to seek innovations and cost-minimisation in fishway design and construction, a risk-averse approach is necessary, where all aspects of fishway design are dealt with conservatively, except those that have been rigorously tested. A technical review committee to oversee projects would assist with this aim.

4.2 Standard fishway designs

The best-tested, most-effective fishway design at this stage is the vertical-slot fishway. Experience so far indicates this design has the capacity to transmit all migrating species and sizes of fish under a wide range of flow conditions for barriers up to 6 m in height. Denil, rock-ramp, pump and Deelder fishways are also capable of transmitting fish effectively, although there has been less experience of their performance in Australian conditions. Lock and trap-and-transport fishways are generally limited to large structures. They also have the potential to function effectively, although there are practical and design problems to be overcome and their operating and capital costs tend to be considerably higher.

The relatively high cost of vertical-slot fishways (Figure 11), when compared with Denil and partial width rock-ramps, is an issue. This has led to pressures for the use both of Denils and of

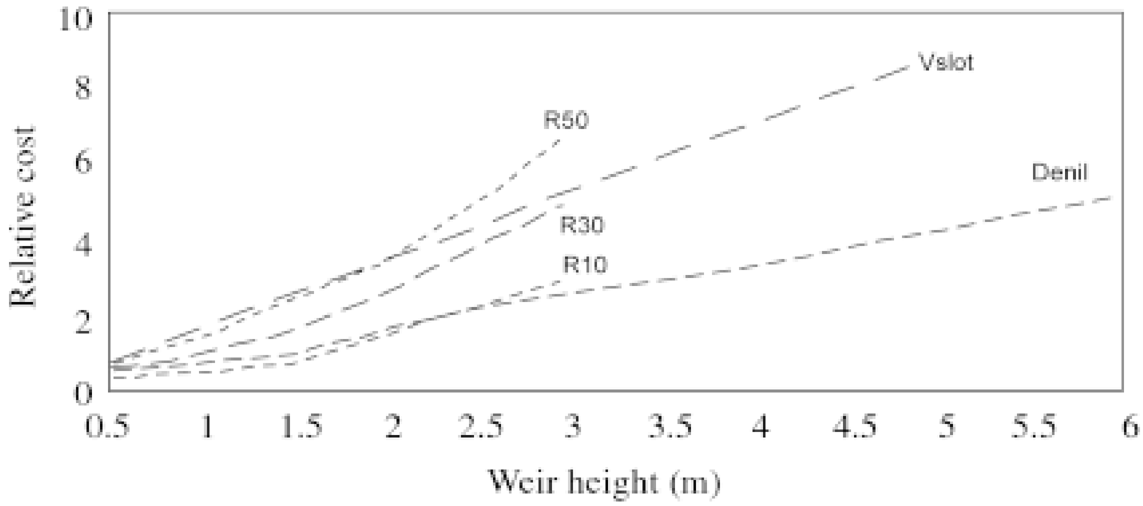


Figure 11. Relative preliminary cost estimates with increasing barrier height for various fishway designs: R50 = rock ramp 50 m wide; R30 = rock-ramp 30 m wide; R10 = rock-ramp 10 m wide; Denil = Denil fishway; Vslot = vertical slot (Source: William Leader, DLWC)

rock-ramps, despite their inherent limitations (refer to section 1.3.2). Again, in situations where there is limited certainty, we should be conservative in selecting fishway designs.

The cost of vertical-slot fishways might be reduced if a different approach to construction were taken. Almost all such fishways have been ‘one-off’ constructions, where concrete for both the foundations and the channel have been poured on-site. This generally requires large amounts of costly coffer-damming and exposure to sudden river rises. A significant saving in time exposed and the cost involved in insuring against flooding can be made if the channel is prefabricated and transported to the site. More resources need to be allocated for determining the feasibility of prefabricated modular fishways, particularly vertical-slot designs.

5. CONCLUSIONS

The fish-passage status of streams in New South Wales has been extensively compromised. All stream fish have some need to migrate and the several thousand artificial barriers that have been built in our streams have contributed significantly to the severe decline of our native fish. The rehabilitation of native fish requires a long-term, well-funded program of fishway development and construction, improvements to weir operation, and removal of barriers wherever possible. Until less costly designs have been rigorously tested, vertical-slot fishways should be used for any new barriers less than 6 m in height and, wherever practical, for restoring passage at existing barriers. The restoration of fish passage and the development of better and cheaper fishway designs require continuing government involvement and support.

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Many reports are also available on our web site at http://freshwater.canberra.edu.au

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