Criteria for Fish Screen Design in Canterbury

Sports Fish

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Executive Summary

There is a high demand for the in-stream flows in Canterbury to be diverted for irrigation or other uses. Appropriately designed fish screens are necessary to prevent the loss of sports fish such as Chinook salmon, brown trout and rainbow trout to water diversions schemes through entrainment and/or impingement.

Most of the fish screens operating in Canterbury were designed and installed prior to comprehensive research that led to the current best international practices. As such they lack the level of effectiveness required to protect sports fish from entrainment and/or impingement.

This report summarises international best practices for fish screening in relation to the Canterbury sports fishery. The report has been complied as a part of the Environment Canterbury Fish Screen Working Party process. No attempt has been made to assess likely cost implications to the water users. This will be one of the issues for Working Party to attend to in the coming months.

The following fish screen design criteria are recommended:

- Fish screen at, or as close as practical to the point of water diversion from the mainstem;
- Approach water velocity of 0.12 m/s;
- Sweeping velocity equal or greater than approach velocity;
- Screen angled relative to the flow to a maximum of 45°;
- Maximum screening material opening size:
  - 3 mm for woven mesh screens;
  - 2 mm for profile bar screens; and
  - 3.2 mm for perforated plate screens.
- Effective bypass system ensuring fish return undamaged to the mainstem;
- Effective maintenance and operation of the screen.

Background

Thriving agriculture and increasing electricity demands is putting pressure of Canterbury's instream flows. Sports fish are susceptible to abstraction through the deterioration of habitat due to the lowering of the flow and/or ground water table lowering. Fish are also lost through entrainment in unscreened (or poorly screened) intakes or impingement in contact with poorly operating screens. There are a large number of irrigation schemes operating in Canterbury. Fish screens are installed on the majority of schemes but some significant schemes, like the Rangitata Diversion Race and the Waitaki intakes (Glova and Boubée, 2000), are not screened resulting in significant losses of sports fish and native fish (Webb, 1999). In excess of 200,000 salmon juveniles and 2500 trout are lost each season in just one unscreened irrigation scheme (Webb, 2000; Unwin *et al.*, 2005). Ideally, fish screens serve to prevent sports fish loss through entrainment and impingement yet enable unimpeded passage of migrating and resident fish safely downstream of the screen and back to the mainstem of the river.

For some time Fish & Game have expressed concerns about the state and effectiveness of fish screen designs and their operation in Canterbury (Lynn, 2000) as well as their maintenance and compliance with consent requirements. Even on screened intakes (e.g. Amuri scheme) fish rescue operations yield in excess of 1000 sports fish each year. Impingement losses to the poorly designed screens are likely to be very significant. A recent review of fish screens in North Canterbury by Fish & Game (Hardy, 2004) has identified a number of issues with the majority of operating fish screens. The review confirmed Fish & Game's view that the design and maintenance of operating screens does not conform to current best international practice (Hardy, 2004; Meredith and Millichamp, *pers. comm.*). Most of the fish screens in Canterbury were designed and installed prior to the completion of overseas scientific work on fish screen design (Hardy, 2004 and references therein) and the subsequent development of guidelines and standards (Bates, 1988; Katopodis 1992; Anon., 1995a; Anon., 1995b, Anon., 1995c; Nordlund,1996; Anon., 1997; Nordlund and Bates, 2000; Anon., 2004).

A fish screen feasibility study (Anon., 2002) for the, now abandoned, Project Aqua on the lower Waitaki River provides an up-to-date summary of all internationally recognized fish screen criteria adapted for Canterbury conditions. With the decreasing availability of ground water in Canterbury there is an increased interest for abstraction from flowing streams and rivers further emphasizing the need for effective fish screen guidelines and standards to be developed and implemented. It is generally accepted that the proportion of fish lost to the unscreened (or poorly screened) water intakes is proportional to the flow diverted from the river (Webb, 2000; Glova and Boubée, 2002). With an increased proportion of flows being diverted to water intakes and the loss of lowland river habitats, detrimental impacts on sports fish populations in Canterbury are becoming unsustainable.

Following the Fish & Game concerns and advice of its own staff, Environment Canterbury has instigated a process of formulating guidelines and standards for fish screens on flowing water intakes in Canterbury in 2004. This document has been compiled as a contribution to this process.

Criteria for fish screen design

Introduction

The design of any fish screen should be such as to enable migrating and resident fish safe passage past the structure. A successful fish screen requires: a barrier to prevent fish entering the intake structure, suitable water velocity at the screen, and a suitable escape route or bypass (Turnpenny *et al.*, 1998). There are many mechanisms that can cause migrational delay and significant mortality on the screen structures: physical contact with the screen; impingement onto the screen; entrainment through the screen mesh if insufficiently dense or over the screen; predation in the screen fore bay; predation at the bypass outfall in the river; poor water quality in the approach canal; appropriate water flow in the approach canal, bypass return or river; debris accumulation on the screen, or bypass; and excessive delays due to a poor bypass design where there are poor hydraulic guidance conditions (Nordlund, 1996).

Various criteria must be taken into account when designing an effective fish screen (Bates, 1988; Katopodis, 1992; Nordlund, 1996; Glova and Boubée, 2002; Anon., 2002). Each of the following will be discussed in greater detail below:

1. Fish species to be screened;
2. Size range of the fish species and likely life stages to be screened;
3. Movement of fish in the water column;
4. Fish swimming ability;
5. Water velocity at the screen;
6. Maximum allowable exposure time over the screen;
7. Maximum screening material opening size;
8. Effective escape route;
9. Efficiency of screening.

Sports fish in Canterbury

Canterbury rivers support an extensive range of aquatic habitats, from pristine alpine-based spring-fed streams in the mountain areas of the Southern Alps to estuarine habitats in the lower reaches (Hardy, 2004). These habitats combine to support an extensive range of fish faunas. All major river systems in Canterbury support internationally significant salmonid sports fisheries.

Three major sports fish species are resident in Canterbury waters:

- Chinook salmon (*Oncorhynchus tshawytscha*);
- Brown trout (*Salmo trutta*); and
- Rainbow trout (*Oncorhynchus mykiss*).

