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Assessment of injury to New Zealand native fish by boat electrofishing

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Abstract

This study investigated the survival, incidence and severity of injuries and physiological reactions to stress caused by boat electrofishing in comparison with standard netting techniques in three New Zealand native fish species. Shortfin eel (*Anguilla australis*), grey mullet (*Mugil cephalus*) and common smelt (*Retropinna retropinna*) were captured from the Waikato River and its surrounding lakes with standardised boat electrofishing techniques (60-Hz pulsed direct current, 45-60% of range with the 0-500-V peak voltage machine setting, 3-4 Amps root mean square output). Fish were captured in water of 133-154 μScm^{-1} ambient conductivity at 18-21^{o}C. Capture techniques used for comparison were fyke netting for eels, gill netting for grey mullet and beach seine netting for smelt.

Survival was assessed in eels that held for 30 days after capture and smelt that were held for 30 min after capture. Several different methods were used to assess the incidence and severity of injuries. External examinations were used to assess branding and abrasions, and internal injuries were assessed by radiographic imaging and bilateral filleting to reveal haemorrhaging and spinal damage. Finally, physiological stress was determined by an analysis of haematocrit and haemoglobin concentration and an analysis of blood plasma ions (sodium, potassium, magnesium and calcium).

Survival over 30 days of shortfin eels captured by electrofishing (92% for Lake Areare eels and 96% for Lake Rotongaro eels) was similar to that for fyke netting (92% for Lake Areare and 88% for Lake Rotongaro). Two eels appeared to have died from fungal infections as no haemorrhaging or spinal injuries were apparent among the mortalities. External examinations revealed that no abrasions or branding occurred in eels captured by electrofishing; however, abrasions occurred in eels captured by fyke netting (24% for Lake Areare eels and 16% for Lake Rotongaro eels).

Rates of internal haemorrhaging immediately after electrofishing were inconsistent (0% in Lake Areare and 28% in Lake Rotongaro); in Lake Rotongaro, this was significantly greater than those captured by fyke netting, in which only 8% had haemorrhages. No haemorrhaging was observed in eels after 30 days from

Lake Areare. Haemorrhages from electrofishing in our study appeared to heal within the 30-day holding period, as the incidence of haemorrhaging in Rotongaro eels reduced from 28% at capture to only 4% after 30 days in captivity. Rates of spinal injury in eels captured by electrofishing was also variable (12% in Lake Areare eels and 8% in Lake Rotongaro eels), compared to the rate of spinal injury in eels captured by fyke netting (0% in Lake Areare eels and 4% in Lake Rotongaro eels). The upper rate of haemorrhaging that we found for electrofishing in shortfin eels (28%) was similar to injury rates for electrofished American eels (25%), but our rates of spinal damage (8-12%) were much lower than for American eels (60%).

In grey mullet, there was no significant difference ($P > 0.101$) in the occurrence of haemorrhages or spinal injuries between the two capture methods. However, physiological stress from electrofishing caused a significantly ($t = 2.37$, $P = 0.02$) reduced sodium ion concentration (139.38 $\pm$ 13.24 mM) compared to that of gill netting (149.06 ± 15.58 mM). Electrofishing also caused a significantly ($t = 4.61$, $P < 0.001$) lower concentration of haemoglobin (86.55 ± 9.21 g L^{-1}) compared to that of grey mullet captured by gill netting (108.81 ± 23.86 g L^{-1}). However, there were no significant differences between capture methods for the other blood plasma constituents tested (haematocrit and the blood plasma ions sodium, potassium, magnesium and calcium).

Survival was high in smelt captured by both electrofishing (94.8%, $n = 1217$) and by seine netting (92.9%, $n = 1271$), with no statistically significant difference between the two fishing methods ($t = -1.021$, $P = 0.320$). In a subsample of smelt analysed for injuries ($n = 40$ for each method), external injuries were observed in 15% ($n = 6$) of smelt captured by electrofishing and in 20% ($n = 8$) of smelt captured by seine netting. No haemorrhages were detected in smelt for either of the capture methods and there was no significant difference ($G = 0.215$, $P = 0.642$) in the rate of spinal injuries in smelt captured by electrofishing (10%, $n = 4$) or by seine netting (5%, $n = 2$).

These results suggest that boat electrofishing as practiced in New Zealand is in the long term generally no more harmful to shortfin eels, grey mullet, and common smelt than other comparable capture sampling techniques. Exceptions to this

conclusion were increased haemorrhaging in electrofished shortfin eels, from which they recovered within 30 days, and reduced sodium and haemoglobin concentrations in electrofished grey mullet, which are signs of physiological stress. All fishing methods examined caused some level of injury, stress, or mortality in the three species studied. Netting techniques (fyke net, gill netting, and seine netting) that are commonly used will also cause harm and these techniques are currently used far more widely than boat electrofishing.

