FISH DON'T LIKE TO LEAP OR CRAWL – AN UPDATE ON ENSURING AND RESTORING UPSTREAM FISH PASSAGE

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ABSTRACT

Degradation of habitat and construction of hydraulic structures such as dams or weirs that prevent fish from accessing suitable habitat have resulted in a decline in freshwater fish populations in New Zealand and other countries.

International expertise in the field of fish passage has improved considerably in the last two decades due to advances in sustainable catchment management, river restoration efforts and increased monitoring of existing solutions.

There are no common fish passage design standards or recommendations in New Zealand. However some regional guidelines exist for selected solutions, e.g. TP 131 and TR 2009/084 for the Auckland Region with a focus on fish-friendly culverts, and a fish screening guideline for Canterbury.

This paper imparts the latest knowledge of the construction and retrofitting of structures that enable or restore the upstream passage of fish, based on recent international expertise. Focussing on New Zealand freshwater fish species performance, the prerequisites that are decisive for the effectiveness and efficiency of fish passage are outlined. These are location (e.g. in-stream location and attraction flow) and passability (e.g. hydraulic conditions, orifice spacings and adaptation to up-/downstream water levels). A range of nature-like state-of-the-art solutions and fishway designs are also illustrated.

KEYWORDS

Fish passage restoration, fishway, fish pass, nature-like fishway, rock-ramp fishway, swimming capacity of New Zealand fish

1 INTRODUCTION

1.1 A BRIEF BACKGROUND TO FISH PASSAGE RESTORATION

Fish populations are highly dependent upon the characteristics of their habitats and the connectivity between them, for reproduction, food, shelter and growth of juveniles. 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.

Rivers all over the world have seen severe anthropogenic modifications due to various uses of water, and urban and rural development. Numerous dams, weirs, hydropower plants, water intake structures and waterway crossings interrupt or impede the continuity of rivers and their tributaries and therewith may delay, hinder or block migrations of fish (Nilsson et al., 2005). Amongst other things this has resulted in a decline in freshwater fish populations in New Zealand (ARC, 2009) and other countries. Of the 35 indigenous freshwater species currently recognized in New Zealand, nine are listed in the International Red List of Endangered Species as under threat of extinction (André, 2002). The world-wide steep decline in populations of eels (Anguilla spp.) with less than 1% of major juvenile resources remaining is just one other example (Figure 1).

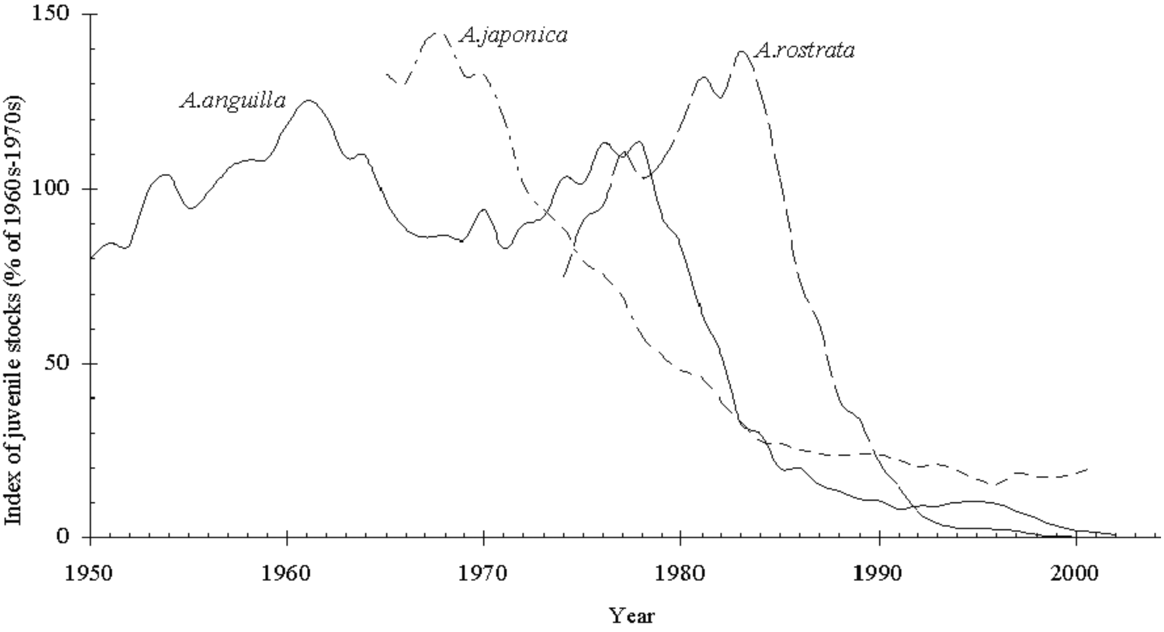


Figure 1: Time trends in juvenile abundance of the major eel stocks of the world. For Anguilla anguilla, the average trend of the four longest data series is shown, which trend appears to occur almost continent-wide; for A.rostrata, data represent recruitment to Lake Ontario; for A.japonica, data represent landings of glass eel in Japan (Québec Declaration of Concern, 2003)

At sites where hydraulic/water management structures are still required and their decommissioning and removal is impossible, upstream fish passes and downstream fishways can be provided to mitigate their impacts.

Worldwide upstream fish passage has increasingly been restored during the last two decades by retrofitting impassable barriers with fishways (fish passes) and modifying waterway crossings, for example by providing ‘fish-friendly’ culverts. Notwithstanding existing legal obligations (e.g. prescribed by the RMA, the Conservation Act / Freshwater Fisheries Regulations and various Regional Plans in New Zealand, the Federal and State Fisheries Management Acts in Australia, and the Water Framework Directive and the EU member states Fisheries Management Acts in Europe) this trend is likely to continue for a variety of reasons, including the implementation of integrated/sustainable catchment management practices and increase in river restoration efforts.

1.2 TYPES OF FISHWAYS AND DESIGN GUIDELINES

There exist various types of fishways for upstream migration (Table 1). Internationally these constructions are well-developed for a wide range of diadromous and potamodromous species. Guidelines for state-of-the-art designs of different types of fishways can be found for example in Armstrong et al. (2004), Clay (1995), DVWK/FAO (2002), DWA (2010), Larinier et al. (2002) and Marmulla et al. (2001).

However there are no common fish passage design standards or recommendations in New Zealand. Some regional guidelines exist for selected solutions, e.g. TP 131 and TR

2009/084 for the Auckland Region (ARC, 2000 and ARC, 2009) and Boubée et al. (1999) with a focus on fish-friendly culverts.