The life cycle of salmonid sports fish in Canterbury, especially the migratory life cycle of Chinook salmon and sea-run brown trout, makes them particularly susceptible to intake structures and screens. The disruption of the downstream migration of juveniles and post-spawning fish and the upstream migration of spawning adults can seriously impact on the health and sustainability of salmonid fisheries (Fox et al., 2003). Fish & Game research indicates that sports fish losses to unscreened races are substantial (Webb, 1999; Webb, 2000; Unwin *et al.*, in press). Considerable numbers of fish are also lost to races which are ineffectively screened (Hardy, 2004). Even on the screened intakes of reasonable effectiveness (e.g. Amuri scheme) fish rescue operations yield in excess of 1000 sports fish each year.

Chinook Salmon

Chinook salmon (*Oncorhynchus tshawytscha*) now forms the basis and the most significant part of a sports fishery along the east coast of the South Island.

Salmon are anadromous fish, beginning their life in freshwater, migrating down the full length of the rivers to the ocean where they spend most of their lives before migrating back to the freshwater to spawn. Salmon are famous for their extreme “homing” ability and most return to their streams of origin to spawn. The spawning run of salmon in Canterbury varies between river systems starting in October, reaching a peak in February but lasting well into April. Spawning occurs in the spawning streams in the upper reaches of the main Canterbury rivers from mid March to the end of June. The female lays an average of 4600 eggs (ranging from 2300-6500) in a nest (“redd”) buried in the stream bed. Adult Chinook salmon die after spawning. The eggs hatch and fry emerge from August to October, after which they may adopt one of a number of downriver migration strategies. Most (over 90%) newly emerged fry 33-36 mm in length migrate into the mainstem immediately after hatching from early August to October, apparently in response to intense competition for rearing habitat within their natal stream (Unwin, 1986). These fry gradually disperse downriver over the next three months, entering the ocean from November to January as fingerlings 60 – 90 mm in length (Hopkins and Unwin, 1987; Davis and Unwin, 1989). A smaller proportion of the emergent fry, around 5%, remain in their natal stream for at least three months after hatching, at which time they appear to migrate downriver relatively quickly so as to reach the ocean at about the same time (i.e., November-January) as the earlier wave of river resident fry. Both of these life history variants are known as “ocean-type” fry, in accordance with their tendency to spend all but the first three months of their first year of life in the ocean (Unwin and Lucas, 1993), followed by a further 1-3 years while they grow to adulthood. The second main life history variant, known as “stream-type” fry, remains in freshwater for all of their first year of life before entering the ocean as yearlings averaging 100-110 mm in length (Unwin and Lucas, 1993). However, the freshwater habitats used by stream-type juveniles are poorly known; a few remain in their natal stream for the whole of their first year, but the great majority are thought to take up residence within the braided mainstems. The precise nature of the habitats occupied by these fish remains unclear. Although they constitute only 5% of salmon smolts entering the ocean, stream-type adults make up a substantial proportion of the salmon returning to most Canterbury rivers, ranging from 29% (Rangitata) to 76% in the Waimakariri (Quinn and Unwin, 1993). Fry and fingerling migration is significantly higher during freshes and moonless nights (Unwin, 1986; Davis and Unwin, 1989). The majority of migrating juvenile salmon are encountered in the top 500 mm of the water column (Glova and Boubée, 2002) and near to the banks of the stream and rivers (Unwin, 1986; Hopkins and Unwin, 1987). Adult salmon return to spawn after one to four years in the ocean. Most of the spawning salmon in Canterbury have spent one or two years in salt water.

Brown Trout

Brown trout (*Salmo trutta*) are present in numerous waterways in Canterbury and in all major river systems. Brown trout in Canterbury are well known for their sea-run characteristics. A number of fish spend significant portions of their life cycle in the sea or in the estuaries and lagoons of Canterbury braided rivers. Brown trout spawn from mid April to September (McDowell, 1990; Graynoth *et al.*, 2003). Trout are capable of spawning more than once and may either remain resident in the river or migrate to sea before returning to spawn. They require clean, relatively silt free, well-aerated gravel to spawn. Spawning occurs throughout the river systems, although mostly in the tributaries of the main rivers. Female trout lay 2,000-3,000 eggs that are then fertilised by the male. After about 40 days the eggs hatch into alevins, which are 20 mm in length. Alevins leave the redd once they have absorbed the yolk sac attached to their stomachs. Alevins emerging from gravels are up to 25-30 mm in length and are called fry. As the fry mature they begin to gather in shoals in the lower reaches of the spawning streams dropping downstream during the night with peak migration occurring during moonless nights (Fox *et al*., 2003). More detailed data on brown trout biology in Canterbury are available from Glenariffe Stream (Fox *et al*., 2003) and the Waitaki River system (Glova and Boubée, 2002; Graynoth *et al.*, 2003). The migration of juvenile brown trout from the spawning grounds downstream to the main river occurs all year round, with peak migration occurring during September-January (86% of the recorded migrants). Significant numbers of juveniles migrate until late April with reduced numbers present from May to August. The average size of the fry increases from 28 mm in September to 78 mm in February. The mainstems of rivers serve as a significant rearing ground for juvenile trout that have emigrated from the spawning streams (Graynoth *et al.*, 2003). As fry and juvenile fish move downstream the trigger to move out to sea is activated in a number of juvenile fish. Significant numbers of brown trout occur in the lower reaches and coastal lagoons of the main braided rivers such as the Hurunui, Waimakariri, Rakaia, Rangitata and Waitaki.

Rainbow Trout

Rainbow trout (*Oncorhynchus mykiss*) are present in most upland rivers and alpine lakes and many other Canterbury waterways (Mc Dowell, 1990). The Waitaki and Waimakariri Rivers are unique in that they support substantial rainbow trout fisheries in the middle and lower reaches as well. The spawning run in Canterbury occurs mainly during August and September (Glova and Boubée, 2002; Graynoth *et al.*, 2003). In Waitaki River all spawning seems to occur in the tributaries (Graynoth *et al.*, 2003). Rainbow trout require clean, relatively silt free, well-aerated gravel to spawn. As rainbow trout fry emerges (average size of 25 mm) from the substrate in the spawning streams, some migrate downstream while others rear in the natal streams for up to a year. Fry migrate downstream from late October to mid December with a peak in mid November (Glova and Boubée, 2002; Graynoth *et al.*, 2003). As for the salmon and brown trout, mainstems of Canterbury rivers are significant rearing grounds for juvenile rainbow trout. No sea-run forms of rainbow trout are known in New Zealand.