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1 Introduction

1.1 The development of electrofishing

Electrofishing is the use of an underwater electrical current in conjunction with conventional nets to capture fish from lentic or lotic habitats (Northrop 1967; Reynolds 1996). The first patent for an electric fishing machine was granted in 1863, to Isham Baggs in London, England. In 1917, H. T. Burkey applied for a patent for an electrified fish screen, he proposed the use of an electric current to direct fish movement; this was the first practical application of electric current for fisheries management (Mahoney et al. 1993; Taylor et al. 1957). In the early twentieth century, electricity was more often used to guide or prevent fish passage than for fish capture (Reynolds 1996). Since then, electricity has also been used to kill, anesthetise, guide, screen or redirect fish (Reynolds 1996; Snyder 2003a; Taylor et al. 1957).

The use of electrofishing devices in fisheries management dates from the work of Haskell (1939), who used a prototype electrofishing unit consisting of two electrodes wired to an alternating current (AC) generator to capture fish. Electrofishing became more commonly used in the 1950s, resulting in significant improvements such as the use of continuous direct current (CDC) and pulsed direct current (PDC), as well as research describing the reaction of fish to electrical fields (Elle & Schill 2000; Hickey 2003; Reynolds 1996; Schill 1994). Research in the 1970s and 1980s focused on the refinement of techniques and the effects of electrofishing on fish (Reynolds 1996).

Early electrofishing units were made by biologists with limited electrical engineering qualifications. In 1974, Novotny & Priegel developed a boat-mounted, multi-anode, boom-array PDC electric fishing system at the University of Wisconsin. This early work led to the development of commercially available electrofishing units (Novotny & Priegel 1974). Today, biologists and fishery managers have a wide variety of choices when it comes to electrofishing equipment that is field tested, safe and dependable (Snyder 2003a).

Electrofishing is now a standard procedure for most freshwater fishery monitoring programmes and has been a valuable sampling technique for over half a century (Clement 1996; Hickey 2003; Miranda 2005). It is an efficient and effective method of fish capture that can provide information on growth, survival, movement, distribution, population size and community structure (Clement 1996). Electrofishing is often used to capture fish that are then released, generally with the assumption that these fish survive and behave normally after release. This assumption is critical when population estimates are being conducted through mark-recapture methods because delayed mortality due to electrofishing would lead to an over-estimate of the fish population (Dolan et al. 2002).

1.1.1 Early evaluation of electrofishing injury

Soon after the implementation of electrofishing techniques for fisheries management in 1939, observations of electrofishing induced injury and mortality were reported. Hauck (1949) used electrofishing to capture 503 rainbow trout (*Oncorhynchus mykiss*) (0.7–2.3 kg) with hand-held electrodes and a 110-V, 60-Hz, 495-W AC generator with a voltage of between 80 and 90-V. Hauck (1949) found that electrofishing caused a number of external injuries, such as haemorrhaging on the operculum and vent as well as branding when physical contact was made between the trout and the electrode. Through necropsy (n = 10), he noted the occurrence of haemorrhaging in numerous places along the spine in combination with spinal injuries. After capture, the trout were transported and released into a hatchery pond; they were then monitored for a 2-5 day period. During this time 26% of rainbow trout captured by electrofishing died (Hauck 1949).

Spencer (1967) conducted a comparison of AC and CDC induced spinal injuries in 1,575 bluegills (*Lepomis macrochirus*) and 70 largemouth bass (*Micropterus salmoides*) with 115-V CDC, 115-V AC and 230-V AC. He reported that the highest injury rates were found in bluegills captured by 230-V AC, which had an average injury rate of 12.2%. Spinal injuries occurred in 4.6% of bluegills captured by 115-V AC electrofishing and in 1.5% of bluegills captured by 115-V CDC electrofishing. Other studies that were conducted during the early years of electrofishing injury evaluation were often secondary to the study's primary

objectives. For example, when work was being conducted on directing brook trout (*Salvelinus fontinalis*) movements in streams, several injuries were found (McLain & Nielsen 1953). A different study on a CDC electrofishing apparatus, found no electrofishing induced injuries in Atlantic salmon (*Salmo salar*) (Smith & Elson 1950).