Fish passes / fishways				**Bottom structures, waterway crossings and other hydraulic structures modified to allow for fish passage**
at or integrated into the migration barrier			**extend extensively around migration barrier**	
Pool-type passes	**Channel-type passes**	**Special technical constructions**	**Bypass channels**	
Vertical slot pass Pool and weir-type pass Pool and orifice-type pass Nature-like boulder-type pass	Baffle/Denil pass Eel pass Bristle-type pass	Fish lock Fish lift (fish elevators)	Nature-like channel e.g. with perturbation boulders	Rock ramp Fish-friendly culvert Duct Sluice gate Flood gate Ship lock Gauging station Flood detention dam

Table 1: Classification of upstream fish passage structures (DWA, 2010)

2 GENERAL REQUIREMENTS OF FISH PASSAGE

2.1 DEFINITION OF 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 river/stream and relates particularly to the engineering and biological aspects of restoring free passage at barriers.

According to Thorncraft & Harris (2000) modified from Clay (1995) "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".

2.2 FACTORS DETERMINING THE EFFECTIVENESS AND EFFICIENCY OF FISHWAYS

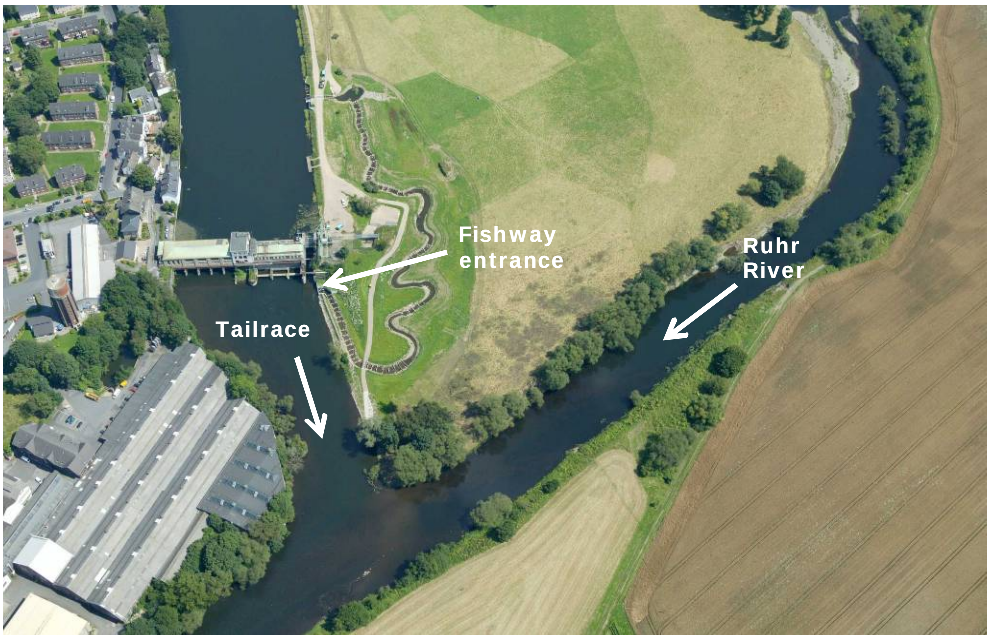
In principle two factors determine the effectiveness and efficiency of fishways:

1. (Ease of) Location: general location of the fishway, entrance position, hydraulic conditions at the entrance and attraction flow.
2. Passability: fishway design including design discharge, flow velocities and patterns, and (with respects to manoeuvrability) water depths, dimensions, slot spacings.

Whereas passability depends on the details of the construction, and the hydraulic and geometric conditions within the fishway, the (ease of) location of the fishway depends on the general layout. The factors that apply to all types of fishways are illustrated in the numerous design guidelines (see section 1.2).

2.2.1 FISHWAY LOCATION, ENTRANCE POSITION AND ATTRACTION FLOW

For a fishway to be effective, the entrance must be sited and designed so that fish locate it with a minimum of delay. However, finding the best fishway location and its entrance(s) is not easy. Compared with the size/width of a watercourse, a fishway entrance always resembles the 'eye of a needle' (Photograph 1).

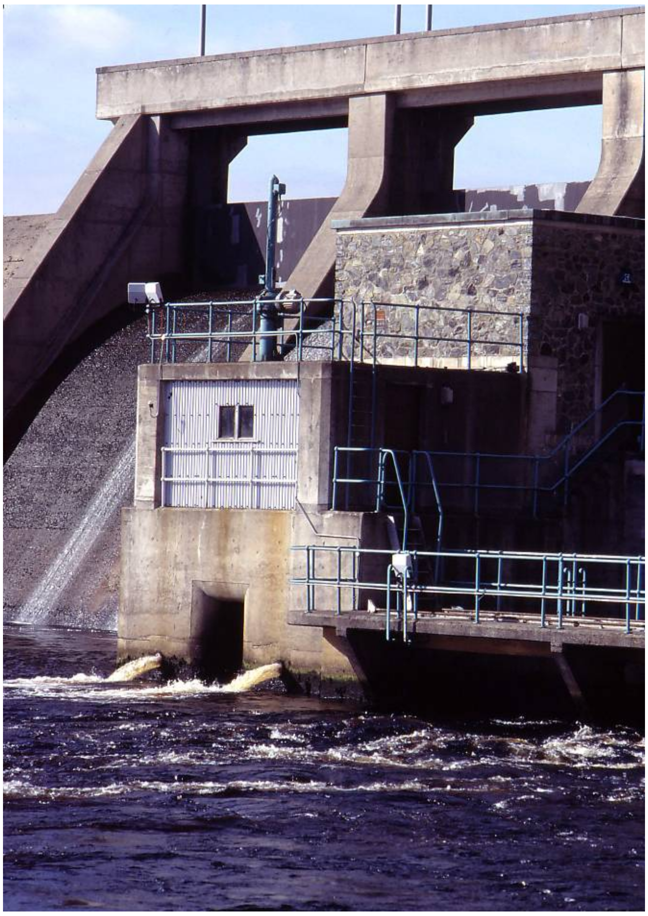


Photograph 1: Comparison of fishway entrance with watercourse. Harkortsee hydropower station and nature-like bypass channel, Ruhr River, Germany (photo: Ruhrverband)

The following layouts represent best practice:

- At obstructions without hydropower facilities the fishway should to be located at the undercut bank where the main current usually concentrates.
- A fishway at an obstruction which is at a marked angle to the direction of flow should be positioned at the most upstream point of the barrier (Photograph 2).

