Taihoro Nukurangi

Fish screening: good practice guidelines for Canterbury

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Summary

Canterbury rivers with intakes to irrigation and stock water systems are habitats for a wide range of fish. Fish species include introduced sport fish such as Chinook salmon and trout and a diverse range of indigenous species. Many of these species are diadromous, meaning they migrate between freshwater and marine habitats as part of their life cycle. This behaviour makes them potentially vulnerable to being caught up in water intakes, particularly when their life cycle involves lengthy migrations up or down river. As demand for surface water for irrigation use has increased, so have concerns about the effect of losses of fish to intakes. In response to these concerns many intakes (both irrigation and stock water) have been screened to prevent the entry of fish, using a variety of technologies, since the 1980's. By early 2005 fish screens were required by regulatory authorities on irrigation and stock water intakes from New Zealand rivers. Irrigation New Zealand (INZ), Environment Canterbury (ECAN) and Fish & Game New Zealand (FGNZ) identified that fish screening requirements at these types of intake were causing considerable problems for both irrigators and regulatory agencies responsible for fisheries management.

Support was therefore sought and obtained from the Sustainable Farming Fund, through Irrigation New Zealand, for a project with the outcome of providing guidelines that represent an agreed position between FGNZ, INZ and ECAN for fish screening at intakes. These guidelines are intended to be a practical guideline document, cover intake sizes of up to 10 m^3s^{-1} surface and 500 ls^{-1} pumped and provide design information and narrative on how features have been selected, and a bibliography. The specific objectives of this report are to:

1. Summarise structural design options currently available.

2. Identify and list of good design features for screening success that, when appropriately incorporated into a design, represent best practice.

3. Identify and summarise the movements of the New Zealand fish species that will be susceptible to water diversions and that will need screening protection.

4. Identify screening characteristics (e.g., mesh sizes) most appropriate to the various fish species.

5. Provide information that would encourage technical innovation by all parties involved with intake design.

6. Identify further work to clarify issues around fish biology, fish behaviour at intakes and information on how intakes perform in practice. This work now also needs to address how to deal with a new invasive alga species (*Didymo*).

7. Provide good working examples of fish screens currently operational in contrasting situations in Canterbury

This report shows that problems with fish screening arise from uncertainty over issues such as: the objectives of screening; the biology of the fish species identified; design features (mesh size, approach velocity etc.); the practicality of operating structures as designed and built and whether screening arrangements will be effective at all. In addition many existing installations face large ongoing direct maintenance and re-consenting costs, as well as losses due to blocked screens and potential enforcement costs.

There is a need for a "whole of intake design" if fish are to be efficiently and effectively diverted without damage from intakes We show that a fish screen will only be effective when all the following features are sufficiently implemented:

1. The site is located to minimize exposure of fish to fish screen structure, and minimizes the length of stream channel affected while providing the best possible conditions for factors 2-6 below:

2. Water velocity ("speed") through the screen ("approach velocity") is slow enough to allow fish to escape entrainment (being sucked through or washed over the screen) or impingement (being squashed or rubbed against the screen).

3. Water velocity across (or past) the screen ("sweep velocity") is sufficient to sweep the fish past the intake promptly.

4. A suitable fish bypass is provided so that fish are taken away from the intake and back into the source channel.

5. There needs to be "connectivity" between the fish bypass and somewhere safe, usually an actively flowing (i.e. not still) main stem of the waterway.

6. Screening material (mesh, profile bars or other) on the screen needs to have openings small enough to exclude fish, and a surface smooth enough to prevent any damage to fish.

7. The intake needs be kept operating to a consistent, appropriate standard with appropriate operation and maintenance. This should be checked or monitored.

International literature has revealed many different combinations of fish screen. These can be divided into two categories: (1) Positive barrier screens (eleven types are illustrated); (2) Behavioural devices (three types are illustrated). Each screen type is described with a list of advantages and disadvantages. A review is presented of appropriate aperture sizes for screening those New Zealand fish species that are likely to be affected by intakes. This review estimates appropriate mesh size for trout, salmon and the following native species: whitebait, non-migratory galaxiids, flatfish, eels, bullies, lamprey and torrent fish. Tables of likely risk to various fish species and life cycle stages at different times of year for various screening options (2mm, 3mm, 4mm and 5mm side square mesh) are presented.

A "Decision Table" is provided that compares the screen types against different locations for deployment, operations and maintenance as wells as a relative ranking of capital costs. Finally, design processes are discussed and examples are given of several good designs that are currently operational in Canterbury.

1. Introduction

1.1. Introduction to fish screening

Canterbury rivers with intakes to irrigation and stock water systems are habitats for a wide range of fish. Fish species include diverse indigenous species, and introduced sport fish such as Chinook salmon and trout. Many of these species are diadromous, meaning they migrate between freshwater and marine habitats as part of their life cycle. This behaviour makes them potentially vulnerable to being caught up in water intakes, particularly when their life cycle involves lengthy migrations up or down river. Species of concern include introduced salmonids (notably brown trout *Salmo trutta*, rainbow trout *Oncorhynchus mykiss*, and Chinook salmon *O. tshawytscha*), and native species such as freshwater eels (*Anguilla* sp.), lamprey (*Geotria australis*), bullies (*Gobiomorphus* sp.), torrentfish (*Cheimarrichthys fosteri*), and several species of the genus *Galaxias*.

As demand for surface water for irrigation use has increased, so have concerns about the effect of losses of fish to intakes. In response to these concerns many intakes (both irrigation and stockwater) have been screened to prevent the entry of fish, using a variety of technologies, since the 1980s.

Fish screen designs adopted for use in New Zealand have been adaptations of designs used elsewhere, particularly the western USA. Designs include inclined flat screen and rotary screen installations for open channel diversions, and screened intakes for pumped systems.

A common type of screen introduced to New Zealand in the early 1980s is the rotary drum screen. (Figure 1). An objective of this design is to use some of the energy of the flow of water to rotate the drum screen and provide self-cleaning of debris, while a relatively fine screen mesh excludes fish.

These were introduced to New Zealand with the best of intentions, but over the last twenty years observations of their actual field performance have caused increasing concern. These observations include:

- Fish accumulate in front of the screen and become food for predators, such as shags.

- Rubber seals around the drum become worn and fish are able to pass into the irrigation supply.

- Continued problems with screen blockage result in ad hoc repairs such as lifting of the drum position – which unfortunately also allows fish to pass into the irrigation supply.

- Screen blockages can occur from sediment and debris accumulation. Willow leaves and algae stripped from the gravel beds of South Island East Coast rivers are notable sources of fouling material.

- Many such structures have excessive approach flow velocities and other design features that may lead to fish mortality. An observation is that the rotary screen design has been used in New Zealand without the level of understanding of risk factors to fish that was available when it was designed in North America.

Figure 1: Drum screen, rotary intake.

This is not a complete list of problems, but suffices to illustrate the need for more effective fish screens, not only in terms of excluding fish, but also to minimise operational problems. It is also apparent that many problems result from insufficient knowledge of how fish behave, a lack of knowledge regarding what is required to protect them at intakes, and from designs that do not take into account the debris loads of some types of New Zealand rivers.

Recent developments have been the proposed use of novel types of fish protection at intakes. These include sound, light and bubble barriers. As with the earlier rotary drum screens these technologies have resulted from experience in other countries with different species, flow regimes and types of water body.

In addition to the developing technology of screening, there have also been important changes occurring in the abundance of, and attitudes towards, particular species. These include:

In east coast South Island rivers, Chinook salmon populations have always been subject to fluctuations. However recent years have seen particularly small catches.

The importance of indigenous fish species is much more widely acknowledged than was the case twenty years ago, and knowledge of their distribution and behaviours has been steadily increasing.

Eel populations, particularly for the longfin eel (*A. dieffenbachii*), are threatened. These are of particular importance due to cultural and commercial fishery considerations.

Initially, screening appears to have been voluntary best practice as part of negotiations over multi-use for water bodies. More recently, screening has become an expected condition of consents for surface water takes. Overall the situation regarding fish screening has reached a point where knowledge of both the fish species being protected, and the technology available, need some attention.

1.2. Background to this project

By early 2005 fish screens were required by regulatory authorities on irrigation and stock water intakes from New Zealand rivers. Irrigation New Zealand (INZ), Environment Canterbury (ECAN) and Fish & Game (FGNZ) identified that fish screening requirements at these types of intake were causing considerable problems for both irrigators and regulatory agencies responsible for fisheries management.

ECAN, FGNZ and the Department of Conservation (DOC) all have regulatory responsibilities related to fish and fish passage. Regional Councils have responsibilities under the Resource Management Act (RMA). This act requires that every person avoid remedy or mitigate any adverse effect resulting from an activity carried out by that person whether or not the activity is in accordance with a rule in a plan or a resource consent. This means that the owner of any structure causing an adverse effect must take the appropriate action to remedy or mitigate this effect. In addition consideration can be made of the various responsibilities placed on Regional Councils by part II of the RMA with respect to the life supporting capacity of the water and ecosystems and the protection of the habitat of trout and salmon.

Management of all fisheries types in New Zealand is governed by the Conservation Act 1987, which includes the Freshwater Fish Regulations 1983 (section 48a Conservation Act), and the Fisheries Act 1983. In relation to fish passage, DOC's responsibilities include:

- Protecting freshwater fish habitats (s.6ab; Conservation Act 1987).

- Advocating the conservation of aquatic life and freshwater fisheries generally (s.53 (3) (d); Conservation Act, 1987).
- Administering the fish passage provisions (Part VI) of the Freshwater Fisheries Regulations 1983.
- Part VI (Regulation 41-50) of the Freshwater Fisheries Regulations 1983 states that:
- The Director General of Conservation may require that any dam or diversion structure has a fish facility (fish pass, fish screen or similar) included and can set conditions on its design and performance.
- Culverts and fords may not be built in such a way as to impede fish passage, without a permit from the Director General of Conservation.

These functions are closely related to those of other agencies including the Ministry of Fisheries, regional councils and Fish and Game New Zealand, which also have specific functions in freshwater management in New Zealand.

The Conservation Law Reform Act (1990) gives Fish and Game Councils statutory responsibilities for the management, maintenance and enhancement of sports fish and game resources in the interests of recreational anglers and hunters.

In recent years, many proposed or existing intakes have been contested on a consent-by-consent basis, at expense and to the exasperation of all parties. Problems arise from uncertainty over issues such as:

- The objectives of screening. (Total exclusion? Which species?)
- The biology of the fish species identified.
- Design features (mesh size, approach velocity etc.).
- The practicality of operating structures as designed and built.
- Whether screening arrangements will be effective.

In addition many existing installations face large ongoing direct maintenance and re-consenting costs, as well as losses due to blocked screens and potential enforcement costs.

1.3. Parties involved in this project

ECAN assembled a group of interested parties in mid 2005. This was the Fish Screen Working Party. A series of meetings were held and the concept of producing a "Guidelines Document" emerged. The project team included:

- Environment Canterbury: Environmental Regulatory agency for the Canterbury region, which has some 60% of irrigated land in New Zealand

- FGNZ, Central South Island and North Canterbury Regions

- INZ: Initiator of the Sustainable Farming Fund project.

- DOC. Soon after the commencement of the project DOC began work on native fish requirements for water intakes in Canterbury, which ultimately resulted in the review "*Native Fish Requirements for Intakes in Canterbury*" in July 2006 (Charteris 2006).

NIWA's role was to provide impartial review of science based information.

1.4. Initial proposal and project process

Support was sought and obtained from the Sustainable Farming Fund, through Irrigation New Zealand, for a project with the outcome of providing guidelines that represent an agreed position between FGNZ, INZ and ECAN for fish screening at intakes. These guidelines are intended to be a practical guideline document for intake sizes of up to 10 m^3s^{-1} surface and 500 ls^{-1} pumped and provide design information and narrative on how features have been selected, and a bibliography. Principles included will be useful for larger intakes, but it is anticipated that such intakes will require extra design consideration.

Initially it was anticipated that initial design parameters could be determined from material to hand. This was to be followed by a process of developing some standard designs that would then be confirmed via a stakeholder workshop and disseminated to the community. However the desire to include indigenous fish information, and to incorporate recently released (late May 2006 and October 2006) and very substantial information from Europe (DWA Topics 2006), North America (U.S. Department of the Interior 2006) and the UK (O'Keeffe & Turnpenny 2005) led to recognition that the project needed to be altered in terms of timing, content and communications.

Key parts of the project process included:

- Review of fish screening requirements for sports fish by NZ Fish and Game Council (attached as **Appendix A**).

- DOC's review of indigenous fish requirements (attached as **Appendix B**).

- Synthesis of requirements of above reviews by NIWA.

- Review of international practices developments in fish screening (**Appendices C, D, E**) and their application to New Zealand conditions.
- Identification of examples of good practice in New Zealand.
- Production of guidelines.
- An important aspect of the project is that it has been based only on existing published information, rather than original work.

1.5. Objectives of this Report

The specific objectives of this project document are to:

1. Summarise structural design options currently available.
2. Identify and list of good design features for screening success that, when appropriately incorporated into a design, represent best practice.
3. Identify and summarise the movements of the New Zealand fish species that will be susceptible to water diversions and that will need screening protection.
4. Identify screening characteristics (e.g., mesh sizes) most appropriate to the various fish species.
5. Provide information that would encourage technical innovation by all parties involved with intake design.
6. Identify further work to clarify issues around fish biology, fish behaviour at intakes and information on how intakes perform in practice (including how to deal with a new invasive alga species – didymo (*Didymosphenia geminata*).
7. Provide good working examples of fish screens currently operational in contrasting situations in Canterbury.

2. Review of information

Reports by FGNZ and DOC (Appendices A and B) covered similar areas that would be relevant in setting requirements for freshwater intakes including current literature review on:

- Fish species distribution, location, movements, swimming ability and size.
- Legal requirements.
- Aspects to prevent entrainment and impingement including screen location, mesh gap size, structure placement, sweep and approach velocities, bypass, monitoring and maintenance, and gaps in knowledge.

The FGNZ review covered published information of salmon and trout, mainly based on North American studies. It identified key references and made recommendations based on material to hand, while work by DOC covered all current information available on the behaviour and distribution of indigenous species and their requirements.

NIWA carried out a literature review of a wide range of “primary sources” (originally published papers and other material) to identify key features relevant to the New Zealand situation. In addition, the New Zealand freshwater fish database (maintained by NIWA) was accessed to identify relevant information on fish distribution.

During the later stages of the original project, three substantial guides on fish screening were published in the USA, Germany and the UK (DWA Topics 2006, O’Keeffe & Turnpenny 2005, U.S. Department of the Interior 2006). These guides are included (in .pdf format) as Appendices C, D and E. These have been made available via web downloads, and contain analysis of a wide range of sources that are additional to those that would normally be located via a one-off literature review for a project of this size. Much of this material is not necessarily relevant to New Zealand, but gives an indication of the complexity and cost of some approaches found in other countries for interested readers.

3. Review of structural options

This section provides an overview of key international approaches to fish exclusion that provide useful background for New Zealand practices. For a full description of alternative and additional concepts readers are advised to consult the guides indicated in Appendices C-E.

Screens can be categorised in various ways, e.g., stationary, moving, and behavioural. The following classification is similar to that used by USDI (2006), i.e., (1) Positive barrier screens and (2) Behavioural devices. These are described below, together with the advantages and disadvantages of each. A Decision Table that can be used to assist in selection of fish screening options is included as Table 7 in Section 4.3.3.

3.1. Positive barrier screens

The method most widely used and accepted by fishery resource agencies to protect fish at water diversions is to provide a physical barrier that prevents fish from being entrained into the diversion. For off-river barriers, the fish are diverted through a "bypass" that safely returns the excluded fish to the water body from where the water was diverted. Hundreds of these positive barrier screens have been built and are reported function very successfully in the USA and elsewhere.

The most common types of positive barrier screens are presented in this chapter. Table 1 summarizes these screen alternatives.

3.1.1. Flat plate screens (diagonal or "V" configuration)

Modern flat plate screens consist of a series of flat plate screen panels set between support beams or guides and placed at an angle to the approach flow (Figure 2). The screen is fixed and does not move. Rather, the diverted flow passes through the screen excluding fish and debris, which are guided to the bypass.