Despite the completion of several early studies revealing electrofishing induced injuries (Hauck 1949; Spencer 1967), other studies at the time found no effect of exposure to electric current on injury rates (Maxfield et al. 1971; Pratt 1955). Maxfield et al. (1971) held rainbow trout to determine the effects of PDC electrofishing on the survival, growth, fecundity of two year classes (young of the year and yearlings) and on the survival of the eggs and fry of the fish that were previously exposed to electrical current. They exposed young of the year (YOY) and yearling rainbow trout to low frequency PDC. The test groups were exposed for 30 s to one of two sets of electrical conditions. The YOY were exposed to a homogeneous field of 8-Hz, 40-ms pulses with a voltage gradient of 1-Vcm^{-1} (32% duty cycle, while yearlings were exposed to 5-Hz, 60-ms pulses a voltage gradient of 0.75-Vcm^{-1} (30% duty cycle). These fish were then held with rainbow trout of the same age group that had not been exposed to any electrical current until maturity. The cumulative mortalities after 3 years for the trout exposed to electrical current as YOY were 9.9% compared to 16% mortality of fish that had not been exposed to electric current. The cumulative mortalities after 2 years for the trout exposed to electric current as yearlings was 7.1% compare to a cumulative mortality of 10.4% for the control fish (Maxfield et al. 1971). Maxfield et al. (1971) concluded that there was no consistent long-term effect of electric shock on survival of rainbow trout.

Early studies that documented that electrofishing had no effect on injury rates or survival contributed to the common misperception among early fishery biologists that electrofishing was a relatively benign capture method (Thompson et al. 1997a). During this early period of research, spinal injuries were not as widely recognised as they are now; often researchers relied on only external examination of injury and did not use radiographic imaging or necropsy. If fish were captured with no notable external injuries and they appeared to recover they were typically classed as uninjured (Snyder 2003a).

More recent studies, suggest that the reports of low or no electrofishing induced injuries were inaccurate and that injuries do frequently occur with standard equipment, power levels and settings that are currently used (Dalbey et al. 1996; Elle & Schill 2000; Schill 1994). This increased awareness of electrofishing induced injuries began with Sharber & Carothers (1988) who collected adult rainbow trout with a mean length of 360 mm total length (TL) from the Colorado River using 60-Hz PDC electrofishing with three different pulse shapes (exponential pulse, 1/4 sine wave pulse and the square wave). Spinal injuries were analysed by radiographic imaging and necropsy techniques. Analysis of the radiographic images for all three treatments showed that a high proportion of trout suffered spinal injuries, with each injury involving an average of eight vertebrae (Sharber & Carothers 1988). Also the number of fish injured by each pulse was significantly different. The exponential pulse caused spinal injuries in 44% of trout, the 1/4 sine wave pulse caused spinal injuries in 67% of trout and finally 43% of trout captured by the square wave had spinal injuries. This trend is also reflected in the average number of vertebrae displaced or broken; the 1/4 sine wave vertebrae displaced or broke an average of 9.5 vertebrae compared to an average of 6.5 vertebrae injured by the exponential pulse (Sharber & Carothers 1988).

1.1.2 Concerns for threatened and endangered fish

The results of Sharber & Carothers (1988) caused great concern to the managers of the National Park Service and U.S. Bureau of Reclamation with regard to the use of electrofishing to monitor populations of the endangered humpback chub (*Gila cypha*). As a result, it was suggested that until concerns over the potential injury to humpback chub could be addressed, electrofishing in Glen Canyon National Recreation Area and Grand Canyon National Park should be minimised. In the United States of America (U.S.A) concerns were also raised about the use of electrofishing in waters that contain other endangered species, such as the Colorado pikeminnow (*Ptychocheilus lucius*), the bonytail (*Gila Elegans*) and the razorback sucker (*Xyrauchen texanus*) (Ruppert & Muth 1997). This prompted more research to be conducted on the effects of electrofishing on endangered species (Hawkins 2002; Holliman et al. 2003a; Holliman et al. 2003b; Nielsen 1998; Ruppert & Muth 1997).

The Alaska Department of Fish and Game conducted studies to determine the effects of 80-Hz PDC electrofishing on all the species of fish for which electrofishing was being used as a common sampling method. These species included rainbow trout, Arctic grayling (*Thymallus arcticus*), northern pike (*Esox Lucius*), humpback whitefish (*Coregonus pidschian*) and least cisco (*Coregonus sardinella*) (Holmes et al. 1990). Their results showed that capture by 80-Hz PDC electrofishing resulted in a high level of mortality (14%) and injury (41%) in rainbow trout and a moderate rate of injury (13%) in northern pike. These findings prompted the Alaska Department of Fish and Game to suspend the use of electrofishing in waters that contained large rainbow trout. The Montana Department of Fish, Wildlife, and Parks also issued regulations to limit injuries to fish, these regulations restricted the use of PDC electrofishing over 30-Hz (Snyder 2003a). The Fisheries Management Divisions of the Alberta, Minnesota, New York, Michigan and the Washington Environmental Protection Agencies all have official policies and guidelines intended to minimise electrofishing injury and mortality (Miskimmin & Paul 1997; Snyder 2003a).