Photograph 2: Fishway at the most upstream point of the inclined St. Martin Weir, Ardeche River, France



Photograph 3: Fish lock entrance adjacent to the draft tube outlet of a hydropower plant and attraction flow entering parallel to the main flow. Lairg Dam, Scotland (photo: Scottish Hydro)

Photograph 4: Entrance of the fishway/bypass channel adjacent to the stilling basin of Beckinghausen Weir, Lippe River, Germany (photo: Lippeverband)

- At run-of-river hydropower sites a position adjacent to the powerhouse / draft tube outlet is essential (Photograph 3).
- At hydropower plants with diversion channels the location has to take into account several aspects such as: discharge from the turbines; plant operating conditions; temporal distribution of the flows in the tailrace; compensation flows in the discharge reach and the flow patterns at the confluence with the pass outlet. As the main flow often passes through the hydropower plant, the correct location is again close to the powerhouse (Photograph 1).
- A fishway entrance in the immediate vicinity of an obstruction (for example draft tube outlet, stilling basin or even hydraulic barrier, e.g. a zone of turbulent water caused by eddies) is considered optimal (Photographs 4 and 5).
- The fishway attraction flow is best meant to enter parallel to the main (river) flow (Photographs 2, 3 and 5).

Photograph 5: Rock-ramp fishway entrance parallel to the river flow at the Reuschenberger Mühle Weir, Wupper River, Germany

- It is essential to create sufficient high velocities at the fishway entrance for fish to perceive and follow the current, and to attract the fish into the facility. On the other hand the velocities must remain compatible with the swimming capacities of all migrating species.
- Downstream water level fluctuations are widespread at obstacles or waterway crossings, and they can amount to several meters. Fishway designs have to take these into account and consider:
  - the fluctuation range with respect to fishway operation time (for example by means of water level gauges or computational hydraulic assessments; typically fishways are required to operate most time of a year, e.g. 300 days p.a. in Germany (DWA, 2010));
  - possible decrease in attraction flow velocity during high downstream water levels; and
  - sufficient entrance velocity is maintained either by manipulating conditions in the fishway (e.g. by increasing the discharge) or at the entrance (e.g. by adjusting its cross-section).

2.2.2 PASSABILITY – GEOMETRIC CRITERIA

Fishways are generally designed for the entire fish fauna (i.e. the various species, development stages and sizes) in a water body, and rarely for certain target species only.

A fishway must provide a continuous 'migration corridor', i.e. water body, of sufficient space (water depth, width and slot openings) to allow fish to manoeuvre upstream. This migration corridor is based on the body size of the largest prevailing (or target) species. Otherwise a fishway will be selective for certain fish species and/or sizes.

For example a recent guideline (DWA, 2010) proposes following criteria:

- Minimum water depth: 2.5 H_{Fish} (to enable fish to move around without colliding with the bottom or the dorsal fin exiting the water column)
- Minimum water depth in short/confined slots, orifices etc.: 2 H_{Fish}
- Minimum width of slots, orifices etc.: 3 W_{Fish} (based on the lateral deflection of the caudal fin)
- Clear length of pool-type structures: 3 L_{Fish} (to provide sufficient space for acceleration/deceleration)

where H_{Fish} = body height of fish
W_{Fish} = body width of fish
L_{Fish} = body length of fish

Name		Fish physique		Fish Passage Requirements		
Family	Common Name	Longest Fish Length (cm)	Fish Height (cm)	Min. Water Depth (cm)	Min. Water Depth in slots (cm)	Min. Pool Length (cm)
Retropinnidae	Common smelt	16.5	3	7	6	50
Prototroctidae	Grayling	30	5	13	10	90
Galaxiidae	Giant Kokopu	40	8	21	17	120
	Banded Kokopu	26	4	10	8	78
	Koaro	18	3	6	5	54
	Canterbury galaxias	12	2	5	4	36
	Inanga	15	2	5	4	45
	Alpine galaxias	11.2	1	3	3	34
Salmonidae	Brown trout	80	18	46	37	240
	Atlantic salmon	83	15	37	30	249
	Rainbow trout	75	17	41	33	225
	Chinook salmon	90	22	54	43	270
Pinguipedidae	Torrentfish	20	4	9	7	60
Gobidae	Redfin bully	12	3	6	5	36
	Common bully	15	3	8	6	45
	Giant bully	15	3	8	7	45
Mugilidae	Grey mullet	50	10	25	20	150

Table 2: Clear length of pool-type structures and minimum water depth requirements for selected New Zealand freshwater species

This approach was applied to native and introduced freshwater species in New Zealand. Data on fish physique was drawn from pertinent literature (McDowall, 2000). Table 2 represents a work-in-progress overview of resulting geometric criteria for clear length of pool-type structures and minimum water depth[1] required for selected species.

2.2.3 PASSABILITY – HYDRAULIC CRITERIA

2.2.3.1 SWIMMING CAPACITY OF FISH

The design of fishways and other fish facilities requires knowledge of the swimming capacity/performance, as well as the behavior of the species concerned so that the fishway does not impede juveniles or weak swimmers. Several guidelines and publications contain information and data on fish swimming ability, e.g. ARC (2000), ARC (2009), Beamish (1978), Bell (1990), Boubée et al. (1999), Clay (1995) Clough & Turnpenny (2006), DWA (2010), Larinier et al. (2002), Mitchell (1989) and Pavlov (1989).

There are three dominant swimming modes (Figure 2):

1. Burst / darting speed: This mode represents the maximum speed a fish can achieve. It is an extremely short (0-15 sec.) but high-speed anaerobic motion and amounts to approximately 10 to 12 (max. ~20) times the body length of fish per second (L_{fish}/s) for adult Salmonids (Salmonidae), Cyprinids (Cyprinidae) and Percids (Percidae) (Beamish, 1978 and DWA, 2010). Fish may require up to 24 hours to regenerate from a burst. The burst speed is used to escape predation and for feeding.
2. Prolonged speed: The performance of fish reduces notably within the first 10 seconds of a burst. Subsequently the swimming speed does not reduce as significantly, and fish can maintain the swimming speed they reach after about 20 to 30 seconds for up to around 200 minutes. The prolonged swimming speed of adult Cyprinidae, Percidae and Salmonidae amounts to about 5 L_{fish}/s (DWA, 2010), and to about 40 to 50 % of the burst speed.
3. Sustained / cruising speed: This represents the 'normal' swimming speed of fish that can be maintained for an indefinite period (> 200 min) without exhaustion. This speed is approximately 2 L_{fish}/s for salmon smolts and potamodromous species.