Flat plate screens have been effectively installed at in-canal, in-river, and in-diversion pool sites. Fish bypasses are typically installed at in-canal sites, and may also be required at in-river and in-diversion pool sites.

With all three siting alternatives, care must be taken to orient the screen in the flow field in such a way that a relatively uniform approach and sweeping flow occurs across the full length of the screen. Establishing desired flow conditions across the screen face requires consideration of flow patterns generated at the specific site and resultant angle to the flow placement of the screen. Baffling to generate uniform approach velocity distribution is required as well. Screens may be placed on a diagonal across the flow, parallel to the flow with a reducing upstream channel section, or in a "V" configuration.

Table 1: Positive barrier screen alternatives.

Screen type	Typical locations	Comments
Flat plate screen	River, canal, diversion pool	Widely used in rivers and canals. Wide range of diversion flow rates
Drum screen	Canal, diversion pool	Suitable where water level is stable (controlled to 0.65-0.85 drum screen diameter). Currently used mostly for small flows, although has been used for large flows
Travelling screen	Secondary screening in bypass, river	Because of expense, usually used for small flows
Submerged "Entry to Pipe" screens	Intake to pumped or gravity piped system	Category here applies to sizes commonly used for pumped intakes to 100l/s.
Cylindrical screen	River, diversion pool	Typically applied at intakes to pumping plants
Inclined screen	Secondary screening in bypass, canal, diversion pool, river	Adverse slope – suitable where water level is controlled. Inclined plate – best applied along river banks
Horizontal flat plate screen	Canal, river	Typically applied in river with good sweeping flow. Currently used for small diversions (e.g. < 3 m^3s^{-1})
Coanda screen	River, canal	Limited to small diversions (e.g. < 4 m^3s^{-1})
Eicher	Closed conduit diversions	Experience limited to application in power station penstocks
Modular inclined screen (MIS)	Closed conduit diversions	Experience limited to application in power station penstocks
Submerged galleries	River, canal, diversion pool	Wide range of diversion flow rates, Suitable in gravel, pebble or boulder beds. May avoid mesh size problems.

Figure 2: Example of flat plate screen "V" configuration, with a terminal fish bypass. – Abstracted water exits via side chambers behind screens while bypassed fish continue straight ahead and return to main channel.

A wide range of screen materials has been effectively applied in fish exclusion facilities. The most common mechanical equipment used in association with flat plate screens is related to cleaning and debris handling at the screens. To minimize maintenance requirements and maintain efficient screen operation, effective screen cleaning must be included with any fish exclusion facility. With small screens and low debris loads, cleaning systems may be no more than a manually operated rake, brush, or squeegee. For larger systems, mechanically driven rakes, brushes, or squeegees may be required.

Because of their excellent fish protection performance and generally low operating cost, flat plate screens are currently widely used at small to large irrigation diversions in USA, where total fish exclusion is required.

Advantages of flat plate screens

- They are effective barriers to fish entrainment.
- They do not require a controlled operating water depth as needed for drum screens.
- They have a proven cleaning capability that removes debris from the screen.
- The screen itself has no moving parts, thus simplifying screen and screen support structure and reducing screen costs.
- Their performance has been widely applied and proven and is accepted by some Regional Councils (E.g. Level Plains intake , Canterbury)

Disadvantages of flat plate screens

- Mechanical screen cleaners require maintenance and add to both the capital and operating cost of the structure.
- Shallow depths caused by low flow rates can result in excessively long screens to meet screen area requirements.
- The bypass will usually have to pass the debris cleaned off the screen.

Examples of flat plate screen installations in New Zealand

- Levels Plains Irrigation Intake (see Fig 25)

3.1.2. Drum screens

Drum screens consist of screen covered (typically woven wire) cylindrical frames that are placed at an angle to the flow with the cylinder axis oriented horizontally (Figures

3 and 4). A screen installation can consist of a single screen at smaller diversion sites or a series of screen cylinders placed end-to-end.

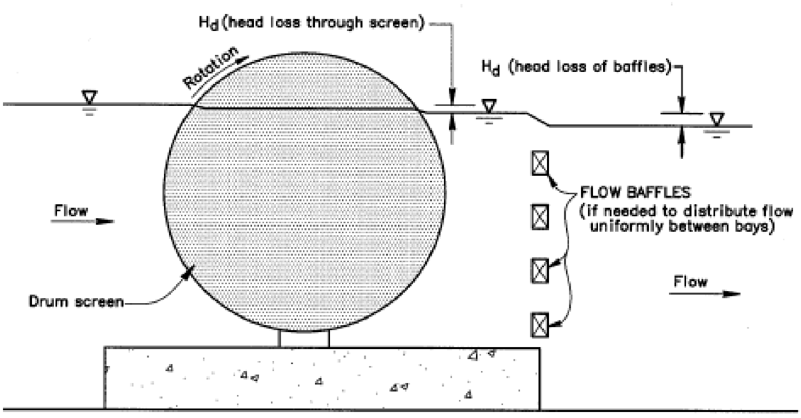

Figure 3: Sectional view through a drum screen

Figure 4: Large drum screens during installation, Washington, USA

The installed drums slowly rotate about their horizontal axis. With the rotation, the lead surface of the drum rotates up and out of the flow while the trailing surface rotates down. The rotation carries any debris up on the drum and it is washed off on the backside as the flow passes through the screen. To provide sufficient fish screen area and optimize debris handling, drum screens must operate in depths of 65 to 85% of their diameter. With this submergence, debris that encounters the screen face will cling to the drum. Drum screens consequently tend to have excellent debris handling and self-cleaning characteristics, with supplemental cleaning systems required only rarely.

Because of the specific submergence requirements, drum screens are typically not used for in-river sites. Drum screens are most often used with in-canal installations and have been used in the pool of some in-diversion sites.

As with flat plate screen concepts, modern drum screen installations place the drum line at an angle across the flow to provide a sweeping velocity. With pier faces shaped like the drum and aligned with the drum, fish that encounter the facility find a fairly continuous screen face guiding them to the bypass. Screen flows, sweeping and approach velocities, and other design criteria are applied to drum screens as previously described for fixed, flat plate screens, including in-diversion pool auxiliary and flow guidance structures. Design features to generate uniform approach velocity distributions may also be required

Numerous drum screen installations exist in parts of USA, notably Oregon, California, Idaho, and Washington with flow rate capacities ranging from ~0.1 m^3s^{-1} to over 30 m^3s^{-1}. Drum screens have been widely used on small to large size irrigation and power diversions (now used mostly for small flows).

Advantages of drum screens

- They are considered self-cleaning and have excellent debris handling characteristics.
- Proper cleaning is independent of the bypass flow.
- Their use has been widely applied and historically been generally accepted by Regional Councils, particularly in Canterbury.

Disadvantages of drum screens

- They pose a more complex design and bypass structure than flat plate screens. Consequently, capital costs tend to be higher than flat plate screens.
- They are applicable only to sites with well-regulated and stable water surface elevations such as canals and in-diversion pool and reservoir sites where water surface elevation can be controlled.
- The seals at the bottom and sides of the drum require maintenance and special attention to prevent undesirable openings where fish may pass.
- They have moving parts that require maintenance. Special attention is needed for the bearings and drive chains because they operate in submerged conditions.

- Continuous rotation (operation) of the drum screen is required for proper cleaning.

3.1.3. Travelling screens

Travelling screens are mechanical screens installed vertically or on an incline, and include screen panels, baskets, trays, or members connected to form a continuous belt (Figure 5). The screens operate with the screen rotating or travelling (intermittently or continuously) to keep the surface clean. The screens with baskets, which were originally developed for debris removal, move up on the leading (upstream) face and down on the back. The screen drive mechanism is positioned above the water surface; however, a spindle with bearings, guide track system, or drum is required at the submerged bottom of the screen. Sediment in and around this lower area may increase maintenance requirements.

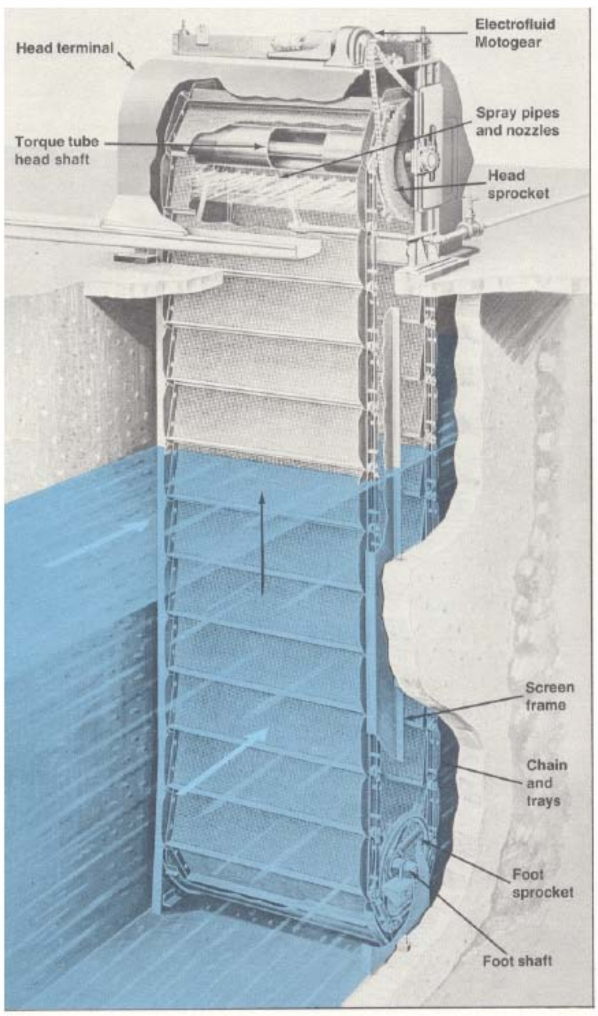

Figure 5: Travelling screen.

Travelling screens have excellent debris handling characteristics and, consequently, may offer an alternative at sites with debris problems. Vertical travelling screens are widely applied at process and cooling water intakes. The flatter the incline (slope) of the travelling screen the greater the chance that fish may be carried over the screen. Because of the relatively high costs, travelling screen application would most likely be limited to capacities of less than 2 m^3s^{-1}.

The most common application for travelling screens at irrigation facilities is for fish exclusion in the secondary dewatering structures used to reduce the bypass flow rates. With such applications, the bypassed flow conveying fish and debris from the primary screen are passed through a second screening facility (travelling screen) where a portion of the bypass flow is pumped back to the irrigation supply canal, thus reducing the flow lost to the diversion; however, both the fish and debris are further concentrated in this reduced bypass flow.

Travelling screen installations are normally configured with the screen face (or faces, in the case of multiple screen installations) placed parallel to or at a shallow angle to the flow. As with other concepts, this generates good sweeping flow and provides fish guidance along the screen face, thus reducing fish contact with the screens.

Advantages of travelling screens

- They have excellent debris handling characteristics.
- They are commercially available which reduces design costs.
- They do not require a controlled operating water depth for proper cleaning as required for drum screens.
- They have been widely applied for many years, have a good performance record, and are accepted by many North American fisheries resource agencies as positive barrier screens.

Disadvantages of travelling screens

- They are expensive for large diversions. They are more commonly used where less flow is diverted such as at small diversions or at secondary dewatering (pumpback) structures in fish bypasses.
- The seals require maintenance and special attention to prevent undesirable openings where small fish may pass. The travelling screen, spray water pump, and conveyor have moving parts which require maintenance.

- Special fabrication may be required to prevent fish passage between the screening trays or baskets and to prevent fish from being trapped on the lips of the basket frames.

- There are no known travelling screen installations in New Zealand. Examples in North America screen intakes ranging from 0.7 to 21 m^3s^{-1}.

3.1.4. Submerged "Entry to Pipe" screens

There are several submerged screen module designs commercially available in North America and New Zealand (Figure 6). Typically, these modules are installed on pump diversion intake tubes at sites where the screen module is fully submerged. These commercially available screen modules have been effectively applied both in rivers and lakes. River applications are preferred because the river flow carries fish and debris away from the screen while diversion flow passes through the screen. Alternative module designs include conical screens with rotating brush cleaners, horizontal flat plate screens, rotating cylindrical screens with fixed brush or spray cleaners, and fixed cylindrical screens with air burst or backwash spray cleaners. Some modules include internal baffling elements that generate uniform screen approach velocity distributions.

Figure 6: Commercially available self cleaning submerged screen

Although cylindrical (see next section) and conical screens are commercially available, there are also submerged screens including the horizontal and inclined screen concepts that are designed for the specific site. Cylindrical screens are commonly used at pumped water diversions, and the inclined and horizontal submerged screens are commonly used at gravity flow diversions.

Advantages of submerged screen intakes

- They have excellent debris handling characteristics.
- They are commercially available which reduces design costs.
- They have been widely applied for many years,
- As an "entry to pipe" screen they protect pumps and sprinklers from damage from blocked screen effects and debris fouling.

Disadvantages of submerged screen intakes

- They are not as economically viable for large diversions. They are more commonly used where less flow is diverted such as at small diversions or at secondary dewatering ('pumpback') structures in fish bypasses.

3.1.5. Cylindrical screens

Submerged cylindrical screens, which compose the most widely applied submerged screen concept, consist of fully submerged screen modules placed at the intake end of pumped or gravity diversion conduits for supplying water for irrigation, process, cooling, and small hydropower applications (Figure 7). These designs may include a single screen module or multiple screen modules where larger diversion flow rates are required.

Figure 7: Raised cylindrical screens (California)

The screens are placed fully submerged in the water body from which the flow is pumped. For irrigation installations, the screens would likely be placed at in-river sites, although they have been applied at in-reservoir or diversion pool sites as well. The fish excluded by the screen remain free swimming in the river or pool and, therefore, a fish bypass is not needed. Screen designs should be based on screen approach velocities and screen materials that fully comply with biological criteria. Where this is done the potential for fish impingement or injury resulting from contact with the screen is minimal.

A retrievable type of cylindrical screen has been developed as another alternative to fixed mounted cylindrical screens. It is typically mounted on a track placed on a canal or riverbank. Components of submerged cylindrical screens typically include the screen with an interior baffling concept that generates uniform through-screen velocity distributions, a water differential measuring system, and a cleaning system. Brushes external or internal to the cylinder are used to clean debris from the screen surface. Commercial concepts are available that generate back flushing through injection of compressed air into the screen cylinder (air-burst cleaning).

Screens are placed in rivers where the passing flow will transport the debris away. Cylindrical screens are commercially available from multiple sources in the USA where there is also substantial experience with a wide variety of fish species and fish. Screens have been designed for both fixed and retrievable installations.

Advantages of cylindrical screens

- They have no need for fish bypass, trash rack, or seals resulting in lower maintenance cost.
- They have a proven cleaning capability that removes debris off the screen.
- A varying water surface is not as critical as with surface screens for proper operation if screen axis elevation is deep enough.
- They are commercially available.
- They have been widely applied, have a good performance record, and have been accepted by the resource agencies as positive barrier screens.
- They provide easy access for inspection, maintenance, replacement, or removal during non-irrigation seasons.

Disadvantages of cylindrical screens

- They have size limitations that may limit applicability to only smaller diversions. Size required increases rapidly with increasing flow if biological criteria are to be met
- Minimum depth of water and clearance requirements may require multiple screens and increased costs.
- An air burst cleaning system is often required, and underwater maintenance of the screens presents more difficult challenges than other screen options (not so much a problem for retrievable screens).
- Sweeping flow is needed to move debris away from the screen.
- Strong sweeping velocity may affect uniformity of flow through the screen.
- Retrievable cylindrical screens have additional moving parts that require maintenance. These parts are for retrieval of the screen and also to rotate the screen for brush cleaning.

Although not technically a "cylindrical screen, the Browns Rock installation in the Waimakariri River is an example of the principles of this type of submerged screen.