Fish size and life stages

An effective fish screen must be able to safely exclude the smallest and weakest life stage encountered in the particular area of the water intake (Bates, 1988; Katopodis 1992; Anon., 1995b; Nordlund 1996; and others). The size of the juvenile fish encountered at the screen will depend on the season and relative position of the screen in the river system.

The size of the smallest fish in Canterbury river systems vary with the season and gradually increase from August (when salmon and trout fry start to emerge) to the later parts of the year (as discussed above). Due to the nature of Canterbury rivers and sports fish populations, and the patterns of spawning and migration of fry of all three salmonid species, relatively small juvenile fish can be encountered throughout the river systems (Table 1). The smallest rainbow trout fry in the lower Waitaki River was only 25 mm (Glova and Boubée, 2002). Salmon fry in the Rakaia, Rangitata and

Waitaki Rivers ranged from 30 mm upwards while the smallest brown trout fry were 28 mm (Unwin, 1986; Davis and Unwin, 1989; Webb, 1999).

Table 1. Seasonal size variation of juvenile Chinook salmon encountered in lower reaches of Canterbury rivers.

* Data for Rakaia River (Hopkins and Unwin, 1987); ** Data for Rangitata River (Webb, 1999).

Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
32-47*	33-60* 30-57**	33-87* 30-87**	36-87 35-102**	42-90* 35-118**	50-100* 73-120**	63-111* 80-132**	72-124* 79-132**	87-154**

Movement of fish in the water column

The majority of migrating juvenile salmon and trout are encountered in the top 500 mm of the water column (Glova and Boubée, 2002) and near the banks of the streams and rivers (Unwin, 1986; Hopkins and Unwin, 1987; Fox et al., 2003) making them especially susceptible to diversion into the water intakes operating on the sides/ banks of the waterways.

Fish swimming ability

The swimming ability of the fish is a primary consideration in designing any fish screen. Research shows that fish swimming ability varies depending on a number of factors related to the particular fish biology, physiology and characteristics of the environment (Bates, 1988; Anon., 1997). Environmental variables such as water temperature and dissolved oxygen level, as well as fish size, stage of development and fish health are the main factors affecting fish swimming ability (Nordlund, 1996).

Fish swimming speeds have been categorised based on the ability of the fish to maintain a particular speed before muscle fatigue occurs (Nordlund, 1996; Turnpenny, 1998, and references therein): burst (or darting) speed, prolonged speed and sustained (or cruising) speed. *Burst* speed is a survival response used for moving away from situations such as predators or ascending riffles and can only be maintained for up to 20 seconds. It requires high energy exertion and is used infrequently. Fish can take many hours (up to 24 hours) to recover from burst speed related exhaustion. *Prolonged speed* can be maintained for longer periods of time, up to 200 minutes, before fatigue occurs. The *sustained speed* can be maintained for long periods of time and is used for routine movement such as foraging. Comprehensive overseas studies of a number of different fish species (summary in Bates, 1988, and Turnpenny, 1998), including the sports fish species present in Canterbury, have shown direct correlation between fish size, water temperature and swimming ability. The size of the fish is a predominant factor affecting swimming ability and maximum burst speed increases linearly with fish length (Bates, 1988; Turnpenny, 1998). This has led overseas fish managers to develop separate fish screen standards for intakes where salmonid fry or fingerlings are encountered (Bates, 1988; Nordlund, 1996; Anon., 1997 and others). Temperature has a strong influence on the swimming ability of juvenile fish. Swimming stamina of juvenile salmon is positively correlated to water temperatures between 4°C and 15°C (e.g. 55 mm/s for every 5°C change for juvenile Chinook salmon). At very low temperatures (around 0°C) muscle activity is inhibited and a fish becomes torpid. Swimming ability increases with higher water temperatures but once over a certain threshold, swimming ability declines. It is important to take seasonal variation in water temperature, and its effect on the swimming ability of fish, when designing an effective fish screen (Turnpenny, 1998). Overseas fish screen standards recommend that the lowest temperatures experienced at the intake be taken into account in the design of fish screens (Bates, 1988; Nordlund, 1996; Anon., 1997 and others). A comparison of overseas data with water temperatures in Canterbury rivers indicate similar seasonal patterns and similar water temperatures experienced by juvenile salmonids. Levels of dissolved oxygen and water quality in general also play a significant role in the swimming ability of the fish. Swimming ability is adversely affected with decreasing levels of dissolved oxygen and increased amounts of pollutants as experienced in urban and industrial areas and areas under intensive agriculture (Turnpenny, 1998).

During migration juvenile salmonids swim with their head facing upstream. Fish swim against the current but net speed is lower than that of the water column and fish are slowly moving downstream. Using their lateral lines juvenile fish are able to sense velocity changes and tend to avoid abrupt changes in velocity and turbulence. If contact is made with an obstacle juvenile fish use darting speed to maneuver away from the obstacle (Nordlund, 1997).

Water velocity at the screen

The water velocity at the screen greatly influences the survival rate of juvenile fish. If the velocity at the screen is too high fish will be impinged upon the screen and damaged or killed. Fish can also be impinged and carried over the screen into the race (Terry, *pers. comm.*). The survival of fish in these situations is largely determined by their swimming ability, which in turn is determined by their size or length and other physiological parameters (Nordlund, 1997). An effective fish screen has to provide water velocity low enough that fish can voluntarily keep themselves from being impinged or entrained through the screen. The velocity of the water moving through the intake channel can be broken into two components, approach velocity (V_a) – the component perpendicular to the screen; and sweeping (or transport) velocity (V_s) – the component parallel to the screen.

$$V_a = V \sin \nu$$

$$V_s = V \cos \nu$$

Where V= intake channel velocity; V_a= approach velocity; V_s= sweeping velocity; and ν = angle of the screen to the flow.