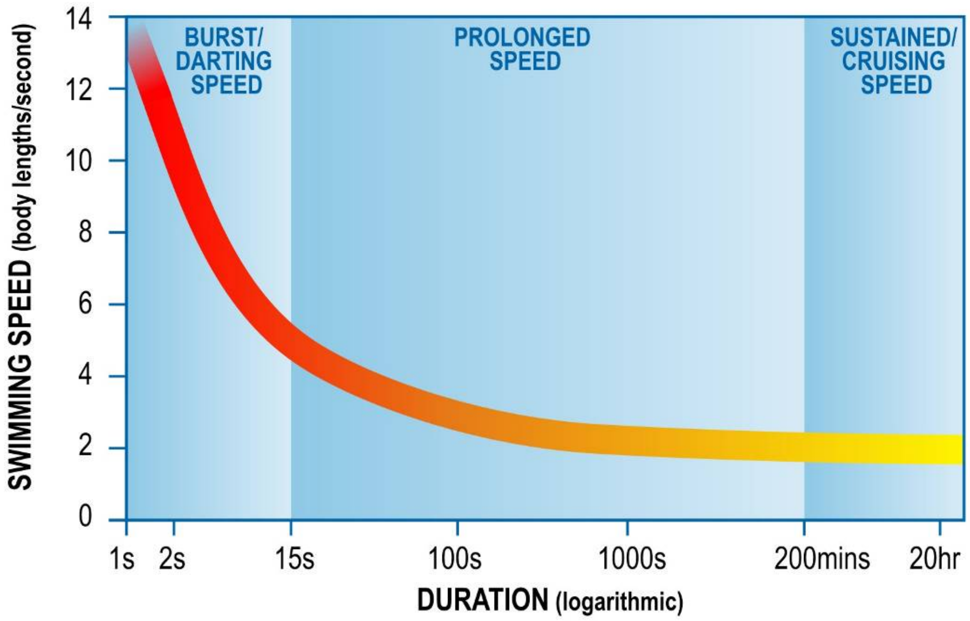


Figure 2: Swimming modes/speeds of fish

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[1] Pool-type fishways require specific water depths to hydraulically function correctly.

Fish swimming ability increases with size and because indigenous New Zealand fish species migrate upstream at a small size (juveniles), they have an even lower swimming ability than larger sized species considered weak swimmers overseas (ARC, 2009). Therefore, New Zealand species are not able to negotiate velocities as high, or distances as long, as most Northern Hemisphere species (Figure 3).

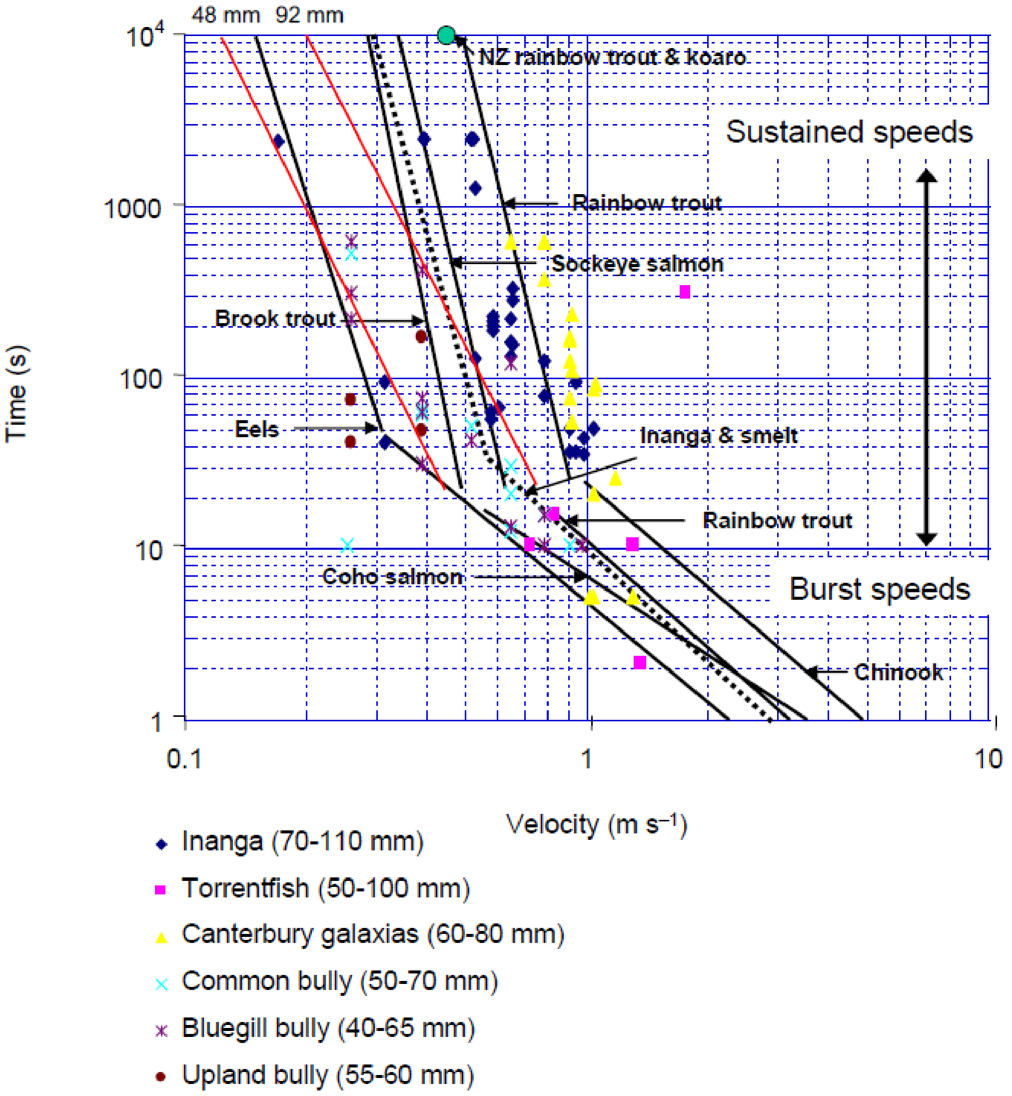

Figure 3: Swimming speeds of New Zealand fish compared to swimming speeds calculated for North American fish species. Lengths of fish are detailed in the key below the figure. Two red lines show the swimming speeds of inanga, 48 mm and 92 mm in length respectively. (ARC, 2009)

Due to their morphology and ability to carry out a degree of cutaneous respiration, some indigenous New Zealand fish species have the ability to climb moist surfaces, These species can negotiate small obstacles that appear to be insurmountable as long as a continuous wetted margin is provided. However there is a lack of evidence as to the possible climbing endurance, speed and distances.