3.1.6. Inclined screens

Inclined screens have been applied in two configurations. One configuration places the screen at an adverse slope on the channel invert (Figure 8). The screens are angled in line with the flow and are completely submerged. The flow, with fish and debris, sweeps over the length of the screen. Due to the adverse slope, sweeping flow velocities across the screen are maintained while flow depths are progressively reduced. The sweeping flow provides a mechanism to guide fish and debris across the screen surface and to the bypass at the upper or downstream end of the screen, while the diverted flow passes through the screen.

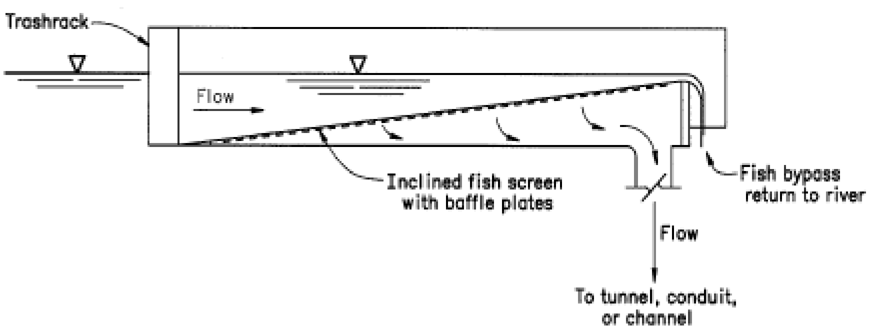

Figure 8: Cross sectional drawing of a fixed inclined screen

Typically, inclined screens are fabricated from non-moving flat screen panels. However, there are installations where the inclined screen panels are installed in a movable support frame that elevates the downstream end of the frame to follow or adjust to changing water surface elevations. Often, flow resistance elements placed behind the screens are included in inclined screen facilities to generate uniform approach velocities across the screen face. The most common methods used to clean the screens are a brush cleaning system (either manual or mechanically operated), a cleaning system that uses compressed air (air burst), or spray water back-flushing. For either cleaning system, the cleaning cycle should start at the upstream end of the screen and work downstream so that the debris is moved off the screen with the passing flow.

Installations are designed in compliance with fishery resource agency velocity and screening criteria. Although existing concepts have been developed based largely on juvenile salmon criteria, screen development based on alternative, non-salmonid criteria is achievable (as is the case for most of the screen concepts presented). Inclined fish installations in North America operate at a range of flows from 0.1 – 20 m^3s^{-1}.

Bypass design issues vary with the screen configuration applied. With inclined screens placed parallel to the passing flow, the bypass discharge and bypass entrance velocities depend on water surface elevations and submergence over the top of the screen. Such screens are best applied at sites with controlled water surface elevations and are generally not applied at in-river sites. Inclined screens are widely applied in juvenile fish sampling and collection facilities that are operated in conjunction with fish screen bypass facilities.

Another configuration places flat plate screens on an incline along the bank of a channel. Typically, these screens are installed with the approach flow sweeping across the screen face from side to side. They may be placed at an angle across a canal, on the canal bank, or, more commonly, on a river bank as an in-river facility (Figure 9). The inclined placement increases the active screen area and allows the screens to be applied in shallower flow depths. These screens are usually fully submerged; however, there may be locations where the top of the screen may be above water when operating with shallower flow depths.

Inclined screens placed in canals require bypasses. The approach channel section defined by the inclined screen must transition carefully to a vertical slot bypass entrance to ensure that bypass approach velocities do not slump and cause fish to either delay or avoid the intake. Use of a bypass entrance configured to match the approach channel cross-section might be considered even though it may require larger bypass discharges.

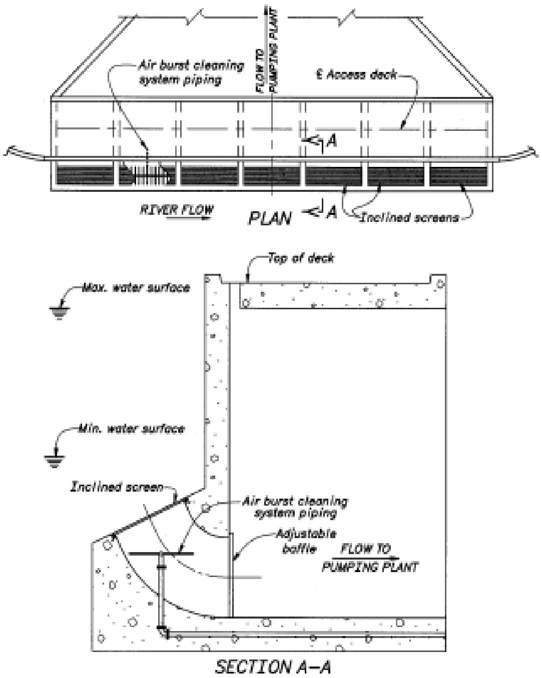

Figure 9: Placement of an inclined plane screen along a river bank

Inclined screens applied in-river with a sweeping or passing flow would not require a bypass unless the screen was sufficiently long to exceed exposure duration criteria.

Advantages of inclined screens

- They can provide effective screen surface areas even with shallow flow applications.
- They have a simple design with few or no moving components, thus minimizing maintenance and reducing capital and maintenance costs.
- They have proven cleaning capability that removes debris off the screen.
- They have been applied for many years, have a good performance record, and are accepted by some fisheries resource agencies in the USA.

Disadvantages of inclined screens

- Sediment and debris (large trees and boulders) may be a major problem, because the inclined screen is a bottom type screen.
- If a cleaning system is used, it will have moving parts that require maintenance.
- The diverted flow rates may vary as a function of water surface and screen fouling.

- The intake channel may require dewatering capability for maintenance.
- Future fishery resource agency criteria may limit the calculated screen area based on the vertically projected height.

3.1.7. Horizontal flat plate screens

The horizontal flat plate screen concept uses a screen with a horizontal face placed near the bottom (invert) of a natural channel (Figure 10). The horizontal screen is used as an in-river installation that would usually be applied in small rivers. The screen can be used in conjunction with either a pumped or gravity diversion. The concept allows placement of a screen with significant active surface area in a shallow stream. The horizontal screen concept is, consequently, more applicable at shallow river diversion sites than flat plate screens and fixed cylindrical screens, both of which require greater river depths. Horizontal screens also offer a cost effective option for a positive barrier screen that complies with agency criteria.

Figure 10: Horizontal flat plate screen, Idaho, USA

Hydraulic laboratory studies evaluated screen configurations and flow conditions across and through the screen. Flow conditions were influenced by river channel geometry, depth of flow on the screen, use of a rectangular or converging screen, the percentage of flow diverted through the screen to the total river flow, and apron treatments approaching and exiting the screen face. Efforts should be made to generate uniform parallel flow patterns across the screen face. Because of the diversion and loss of flow, sweeping velocities tend to decrease as flow passes down the length of the screen.

Probable components of a horizontal flat plate screen include the screen, an adjustable side weir that controls the diverted flow rate and ensures that the chamber below the screen will not be dewatered even with a complete debris blockage of the screen, and a sediment trap positioned upstream from the screen that would prevent bedload passage across the screen. A schematic view of a horizontal screen is shown in Figure 11. The design usually does not require interior baffling to generate uniform screen approach velocity distributions.

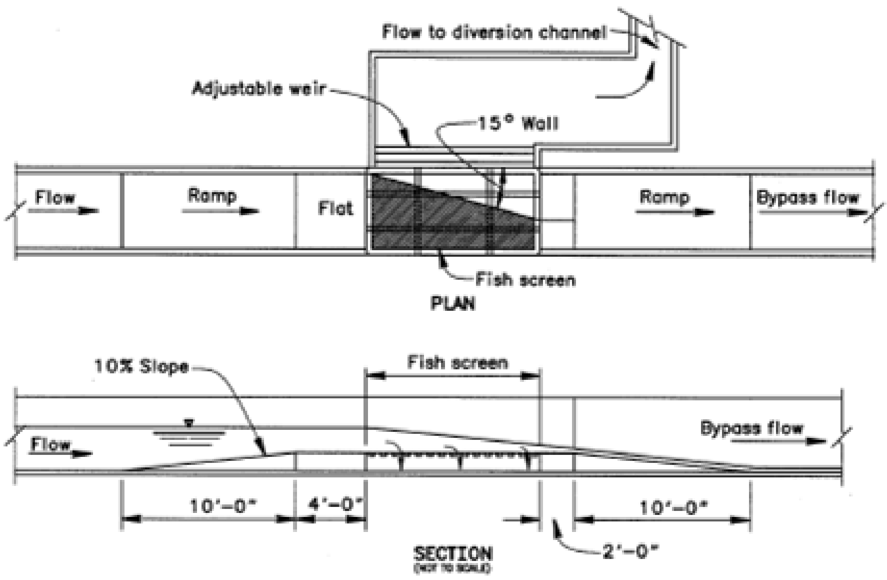

Figure 11: Schematic diagram of a horizontal flat plate screen showing bypass, and water diversion channel

Horizontal screens can be designed to fully comply with fishery resource agency screen approach velocity criteria; however, like the inclined screens, resource agencies should be consulted to ensure acceptable screen area is being provided. Screen designs have been considered that include air burst and backspray cleaners; however, cleaning systems have not been installed in the screens that have been constructed to date.

Advantages of horizontal flat plate screens

- They can be effective at shallow in-river diversion sites.
- They have a simple design with no moving parts.
- They offer a cost effective positive barrier screen concept that complies with fishery resource agency criteria.

Disadvantages of horizontal flat plate screens

- Debris and sediment handling characteristics are not fully proven and may be a problem.
- Diversion flow rates will vary as a function of water surface elevation and screen fouling. This design may be particularly susceptible to fouling by algae in New Zealand.
- Applications are likely limited to relatively small diversions (less than ~3 m^3s^{-1}).
- The concept may be considered unproven by fishery resource agencies.
- There may be high exposure of bottom-oriented fish to the screen surface.
- Comments about the use of 2 horizontal flat plate screens, 0.5 and 2 m^3s^{-1} (U.S. Department of the Interior 2006) include "…To date, debris and sediment handling characteristics of these screens has proven good. The biggest fouling problem that has been encountered is algal growth on the bottom of the perforated plate. This growth traps fine sediment and leads to screen fouling. A removable barrier device that sweeps across the screen to generate increased differential across the screen face, creating a flushing action, has proven effective in removing the algal growth".

3.1.8. Coanda screens

The Coanda screen is typically installed on the downstream face of an overflow weir, as shown in Figures 12 and 13. Flow passes over the crest of the weir, down a solid acceleration plate, and then across the screen panel, which is constructed with profile bar (wedge-wire), with the wire oriented perpendicular to the flow. The weir crest provides a smooth acceleration of the channel flow as it drops over the acceleration plate and flows tangentially onto the screen surface. Typically, the screen panel is a concave arc, although a planar (flat) screen panel could also be used. Diverted flow, passing through the screen, is collected in a conveyance channel below the screen, and the overflow (bypass flow), which may include fish, and debris pass off the downstream end of the screen. Flow velocities across the face of the screen are relatively high, varying as a function of the drop height from the upstream pool to the start of the screen.

Sufficient flow depths must be maintained over the lower end of the screen to prevent excessive fish contact with the screen surface, which could result in fish injury or mortality.

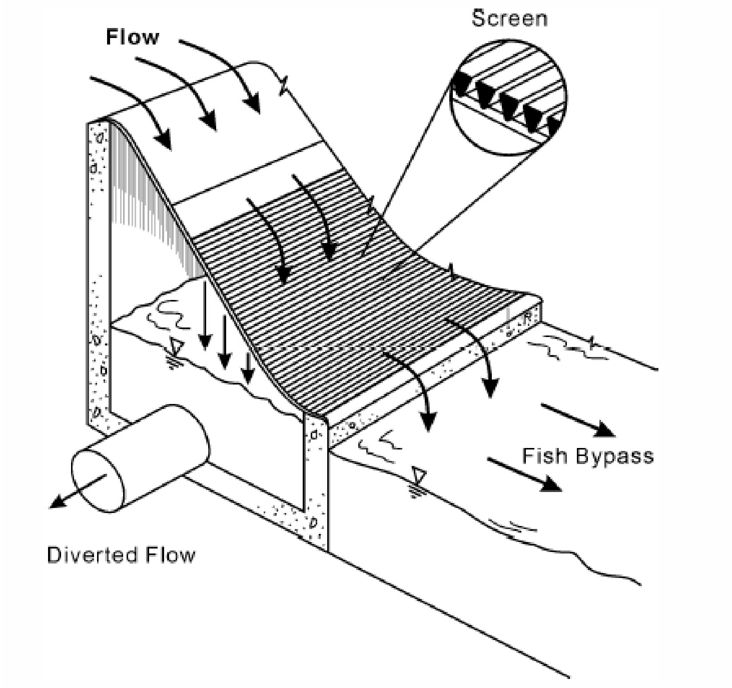

Figure 12: Diagram of a Coanda screen

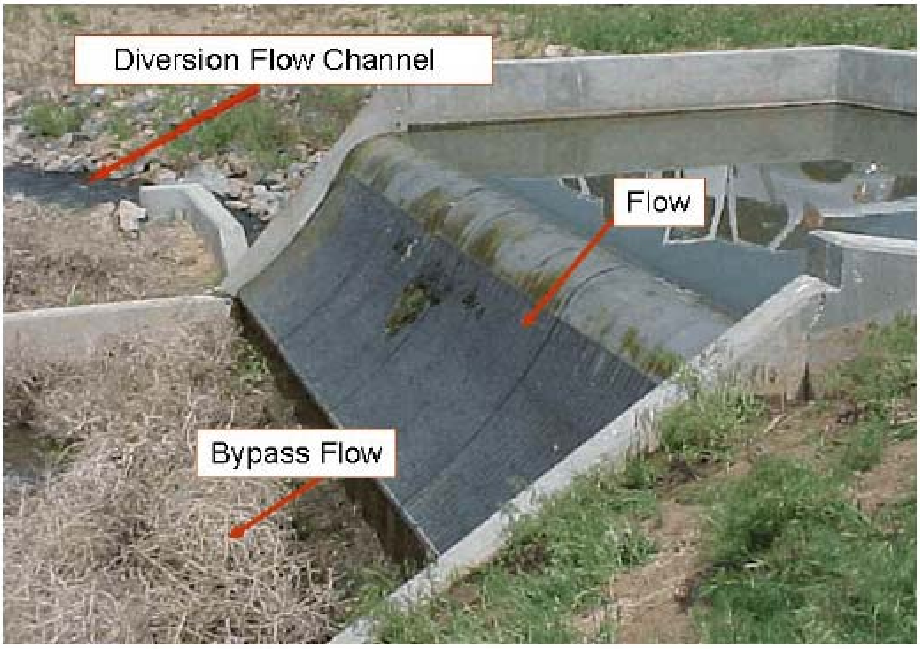

Figure 13: Coanda screen in operation, Colorado, USA

The Coanda screen is a non-traditional design in that relatively shallow; high velocity flows occur on the screen face. Coanda screens are very efficient at diverting large quantities of flow for their size. They are essentially self-cleaning and have the ability to exclude very fine debris and small aquatic organisms. The high velocity flow across the screen face, typically in the range of 2 to 3.5 ms^{-1} depending on the specific design of the structure, provides the self-cleaning characteristic. In recent years, this self-cleaning screen with no moving parts has been successfully used for debris and fish exclusion at several water diversions.

Compared to traditional fish screen structures, impingement of fish against the screen is not a significant concern, since the sweeping velocity carries fish immediately off the screen. However, additional biological testing is still needed to demonstrate fish survival and evaluate other side effects of fish passage over the screen (e.g., descaling injuries, disorientation, delayed passage, etc.). Researchers have obtained promising results from evaluations of passage of salmon fry and smolt over a prototype Coanda screen installed on the East Fork Hood River, Oregon. Limited evaluations of fish injury potential were also conducted.

Another benefit resulting from application of Coanda screens is improvement of water quality at sites with low dissolved oxygen (DO) levels or in waters supersaturated with total dissolved gases (e.g., below spillways and dam outlet facilities). The fine jets of water discharged through these screens are exposed to the atmosphere, which allows for stripping of excess gas or re-aeration of low-DO waters.