Approach or escape velocity is the water velocity component into or perpendicular to the face of the screen. It is considered to be the velocity measured at about the edge of the boundary layer at the screen face (7.5-10 cm in front of the screen, Nordlund (1996)). Approach velocity at the screen has to match the swimming ability of the weakest fish present at the time of the screen operation. It should be maintained at a level low enough to prevent juvenile fish coming in contact with the screen, being impinged or over exerted and disoriented (Bates 1988; Turnpenny, 1998). Prolonged or sustained speed is the safest guideline for defining the approach velocity when designing an effective fish screen (Nordlund, 1996; Turnpenny, 1998; Nordlund and Bates, 2000). Two body lengths per second are generally accepted as a sustainable swimming speed by UK authorities (Turnpenny, 1998 and references therein). In the United States, fish screen standards were developed using extensive research into the swimming ability of different species of juvenile fish, mainly salmonids. The approach velocity of 0.122 m/s is prescribed for areas where salmonid fry are present or twice that if only fingerlings are encountered at the screen (Bates, 1988; Anon., 1995b; Nordlund, 1996; Anon., 1997; Nordlund and Bates, 2000; Anon., 2004). In Canada (Katopodis, 1992), authorities specify approach velocities at the screen using information about the size of the fish encountered. Katopodis (1992) provides the following empirical formula, based on the analysis of swimming speed and endurance of 20 fish species of similar swimming mode and capability, to calculate approach velocity based on sustained speed (up to 30 minutes) of juvenile fish:

$$V_a = 0.02L^{0.56}$$

where L=length of fish (mm); V_a =approach velocity (m/s).

Using this formula approach velocities for juvenile sports fish in Canterbury are:

- Salmon V_{salmon} @ 40 mm = 0.16 m/s; and
- Trout V_{trout} @ 25 mm = 0.12 m/s.

Sweep velocity is the water velocity component parallel and adjacent to the face of the screen. The angle of the screen to the flow determines this component of water velocity. Lower angles of the screen to the flow ensure higher sweep velocity and shorter exposure of the fish to the screen. The successful guidance of the fish to the escape route at the downstream end of the screen depends on this component of water velocity. Sweep velocity utilises the ability of juvenile fish to sense velocity changes and water turbulence (at the face of the screen) and move to the areas of lower turbulence avoiding contact and impingement on the screen (Nordlund, 1996). Overseas (Turnpenny, 1998) and, unfortunately, in Canterbury (Hardy, 2004) many older structures are placed across the intake channel perpendicular to the flow. This screen arrangement represents the worst case scenario for the effectiveness of the screen causing juvenile fish significant difficulty in locating the escape route. Fisheries agencies in North America require a minimum fish screen angle of 45° (Bates, 1988; Anon., 2000; Anon., 2004) for larger intakes. Overseas research (summary in Bates, 1988; and Turnpenny, 1998) showed significantly higher survival of juvenile salmonids where oblique angles of the screen to the flow were adopted ensuring sweeping velocities at the screen were higher than approach velocity. Two experimental studies on screen angle effects on juvenile fish survival and fish screen effectiveness by Kano (1982, as reported in Bates, 1988) found significantly higher survival of Chinook salmon fry with angled screens compared to screens perpendicular to the flow. In a laboratory study Neitzel et al. (1996), for smaller intakes, found there was no significant difference in effectiveness between angled and perpendicular screens for Chinook salmon fry when operated under the prescribed approach velocity of 0.12m/s . A review of the literature on the evaluation of fish screens operating in USA (Bejakovich, 2005a) showed that all screens on major intakes are placed at an angle to the incoming flow (ranging from 15° to 26°).

Water velocity even in the straight intake channel is not consistent. Bed and wall friction tend to reduce marginal velocities and increase the velocities in the mid channel and near the water surface (Turnpenny, 1998). The situation is more complicated in curved intake channels. Understanding water velocity profiles is significant for the effective screen and bypass position design as fish will tend to select areas of lower water velocity in preference to areas of higher velocity and increased turbulence. To ensure relatively uniform water velocity approaching the screen, the intake channel should be relatively straight with a smooth bed and walls. There are a number of technical solutions to ensure uniform water flow approaching the screen (for design information see Nordlund 1996; Turnpenny, 1998; Nordlund and Bates, 2000; and others).

As discussed earlier, salmonid fry and smaller fingerlings are present all through the major Canterbury river systems (Unwin, 1986; Hopkins and Unwin, 1987; Davis and Unwin, 1989; Fox *et* al., 2003). Unwin (1986) also noted that salmon migration occurs earlier in New Zealand than in North American streams possibly due to milder temperatures and smaller eggs with migrating fish being up to 10 mm smaller than their North American counterparts. Based on this research Fish & Game recommends that a maximum approach velocity of 0.12 m/s is adopted for fish screens in the Canterbury region. Also, effective fish screen design for screens lengths of 1.2 meters and more, needs to allow for sweep velocities higher than approach velocities, preferably at least twice the approach velocity allowing a maximum angle of the screen to the flow of 45°.

Maximum allowable exposure time

Overseas studies (e.g. Nordlund and Bates, 2000) on juvenile salmon stamina and swimming capability have shown that travel time past the screen should be no more than 60 seconds to ensure high survival of the fish. This criterion was accepted by the Project Aqua design team (Anon., 2002) following the recommendation from NIWA (Glova and Boubée, 2002). The screen should be designed in such a manner that sweep velocity ensures that fish travel the full length of the screen in less than 60 seconds. If this criterion cannot be satisfied then the screen design should include multiple bypasses.

Maximum screening material opening size

The screening material opening size is set so as to exclude all at risk fish species and life stages from the water intake. Fish should be stopped from passing through the screen by the bony part of its head (Bates, 1988; Turnpenny, 1998). Obviously, the opening size depends on the size of the smallest life stage encountered. Consequently, in Canterbury rivers fish screens should be designed to exclude juvenile salmonid fish of greater than 25 mm.

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 drum 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 was 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 (Attewell, personal communication).