If worst comes to worst, certain species (e.g. Salmonids and rheophilic Cyprinids) are known to be capable of leaping, thereby exiting their environment, providing that they find at the foot of an obstacle conditions (e.g. sufficient water depth) that enable them to use this skill. However, leaping does not represent the universal and preferred upstream movement mode.

The ability of fish to migrate upstream is influenced by several factors (Beamish, 1978 and Boubée et al., 1999). These can limit the swimming performance considerably.

- Biological constraints on performance: size (body length and weight), sex and disease (e.g. parasitic infections).
- Environmental constraints on performance: water temperature, oxygen concentration, carbon dioxide concentration, salinity and water pollution.

Although knowledge of the swimming performance of fish has been significantly advanced in the last 30 years, there are still many specific questions awaiting clarification. These questions relate to both environmental factors (e.g., water temperature, turbulence, sediment concentration, pollutants, light and food) and to physiological factors (e.g., scale, age, sex, oxygen debt and fatigue), which may have varying effects on performance dependent upon the mode of swimming and species.

2.2.3.2 FLOW VELOCITIES AND TURBULENCE IN FISHWAYS

The maximum distance fish can overcome depends on their swimming capacity and the flow velocity they have to swim against. As outlined above, endurance is limited, as soon as fish are required to apply their prolonged or even burst speeds for upstream migration. For example: A fish swimming upstream at a speed of 2 m/s against a flow velocity of 1 m/s moves at an absolute speed (above ground) of 1 m/s. An increase in flow velocity will result in a surplus time (and energy) requirement to overcome the same distance. Whereas a swimming speed of 2 m/s might represent the prolonged speed for a certain species, this might relate to the burst speed of another species.

Fish are only able to apply their maximum swimming performance under favorable conditions and if they are unhurt and in a good physical condition (see section 2.2.3.1). Therefore the hydraulic design of fishways may not be based on the maximum swimming performance.

Maximum flow velocities in fishways are commonly based on

- the swimming performance of the weakest prevailing (or target) species or development stage;
- the type of fishway; and
- the length of the fishway and obstacle height respectively.

It is important to consider the type and length of fishway, as the swimming behavior varies in the different fishway types. For example, in pool-type fishways the maximum flow velocity only occurs locally at the slot/orifice between the pools, and fish only need to apply a high swimming speed for a short duration. However in channel- and baffle-type fishways and on rockfill ramps, fish cannot rest and therefore need to pass the entire structure in a single high speed motion. Therefore maximum flow velocities in channel- and baffle-type fishways and on rockfill ramps must be lower than in pool-type fishways.

In pool-type fishways the maximum flow velocity created at/by the drop is approximated to:

$V_{max} = (2 * g * \Delta h)^{0.5}$

where: g = gravity constant

Δh = head difference between pools

Head differences between pools of 0.05 m, 0.10 m, 0.15 m and 0.2 m, correspond to maximum flow velocities of approximately 1 m/s, 1.4 m/s, 1.7 m/s and 2 m/s respectively.

In channel- and baffle-type fishways and on rockfill ramps the flow velocity is generally a function of the slope, the roughness (coefficient) and hydraulic radius. The Darcy-Weisbach friction loss formula, for example, is used to calculate the mean flow velocity on rockfill ramps (DWA, 2010).

In principle, the smaller the head difference between two pools and the flatter a channel- and baffle-type fishway or rockfill ramp, the easier it is for the fish to pass. Therefore, the drop in pool-type structures and the slope of channel- and baffle-type fishways and on rockfill ramps generally needs to be selected above all as a function of the swimming capacity of the species concerned.

Overseas guidelines recommend drop heights in pool-type fishways of

- up to 0.3 -0.45 m for Salmonids in France (Larinier et. al, 2002);
- 0.1 - 0.2 m for coarse fish and up to 0.3 -0.45 m for Salmonids in the UK (Armstrong et al., 2004);
- 0.1 - 0.2 m depending on the fish zone in Germany (DWA, 2010); and
- 0.05 m in coastal streams at tidal influence and 0.1 - 0.165 m in coastal streams above tidal influence in Australia (Thorncraft & Harris, 2000), and 0.1 m on the Murray River (Barrett & Mallen-Cooper, 2006).

In view of the limited swimming capacity of New Zealand freshwater fish (ARC 2009 and Figure 3), drop heights of 0.05 -0.1 m and ramp slopes of around 1:30 (5%) to 1:100 (1%) are deemed advisable for native New Zealand species.

The difficulty of passage increases with turbulence and aeration in the fishway. A simple indication of the turbulence and agitation levels in the fishway is given by the power dissipated per unit (pool) volume, so called volumetric disspated power, which is expressed as:

$P = (Q*\rho*g*\Delta h)/V$

where: P = power dissipation per unit volume or power density (W/m^3)
Q =flow in the fishway
ρ = the density of water
g = gravity constant
Δh = head difference between pools
V = volume of water, e.g. pool (m^3)

This criterion allows the minimum volume of water in a fishway to be determined when the head difference between pools (or the gradient) and the discharge in the fishway are fixed, or alternatively, the maximum flow that may pass if the head differences and the volume of the pools are fixed.

Maximum recommended values range from 200 W/m^3 for Salmonids to less than 100 W/m^3 for small species, weak swimmers and juveniles (Larinier et. al 2002 and DWA 2010), and even as low as 40 W/m^3 in certain countries (Barrett & Mallen-Cooper 2006).

Analogous to the recommended flow velocities, volumetric disspated power values of less than 100 W/m^3 are deemed advisable for native New Zealand species.

Another design aspect relates to the phenomenon of “short-circuiting”,e.g. direct passage of a high velocity jet from one pool to the next without sufficient dissipation of the kinetic energy. Short-circuiting should be avoided in principle.

3 NATURE-LIKE FISHWAYS

3.1 BRIEF DESCRIPTION OF NATURE-LIKE FISHWAYS

The design philosophy of nature-like fishways is ecological, aiming to achieve compatibility with the specific riverine environments as well as the landscape in which they are constructed. The idea is to observe and apply some of the features of a natural riverine system when designing the structures, i.e. to simulate natural channel characteristics.

Nature-like fishways resemble natural formations, such as pool-riffle sequences, step-pool, cascades, rapids and plane bed formations. Natural materials, such as boulders, crushed stones, cobbles and finer sediments are predominantly used for their construction. The toes and banks of the fishways are usually protected using bioengineering techniques, such as dead or live wood (e.g. debris, root stocks, wattlings, brush matting, live cuttings and stakes), fascines, geotextiles and planted riprap.