Advantages of Coanda screens

- They have good self-cleaning characteristics that minimize maintenance requirements.
- They are relatively compact and include no moving parts.
- They can be effectively used to exclude sediment from the diversion.

Disadvantages of Coanda screens

- Available commercial designs require a substantial head drop (approximately 1 m), which may be restrictive where there is insufficient available head.
- To satisfy minimum flow depths at the bottom of the screen, a substantial amount of bypass flow may be required.
- Fish injury and mortality characteristics of the screen have not been fully evaluated and documented. Potential for fish injury (e.g. descaling) is recognized.
- The concept may be considered not proven by fisheries resource agencies.
- Applications are likely to be limited to relatively small diversions (less than 5 m^3s^{-1}).

- Potential to dewater entire stream if not carefully operated.
- Barrier to upstream fish migration, particularly for native fish.

3.1.9. Closed conduit (Eicher and MIS) screens

Two options that have been developed for closed conduit fish screen exclusion are the Eicher Screen and the Modular Inclined Screen (MIS). Both are considered high velocity screens.

The Eicher screen was developed for hydroelectric applications (Figure 14). The concept does, however, offer application potential in a broad range of closed conduit diversions, although experience is limited to larger hydro-power installations.

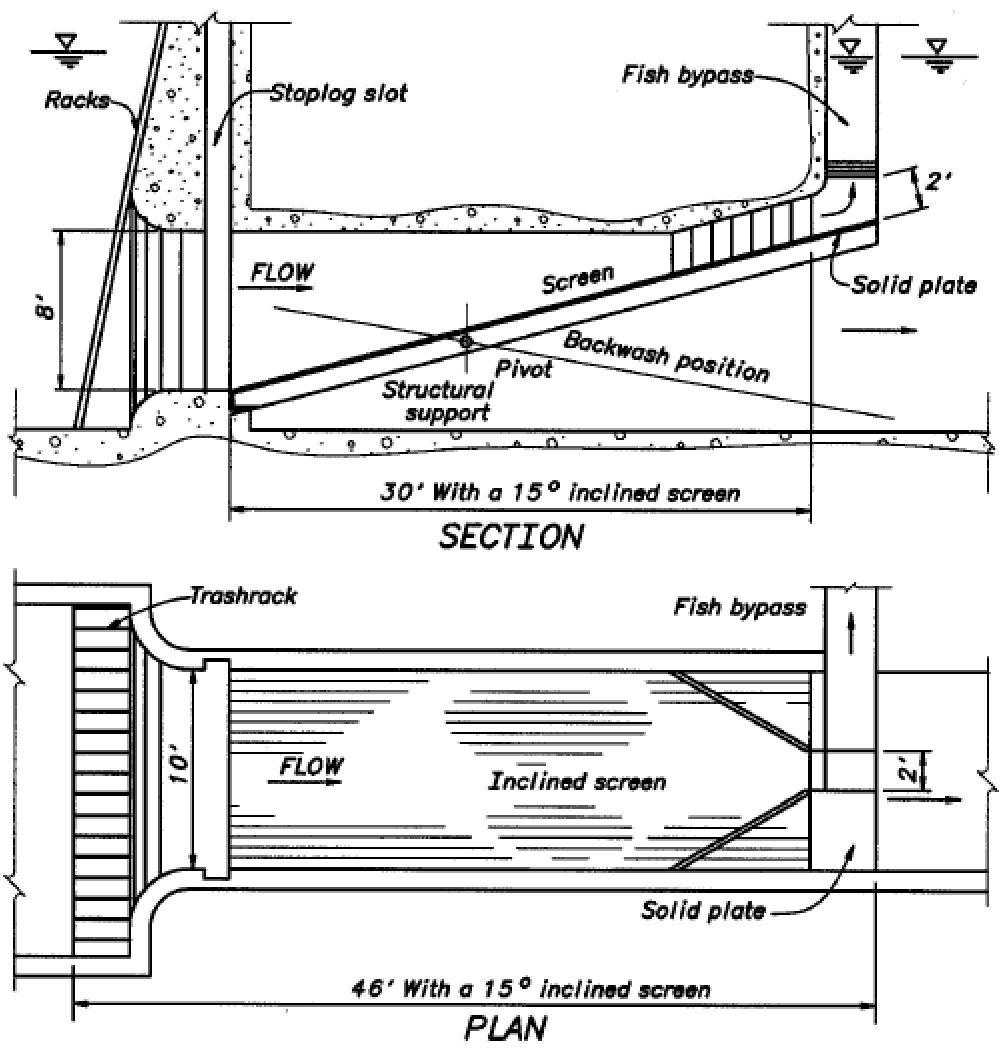

Figure 14: Eicher screen.

This concept was patented in the United States and Canada by George Eicher. The screen concept has been developed through extensive use of laboratory and field investigations of hydraulic, fish handling, and mechanical features of the design. The Eicher screen has a significant history of field application being applied at Portland General Electric's T.W. Sullivan Plant, Oregon, since 1980; British Columbia Hydro's Puntledge Plant, British Columbia, since 1993; and multiple years of study of a prototype installation at the Elwah Hydroelectric Plant, Washington.

The MIS screen was developed for application in a broad range of diversion and water intake structures including hydro-power and pump intakes. The concept was developed as a standard design screen module with an inclined screen placed in a length of rectangular cross section conduit. The MIS screen modules were developed to be included in the intake structure positioned immediately downstream from the intake trash racks. The configuration of the module with included transitions was developed for the specific hydraulic flow patterns generated by this configuration. The MIS concept is patented in the United States by EPRI. The screen concept was developed through use of laboratory studies that refined and evaluated hydraulic and fish passage characteristics of the design. Field application experience is limited to a pilot facility evaluation that was conducted at Niagara Mohawk Power Corporation's Green Island Hydroelectric Project, New York, in 1996. As a consequence, the field experience base with MIS screens is marginal.

Extensive laboratory and field prototype studies have been conducted to support development of the Eicher and MIS screens in the USA. These include detailed studies to develop the hydraulic characteristics of the design and extensive evaluations of fish passage characteristics with numerous fish species and development stages. These studies have not includede the needs of New Zealand native species.

Closed conduit fish screens typically include a flat screen panel placed on a diagonal to the flow within a circular or rectangular cross-section conduit. In a gravity diversion pipe or pump suction tube, the screen might be a component of a closed conduit intake structure. The screen panel is supported by a pivot-beam that runs horizontally across the panel at mid-section of the conduit. As with other angled screen placement concepts, the flow approaching and passing the screen guides fish over the screen surface and to the fish bypass. The intercepted fish are then transported through a bypass conduit and released back to the river, usually in the diversion dam tailrace (a significant head drop is required at the site to provide sufficient bypass flow).

Generation of uniform flow velocities across the screen is simplified by placing the screen panel in a conduit section that has uniform, well-aligned flow. Flow patterns across the screen can be adjusted and uniform through-screen flow distributions established by use of flow resistance screen backing or variable screen porosity (adjustment of screen percentage open area). Head or energy losses across clean screens are generally less than 0.3 m of water.

Closed conduit screens, by their nature, are installed in a very confined space. Velocities through the screen section are a function of velocities in the conduit itself. The in-conduit fish screen involves significantly higher approach velocities than conventional types of screens. Typically, screen approach velocities greatly exceed normal fishery resource agency velocity criteria. This increases the potential for fish injury. However, fish exposure time to the screens is often less than 10 seconds, which minimizes fish contact potential. Field and laboratory studies have shown that near zero mortality and injury rates can be achieved for many fish species and life stages.

The screens are cleaned by pivoting the screen panel about the support beam to a position that generates a back-flushing flow to the screen. Backflushing may be initiated periodically as part of a routine cleaning operation or may be initiated by a monitored pressure drop across the screen. Fish protection and exclusion is lost during the cleaning operation. Frequency of cleaning depends on debris load.

Advantages of closed conduit screens

- Can be used with a wide variety of fish species and fish development stages.
- Closed conduit screens can be directly incorporated in diversion conduits, which minimizes required civil structures and allows application at sites with little space.
- The back-flush cleaning design has proven effective and mechanically simple.
- Costs associated with maintaining and operating the facility are low.

Disadvantages of closed conduit screens

- Both the Eicher and MIS screen concepts are patented.
- Bypass flows can be significant for small conduits. Bypass diameters of less than 0.6 m have not been field evaluated.
- During back-flushing operations, the screen does not exclude fish from the diversion.
- Head losses of up to 0.75 m may occur with fouling, although under typical operation, head losses of approximately 0.3 m can be expected.
- Access to the screen for inspection or maintenance is limited and requires shutdown and dewatering.

- Potential fish injury may be associated with high velocity flow across the screen surface.
- Although experience exists at several sites with closed conduit screen concepts and with a range of fish species and fish sizes, the concept may be considered experimental by fishery resource agencies.
- Fish protection and exclusion is lost during cleaning.

Closed conduit screens have been applied primarily in penstocks at hydro-power sites. The concept is however applicable at closed conduit irrigation diversions. In North America, these screens are installed at facilities whose flows range from 6 – 15 m^3s^{-1}.

3.1.10. Submerged galleries (known as sub-gravel intakes and wells in UK)

Submerged galleries are not a conventional screen, but utilise a perforated intake pipe buried beneath substrate (usually size-graded). The above ground works for an intake of this type are shown in Figure 23. They are usually located on the river bank adjacent to the main river channel or a large braid, and placed at right angles to the flow. Head is maintained by placing the gallery at the bottom of an excavated hole, either below the water table, or with additional water diverted into the hole. Water seeps through the substrate and enters the pipe. Fish are excluded principally by maintaining small interstitial spaces between the substrates; some secondary exclusion can be provided by having small pore or slot sizes in the pipe. If the gallery is intercepting groundwater only, then there is no requirement for a downstream bypass for small fish; however, if water is diverted into the upstream area of the gallery, then a downstream bypass back to the main river is required.

River-side galleries may need to be rebuilt if damaged by floods, but a significant advantage of this type of screening is the lack of moving parts, the simplicity of the principle, and their ability to exclude fish of a wide range of sizes. Accumulation of sediment from groundwater is not an issue, but if diverted water contains a significant sediment load, then some back- flushing of galleries may be required to ensure they continue to work effectively. Galleries are most frequently used where small volumes of water are required (e.g. < 0.5 m^3s^{-1}), although multiple galleries can be linked to provide a total abstraction of several cumecs.

Small galleries are in use on some Canterbury rivers. A recent proposal for a 6 m^3s^{-1} abstraction in Canterbury plans to use a series of up to 14 submerged galleries to achieve the required flow.

Advantages of submerged galleries

- Relatively low capital cost

- Conceptually and mechanically simple
- Avoids mechanical screens
- Can be built in a modular way to increase total output
- Effective at screening fish of a wide range of sizes, and with a high level of certainty if well maintained

Disadvantages of submerged galleries

- May require periodic back-flushing when operating in times of high sediment load
- To achieve a long operational life in sediment-prone areas, the collection area needs to be generously designed
- A large gallery complex can occupy a considerable area of land
- May need to be rebuilt if subject to anything larger than a moderate flood

3.2. Behavioural devices

A behavioural avoidance or exclusion barrier, as compared to a positive screen barrier, requires action on the part of the fish to avoid entrainment. Examples below give an indication of the range of approaches being used and trialled.

Behavioural devices in many cases are experimental and performance capabilities may not be well documented. The literature contains enough information, however, to give indications of possible beneficial performance. Use of behavioural devices often offers a lower capital and operating cost option that may at least partially reduce fish entrainment. Behavioural devices might also offer a fish exclusion option at sites that would otherwise be difficult to screen, such as at penstock entrances positioned at great depth in a reservoir.

3.2.1. Louvers

Louvers consist of an array of vertical slats that are placed on a diagonal structure across a channel (Figures 15 and 16). Spacing between louver slats is typically larger than the width of the smallest fish that are being excluded. Louvers achieve fish exclusion by creating a series of elements that generate flow turbulence that the fish tend to avoid. Fish will maintain their position off the louver face while the sweeping flow (generated by the angled louver placement) guides the fish along the louver line to bypasses.

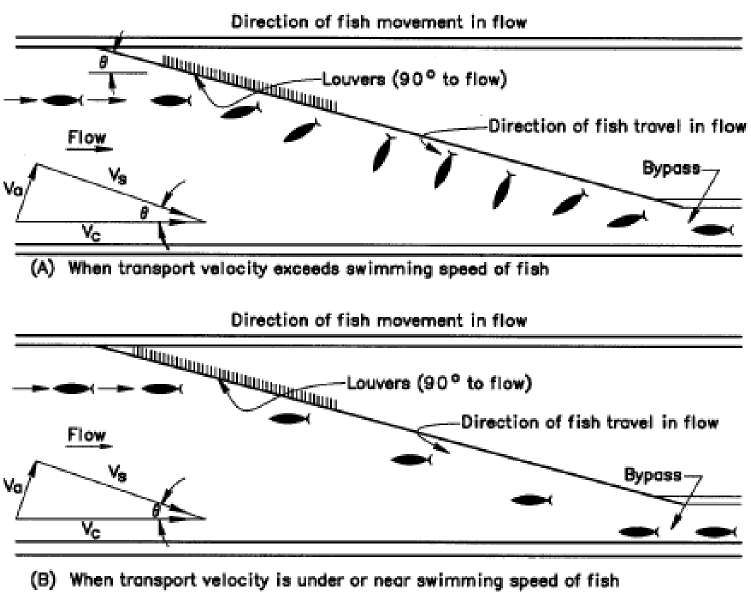

Figure 15: Diagram of fish reactions to louver screens

Figure 16 : Experimental louver arrangement, Gruissan, France (photo M. Larinier).

Louvers are, therefore, a behavioural device that depends on fish avoidance for effective exclusion. Behavioural barrier effectiveness varies as a function of fish species, fish life stage, fish size, and fish swimming strength. Documented exclusion efficiencies for louvers range from greater than 90% for juvenile Chinook salmon with fork length longer than 45 mm to efficiencies below 30% for juvenile Chinook salmon with fork length shorter than 30 mm, for striped bass with length shorter than 10-mm, and for white catfish with length shorter than 45 mm (U.S. Department of the Interior

2006). Although numerous studies have been conducted to evaluate louver efficiencies as a function of design parameters, substantial uncertainty still exists with development of a specific louver design for a specific fishery.

Louver structures are an attractive fish exclusion option in that they are fairly inexpensive and the openings between slats are large, which may allow sediment and debris passage. Louvers also operate at higher velocities than typical screens, which allows for a smaller overall structure. Mechanical equipment is required for cleaning and debris handling facilities. Depending on debris type and quantity, cleaning and debris handling demands may be minimal or may be substantial.

Advantages of louvers

- Louvers typically operate with higher approach velocities than screens, which leads to reduced overall structure size and cost.
- Louvers will pass small debris and sediment, which can reduce debris and sediment handling requirements.
- Louvers have a reduced sensitivity to flow blockage caused by debris fouling as compared to fine mesh screens. Consequently, more time is available between required cleaning cycles, and automated cleaners are typically not used.
- Louvers offer an effective exclusion option for larger, stronger swimming fish and may provide a reduced-cost fish exclusion option at sites where 100 % fish exclusion is not required.

Disadvantages of louvers

- Louvers are not “absolute” fish barriers. . Fish exclusion efficiency varies as a function of fish species, life stage, size, and fish swimming strength.
- Some debris types (fibrous aquatic plants and woody plants) will intertwine or embed in the louver, which leads to difficult debris removal and cleaning.
- Louvers are not yet widely accepted throughout North America
- Louver installations within North America are installed at flows ranging from 7 – 255 m^3s^{-1}.

3.2.2. Light and sound behavioural devices

Behavioural devices have had wider application at hydroelectric facilities and process (cooling) water intakes than at irrigation diversions. However, the observed performance characteristics and evaluation at these facilities are applicable for irrigation diversions.

Some behavioural devices attempt to exclude or guide fish away from intakes and diversions through use of stimuli (typically light or sound). Strobe lights or sound of specific frequencies and magnitudes can serve as an irritant to direct fish away from a diversion. However, in other cases, Mercury lights might be used as an attractant. Work has also been done with numerous other lighting options in attempts to generate attraction or avoidance. Effectiveness of behavioural devices varies with fish species and fish size, site conditions (including layout and flow patterns), and ambient conditions (including water turbidity and naturally occurring light).