A review of the literature and contact with overseas researchers (Bates, personal communication) on screening material opening size effects on juvenile salmonid survival revealed a paucity of the published data. Several laboratory and just a few field studies were located. Bates and Fuller (1992) actually tested a number of screening materials: perforated plate (opening size 3.18-4.76 mm), woven wire mesh (opening size 2-7.8 mm) and profile bar (horizontal and vertical, space between bars 2-4.8 mm). A perforated plate with 3.2 mm openings was sufficient to exclude all of the Chinook salmon fry (larger than 33 mm) but allowed entrainment of some smaller salmonid fry. In these tests, a woven wire mesh with a 3 mm opening size was found to exclude all Chinook salmon fry and most other salmonid fry. The 3.2 mm profile bar spacing was effective in excluding most of the Chinook salmon fry (larger than 30 mm) but proved ineffective in excluding smaller fry of other species. The 2 mm profile bar spacing ensured exclusion of all Chinook salmon fry and most small fry of other species. In the same study authors also anlalysed the results of the other researchers. Fisher (1978) evaluated perforated plate and woven wire mesh screens in a laboratory study. A perforated plate with an opening of 4 mm and woven wire with 3.2 mm openings were reported to be adequate to exclude Chinook salmon fry larger that 32 mm. Kano trialed a profile bar screen with bars spaced at 2.4 mm and found it to be sufficient to exclude Chinook salmon fry larger that 30 mm.

Evaluation of several operational fish screens on the Yakima River (Washington, USA) using releases of marked Chinook salmon fry (50-60 mm FL) showed 94-99% effectiveness (Neitzel et al., 1988), for woven mesh rotary drum screens with openings of 3.2 mm when operated as prescribed by current standards (Anon., 1995; Nordlund and Bates, 2000; Anon., 2004). Screens were installed at 26° to the canal flow ensuring a sweeping velocity to approach velocity ratio of more than 2:1. -. The same methodology used in previous study revealed that up to 17% of wild Chinook salmon fry is entrained through the 3.2 mm mesh at Westside Ditch fish screening facility (Neitzel et al, 1990). A similar experiment undertaken to evaluate the effectiveness of the Dryden fish screen (Wenatchee River, Washington, USA) for rainbow trout fry (23-27 mm FL) revealed that almost 40% of fry got entrained through the profile bar screen with 3.2 mm openings (Mueller et al, 1995). During the same experiment an estimated 6% of Chinook salmon fry (36-42 mm FL) was entrained even though the approach and sweeping velocity criteria were satisfied (15° angle of the screen to the flow). Based on other studies, the authors concluded that a 2.4 mm profile bar screen would exclude all Chinook salmon fry. Both of the above mentioned studies emphasized the need for proper maintenance of the screens to prevent impingement due to debris accumulation on the screen or blockage of the bypass entrance.

Trout fry and fingerlings, the smallest of the juvenile salmonid fish to be screened, are encountered throughout the Canterbury river systems, even in the lower reaches of rivers (Glova and Boubée, 2002; Fox et al., 2003; Graynoth et al., 2003). Beside trout juveniles, very small salmon fry is present in the Canterbury rivers for a good part the year. To ensure effective protection of the salmonid juveniles following maximum screening material opening size is recommended for fish screens in Canterbury:

- 3 mm for woven mesh screens;
- 2 mm for profile bar screens; and
- 3.2 mm for perforated plate screens.

Effective escape route

Ideally a fish screen should be positioned flush with the banks of the river at the very beginning of any water intake. However this is often impractical or impossible and water is taken through the specially designed intake channels. Consequently, the effectiveness of any fish screen is critically dependent on the provision of an effective escape route for the juvenile fish. A screen placed at the end of the intake channel with no escape route serves purely as a trap for juvenile fish (Turnpenny, 1998). The entrance to the escape route or bypass should be positioned in such a way as to maximize the chances of the fish locating it. All the fish that are protected by the screen must freely and voluntarily enter the bypass. The bypass canal should always be placed at the downstream end of the screen, ideally in the cleft formed by the screen and the bank, or as close as possible to it (Nordlund, 1996; Anon., 1997; Turnpenny, 1998; Nordlund and Bates, 2000; and others). Also, the maximum exposure time of 60 seconds should be taken into account as fish have to reach the bypass before they become exhausted and disoriented from traversing the screen. On large screens there may be a need for a number of bypasses to be installed.

Juvenile fish tend to avoid the areas of abrupt changes in velocity and turbulence (Nordlund, 1996; Nordlund and Bates, 2000). The flow entering a bypass should therefore be smooth. A sufficient amount of flow at the intake must be allocated for the bypass channel (2-5% of intake flow by UK standards). To prevent fish from swimming back and getting caught on the screen, the water flow in the bypass channel should accelerate slightly and gradually to a velocity higher than the escape capability of the fish. To enable all the fish to escape safely the bypass entrance should cover the entire depth of the intake channel – depth of the screen (Nordlund and Bates, 2000). The entrance to the bypass needs to be an open channel due to the juvenile fish responding to visual clues and actively avoiding darkened areas (e.g. pipes, tunnels etc.). Ideally, the bypass entrance should blend visually with the surrounding area so as not to repel fish from entering (Turnpenny, 1998). Most important of all criteria for the effective bypass design is ensuring that fish are returned into the river as soon as possible.

Technical design details for effective bypass design are readily available (for design information see Nordlund 1996; Turnpenny, 1998; Nordlund and Bates, 2000; Anon., 2004; and others).

One of the distinguishing characteristics of Canterbury rivers is their braided riverbed. It is of crucial significance for any effective fish screen and bypass design in Canterbury to ensure that juvenile fish are returned to a flowing braid that joins the mainstem of the river thus ensuring unimpeded and safe passage for migrating or resident fish. The responsibility for mitigating the environmental effects of abstraction shall extend to the point where the bypass water enters the mainstem.

Efficiency of screening

Fish screens should provide safe and unimpeded passage for migrating and resident sports fish. Most overseas agencies fish screen standards are committed to 100% fish screen effectiveness in order to protect endangered salmonid species (Bates, 1988; Anon., 1995b; Nordlund, 1996; Anon., 1997; Nordlund and Bates, 2000; Anon., 2004).

In the light of the recent decline in salmon numbers and taking account of the increasing number and cumulative effects of the numerous water diversions and habitat deterioration in Canterbury, Fish & Game is seeking as close as possible to 100% effectiveness of fish screens installed in Canterbury.

Summary: Proposed Fish Screen Requirements

Fish & Game have compiled a set of fish screen design criteria based on the analysis of best international practices and local conditions in Canterbury. The recommendations closely follow North American and UK fish screen design standards (Bates, 1988; Katopodis, 1992; Anon., 1995b; Nordlund 1996; Anon., 1997; Turnpenny, 1998; Nordlund and Bates, 2000; Anon., 2004) due to the similarity of sports fish species it intends to protect and conditions in general.