The key to fish passage in all of the designs is the diversity of hydraulic conditions. The natural materials create areas with low and high flow velocities that may change as the general flow in the river fluctuates.

3.2 EMPLOYMENT OF NATURE-LIKE FISHWAYS

Within the last two decades nature-like fishways have preferably been built in Germany, Austria, Switzerland, Australia, Canada and Japan. More recently nature-like designs have also been gaining acceptance in the USA, Great Britain and Ireland. However the design concept of nature-like fishways is not new at all. Gerhard for example describes them already in 1904, e.g. a rock-ramp fishway built at a weir in Steinbusch on the River Drage in 1892.

The nature-like fishways constructed today can be subdivided into three different main construction types (DWA, 2010):

1. rock-ramp fishways
2. pool and boulder-type passes
3. nature-like / stream-like bypass channels

The old German fishway guideline published in 1996 by DVWK and co-published in 2002 in English by the Food and Agriculture Organization of the UN recommended the employment of nature-like fishways. It highlighted several advantages, such as good incorporation into the landscape, creation of new habitat in degraded river reaches, provision of appropriate natural riverine structures and comparatively low cost. These advantages lead to their widespread distribution in Germany where many water authorities preferred these types of construction to more technical solutions, often regardless of specific disadvantages, such as difficulties in design, practicability, operation, maintenance and costs.

Until now nature-like fishways have only been constructed at low or medium-head weirs and dams. Due to their comparatively small gradient the lengths of the constructions are substantial - especially of the channel-type constructions that are the first option when retrofitting impounding structures. They therefore require a great amount of space near the obstacle. For example, the total length of the nature-like bypass channel at the 7.8 m high Harkortsee Power Station on the Ruhr River in Germany is 370 m (Photograph 1). Therefore it is not always possible to install nature-like fishways.

The feasibility of nature-like structures has proven to be site-specific and depends on local conditions, such as

- resource consent conditions;
- local infrastructure;
- land ownership;
- availability of area adjacent to the migration obstacle;
- local geological conditions;
- services, e.g. transmission and telephone lines, water and sewage pipes;
- river bank and flood protection structures;
- accessibility for construction, operation and maintenance; and
- the specific fishway characteristics, such as construction type, channel course, dimensions, (available) design flow etc.

3.3 NATURE-LIKE FISHWAY DESIGNS

3.3.1 ROCK-RAMP FISHWAYS

Ramps were originally developed to stabilize river bottoms and did not consider fish passage. Older constructions are often steep (> 1:20) with characteristically high flow velocities and therefore in the majority of cases not passable for aquatic organisms.

Nowadays ramp constructions are designed to enable fish passage. According to their hydraulic working principle there exist three different types of rock-ramp fishways (Figure 4).

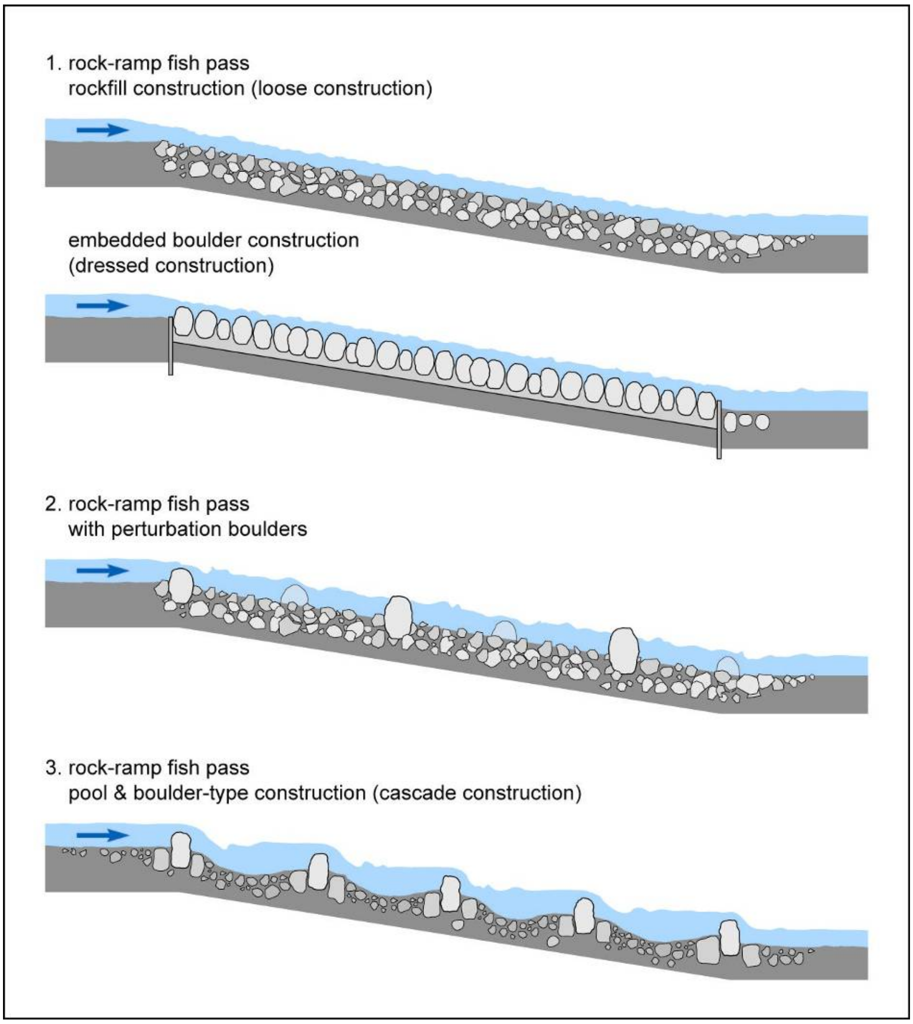

Figure 4: Types of rock-ramp fishways

At drop structures the hydraulic energy is dissipated below the overfall in a hydraulic jump. However on rock-ramps the energy dissipation takes place on the ramp surface and at its foot by means of turbulence created by large-scale roughness (Figure 4, no. 1 and 2). The energy in pool and boulder type rock-ramps (Figure 4, no. 3) is additionally dissipated in the pools. Depending on the head, gradient and discharge, different flow conditions develop on the ramp which determine the stability of the construction, the size of materials used and the ramp geometry.