Various sonic systems have been applied in prototype or developmental mode at numerous hydroelectric facilities in attempts to generate fish avoidance and through either fish guidance or exclusion. Again, fish guidance objectives, design and ambient conditions, and observed effectiveness varied widely. A prototype sonic barrier (installed at the mouth of Georgiana Slough and Sacramento River in the 1990's) consists of a 240 m linear array of acoustic transducers suspended from buoys located approximately 300 m upstream from the slough entrance. The acoustic barrier angled out from the shore with the objective of diverting the out-migrating fish to the far side of the river, away from the slough entrance. Guidance/exclusion efficiencies (percentage of fish excluded from the slough) were influenced by flow and hydraulic conditions. Observed efficiencies ranged from 50% – 80% for typical operating conditions, but dropped to 8% – 15% (very inefficient) during flood events on the river. On occasion, damage occurred to the sound barrier system during flood events.

Some investigators have experimented with intense, low-frequency sound, as low as 10 Hertz, to repel eels from intakes (e.g., Sand et al. 2001). Although eels display a negative response to such sounds, this response usually occurs when eels are within a few metres of the sound source, limiting the effectiveness of sound as a deterrent at large scale sites. Generally, sound systems appear to be most effective in lakes and estuaries, but have yet to been proven in high velocity areas, deep water, or where background noise is substantial (as is usually the case in large New Zealand rivers). A review of the use of infrasound detection in fish and the use of intense infrasound as a fish deterrent Sand et al. (2001) optimistically concluded that intense infrasound has a great potential in acoustic fish barriers; they cited a study where 10 Hz sound effectively blocked passage of Atlantic salmon smolts, while for downstream migrating European silver eels *A. anguilla*, the proportion of silver eels entering the tap section closest to the sound source was reduced to 43% of the control value.

A more recent review (DWA Topics 2006) concluded that the "results available so far on the effectiveness of deflection facilities ….range from an entire failure to efficiencies between 50 and 100 per cent". The review concluded that this extreme variation reflected experimental design, but also species-specific behaviour. Overall, such facilities were regarded as offering considerable potential for diverting preventing salmonids and eels in particular.

There is considerable interest in the trial installation of a BAFF bioacoustic fence at the intake of the Rangitata Diversion Race. To reduce the impact of background noise, the BAFF screen will be some distance (~1.3 km) from the intake at Klondyke.

There is a growing body of literature on the use of various types of lights (filament lamps, mercury vapour lamps, fluorescent lamps, strobe lights etc), but these are mostly employed at large intakes associated with hydro dams. For example, strobe lights have proved effective in diverting eels, including silver (migrating) eels (Patrick & Poulton 2001, Patrick et al. 1982). A review of various studies (DWA Topics 2006) indicated that deflection rates using stroboscope lamps at power stations ranged from 0 to 94%, and cautioned that success rates gained in the laboratory were seldom transferable to practical field situations where localised impacts of turbidity, flow, and approach velocities often produced unfavourable conditions.

Advantages of behavioural devices

- Light and sound systems have a relatively low capital and maintenance cost.
- They are applicable at sites that would otherwise be difficult to screen.

Disadvantages of behavioural devices

- They do not create an absolute exclusion barrier (not a positive barrier screen).
- Exclusion efficiencies can vary with fish species, fish development stage, and ambient conditions (river flow discharge and patterns, water quality, and ambient lighting).
- They are not generally accepted by fishery resource agencies for fish exclusion applications.

In New Zealand, submerged lamps have been trialled as a means of diverting silver eels at Karapiro Dam on the Waikato River; unfortunately, persistent turbidity associated with the higher flows when eels migrate meant the lights were ineffective, plus feeding eels initially displayed some avoidance of lights but then indifference to them (J. Boubee NIWA, pers. comm.). Also, the lights served to attract other species, especially salmonids, which further compromised their effectiveness as a deterrent to migrating species. Other problems included the build-up of algae on lights, and the need to keep debris off cables etc. (Boubée & Haro 2003).

3.2.3. Other behavioural barriers

A variety of concepts that establish curtain-like barriers have been developed and applied. These behavioural avoidance concepts potentially discourage fish passage to diversions. Included are manifolds that release a series of compressed air driven bubble plumes that, in combination, form a bubble curtain, a series of hanging chains forming a curtain of chains, manifolds that release a series of submerged water jets that form a turbulent jet flow curtain, and electrodes that form electrical fields.

These concepts have been evaluated at a scattering of sites over the years. The US Department of the Interior (2006) comments that all of them have generally proven ineffective.

"The results of these studies, combined with conclusions of ineffectiveness from past studies, do not support further testing of air bubble curtains. A variety of other behavioural devices have been evaluated in the past with little or no success. These include water jet curtains, electrical barriers, hanging chains, visual keys and chemicals".

An exception is the possible coupling of multiple exclusion concepts into a hybrid system (e.g. the coupling of air bubble curtains with strobe lights to increase strobe light exclusion efficiency). It may be that other combinations of behavioural systems can yield improved fish exclusion and guidance characteristics; for example, the use of high-frequency sound to repel blueback herring from pumpback intakes, and overhead lights to attract them to low-velocity safe areas, proved to be very effective.

Advantages of behavioural barriers

- Capital and maintenance costs of behavioural systems are relatively low.
- They might be applicable at sites that would otherwise be difficult to screen (complex sites with odd configurations that might not be accessible for maintenance).

Disadvantages of behavioural barriers

- Performance capabilities are very uncertain. Fish exclusion and guidance efficiencies are likely to be low.
- Fishery resource agencies will likely not accept behavioural barriers as a fish exclusion alternative or will likely require extensive field evaluation to verify effectiveness.

4. Review of good practice

4.1. Key factors in screen design

The project working party came to a view that a balanced design, which gives weighting to all the following key factors is likely to yield the most effective solution:

4.1.1. Location

The location of an intake should be chosen to allow good design attributes for all following factors to be achieved. A number of options may need to be considered to identify which gives the best mix of fish protection and operational characteristics.

4.1.2. Approach velocity

Approach velocity refers to the velocity of water approaching – i.e., flowing onto – a fish screen. It is more precisely defined as "…the water velocity component perpendicular to, and approximately three inches in front of, the screen face." (NMFS 1997). However it is defined, the approach velocity is important for the survival and safety of fish near irrigation intakes, as in order to escape from a fish screen a fish needs to be able to swim upstream against the water flow for a sustained period. If the approach velocity exceeds the fishes sustained swimming ability, then the fish will become exhausted and be impinged (stuck) on the screen. Thus to minimise the risk to fish, the maximum approach velocity of water upstream of a screen should be less than the sustained swimming capability of fish.

There have been many studies and reviews of fish swimming abilities and performance, including some based on New Zealand native species (see Boubée et al. 1999). Fish are capable of two types of swimming based on which set of muscles are utilised. In a sustained swimming mode, the fish utilises small volumes of red muscle tissue that have good blood supply – so that these low power muscles can be used to propel the fish for long periods without oxygen deficit or lactic acid build up. When the fish needs to move quickly (to avoid danger, or to capture prey, in what is known as burst swimming mode) it utilises large volumes of white muscle tissue, which has poor blood supply and only provides high power for a very short time.

For avoiding or escaping fish screens, it is the sustained mode swimming ability that is critical, and several factors about sustained swimming ability need to be considered:

- The most significant factor affecting a fish's sustained swimming ability is its size; smaller fish are not capable of swimming as fast as larger fish.

- Different species of fish have different swimming abilities, and these roughly correspond to general features such as body shape and swimming action. Swimming abilities also vary through fish life stages.

- Water temperature affects swimming performance, and sustained swimming speeds may decrease significantly at extremely high or low temperatures.

For design and operation of irrigation intakes, the most critical factor in determining the appropriate approach velocity is the sustained swimming ability of the smallest fish present. Criteria and standards used overseas, particularly in North America and Canada, stipulate approach velocities no higher than about 0.12 ms^{-1}, and are based on experimentally derived data for North American species of freshwater fish. Information on the swimming abilities of New Zealand fish has been gathered for various species and by a range of methods; Boubée et al. (1999) summarised much of this, and concluded (a) that there was little difference between species, and (b) that fish length was the main factor in determining swimming ability.

As fish size is the critical factor, literature suggests the following general rule of thumb as the most appropriate method of determining maximum approach velocity, namely **that the approach velocity should not exceed four times the body length of the smallest fish present per second**. In most situations in Canterbury, the smallest salmonid fish at the intake would be about 30 mm in length, so that approach velocity should not exceed 4 x 30 mm per second; i.e. 0.12 m/s. Approach velocity set in this way is likely to account for the impacts of extreme temperatures and for any discrepancies in the swimming performance of various native species as well. A design consideration could be to provide a substantially reduced approach velocity to balance against the criteria that cannot be as easily met.

Note that a 30 mm length fish has been chosen for this example based on analysis contained in the mesh size section below.

4.1.3. Sweep velocity

Sweep velocity is the term used to describe the velocity of water across the screen, at right angles to the approach velocity (Figure 17). Water flowing across the screen will move fish across the screen and minimize the risks of becoming impinged (i.e. stuck on the screen or in the mesh) or entrained (penetrating) through the screen into the irrigation supply. Sweep velocity should carry the fish away from the screen and back to the main flow/channel either directly or via a bypass.

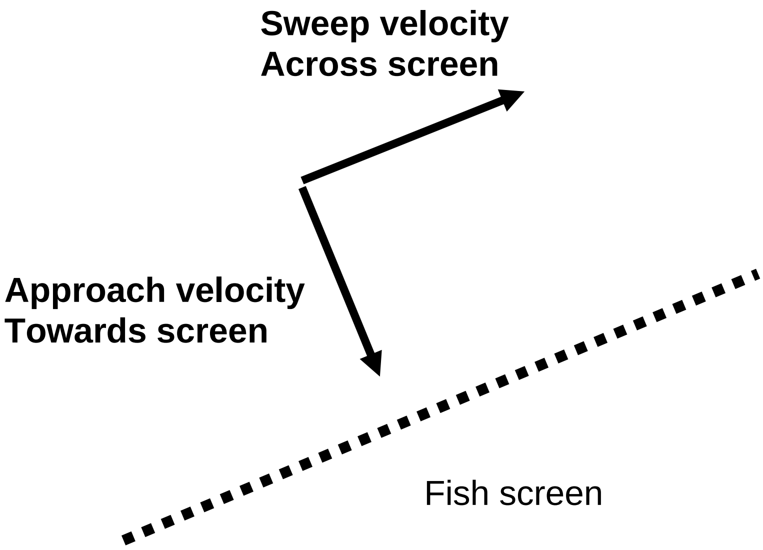

Figure 17: Sweep velocity and Approach velocity in relation to screen position.

Screen angle refers to the angle at which the screen is placed relative to the direction of the water flow. Overseas criteria or standards typically specify a maximum screen angle of 45°.

Placing the screen correctly as close to parallel with the supply flow will create a sweep velocity across the screen and effectively "bypass" the fish downstream of the screen – avoiding over-reliance on appropriate mesh sizes, approach velocities, and bypass systems. This may be further enhanced by the use of diversion louvers installed in front of the screen to divert fish (and debris) away from the screen. A substantially reduced approach velocity could enable the fish to more easily migrate past the screens which would diminish the impact of the sweep velocity and could ultimately reduce the extent of the diversion.

4.1.4. Fish bypass design at screen

Fish moving downstream, either voluntarily or involuntarily, toward an irrigation intake need to be transported (bypassed) back into the main or supply flow, rather than being impinged on the screen or penetrating the screen and getting into the irrigation supply (Figure 18). Thus the objective of a bypass is to safely transport the fish away from the screen back into the main flow; and general requirements of a bypass are:

- Entrances to the bypass should be easily located by fish, and preferably they would be situated on the downstream end and flush with or close to the screen (or on both sides/ends when screen is placed across the intake flow). If there is a strong sweep velocity across the face of the screen for smaller intakes, one entrance on the downstream side/end may be sufficient, but for large screens several by-pass entrances might be necessary. Obviously, a bypass should work in tandem with the sweep velocity across the screen – fish should be swept across and away from the screen and into a bypass.

- Bypass entrances should extend from the floor or base of the intake channel to the water surface – i.e., a slot rather than a pipe. As some fish, particularly juvenile salmonids, tend to avoid enclosed/darkened spaces, the entrance should be open at the top to provide ambient light conditions.

- The flow velocity should draw the fish into the bypass entrance, and there should be sufficient flow into and through the bypass to prevent fish returning – i.e., once a fish enters the bypass it cannot easily get back to the screen face.

Figure 18: Flat screen barrier. Red Arrow points to Fish bypass entry at flat screen. Green arrow indicates height of slot to handle water level fluctuations (USA).

4.1.5. Fish bypass design for "Connectivity"

Once a fish has been diverted from a screen and entered a bypass (see section 3 above), it is important that it is then delivered safely back to its source river. To ensure this:

- The interior of the bypass should pose no risks to fish travelling through, so that extreme bends, obstacles, rough surfaces, hydraulic jumps and free-falls should be avoided.

- The bypass outfall, where the water and fish from the bypass re-join the main flow downstream from the screened intake, should also not pose risks to the fish. Generally this means the fish should not be exposed to an excessive free fall, or impact onto hard surfaces and/or shallow water. The bypass outfall should also return fish to active water and generally avoid returning fish to the mainstem in such a way as to expose the fish to predation from other (larger) fish or from birds.

Table 2: Seven critical factors directly and conveniently measured.

Attribute	**Location**	**Approach velocity**	**Sweep velocity**	**Fish bypass at screen**	**Mesh gap size**	**Connectivity**	**O&M**
Method	**Assessed**	**Calculated Maximum**	**Calculated Minimum**	**Assessed Effective**	**Measured Maximum**	**Assessed**	**Assessed**
	Good/ neutral/ bad	0.12m/s	"Ideal" or "intermediate" Sweep velocity >Approach velocity	Yes or no	3mm (smaller in critical locations)	Yes or no	Yes or no

4.1.6. Screening materials

Fish screens are constructed using different types of screening material. Three materials are commonly used: woven wire mesh, perforated plate and profile bars. Woven wire mesh is mostly used for rotary drums, and to a lesser extent for flat panel screens. Perforated plates are used for construction of flat panel screens and much less for rotating drum screens. Profile bars are most commonly used for flat panel screens. The size of the openings of the screening material is critical for the successful operation of fish screens and safe passage of the juvenile fish. In Canterbury, woven mesh has been the most commonly used screening material. More recently profile bars have become a more attractive screening material option due to its quality and (reasonable) cost. A review of minimum mesh sizes for screening materials is provided for a number of fish species in Section 4.2 below.

4.1.7. Operations and Maintenance

The principal objective of designing and installing fish screens on irrigation screens is to exclude and divert fish from the intake with minimal impact. Whatever features are incorporated into an intake, it is important they work effectively and efficiently at all times, so that:

- Maintenance of the fish screening features will be necessary. Generally this means checking, repairing or replacing screen mesh, seals and bypasses regularly. Sediment deposits that alter the flow characteristics of the channel will need to be dispersed, and debris that collects in or near the structure will need to be removed particularly if these changes lead to inappropriate increases in approach velocity or lowered sweep velocity.

- The design and installation will need to incorporate some leeway to ensure that the screen and bypasses operate efficiently under all conditions – e.g., extremes of flow and/or water level, or periods when there are high sediment loads, lots of debris etc. This is partly an issue of capacity; screening structures need to be able to cope with higher water levels that may occur during floods and freshes, without fish overtopping screens. This is particularly important for salmonid fry which migrate in larger numbers during fresh events, and are therefore at greater risk of entrainment or impingement during higher flow periods.

- Contingency plans need to be negotiated in advance with relevant authorities where damage from floods and freshes is foreseeable. These contingency plans need to be practical while providing reasonable ongoing protection for the fishery. It is recommended that such plans be documented for all intakes.