Screen Criteria for Sports Fish in Canterbury

A. Structure Placement

i) Any fish screen shall be installed/constructed at the intake (water diversion) entrance if practically possible. If constructed at the entrance, the screen should be flush with the banks thus negating the need for a bypass.

ii) If screening at the entrance is not feasible, the fish screen shall be installed downstream at the intake channel and provided with an effective bypass system. The angle of the screen shall be adequate to effectively guide fish to the bypass.

B. Water Velocity

i) Approach velocity is the water velocity component perpendicular to the face of the screen (7.5-10 cm in front of the screen face). Due to the likely presence of salmonid fry throughout the Canterbury river systems, the approach velocity shall not exceed 0.12 m/s;

ii) Sweeping velocity is the water velocity component parallel and adjacent the screen face. The sweeping velocity shall be greater than the approach velocity. This is achieved by ensuring that the screen has a maximum angle of no more than 45° relative to the intake flow. For small intakes (i.e. less than 0.675 m^3/s) and screen lengths of 1.2 m or less, the screen orientation may be angled or perpendicular to the flow.

C. Screen Face Material and Opening Size

i) The total submerged screen area required shall be calculated by dividing the maximum diverted flow by the allowable approach velocity on the assumption that there is no screen clogging. The screen area shall be increased if there is no provision for self cleaning and likely debris clogging. For rotary drum screens to ensure effective operation, the screen submergence shall be 75% and shall not exceed 85% for flood flows nor be less than 65% of the drum diameter;

ii) The water flow over the face of the screen shall be uniform thus minimizing the approach velocity and any turbulence;

iii) The screen material shall be corrosion resistant and sufficiently durable to maintain a smooth uniform surface;

iv) Screen material opening size shall be:

- 3 mm for woven mesh screens;
- 2 mm for profile bar screens; and
- 3.2 mm for perforated plate screens.

D. Bypass and Escape Routes

Juvenile bypass systems are channels or other structures that transport fish from the face of the screen to a relatively safe location in the mainstem.

i) The bypass entrance shall be positioned so it is easily located by the juvenile fish to the downstream end of the screen. Multiple bypass entrances shall be installed if the maximum exposure time of juvenile fish to a sweeping velocity under that prescribed exceeds 60 s;
ii) Sufficient water flow, that is a minimum of 5% of the intake, shall be diverted to the bypass to ensure effective operation of the bypass;
iii) The water velocity at the bypass entrance shall be equal to or greater than that in the main channel above the screen. A gradual acceleration of the flow up to 1.5-3.0 m/s is required to minimize the delay to the out-migrants. This is achieved by a hydraulically efficient ”bell-mouth” entrance shape;
iv) The bypass entrance shall be at least 0.3-0.6 m wide and extend from the floor to the water surface;
v) The bypass entrance shall blend visually with the surroundings and be subject to ambient lighting conditions;
vi) The bypass system when open shall have a minimum depth of 0.25 m;
vii) The bypass system shall have no sharp bends;
viii) The bypass outfall shall be located in receiving water of sufficient flow (i.e., minimum velocity of 1.2 m/s);
ix) The bypass return chute (if present) shall be smooth with no sharp edges and discharge into a minimum depth of 0.9 m in the mainstem or flowing braid.

E. Operations and Maintenance

i) The fish screen shall be cleaned automatically as frequently as necessary to prevent any accumulation of debris;
ii) The design of a screen for open channel intakes shall include trash racks or similar to prevent any accumulation of debris and damage to the screen;
iii) Screen and bypass facilities shall be evaluated for biological effectiveness and to verify that the hydraulic design objectives are achieved (e.g. water velocity components, bypass velocities, uniformity of the flow at the screen face etc.) by an independent research organization according to the guidelines (Appendix A).

Summary: Proposed Pump Intake Fish Screen Requirements

Fish & Game have compiled a set of pump intake fish screen design criteria based on the analysis of best international practices and local conditions in Canterbury. The recommendations closely follow Canadian and US pump intake fish screen design standards (Anon., 1995; Anon., 1996). This guideline has been aimed at protecting salmonid fry and later juvenile developmental stages.

Pump Intake Fish Screen Criteria for Sports Fish in Canterbury

A. Structure Placement

i) Any pump intake shall be installed/constructed at or as close as possible to the mainstem of the river thus negating the need for a bypass.
ii) Where possible screen shall be placed in locations with sufficient sweeping velocity.
iii) Screen shall be located in the areas with likely low concentration of fish and away from the likely juvenile fish migration routes or spawning and rearing grounds. In the reservoirs, lakes and ponds the intake screen should be positioned as deep as practical to avoid areas of juvenile salmonid congregation.
iv) Screen shall be submerged to a depth of at least one screen radius from the minimum flow water surface.
v) Screen shall be installed at minimum of 300 mm above the bottom of the watercourse to prevent entrainment of sediment and aquatic organisms associated with the bottom area.
vi) The screen face shall be oriented in the same direction as the flow.

B. Water Velocity

Two type of pump intake screens are operating in Canterbury: active screens, equipped with an effective self cleaning system, and passive, with no cleaning system. Effective screen area and approach velocities differ for these two types of the screens.

i) Approach velocity is the water velocity component perpendicular to the face of the screen (7.5-10 cm in front of the screen face). Due to the likely presence of salmonid fry throughout the Canterbury river systems, the approach velocity shall not exceed 0.12 m/s for active screens and 0.06 m/s for passive screens;
ii) Sweeping velocity is the water velocity component parallel and adjacent the screen face. For the passive screens (where no active cleaning system is installed) the sweeping velocity shall be greater than the approach velocity to eliminate debris build up.

C. Effective Screen Area, Screen Face Material and Opening Size

Effective screen area is the area of the screen available for the free flow of water. Water velocity at the face of the screen is a function of effective screen area and maximum pump capacity when in full operation.

i) To satisfy required approach velocity the minimum effective size of the screen can be calculated by dividing the maximum flow rate of the pump (m^3/s) with the approach velocity (m/s).
ii) The screen material shall be corrosion resistant and sufficiently durable to maintain a smooth uniform surface;

iii) Screen material opening size shall be:
  - 3 mm for woven mesh screens;
  - 2 mm for profile bar screens; and
  - 3.2 mm for perforated plate screens.