To enable fish passage over rock-ramps the prerequisites described in section 2.2 have to be met. Evaluations of recently constructed rock-ramp fishways have highlighted the fact that they need to be constructed with even flatter gradients than formerly assumed due to insufficient water depths, especially if larger species need to be considered. Nowadays gradients of rockfill and embedded-boulder ramps and ramps with pertubation boulders typically range from 1:20 to 1:40 depending on the site-specific hydrological conditions, the swimming capacity of the species concerned and the head (Photographs 6 & 7)

Photographs 6 & 7: Rockfill ramp with perturbation boulders (S ≈ 1:35) in Hüsten, Ruhr River, Germany during extreme low and mean flow conditions

Rock-ramps in the upper reaches of rivers are particularly difficult to design. As these river regions are typically characterized by long periods of low flows and short periods of flood flows, there is frequently a problem in ensuring sufficient water depths on the ramp during the periods of low and mean flows. Pool and boulder constructions (Photograph 8) and combined rock-ramp fishways (Photograph 9) enable fish passage due to satisfactory water depths and are therefore appropriate solutions at sites with sustained low-water flow periods. Combined rock-ramps have been developed recently. Here, one part of the construction is designed as a pool and boulder ramp and the other as an embedded-boulder or rockfill ramp. The pool and boulder section enables fish passage during the periods with lower flows due to its greater depths of water and slots between the boulder rows for fish to swim through. The embedded-boulder or rockfill section is negotiable during periods of higher flows in which the depth of water at the ramp's surface is higher and where the energy dissipation in the pools of the other section may exceed critical values.

The design of rock-ramps is probably the most demanding of all fishway designs. The variety of construction types whose design criteria are often not clearly established means that there are a number of different approaches and formulae for the hydraulic and structural calculations. Because these have usually been derived for laboratory tests and/or in-situ experiments, they are often only valid for a certain gradient range or material sizes.

Photograph 8: Pool & boulder-type ramp in Olsberg, Ruhr River, Germany during mean flow conditions

Photograph 9: Combined rock-ramp fishway in Olsberg, Ruhr River, Germany during high flow conditions

The hydraulic design of rock-ramps is highly complex. Different flow conditions depending on the discharge and gradient have to be assessed (Figure 5). The hydraulics of rock-ramp fishways have been investigated in several recent research projects, e.g. Vogel (2003) and Chorda et al. (2004). Future research and development projects will be required to investigate specific areas, for instance velocity distribution in flow layers or turbulence characteristics, and to transfer the findings to rock-ramp fishway designs.

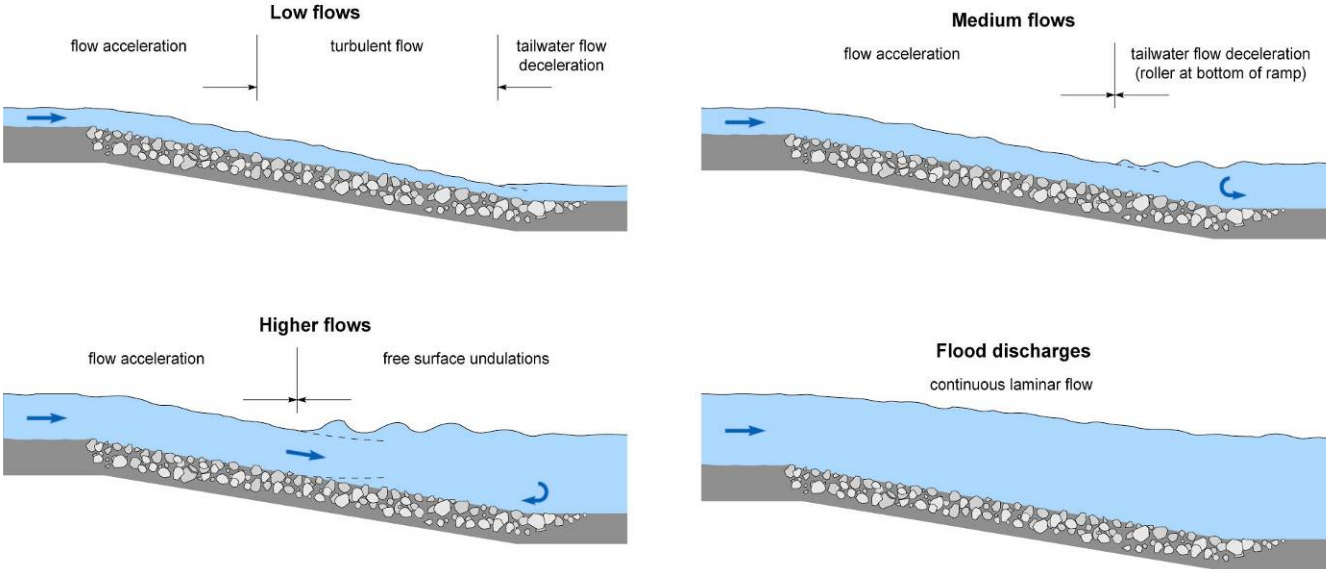

Figure 5: Flow conditions on rock-ramp fishways

Despite the uncertainties, practically oriented design guidelines exist for rock-ramp fishways, e.g. LUBW (2006) and DWA (2010). They incorporate and integrate a number of formulae and design recommendations.

In principle appropriately designed rock-ramp fishways are suitable for both upstream and downstream passage. This type of construction is convenient, especially for retrofitting existing low head weirs or bed drops, either over the full width (full-width rock-ramp fishway) or part of the river width (partial-width rock-ramp fishway). Rock-ramp fishways can be found easily by migrating fish due to their substantial width and attraction flow. Given their nature-like appearance rock-ramp fishways blend well into the landscape and therefore represent a popular type of construction in river restoration projects. At sites with high bed loads, distinct upstream water level fluctuations or sustained low flow periods, the hydraulic and structural design requires particular attention and may call for special solutions. Occasionally rock-ramp fishways may not be suitable. Rock-ramp fishways are easier to maintain and operate than other nature-like constructions.

3.3.2 POOL AND BOULDER-TYPE PASSES

Pool and boulder-type passes are channel-like constructions in which rock boulders are placed in rows across the channel more or less regularly over its entire length. The side walls can either be made of concrete, masonry, gabions, or a sloped embankment.

The boulders create a series of pools of a sufficient length and depth to adequately dissipate the energy. The drop between the pools occurs at the rows of boulders. The flow in this type of construction, therefore, resembles that of a conventional technical pool-type fish pass but with the difference that the flow passes through the several slots between the rock boulders. Occasionally the water even overflows the boulders, e.g. during flood flows.