- Monitoring of the effectiveness of intakes is important to build knowledge on actual field performance of intake designs. Lack of information of fish species and how they behave in New Zealand is a critical information gap and monitoring information will help fill this gap and ensure that future screening requirements are efficient and effective.

4.2. Review of minimum apertures (mesh size) for screens

Screening material opening size (mesh size or profile bar gap) is often regarded as the most critical factor in setting screening standards. The extent to which opening size affects construction cost or O&M is uncertain, and indeed in some circumstances smaller opening size may reduce debris build up. In Canterbury, there are many species of native and sports fish to be considered – at least 20 species – but our approach to determining appropriate mesh for all species was to look initially at appropriate size for protection of juvenile Chinook salmon and then to consider trout, followed by native species. Unfortunately, apart from salmon, there is only fragmented, generalised information on the dimensions and migratory behaviour for most other species of freshwater fish. DOC's review of screening requirements for native fish (Charteris 2006) concluded that implementing screens to protect salmon fry would protect the majority of native species. Once appropriate mesh sizes were calculated for Chinook salmon for each month of the year, it was possible to make an estimate of the adequacy of mesh size to exclude all other fish species including native fish.

4.2.1. Estimating mesh size for Chinook Salmon

There is well documented information on the dimensions (size) of juvenile Chinook salmon, and on the timing of their migrations in New Zealand rivers. This made it possible to accurately calculate appropriate mesh sizes for all months of the year. Juvenile salmon are small (the smallest barely 30 mm long) but they exhibit strong downstream migratory behaviour on their way to the ocean and preferentially locate themselves along river margins, thus they are likely to be at a high risk in or near irrigation intakes.

Migrating salmon fry have been measured regularly in separate studies from several locations around Canterbury. Chinook salmon emerge from the gravel of the spawning streams and begin to migrate at an average length of about 33mm (range approx 28 to 40mm). This average length is maintained over the period from about mid July until November as further salmon progressively emerge; the migrating salmon (known as "fry") may move downstream quite quickly, so that in the middle and lower sections of the large Canterbury rivers the salmon fry present have had little time to grow, and are essentially the same size as emergent fry in the headwaters. By about November the supply of emergent fry tails off and ceases, and after this time any Chinook salmon in the rivers have been present for some time and grown, so that the minimum length ranges from about 45-75 mm in January, and 62-75 mm in March.

Overall, data from studies in several Canterbury rivers conform to the same patterns and have similar limits. The most appropriate and representative data for Chinook salmon lengths were collected at the Glenariffe stream trap in the headwaters of the Rakaia River, where many thousands of migrating fry were measured over several seasons. This set of data was used to test mesh gap size required at water intakes to prevent entrainment. For each month the appropriate perforation or gap dimensions were calculated using two "minimum" lengths – the actual minimum (i.e. the smallest fish measured), and an estimated "95% minimum" (i.e. a length which 95% of the fish exceeded).

Formulae presented in three publications (Bell 1986, DWA Topics 2006, Turnpenny 1981) were then applied to the minimum length and 95% minimum length information from Glenariffe to calculate perforation and gap sizes required to exclude salmon in each month of the year (Table 3). The mesh size minimums are based on diagonal measurements of the mesh aperture (equivalent to circular perforations), and have been recalculated as "side-of-square" measurements in Table 4.

Table 3: Estimated size (mm) of perforation or mesh (diagonal) gap required to exclude Chinook salmon each month, calculated from formulae recommended in the literature (Bell 1986, DWA Topics 2006, Turnpenny 1981). Chinook salmon lengths (minimum and estimated 95% minimum) are from Glenariffe Stream, Rakaia River. Bar gap included for DWA only

	Fish length (mm)		DWA 2006		Bar gap (DWA)		Turnpenny 1981		Bell 1986	
Month	min	est 95%	min	est 95%	min	est 95%	min	est 95%	Min	est 95%
July	30	35	5.1	6.0	3.0	3.5	3.7	4.3	6.8	7.7
August	30	35	5.1	6.0	3.0	3.5	3.7	4.3	6.8	7.7
September	30	35	5.1	6.0	3.0	3.5	3.7	4.3	6.8	7.7
October	28	35	4.8	6.0	2.8	3.5	3.4	4.3	6.4	7.7
November	28	35	4.8	6.0	2.8	3.5	3.4	4.3	6.4	7.7
December	34	40	5.8	6.8	3.4	4.0	4.1	4.9	7.5	8.7
January	38	45	6.5	7.7	3.8	4.5	4.6	5.5	8.3	9.7
February	45	50	7.7	8.5	4.5	5.0	5.5	6.1	9.7	10.6
March	50	55	8.5	9.4	5.0	5.5	6.1	6.7	10.6	11.6
April	55	60	9.4	10.2	5.5	6.0	6.7	7.3	11.6	12.6
May	60	65	10.2	11.1	6.0	6.5	7.3	7.9	12.6	13.5
June	65	70	11.1	11.9	6.5	7.0	7.9	8.5	13.5	14.5

Table 4: Estimated size (mm) of mesh (side-of-square) gap required to exclude Chinook salmon each month, calculated from formulae recommended in the literature (Bell 1986, DWA Topics 2006, Turnpenny 1981). Chinook salmon lengths (minimum and 95% minimum) from Glenariffe Stream, Rakaia River.

	Fish length (mm)		DWA 2005		Turnpenny 1981		Bell 1986	
Month	Min	est 95%	min	est 95%	min	est 95%	Min	est 95%
July	30	35	3.6	4.2	2.6	3.0	4.8	5.5
August	30	35	3.6	4.2	2.6	3.0	4.8	5.5
September	30	35	3.6	4.2	2.6	3.0	4.8	5.5
October	28	35	3.4	4.2	2.4	3.0	4.5	5.5
November	28	35	3.4	4.2	2.4	3.0	4.5	5.5
December	34	40	4.1	4.8	2.9	3.5	5.3	6.2
January	38	45	4.6	5.4	3.3	3.9	5.9	6.9
February	45	50	5.4	6.0	3.9	4.3	6.9	7.5
March	50	55	6.0	6.6	4.3	4.7	7.5	8.2
April	55	60	6.6	7.2	4.7	5.2	8.2	8.9
May	60	65	7.2	7.8	5.2	5.6	8.9	9.6
June	65	70	7.8	8.4	5.6	6.0	9.6	10.3

From the required mesh sizes calculated from the three methods, it is apparent that there are significant discrepancies. For instance, the mesh size required to exclude salmon of 30mm length calculated from the methods described by DWA 2005, Turnpenny 1981, and Bell 1986 are 3.6mm, 2.6mm, and 4.8mm respectively.

Note that:

- Data from the Rangitata Diversion Race (RDR) study (Unwin et al. 2005) could not be used as the trapping programme for this project began in late September and therefore did not include Chinook salmon fry migrating downstream from late July to late September, during which time roughly two-thirds of fry migration is likely to have occurred (Unwin et al. 2005)(Unwin 1986)(Hopkins & Unwin 1987)(Davis & Unwin 1989).

- Criteria in Turnpenny (1981) are based on head size of the fish, and mesh of a size that would not allow the fish to penetrate through the gap beyond the orbit of its eye, so that the fish would be physically stopped from penetrating through the mesh by the bony part of the head.

- The formulae presented in DWA (2006) are based on other literature (Höfer & Riedmüller 1996, Holzner 1999, Pavlov 1989), and use fish body dimensions such as length, height, depth, and maximum body diameter to calculate mesh sizes required to exclude fish. As head size is not specifically indicated in DWA (2006), we have assumed that “exclusive mesh” size is that which the fish can not squeeze its entire body through.

- Formulae presented by Bell (1986) are also based on the measurement of fish at the bony part of the head, although this publication acknowledges that the formulae presented should only be used as guides, as they are based on few measurements of fish.

- The formulae presented are apparently all based on the measurement of (dead) fish, and provide theoretical limits only. In addition, the preservation of fish (freezing, liquid preservatives) may distort body shapes and sizes. There is a lack of published information (none from New Zealand) on the actual performance of screens.

- Several laboratory and field studies overseas (particularly Bates & Fuller 1992) tested different screening materials and concluded that the following materials were sufficient to exclude almost all of juvenile salmon: a perforated plate with 3.2 mm round openings; a 3 mm woven wire mesh; and a profile bar screen with bars spaced at 2.4 mm.

The discrepancies between calculated mesh size, and the lack of performance testing, mean that we have to rely on the findings of the limited number of empirical studies and the more conservative criteria (based on Turnpenny 1981) in the knowledge that it will, firstly, exclude close to 100% of salmon from irrigation intakes, and secondly, exclude a significant proportion of other fish (trout and native species). Overall, a minimum bar gap of 2mm or mesh size of 3 mm (side-of-square) is adopted, particularly if the screen design has no other attributes to prevent fish passage.

4.2.2. Estimating mesh size for trout

Appropriate mesh size can be calculated for trout in Canterbury rivers, using formulae similar to those applied to salmon, combined with information of trout lengths at various times of the year (Bonnett 1986, Davis et al. 1983). There is a lack of published data on rainbow trout lengths by month in Canterbury rivers, thus for the purposes of estimating appropriate mesh size we have used brown trout data as the basis for assessing the requirements of both brown and rainbow trout. Rainbow trout spawn later in the year than brown trout, and subsequently rainbow trout fry growth "lags" behind that of brown trout – so that rainbow trout may be of "susceptible size" at irrigation intakes later than brown trout.

Small (<30mm long) brown trout fry are present in Canterbury waterways from about September onwards; by about December they are mostly >40mm long. To calculate appropriate mesh sizes we used the lengths measured in the Lower Rakaia River by Davis et al 1983. The same formulae used to calculate appropriate mesh size for salmon was then applied to the trout minimum length and 95% minimum length information to calculate mesh and gap sizes required to exclude trout in each month of the year (Table 5) and side-of-square mesh sizes (Table 6).

Profile bar with a gap of 2 mm and 3 mm side of square mesh (as recommended for Chinook salmon) would also be appropriate for excluding brown trout in all months except September and October where some losses may occur. Overall, the recommended "salmon" mesh size criteria should protect the majority of trout in Canterbury rivers if other facets of screen design are appropriately allowed for.

4.2.3. Estimating mesh size for New Zealand native fish species

DOC's recent review (Charteris 2006) assembles and presents information on native species. Information on fish size at different life stages is also included in Table 7 of that report. A note below this table is as follows: "*Native fish would be best protected if water intake systems in areas of importance for spawning and/or on main migration pathways prevented fish of 3-10 mm (the size of the smallest life stage) from passing through.*

Table 5: Estimated size (mm) of perforation or mesh (diagonal) gap required to exclude brown trout each month, calculated from formulae recommended in the literature (Bell 1986, DWA Topics 2006, Turnpenny 1981). Brown trout lengths (minimum and 95% minimum) from Lower Rakaia River (Davis et al. 1983). Bar gap included for DWA only.

	Estimated perforation of mesh (diagonal) size to exclude									
	Fish length (mm)		DWA 2005		Bar gap (DWA)		Turnpenny 1981		Bell 1986	
Month	min	est 95%	min	est 95%	min	est 95%	min	est 95%	min	est 95%
July	125	125	21.3	21.3	12.5	12.5	15.2	15.2	25.1	25.1
August	95	105	16.2	17.9	9.5	10.5	11.6	12.8	19.3	21.2
September	25	25	4.3	4.3	2.5	2.5	3.0	3.0	5.8	5.8
October	25	25	4.3	4.3	2.5	2.5	3.0	3.0	5.8	5.8
November	30	35	5.1	6.0	3.0	3.5	3.7	4.3	6.8	7.7
December	40	45	6.8	7.7	4.0	4.5	4.9	5.5	8.7	9.7
January	50	55	8.5	9.4	5.0	5.5	6.1	6.7	10.6	11.6
February	65	70	11.1	11.9	6.5	7.0	7.9	8.5	13.5	14.5
March	60	75	10.2	12.8	6.0	7.5	7.3	9.1	12.6	15.4
April	75	85	12.8	14.5	7.5	8.5	9.1	10.3	15.4	17.4
May	85	95	14.5	16.2	8.5	9.5	10.3	11.6	17.4	19.3
June	90	105	15.3	17.9	9.0	10.5	11.0	12.8	18.3	21.2

Table 6: Estimated size (mm) of mesh (side-of-square) gap required to exclude brown trout each month, calculated from formulae recommended in the literature (Bell 1986, DWA Topics 2006, Turnpenny 1981). Brown trout lengths (minimum and 95% minimum) are for the lower Rakaia River (Davis et al. 1983).

			Estimated mesh (side of square) size to exclude					
	Fish length (mm)		DWA 2005		Turnpenny 1981		Bell 1986	
Month	min	est 95%	min	est 95%	min	est 95%	min	est 95%
July	125	125	15.1	15.1	10.8	10.8	17.8	17.8
August	95	105	11.5	12.7	8.2	9.1	13.7	15.1
September	25	25	3.0	3.0	2.2	2.2	4.1	4.1
October	25	25	3.0	3.0	2.2	2.2	4.1	4.1
November	30	35	3.6	4.2	2.6	3.0	4.8	5.5
December	40	45	4.8	5.4	3.5	3.9	6.2	6.9
January	50	55	6.0	6.6	4.3	4.7	7.5	8.2
February	65	70	7.8	8.4	5.6	6.0	9.6	10.3
March	60	75	7.2	9.0	5.2	6.5	8.9	11.0
April	75	85	9.0	10.2	6.5	7.3	11.0	12.3
May	85	95	10.2	11.5	7.3	8.2	12.3	13.7
June	90	105	10.9	12.7	7.8	9.1	13.0	15.1

Mesh/aperture criteria for salmon and trout have been determined from known size limits and migration patterns, however for native species, sizes and migration patterns are poorly defined. Our approach has therefore been to estimate and assess the suitability of salmon/trout criteria (i.e., 3 mm mesh) for excluding native fish from irrigation intakes. For convenience the native fish are grouped as follows:

4.2.3.1 Whitebait

Whitebait are the juveniles of five species of Galaxias; inanga (*Galaxias maculatus*), koaro (*G. brevipinis*), banded kokopu (*G. fasciatus*), giant kokopu (*G. argenteus*), and shortjawed kokopu (*G. postvectis*). In Canterbury, and in many other regions of New Zealand, the whitebait catch is dominated almost completely by inanga. Samples from Canterbury and Otago (McDowall 1965) comprised 98.5% inanga, and the numbers of koaro or kokopu whitebait were regarded as insignificant. The high proportion of inanga whitebait in the annual "runs' is important, as inanga whitebait do not penetrate far upstream from the sea, and are generally regarded as lowland or even estuarine fish. It thus seems unlikely that they would be exposed to significant risk from irrigation intakes on rivers, unless these were placed at very low elevation and in close proximity to the sea. Should this occur effective specific approaches would be required to protect these populations.

The other four whitebait species are much less common throughout Canterbury, and are mostly associated with small, steep streams such as those around Banks Peninsula and along the Kaikoura coast. Some koaro whitebait may migrate upstream in the larger snow-fed east coast rivers, and some populations of this species (e.g., Lake Coleridge) have become landlocked. All of the whitebait species have similar life history patterns – adults spawn in fresh water during autumn, eggs hatch in autumn or early winter and the larvae (<10mm long) are washed downstream into the sea. The larvae remain in the sea and grow for about 6 months, then migrate upstream as whitebait approximately 45-60mm in length.

Adults of the five whitebait species are of a size (variously 60 – 400 mm) to be at negligible risk of becoming entrained in an irrigation intake screened with 3 mm mesh. Whitebait moving upstream in Canterbury rivers may be at risk, as they are from about 45 to 60 mm in length and slender. To determine if whitebait would be able to penetrate through 3 mm mesh screen, preserved specimens of whitebait were measured in the laboratory. Preserved whitebait 55 mm in length were found to have a head size of c. 3 mm wide by 3 mm deep, and were therefore found to be unlikely to be able to penetrate 3 mm mesh (although smaller whitebait may be able to do so). In addition, the standard whitebait mesh cloth, as used in whitebaiters nets, has openings ~2.5 mm in diameter, and that whitebaiters would not use it if some whitebait could penetrate through it.