D. Bypass and Escape Routes

Juvenile bypass systems are channels or other structures that transport fish from the face of the screen to a relatively safe location in the mainstem.

i) Where pump intake is installed at the diversion intake channel than it has to be provided with an effective bypass system.
ii) The bypass entrance shall be positioned so it is easily located by the juvenile fish to the downstream end of the screen.
iii) Sufficient water flow, that is a minimum of 5% of the intake or 0.12 m^3/s, shall be diverted to the bypass to ensure effective operation of the bypass;
iv) The water velocity at the bypass entrance shall be equal to or greater than that in the main channel above the screen. A gradual acceleration of the flow up to 1.5-3.0 m/s is required to minimize the delay to the out-migrants. This is achieved by a hydraulically efficient ”bell-mouth” entrance shape;
v) The bypass entrance shall be at least 0.3-0.6 m wide and extend from the floor to the water surface;
vi) The bypass entrance shall blend visually with the surroundings and be subject to ambient lighting conditions;
vii) The bypass system when open shall have a minimum depth of 0.25 m;
viii) The bypass system shall have no sharp bends;
ix) The bypass outfall shall be located in receiving water of sufficient flow (i.e., minimum velocity of 1.2 m/s);
x) The bypass return chute (if present) shall be smooth with no sharp edges and discharge into a minimum depth of 0.9 m in the mainstem or flowing braid.

E. Operations and Maintenance

i) The design of a screen for open channel intakes shall include trash racks or similar to prevent any accumulation of debris and damage to the screen;
ii) Screens shall be maintained regularly and cleaning system operational at all times.
iii) Screen and bypass facilities shall be evaluated for biological effectiveness and to verify that the hydraulic design objectives are achieved (e.g. water velocity components, bypass velocities) by an independent research organization.

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APPENDIX A: Protocol for Fish Screen Efficiency testing in Canterbury - Draft

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Background

Canterbury rivers have been a source of valuable irrigation and stock water resource for local agriculture. A number of irrigation water schemes in Canterbury have been in place for a long time and design of fish screens at these (if installed) is not complying with contemporary fish screening design criteria (Hardy, 2004; Bejakovich, 2005).

Literature Review

Following reviews of fish screening guidelines in North America (Eastbrooks, 1984; and others as in Bejakovich, 2005) fisheries managers evaluated existing and newly developed screening facilities to assess compliance with prescribed criteria (Mueller *et al*, 1995; Neitzel *et al*., 1985; Neitzel *et al*., 1987; Neitzel *et al*., 1988). The assessments involved effectiveness evaluation of all components of the diversion including physical properties of the screen (approach and sweeping velocity, seal effectiveness) and biological factors (e.g. predator exposure, juvenile fish de-scaling, impingement and entrainment). The assessments were conducted at the range of water flow conditions likely to be encountered at the facility.

Biological Evaluation

Biological assessment of the fish screening facilities consisted of juvenile fish release-recapture studies, recaptured fish condition assessment (de-scaling and survival) and visual monitoring. In some studies video cameras were used to monitor juvenile fish behaviour in contact with the fish screen and in the bypass entrance.

Hatchery reared juvenile fish, of species likely to be encountered at the facility, were used for release-recapture studies. Size of the fish used was selected to match the likely size of the wild juvenile fish migrating through the facility. Fish screening efficacy studies comprised of recapture equipment effectiveness assessment followed by the facility assessment. Assessment process consisted of four major phases (Neitzel *et al*, 1987).

- **Phase I** – tests were conducted to determine the condition of juvenile fish after they pass through components of the diversion facility;
- **Phase II** – tests were designed to evaluate the change in conditions of fish released upstream of the trash rack to the condition of fish that have passed through the bypass system (Phase IIa) or through individual fish passage components of the screening facility (Phase IIb);

- **Phase III** – tests were designed to evaluate screen operating conditions and canal flow changes that may affect the screen efficiency;
- **Phase IV** – tests were designed to monitor the presence and temporal distribution of predators and other (non target) fish populations near the screen structures (Phase IVa) and to examine rate of fish impingement and/or entrainment on the screen.

Information gathered in all four phases was processed and combined using statistical analysis (for details see Netizel *et a*l, 1988) and recommendation to the facility operators and fisheries managers produced.

Recapture equipment was designed for each particular facility and involved fyke nets (used for trapping part or whole of the outlet canal and bypass end), inclined plane traps (at the bypass mouth – weir) and electro-fishing equipment. Recapture equipment efficacy was also assessed by releasing juvenile fish: i) in the bypass system (recaptured at the system end); and ii) behind the fish screens (to assess recapture rate for potentially entrained fish).

Results of the fish screening facility valuations were used later to amend recommended fish screen design criteria.

Proposed Fish Screen Biological Evaluation Protocol for Canterbury

Based on the literature review Fish and Game recommends that protocol used in evaluation of fish screening facilities in North America (Neitzel *et al*, 1987) be applied to Canterbury fish screens. Evaluation process would consist of four phases (as in Neitzel *et al,* 1987). The species and the size of juvenile fish used in biological evaluation of fish screening facilities will depend on the facility tested and should include fish species and life stages that are most likely to be adversely affected by the facility.

PHASE I

Phase I tests are conducted to determine the condition of juvenile salmonids after they pass through components of the diversion facility.

Phase I tests are accomplished by releasing branded fish (e.g. adipose fin clipped) at the entry to the fish bypass system. Released fish are collected near the end of the system where it enters the mainstem/flowing braid of the waterway. The proportion of fish that are de-scaled, the number of fish killed (both immediately and after four days), and the rate and extent of other injuries are recorded. The number of the fish released for Phase I tests will depend on the complexity of the bypass structures and size of the system.

Several collection systems may be used, including a net at the end of the bypass system or a modified inclined plane placed near the end of the diversion system (at a bypass entrance). The most appropriate collection systems will be chosen based on site-specific characteristics. Collection systems have to be tested to ensure their effectiveness and to verify that fish are not injured or stressed by the collection equipment. These tests are conducted by releasing fish in and near the collection system. Efficiency and handling tests are conducted throughout the evaluation programme.