Pool and boulder-type passes are constructed with large slender quarry-stone boulders (L ≈ 1,2 - 1,8 m) that are placed upright and embedded into the bottom layer of the pass. The boulders normally need to be embedded for up to half of their total length, although this may vary depending on the expected hydraulic load and type of embedment and in this way additional concrete foundation support should not be necessary (Photograph 10).

Photograph 10: Pool & boulder-type fish pass Harkortsee, Ruhr River, Germany during construction

Photograph 11: Pool & boulder-type fish pass Harkortsee, Ruhr River, Germany during test runs

This arrangement allows greater water depths and steeper gradients than do conventional rock-ramp constructions. Nevertheless the decisive features for the ease of passage of this type of construction are the head between the pools (and thus the local maximum velocity in the fishway), the slot spacings (Photograph 10), the pool dimensions and the water depth (Photograph 11) – see section 2.2.

Altogether, nature-like pool and boulder-type fish passes represent a good alternative to technical pool-type fish passes. However special care has to be taken during their construction and tests runs are advisable. They are especially suitable for sites with confined space or limited length for construction and where only a limited amount of flow is available for the operation of a fish pass. If designed as a pool and boulder rock-ramp the construction can ensure operation during low and mean-water flow periods. Like rock-ramp constructions, pool and boulder-type fish passes are only suitable for sites with no or limited upstream water level fluctuations, as baffle overflows will result in an excessive increase in fish pass discharge and corresponding energy dissipation. Due to the comparatively small slot spacings, pool and boulder-type fish passes are liable to clogging by debris. Like technical pool-type passes they therefore require thorough maintenance.

3.3.3 BYPASS CHANNELS

Nature-like and/or stream-like bypass channels are artificial shallow sloping channels ($S \approx 1:100$ to $1:30$) that mimic natural watercourses and link the headwater with the tailwater. They may even bypass the entire impoundment up to the backwater. Therefore the channel can be of considerable length (Photograph 1).

The velocity in the channel is reduced by the roughness of the bottom, the banks and by a series of constrictions and expansions created by perturbation boulders (e.g. rock boulders, blocks etc.), groynes or riffles positioned more or less regularly throughout the entire channel (Photograph 12). Bypass channels can also be designed in sections as pool and boulder-type fish passes but, in general, basic river rehabilitation principles can be applied to their design.

Photograph 12: Nature-like bypass channel Hadamar, Elbbach, Germany with perturbation boulders

In some countries, for example France, some bypass channels cater for both fish passage and canoes, kayaks or rafts (Larinier et al., 2002). However these facilities require a number of additional criteria to be taken into account at the design stage. In other countries, e.g. Germany, they are restricted to fish passage and, quite frequently, to the creation of new habitat, mainly for rheophilic species in degraded river reaches.

The hydraulic design of bypass channels with perturbation boulders have been carried out using the Darcy-Weisbach friction loss formula. DWA (2010), for example, contains the hydraulic design principles and process.

Bypass channels are particularly suitable for retrofitting existing low or medium-head weirs and dams, since their construction generally requires no structural alterations of the impounding structures. As with all other nature-like fishway constructions, bypass channels are only suitable for sites with limited upstream water level fluctuations, as surplus flow in the channel may result in higher velocities and turbulence. However special provisions such as inlet gates or skirt walls can be installed that ensure functioning during varying headwater levels. The main disadvantage of a bypass channel is the comparatively large space required for its construction. Footpath bridges and culverts are often required along their course. Local conditions determine whether or not a bypass channel can be implemented and will also have major influence on the general layout and actual design. Where bypass channels can be realized, they normally blend pleasantly into the landscape.

4 OPERATION AND MAINTENANCE OF FISHWAYS

Fishways are man-made purpose-built structures. They require appropriate operation and maintenance in order to function permanently. A lack of maintenance often results in fishway efficiency problems (DWA, 2010). Yet certain constructions types, as for example rock-ramp fishways, seem less prone to problems due to lack of maintenance (Photographs 6-9). Among the operation and maintenance aspects to be considered are: diurnal, seasonal and incident-related adjustments of the fishway inlets if these are not automatized, responsibility or participation in fishway monitoring works, health and safety, debris and sedimentation removal, repair works etc.

5 CONCLUSIONS

The design of fishways requires knowledge of the swimming capacity, as well as the behavior of the fish species concerned. Although knowledge of the swimming capacity of fish has advanced, data on New Zealand fish species is comparatively scarce and there are still many questions awaiting clarification. These questions relate to both environmental and physiological factors, which may have varying effects on performance dependent upon the mode of swimming and species.

There exist various types of fishways for upstream migration. Internationally these constructions are well-developed for a wide range of diadromous and potamodromous species. Standards and guidelines for state-of-the-art designs of different types of fishways are available. However there are no common fish passage design recommendations in New Zealand. Some regional guidelines exist for selected solutions, e.g. for the Auckland Region, with a focus on fish-friendly culverts. However, these guidelines do not translate the swimming capacity of native and introduced species into geometric and hydraulic design requirements/specifications for fishways in New Zealand. Limitations of certain technologies are not always stated.

This paper outlines the principle two factors that determine the effectiveness and efficiency of fishways:

1. (Ease of) Location: general location of the fishway, entrance position, hydraulic conditions at the entrance and attraction flow.
2. Passability: fishway design including design discharge, flow velocities and patterns, and (with respects to manoeuvrability) water depths, dimensions, slot spacings.

Geometric and hydraulic design criteria for native New Zealand and introduced fish species based on their physique and swimming capacity are also proposed.

Nature-like fishways have been built in Germany, Austria, Switzerland, Australia, Canada and Japan within the last two decades. More recently nature-like designs have also been gaining acceptance in the USA, Great Britain and Ireland. The three main types of nature-like fishways are described:

1. rock-ramp fishways
2. pool and boulder-type passes
3. nature-like / stream-like bypass channels

The latest developments and recent experience with nature-like fishways are outlined in this paper, e.g. the design for large and weak fish species and the combined rock-ramp fishways that are suitable for long periods of low flows. Numerous advantages and disadvantages of the different constructions are also addressed.

Fishways are commonly designed for various species and life stages of the prevailing fish fauna. In principle nature-like fishways, if designed and built correctly, are capable of passing a wide range of species at sites with varying conditions. Nature-like fishways are also more aesthetically acceptable than other types, and therefore are most suitable for river restorations. There exists a great potential for these facilities in New Zealand.

Any fish passage solution, whether nature-like or technical, always has to take into account the ecology and other site-specific boundary conditions. In combination with other aspects, such as practicability, operation, maintenance and costs these should determine the applicability of nature-like designs rather than subjective preferences for certain construction types.

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