Galaxiid larvae in Canterbury waterways (approximately 8 to 10 mm long) are very likely to be at risk of being entrained in irrigation intakes, being small enough to easily penetrate through fine mesh while passively drifting downstream with the flow on their journey out to sea. However, their risk of being entrained should be lessened by the seasonal timing of their downstream migration, which mostly occurs during late autumn or early winter when irrigation demand is low. In summary:

- Adults of the five whitebait species are at little risk from screened irrigation intakes because of their size. The most common species, inanga, is very coastal in habitat and is less likely to be exposed to irrigation intakes.

- A proportion of whitebait (those less than about 55mm long) are probably small enough to penetrate 3mm mesh screens at irrigation intakes, whereas larger whitebait (mostly inanga) would not. The risk to whitebait may be small, because these fish are migrating upstream.

- Galaxiid larvae are the life stage most at risk at irrigation intakes – they are small enough to easily penetrate 3 mm mesh, have little swimming ability, and are migrating passively downstream to the sea. The risk of entrainment is probably markedly reduced as they move downstream during late autumn/early winter when little water is being drawn off into irrigation intakes. Intakes that operate years round (e.g. stockwater) need careful operation to minimise risk to larvae.

Overall, 3 mm mesh would protect a significant proportion of migrating whitebait and close to 100% of adult whitebait. To exclude larval whitebait moving downstream would require a mesh size of about 1 mm or less.

4.2.3.2 Non-migratory galaxiids, including mudfish

These fish do not migrate between the sea and freshwater, but may move within waterways. Some adult non-migratory galaxiids are of a size and shape that may allow them to penetrate through 3 mm mesh screens; of particular concern are the two species of longjawed galaxias, *G. prognathus* and *G. cobitinis*. These two species are very slender, and frequently less than 60 mm long. Some adults may be able to penetrate 3 mm mesh. Juvenile fish, especially larvae which may drift passively downstream, are at even greater risk. These species are of particular concern, as both have very limited distributions, and are regarded as threatened species.

Canterbury mudfish are also regarded as nationally threatened. Most adult mudfish are found in slow moving streams or isolated wetlands and are large enough to be excluded from intakes screened with 3 mm mesh. However juvenile, especially larval, mudfish would be at greater risk because of their size, and also because they may encounter irrigation intakes during floods when they may disperse into flowing water. Therefore DOC recommends a mesh size of 2 mm where mudfish occur (Charteris 2006). Overall, however, the risk appears to be only slight.

Overall there is significant risk to rare and threatened non-migratory galaxiids, and we recommend that irrigation intakes operating where populations of these fish occur should be subject to more rigorous criteria for mesh size, certainly no greater than 2 mm mesh size. Guidance on the presence of threatened species is available from DOC (Charteris 2006, section 6.1 and Table 2).

4.3.2.3 Flatfish

Although some black flounder (*Rhombosolea retiaria*) are known to penetrate significant distances upstream into Canterbury waterways, generally flatfish in freshwater are confined to lowland or estuarine habitats. Black flounder spawn at sea, and juveniles enter estuarine waters at about 10-15mm in length; any that migrate further upstream into Canterbury waterways are likely to be of a size that would prevent them being entrained in irrigation intakes. Overall we consider that there is little potential risk to flatfish.

4.3.2.4 Eels

Shortfin and longfin eels are present in many Canterbury waterways and longfin eel are nationally threatened. Adult eels are of a size that precludes their entrainment into irrigation intakes through mesh/gaps of 3 mm, but are well known for their ability to travel over land or other obstacles and may thus be found in irrigation systems. Juvenile eels (known as glass eels) enter freshwater during spring as transparent glass eels about 60-70 mm long, sometimes in large numbers. Glass eels are slender, and a few are able to penetrate 2 mm mesh.

Glass eels are generally only found close to the river mouth; they grow (and become pigmented) as they migrate upstream, at which stage they are known as elvers. DOC recommends use of 1.5 mm mesh (Charteris 2006). It may be several months (and some distance upstream) before their size would prevent elvers from entering irrigation intakes screened with 3 mm mesh.

Therefore in summary

- Glass eels are only found near the mouth and so lower river irrigation intakes would need to use 1.5 mm mesh to screen glass eels.

- Upstream from the mouth juvenile eels (known as elvers) are found; these are pigmented and are larger than glass eels. Some elvers may penetrate through

3 mm mesh, but the further upstream they go, the larger the elvers grow, and the lower the proportion that can penetrate 3 mm mesh.

Overall 3 mm mesh would exclude many elvers from irrigation intakes; intakes closer to the sea would need to be fitted with 1.5 mm mesh screens to exclude a significant proportion of migrant glass eels and elvers.

4.2.3.5 Bullies

Both diadromous and non-diadromous bully species occur in Canterbury waterways, and small juvenile bullies (<20 mm) may be present from early spring through to late autumn in many parts of our rivers and streams. Adult bullies (mostly > 40 mm long) would be at little risk from irrigation intakes, as they are generally stockily built and are unlikely to penetrate 3 mm mesh screens. However younger, smaller fish of all bully species would be at greater risk. Juveniles of migratory species (e.g., bluegill, redfin and common bully) are more frequently encountered in reaches of the rivers and streams close to the sea, mostly during the spring. They grow as they migrate upstream, so with time and distance from the sea the risk may lessen.

Juvenile non-migrant bullies, however, may be found throughout the length of the river from spring right through until autumn. Because these juveniles are small (as little as 5 mm long) they have the ability to pass intakes screened with 3 mm (or even finer) mesh. Many of these species (such as upland bullies found widely in Canterbury) are not threatened and are commonly found living in and around intakes.

Juvenile bullies are present virtually throughout Canterbury waterways from spring through to autumn. They are not threatened species, and become resident in and around many intakes. Because they are small, they can pass even small screen sizes. Therefore there is a risk of entrainment in irrigation intakes screened with 3 mm mesh, but the consequences are not thought to be severe.

4.2.3.6 Lamprey

Lamprey are widespread around New Zealand, including many Canterbury waterways, but are regarded as threatened due to declining numbers and because species knowledge is data poor. They have an unusual life cycle; adults live at sea and become parasites on marine fishes. When they are ready to spawn they move into freshwater streams and rivers. Little is known of their spawning habits, but larvae (known as ammocoetes) are initially about 11 mm long and generally live in burrows amongst sandy or silty stream substrates although they have also been observed in stony streams in areas such as Banks Peninsula. They grow slowly and migrate gradually downstream over 4 or 5 years until they are about 100 mm in length. At this stage they metamorphose into macropthalmia and migrate to sea, mostly during winter.

Adults moving upstream to spawn are large (450-750 mm) and would be at very little risk at screened irrigation intakes. Ammocoetes may be at risk as they gradually move downstream and grow, and until they get close to maximum size (c. 100 mm) would be able to penetrate 3 mm mesh. Macropthalmia would be at less risk – they are of a size (c. 100 mm) that should preclude their penetrating 3 mm mesh, and they migrate downstream to the sea during winter when little water is taken for irrigation.

Overall, information on the migration and habits of juvenile lamprey is sparse, but it is thought some juvenile lamprey (ammocoete stage) are at risk at irrigation intakes utilising 3 mm mesh. Adult and macropthalmia stages are at little risk. In areas identified as important to juvenile lampreys a mesh size as used for elevers (1.5 mm) would be appropriate.

4.2.3.7 Torrentfish

Torrentfish are quite common in Canterbury waterways, particularly in braided rivers, where they are found from close to the sea up into the high country. Adult fish probably migrate within the river to spawn, but are of a size (up to 150 mm) to be at little risk from entrainment in well designed screened irrigation intakes. Little is known of the spawning site, eggs, or development of this species, but spawning probably occurs in autumn with eggs or larvae being washed out to sea to develop and grow. Juvenile torrentfish up to c. 20 mm long migrate upstream from the sea in spring and summer, and are thus at risk in irrigation intakes until of sufficient size (perhaps 30 mm) to be excluded by 3 mm mesh. The ‘chunky’ shape of torrentfish also assists in preventing passage through screens. Overall, small juvenile torrentfish will be at slight risk at irrigation intakes utilising 3mm mesh, but well designed intakes should minimise this risk and the species is not considered threatened so this size mesh is considered appropriate.

4.2.3.8 Other species

Several other species of native fish occur in Canterbury waterways (Davis et al. 1983, McDowall 1990). Several of these (such as yelloweye mullet, common smelt, Stokell’s smelt) are predominately marine or estuarine in habit, and it is unlikely that significant numbers of such species would penetrate far enough upstream to be at risk in irrigation intakes. In any case, these fish are mostly too large (>60 mm) to be able to penetrate 3 mm mesh.

4.2.4. Alternative mesh sizes and combinations

From information presented in the above sections, various species of fish are at different levels of risk each month of the year at irrigation intakes, and susceptibility also varies with mesh/aperture size. Our assessment of the susceptibility of fish each month to any one mesh size is presented in the following charts, which summarise the risk to each species or group of fish as low, moderate, or high for mesh sizes ranging from 2 mm to 5 mm mesh gap (Figures 19 to 22 respectively).

4.3. Review of good practice design process for intakes

4.3.1. Establish fish protection objectives and requirements

Fish protection objectives should be established through a process of reviewing the composition of the fish community and the potential impact on the fishery during the diversion operation. Seasonal changes in both the fish community and the diversion operation should be considered. Input from this guideline document gives an overview of issues. Information from FGNZ and DOC as well as diversion owners and the public should also be sought. The selected protection objectives will strongly influence fish exclusion concept selection and the design development process. It must be given due attention to avoid later problems.

4.3.2. Collect and identify design data and identify limitations

A wide range of data should be gathered to support fish exclusion concept selection and design. Specific constraints and limitations that may eliminate concepts from consideration because of the site, future operation and maintenance, and cost considerations should be identified, including:

- Documentation of fishery composition
- Maps and plans of the site layout showing natural water bodies, diversion structures (diversion dams and diversion head-works), canals and constructed waterways, and topography
- Drawings and photos of existing structures at the site
- Data establishing the hydraulic characteristics of the site
- Estimates of quantities and types of debris and times of occurrence
- Estimates of sediment (and ice) loading and probable times of occurrence

Shade			
Assessed risk	high	mod	low

	Month											
Fish species/group	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**
Salmonids												
Juvenile salmon												
Juvenile trout												
Migratory galaxiids												
Adult Inanga												
Adult Koaro												
Adult Giant kokopu												
Adult Banded kokopu												
Adult Shortjawed kokopu												
Whitebait												
Larvae												
Non-migratory galaxiids												
Adult Canterbury galaxias												
Adult Alpine galaxias												
Adult Bignose glaxias												
Adult Upland longjawed galaxias												
Adult Lowland longjawed galaxias												
Adult Dwarf galaxias												
Adult Canterbury mudfish												
Larvae												
Eels												
Adult												
Glass eel												
Elvers												
Lamprey												
Adults												
Ammocoetes												
Macropthalmia												
Bullies												
Adult Common bully												
Adult Upland bully												
Adult Bluegill bully												
Adult Redfin bully												
Adult Giant bully												
Larvae												
Others												
Flatfish												
Smelt												
Mullet												
Torrentfish – adults												
Torrentfish – juveniles												

Figure 19: Assessed risk of entrainment (low, moderate, or high) to fish at irrigation intakes screened with 2 mm side-of-square mesh in each month of the year.

Shade	(dark)	(grey)	(hatched)
Assessed risk	high	mod	low

Fish species/group	J	A	S	O	N	D	J	F	M	A	M	J
	Month											
Salmonids												
Adult Juvenile salmon		low	low	low	low	low						
Adult Juvenile trout			mod	mod	low	low	low					
Migratory galaxiids												
Adult Inanga	low	low	low	low	low	low	low	low	low	low	low	low
Adult Koaro	low	low	low	low	low	low	low	low	low	low	low	low
Adult Giant kokopu												
Adult Banded kokopu												
Adult Shortjawed kokopu												
Whitebait	mod	mod	mod	mod	mod							
Larvae	high	high					high	high	high	high	high	high
Non-migratory galaxiids												
Adult Canterbury galaxias	low	low	low	low	low	low	low	low	low	low	low	low
Adult Alpine galaxias	low	low	low	low	low	low	low	low	low	low	low	low
Adult Bignose glaxias	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod
Adult Upland longjawed galaxias	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod
Adult Lowland longjawed galaxias	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod
Adult Dwarf galaxias	low	low	low	low	low	low	low	low	low	low	low	low
Adult Canterbury mudfish	low	low	low	low	low	low	low	low	low	low	low	low
Larvae			high	high	high	high	high	high	high			
Eels												
Adult												
Glass eel		mod	mod	mod	mod							
Elvers	low	low	low	low	low	low	low	low	low	low	low	low
Lamprey												
Adults												
Ammocoetes	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod
Macropthalmia	low	low	low	low								
Bullies												
Adult Common bully	low	low	low	low	low	low	low	low	low	low	low	low
Adult Upland bully	low	low	low	low	low	low	low	low	low	low	low	low
Adult Bluegill bully	low	low	low	low	low	low	low	low	low	low	low	low
Adult Redfin bully	low	low	low	low	low	low	low	low	low	low	low	low
Adult Giant bully	low	low	low	low	low	low	low	low	low	low	low	low
Larvae				high	high	high	high	high	high			
Others												
Flatfish	low	low	low	low	low	low	low	low	low	low	low	low
Smelt	low	low	low	low	low	low	low	low	low	low	low	low
Mullet												
Torrentfish - adults												
Torrentfish - juveniles			mod	mod	mod	mod	mod	mod	mod	mod		

Figure 20: Assessed risk of entrainment (low, moderate, or high) to fish at irrigation intakes screened with 3 mm side-of-square mesh in each month of the year.

Shade	■	■	■
Assessed risk	high	mod	low

	Month											
Fish species/group	J	A	S	O	N	D	J	F	M	A	M	J
Salmonids												
Adult Juvenile salmon		mod	mod	mod	mod	mod	low					
Adult Juvenile trout			high	high	mod	mod	mod	low				
Migratory galaxiids												
Adult Inanga	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod
Adult Koaro	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod
Adult Giant kokopu												
Adult Banded kokopu												
Adult Shortjawed kokopu												
Whitebait	high	high	high	high	high							
Larvae	high	high					high	high	high	high	high	high
Non-migratory galaxiids												
Adult Canterbury galaxias	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod
Adult Alpine galaxias	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod
Adult Bignose glaxias	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod
Adult Upland longjawed galaxias	high	high	high	high	high	high	high	high	high	high	high	high
Adult Lowland longjawed galaxias	high	high	high	high	high	high	high	high	high	high	high	high
Adult Dwarf galaxias	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod
Adult Canterbury mudfish	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod
Larvae			high	high	high	high	high	high	high			
Eels												
Adult												
Glass eel		high	high	high								
Elvers	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod
Lamprey												
Adults												
Ammocoetes	high	high	high	high	high	high	high	high	high	high	high	high
Macropthalmia	mod	mod	mod	mod								
Bullies												
Adult Common bully	low	low	low	low	low	low	low	low	low	low	low	low
Adult Upland bully	low	low	low	low	low	low	low	low	low	low	low	low
Adult Bluegill bully	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod	mod
Adult Redfin bully	low	low	low	low	low	low	low	low	low	low	low	low
Adult Giant bully	low	low	low	low	low	low	low	low	low	low	low	low
Larvae				high	high	high	high	high	high			
Others												
Flatfish	low	low	low	low	low	low	low	low	low	low	low	low
Smelt	low	low	low	low	low	low	low	low	low	low	low	low
Mullet	low	low	low	low	low	low	low	low	low	low	low	low
Torrentfish - adults												
Torrentfish - juveniles			high	high	high	high	high	high	high	high		

Figure 21: Assessed risk of entrainment (low, moderate, or high) to fish at irrigation intakes screened with 4 mm side-of-square mesh in each month of the year.

Figure 22: Assessed risk of entrainment (low, moderate, or high) to fish at irrigation intakes screened with 5 mm side-of-square mesh in each month of the year.