Collection of released fish begins immediately after their release. Recovery/recapture duration should be adapted depending on the site and the test objective. If the primary objective is to estimate the proportion of released fish that are killed or de-scaled, collecting should continue until an acceptable 95% confidence estimate is obtained. When estimating travel time through a component of the screening facility, a similar criterion is used to determine sample duration. Whenever possible, samples should be collected continuously during the first 24 to 48 hr after release. If, after 48 hr, the total catch is insufficient to obtain an accurate estimate, the collection period might be extended up to 96 hr.

Phase I will help develop a hypothesis about the fate of missing fish from each release. The hypothesis will be based on catch efficiency data that we collect during the control tests, duration of the sample effort, and data from replicate tests.

Expected results from Phase I tests include determination of the proportion of fish that are killed or de-scaled during passage through the fish bypass system, the change in condition of fish that survive passage through the bypass, suspected fate of missing fish, effects of sampling equipment, and handling effects from marking, release, and recapture techniques.

PHASE II

Phase II tests evaluate the change in condition of fish by comparing the condition of fish released upstream of the trash rack to the condition of fish that have passed through the bypass system (Phase IIa) or through individual fish passage components of the screening facility (Phase IIb). Whether Phase IIa or IIb tests are conducted depends on whether fish are killed or injured during Phase I. If no mortalities or injuries occur after passage through the bypass system during Phase I, Phase IIa follows Phase I. If there are mortalities or injuries during Phase I, Phase IIb follows Phase I.

Phase IIa

If no effect is observed in Phase I, the condition of fish that pass through the screening facility (from upstream of the trash rack through the bypass) is determined. Fish are released at the trash rack and collected at the end of the bypass system. The percentage of fish de-scaled, number of fish killed (immediately and after four days), and rate and extent of injuries are noted. Releases are also made in and near the collection/recapture system to determine collection efficiency and handling effects.

Phase IIa studies evaluate the condition of fish that have been diverted into a intake canal and returned to the river through the bypass system. Additionally, the transit time of fish from the trash racks to the bypass discharge is determined.

Expected results from Phase IIa tests include determination of the change in condition of fish that travel through the entire fish diversion and are returned to the river, suspected fate of missing fish, transit time for fish traveling through the diversion facility, and collection efficiency and handling effects.

Phase IIb

If a detrimental effect is observed in Phase I tests, the condition of fish that pass through or by specific components of the fish bypass system (i.e., entrance to the system, the intermediate bypass pipe, and the fish return pipe) is determined. The number of fish released is determined by the same criteria used in Phase I. Fish are released into specific components of the bypass system and collected at the terminal end of the component or bypass system, depending on the data needed and the probability of successfully sampling within the component.

The study evaluates the condition of fish after they have passed through the bypass system components and to the discharge, the transit time of fish through specific components of the screening facility, and the transit time of fish through the entire facility.

Expected results include the determination of bypass components that adversely affect the condition of fish passing through the screening facility, suspected fate of missing fish, and possible changes to the screening facility that may reduce identified effects.

PHASE III

Phase III tests evaluate screen operating conditions and canal flow changes that may affect the screen efficiency. Test design, test species, and most of the study objectives are the same as in Phases I and IIa. The study evaluates operating conditions that maximize screen efficiency, the effectiveness of the screens over a range of flows, and factors that affect fish transit time through the facilities.

Expected results include determination of any change in the facility effectiveness over a range of canal flows and examination of operating conditions that may change transit time of fish through the facility.

PHASE IV

Phase IV tests are designed to monitor the presence and temporal distribution of predators and other fish populations near the screens (Phase IVa) and to examine rates of fish impingement on the screens, and to determine if fish can pass through, around, under, or over the screens and be lost in the irrigation (Phase IVb).

Phase IVa

Phase IVa includes use of an inclined plane, fyke nets, beach seines, or electro-fishing machines to monitor the presence and temporal distribution of local fish populations near the screening facility. Proposed locations for monitoring are downstream of the head-gates, in the fish bypass slot of the screening facility, and in the river downstream of the bypass discharge. In most cases, collection can be conducted concurrently with other phases. Phase IVa monitoring of the occurrence of native out-migrant salmonid and predatory fish populations will be conducted during all release/capture tests in Phases I, II, and III.

Expected results include a qualitative determination of fish predator populations near the facility and expected dynamics of the native and salmonid populations at the screening facility.

Phase IVb

Phase IVb monitoring evaluates the rotary and vertical travelling screens. Visual (and/or video camera) observations will be made to determine if fish are impinged on or can pass over the screens. Fish screen integrity should be determined by releasing marked fish upstream of the screens and monitoring for their presence in the outlet (i.e. irrigation canal) downstream of the screens. Marked fish would also be released behind the screens to evaluate collection/recapture gear and sampling efficiency.

Expected results include determination of the rate of fish impingement on fish screens and effectiveness of the screens in preventing fish from entering the outlet canal downstream of the screens, and the operating conditions that might result in fish impingement/entrainment.

Fish Species

Chinook salmon (*Oncorhynchus tshawytscha*) is the sports fish species readily available for use in biological evaluation of fish screening facilities in Canterbury. Juvenile fish are readily available from Fish and Game operated Montrose hatchery or NIWA operated Silverstream hatchery. Size of the juvenile fish used in tests will depend on the location of the screening facility and the size of smallest juvenile salmon most likely to be encountered at the facility.

In the waterways with predominant trout populations effort should be made to use appropriate trout species in trials, although source of the fish might be a problem.

All fish used in tests should be clearly marked so it is easily distinguished from wild fish.

Fish Release Locations

Release location at the facility will depend on the tests conducted. For Phase I tests fish will be released at the entrance to the bypass system. For Phase IIa tests fish should be released uniformly on the downstream end of the trash racks or at the specific parts of the bypass system for Phase IIb tests. For Phase IV tests fish should be released uniformly across and downstream of the trash rack and on the downstream end of the fish screen.

Released Fish Control

The condition of released fish needs to be monitored for the duration of the experiments by sub-sampling and assessing the condition (i.e. de-scaling etc.) the fish before they are released.

Fish Recapture and Condition Evaluation

Numbers of fish recaptured for assessing recapture gear effectiveness and/or screening system evaluation must be precisely recorded. Recaptured fish shall be kept alive in fish holding tanks to assess long term survival effects and sub-sample assessed for de-scaling (as in Neitzel *et al*, 1985).

Statistical Analysis

Detailed procedures for analysis of gathered data are presented in paper by Neitzel *et al*, (1988).

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