- Documentation of resource consents
- Review of site geology
- Land ownership and potential easement needs for construction access with identification of preferred locations for structure placement
- Identification of the irrigation season and any operating constraints that would affect construction
- Identification of construction season constraints
- Identification of limitations on river access for construction
- Determination of the availability of electric power at the site
- Determination of local maintenance capabilities and desired limitations on maintenance
- Any information on well-performing local fish exclusion facilities

4.3.3. Identify alternative designs : Decision Table

The Decision Table (Table 7) provides a method to document and support selection of alternative concepts that could be developed for a conceptual design.

Summaries of the gradings for options included in the Decision Table are:

Site location – A rating of “good” indicates that the identified fish exclusion concept should be appropriate for the particular siting option and stated fish protection objectives, and that documented applications of the concept in that siting mode are available. A rating of “fair” indicates that application of the concept in the particular siting mode is possible but that previous experience is limited. A rating of “poor” indicates that the concept is not applicable in the particular siting mode.

Exclusion effectiveness/performance – A rating of “good” indicates that full exclusion of fry and larger fish is achievable. A rating of “fair” indicates that exclusion of a portion of the entrained fish (that may depend on size and species) can be expected and/or that injury of certain sizes and species of fish is possible. A rating of “poor” indicates that the concept may be ineffective in excluding fish.

Diversion discharge – Although fish exclusion concepts might be applied to wide ranges of flow rate, the size of existing installations tends to indicate discharge ranges that the specific concepts are best suited for. Application discharges presented in the decision chart summarise sizes of existing installations. Application ranges are typically limited by structural, functional, hydraulic, and cost considerations.

Table 7: Decision Table for fish screening options. Details of the grading for each option are presented above.

	Site location				Operation and cost					
	In - canal	**In -River**	**In – Diversion pool**	**Closed conduit**	**Exclusion effectiveness (fish species and size dependence)**	**Equipment operation and maintenance**	**Debris handling and cleaning**	**Sediment influences**	**Proven technology**	**Capital costs**
Positive barrier screens										
Linear flat plate screen	✷	✷	✷	NA	✷	✷	○	○	✷	$$$
Drum screen	✷	●	○	NA	✷	○	✷	○	✷	$$$$
Travelling screen	✷	○	✷	NA	✷	○	✷	●	✷	$$$$
Submerged screens										
Cylindrical	○	✷	○	NA	✷	○	○	○	✷	$$
Inclined	○	○	○	NA	✷	○	○	●	✷	$$$
Horizontal	○	○	●	NA	✷	○	○	●	○	$$
Coanda screen	○	✷	●	NA	✷	✷	✷	✷	○	$$$
Closed conduit screen (Eicher and MIS)	●	●	●	✷	○	○	○	●	○	$$
Under-gravel device: Submerged galleries	✷	✷	✷		✷	✷	✷	○	○	$
Behavioural devices										
Louvers	○	○	●	NA	○	○	○	✷	✷	$$
Sound	○	●	○	NA	●	○	✷	✷	○	$
Light (strobes)	○	●	○	NA	○	○	✷	○	○	$
Electric fields	○	●	○	NA	○	○	✷	✷	○	$$
Other (air bubble curtains, hanging chains, water jets	●	●	●	NA	●	○	○	✷	●	$

Rating		Costs	
✷	Good	$	Low
○	Fair	$$	↓
●	Poor	$$$	↓
NA	Not applicable	$$$$	High

Operation and Maintenance demands/debris handling and cleaning – A rating of "good" indicates that infrequent maintenance and repair would be required and that adverse influences on performance caused by debris is unlikely. A rating of "fair" indicates that periodic maintenance would be required and that debris fouling could substantially reduce concept performance. A rating of "poor" indicates that frequent maintenance and repair would be required, depending on site conditions, and that poor performance caused by debris loading is likely.

Sediment and ice – A rating of "good" indicates that the presence of sediment and ice will have minimal effect on performance and will not yield equipment damage. A rating of "fair" indicates that sediment and ice may reduce concept performance and may yield increased maintenance demands. A rating of "poor" indicates that sediment and ice can substantially reduce performance (which could require shutdown) and result in equipment damage.

Proven technology – A rating of "good" indicates that the concept has been widely applied and that effective performance for the stated fish protection objectives has been widely validated. A rating of "fair" indicates that limited application experience exists and that documentation of performance shows either mixed effectiveness (the concept has proven effective at some sites and ineffective at others) or that related adverse impacts on components of the fishery are possible (e.g., injury of certain sizes and species of fish is possible). A rating of "poor" indicates that either application experience is very limited or that documentation of performance shows substantial uncertainty.

Cost – This column is approximate and qualitative. It indicates capital cost of concepts relative to each other. Actual costs will be established through the design process. Costs depend largely on the fish exclusion option, fish species and sizes, and site requirements (the characteristics of the specific application site greatly affect cost).

4.3.4. Application of the Decision Table

Application of the decision table (Table 7) includes evaluation of all parameters shown in the Table plus:

- Identifying the siting possibilities that could work for the specific application (in-canal, in-river, etc.) and the size of the diversion.
- Identifying appropriate fish exclusion requirements. This is a critical factor that will vary from site to site.
- Identifying acceptable levels of operation and maintenance requirements

- Operational issues associated with debris and sediment.

- Deciding whether application of unproven technology (uncertain effectiveness and possible requirements for the additional cost of field verification of performance) is an acceptable risk to the developer.

- Determining whether capital cost are acceptable

- Determining the applicable discharge range

Based on the above requirements, the chart can be referenced and concepts identified that comply with desired requirements.

For example, louvers are a good option if:

- Diversion sites allow placement of the facility either in the canal or in the diversion pool

- Partial exclusion (exclusion of predominately the larger fish, for example) is acceptable

- Limited maintenance is desired

- Limited sediment (and ice) issues exist

- The desired assurance of intended performance is fair to high

- Capital costs are to be maintained at a moderate level or below

- The diversion discharge is large

Linear flat plate screens, drum screens, travelling screens, and inclined screens are options if:

- Siting is limited to canals

- All fish are to be excluded

- Increased maintenance is acceptable

- High endurance of performance is required

- Moderate to high capital costs are acceptable

- Diversion discharge range is medium or large

For gravel bed rivers:

- Submerged galleries are an option that look very effective

Operation and maintenance issues are an important factor. As scrutiny of screen effectiveness increases, robust designs with lower maintenance requirements become more attractive to avoid both the cost of keeping the fish exclusion working effectively and to reduce consequential costs due to loss of irrigation water supply.

4.4. Information gaps for improving future practices

In developing this document for New Zealand conditions it has become apparent that there is a lack of information in several key areas. These information gaps cannot be filled by work in other ecosystems and river forms at overseas locations. The key information gaps are:

- Fish populations on key New Zealand rivers. An obvious question is whether particular species are present and whether they are in a vulnerable state during times of abstraction. This can be a guide to both the type of exclusion facility needed and its requirements for effectiveness.

- Actual effectiveness of intake designs. How many fish actually through the screen or come into contact with the screen face and suffer damage as a result? Field trials are a preferred approach to these questions

- Fish behaviour around intakes. Even if fish are present, do they move towards a “hazardous” location or do they move away from it? Laboratory flume and finally field experiments will be needed to quantify such responses.

- Effectiveness in the face of dense algal proliferations. The recent invasion and rapid spread of didymo, and its downstream movement in thick mats, will pose special problems for screening. It may incur considerable operational and maintenance costs or redesigns of the screens.

5. Canterbury Good Practice Design examples

Ideally a series of prescriptive designs would be given in this section. However as noted earlier in this report there are significant information gaps and many 'fit for purpose' designs in different river types that currently make prescribed approaches impractical.

However, a set of examples of "good" practice screening for contrasting situations in Canterbury are given as a guide to possible design options. Each location shown is evaluated against the seven features identified in this document.

5.1. Gallery intake

The intake shown in Figure 23 has been constructed using a depth of over 1m of stone material over a grill screen. It is located on a pond fed by an open channel from a main river stem.

Figure 23: General view of gallery intake

Location

In this case in a relatively large pond fed by a diversion. Plenty of space and flexibility for other design features.

Approach velocity

Very low – well within limits

Sweep velocity

Low – but appropriate given minimal approach velocity

Bypass

Excellent bypass structure – see Figure 24.

Figure 24: Bypass intake structure – "bell mouth" shape of the entrance ensures gradual increase in the by-pass flow while high flow plus high velocity in by-pass channel means no opportunity for fish to return to intake zone via this passage.

Connectivity

Good channel to river. Longer channel than for an intake sited directly on a river bank.

Screening material

"Stone-picker" size rocks have been used in this case. Depth of material not checked.

Operation and Maintenance

Information being gained as intake operates. Site had run one season with no deposition problems, despite low velocities suggesting this could be an issue. Anecdotal comments are that some fine material is carried through intake from time to time. This is more likely to be a problem for pump/pipe system operation than for fish.

5.2. Drum screen rotary intake

The rotary intake shown in Figure 25 has been located flush against the banks of a channel fed from a major river.

Figure 25: Drum screen rotary intake

Location

Directly against bank - excellent

Approach velocity

Appears within limits.

Sweep velocity

Good sweep velocity

Bypass

Bypass action by main stem.

Connectivity

Directly connected (part of) to main stem

Screening material

3mm mesh – appropriate size for location.

Operation and Maintenance

Rotary screen require careful maintenance, both planned and unplanned. Mechanical and seal system are complex and the fine mesh is vulnerable to damage.

5.3. Flat screen intake

Figure 26 shows a substantial structure installed in the late 1980s.

Figure 26: Flat screen intake (Levels Irrigation scheme)

Location

Away from main stem. Distance provides protection for complex and expensive structure, but provides challenges for bypass/connectivity etc that must be balanced against this.

Approach velocity

Appears within limits.

Sweep velocity

Good sweep velocity

Bypass

Good intake at far end of screen (see Fig 26)

Connectivity

Pipe back to main stem

Screening material

Appropriately sized screen material

Operation and Maintenance

Complex mechanical structure. Has been subject to unauthorised interference. Fine mesh can be blocked by willow leaves and other small debris.

5.4. Self cleaning submerged screen pump intake

These devices are commercially available. A multi-unit example is shown in Figure 27. Their main purposes are to avoid blocked intakes, which can cause expensive pump failures, and to exclude material that can block sprinklers on travelling irrigators. When correctly sited (with acceptable bypass design and approach velocity) they also exclude fish.

Figure 27: Self cleaning pump intakes

Location

In pond fed from river. Considerable distance from river main stem.

Approach velocity

Appears within limits.

Sweep velocity

Not apparent from Figure 27, but good sweep velocity anticipated

Bypass

Bypass not shown

Connectivity

Relatively long bypass to main stem (not shown)

Screening material

3mm mesh – appropriate size for location.

Operation and Maintenance

Units are designed for automatic operation, but will require regular checking and planned maintenance. Frequency of maintenance is likely to be dictated by risk to equipment from intake blockage. This is strong financial incentive for good maintenance in addition to regulatory requirements.

6. References

Bates, K.; Fuller, R. (1992). Salmon fry screen mesh study. *Washington Department of Fisheries Report.* Washington Department of Fisheries, Olympia, WA.

Bell, M.C. (1986). Fisheries handbook of engineering requirements and biological criteria. US Army Corps of Engineers, Portland, OR.

Bonnett, M.L. (1986). Fish and benthic invertebrate populations of the Rangitata River. *Fisheries Environmental Report 62.* 72 p.

Boubée, J.; Jowett, I.G.; Nichols, S.; Williams, E. (1999). Fish passage at culverts : a review, with possible solutions for New Zealand indigenous species. Department of Conservation, Wellington, New Zealand.

Boubée, J.A.T.; Haro, A. (2003). Downstream migration and passage technologies for diadromous fishes in the United States and New Zealand: tales from two hemispheres. *In*: Downstream movement of fish in the Murray-Darling Basin, Canberra, pp. 24-32.

Charteris, S.C. (2006). Native fish requirements for water intakes in Canterbury. Department of Conservation, Christchurch.

Davis, S.F.; Eldon, G.A.; Glova, G.J.; Sagar, P.M. (1983). Fish populations of the lower Rakaia River. *Fisheries Environmental Report 33.* 109 p.

Davis, S.F.; Unwin, M.J. (1989). Freshwater life history of chinook salmon (*Oncorhynchus tshawytscha*) in the Rangitata River catchment, New Zealand. *New Zealand Journal of Marine and Freshwater Research 23*: 311-319.

DWA Topics. (2006). Fish protection technologies and downstream fishways: dimensioning, design, effectiveness inspection. 226 p.

Höfer, R.; Riedmüller, U. (1996). Fischschäden bei Salmoniden durch Turbinen von Wasserkraftanlagen. *Report for Auftrag des Regierungspräsidiums, Freiburg* 85 p.

Holzner, M. (1999). Untersuchungen zur Vermeidung von Fischschäden in Kraftwerksbereich, dar gestellt am Kraftwerk Dettelbach am main / Unterfranken. *Landesfischereiverband Bayern 1.* 224 p.

Hopkins, C.L.; Unwin, M.J. (1987). River residence of juvenile chinook salmon (*Oncorhynchus tshawytscha*) in the Rakaia River, South Island, New Zealand. *New Zealand Journal of Marine and Freshwater Research 21*: 163-174.

McDowall, R.M. (1965). The composition of the New Zealand whitebait catch, 1964. *New Zealand Journal of Science 8*: 285-300.

McDowall, R.M. (1990). New Zealand freshwater fishes: a natural history and guide. 2nd edition. Heinemann Reed, Auckland.

NMFS. (1997). Fish screening criteria for anadromous salmonids. US National Marine Fisheries Service, Southwest Region, Long Beach, CA.

O'Keeffe, N.; Turnpenny, A.W.H. (2005). Screening for intake and outfalls: a best practice guide. *Science Report SC030231*. 153 p.

Patrick, P.H.; Poulton, J.S. (2001). Responses of American eels to strobe light and sound (preliminary data) and introduction to sound conditioning as a potential fish passage technology. *American Fisheries Society Symposium 26*: 1-11.

Patrick, P.H.; Sheehan, R.W.; Sim, B. (1982). Effectiveness of a strobe light eel exclusion scheme. *Hydrobiologia 94*: 269-277.

Pavlov, D.S. (1989). Structures assisting the migrations of young fishes in rivers: USSR. *FAO Fisheries Technical Paper 308*. FAO, Rome, Italy.

Sand, O.; Enger, P.S.; Karlsen, H.E.; Knudsen, R. (2001). Detection of infrasound in fish and behavioral responses to intense infrasound in juvenile salmonids and European silver eels: a mini review. *American Fisheries Society Symposium 26*: 183-193.

Turnpenny, A.W.H. (1981). An analysis of mesh sizes required for screening fishes at water intakes. *Estuaries 4*: 363-368.

U.S. Department of the Interior. (2006). Fish protection at water diversions: a guide for planning and designing fish exclusion facilities. *Water Resources Technical Publication*. Bureau of Reclamation, Denver, Colorado.

Unwin, M.J. (1986). Stream residence time, size characteristics, and migration patterns of juvenile chinook salmon (*Oncorhynchus tshawytscha*) from a tributary of the Rakaia River, New Zealand. *New Zealand Journal of Marine and Freshwater Research 20*: 231-252.

Unwin, M.J.; Webb, M.W.; Barker, R.J.; Link, W.A. (2005). Quantifying production of salmon fry in an unscreened irrigation system: a case study on the Rangitata River, New Zealand. *North American Journal of Fisheries Management 25*: 619-634.

7. Glossary

Approach velocity: Speed of water **through** the screen

Bypass: Route through which fish can safely move from being in front of a screen to a safe location in the source channel

Connectivity: Ensuring the bypass connects with the source channel in a way that allows safe fish passage to a location where fish are not in danger.

Diadramous: Fish that migrate between freshwater and marine habitats as part of their lifecycle

"Mesh size": This is defined differently depending on the material used for a physical screen. The three most common screen materials have sizes measured as follows:

> ***Perforated plate*** (round holes): size = diameter of hole
>
> ***Mesh*****:** length of each side of opening. Therefore effective opening is larger than size indicated (diagonal is longer than side)
>
> ***Profile bars*** : gap between bars. Effective opening is longer given "long" gap along screen

Sweep velocity: Speed of water **across (or past)** the screen