The results of Sharber & Carothers (1988) have prompted similar investigations elsewhere, which has resulted in a large body evidence on the effects of PDC electrofishing on salmonids, especially in rainbow trout (Snyder 2003a). The effects of electrofishing on other fish species have been investigated but to a much lesser extent with only a limited number of investigations.

Despite the frequent use and importance of electrofishing, there is a lack of well-designed investigations into electrofishing related injury to fish. Investigations are often have a very limited scope and are very difficult to compare to other studies because of differing electrofishing equipment, techniques, species, sizes and environmental conditions, which are often not detailed (Mahoney et al. 1993). As a consequence there are often wide ranging values in the reported incidences of mortality, spinal injury and haemorrhages (Appendix 1).

1.2 Electrophysiology

The basic principle of electrofishing is the transfer of electrical current to the water and through the fish with a sufficient current density to incite behaviours that allow capture (Mahoney et al. 1993). Electrical current types used for electrofishing can be divided into two main types, alternating current (AC) and direct current (DC). Direct current can then be further categorised into continuous direct current (CDC) and pulsed direct current (PDC) (Reynolds 1996; Reynolds 2000). Fish capture is possible with the use of any electrical current as long as the electrical field is sufficiently strong, but the selection of electrical current type is important to maximise efficiency and minimise injury to the fish (Allen-Gil 2000).

In alternating current the direction of current flow between the two electrodes reverses a number of times per second as the polarity of the power source reverses rapidly (Reynolds 1996). The rate at which the direction of polarity changes is determined by the speed of the generator, this is usually 60-Hz (60-cycle AC). In AC, the voltage is usually a sine wave, increasing from zero to a maximum voltage and then reducing back to zero in one direction, this pattern is then repeated in the opposite direction. Waveforms are characterised by the peak voltage and the peak to peak voltage, which is the difference between the positive and negative peaks of the voltage. An AC can be either a single-phase or a multi-phase, usually three-phase. In single-phase the sine wave voltage crosses zero before reversing its polarity, whereas in an three-phase AC the three sine waves differ by a third of a cycle thus it is always delivering power in one of its phases (Figure 1.1 A and B) (Allen-Gil 2000).

Direct current is the simplest waveform, which is a constant voltage applied over time. Electrons flow in one direction only, from the cathode (─) to the anode (+) with a constant polarity. However, a drawback of CDC generators is that they need a high power input that can quickly exhaust batteries. They are also more expensive, heavier and less reliable compared to AC generators. For these reasons, CDC is usually produced by conditioning power from an AC generator (Mahoney et al. 1993; Reynolds 2000; Snyder 2003a). When CDC is produced by a CDC generator, it has a smooth current. However, if it is produced by a rectified current from an AC generator, it often tends to have a noticeable ripple resulting from

inefficient smoothing of the AC source (Figure 1.1 C and D). When CDC is produced by a three-phase AC generator, the current is already relatively smooth and therefore requires much less conditioning than a current produced by a single-phase AC generator (Reynolds 1996; Snyder 2003a).

Pulsed direct current can be produced by the modification of both AC and CDC, and is characterised by a unidirectional current with periodic interruption that forms waves of voltage (Reynolds 1996). Waveforms are characterised by the maximum voltage and the average voltage, which is determined by the maximum voltage, the pulse width (the time the current is "on"), and the spacing between pulses (Allen-Gil 2000). One cycle is measured from the beginning of one pulse to the start of the next pulse; the number of pulses per second is the pulse frequency or hertz (Hz). The ratio of the "on" time and one cycle is called the duty cycle and is expressed as a percentage, for example a duty cycle of 50% would mean that the current is flowing through half of each cycle. Depending on the source generator and transformers, rectifiers and filters used there can be many different PDC waveforms (Figure 1.1 E and F) (Allen-Gil 2000; Reynolds 1996).

The electric field required for electrofishing is induced by two electrodes (the anode and the cathode) that are immersed into the water. The maximum voltage occurring near the anode, while the minimum voltage occurs near the cathode (Snyder 2003b). The response of fish in the electrical field is dependent on the strength of the current and the on the duration of exposure. Field strength has three interrelated variables, these are 1) the voltage gradient (the average voltage differential per unit distance along lines of current, expressed as Vcm^{-1}); 2) the current density and 3) the power density (Mahoney et al. 1993; Snyder 2003a).

The behavioural response caused by the electrical field established during electrofishing can be divided into four zones of current density which are centred on the anode, the zone of indifference, the zone of perception and repulsion, zone of attraction zone and the zone of tetany or narcosis. Some of these zones are common to all electric field types, while others only occur with specific current types (Bayley & Austen 2002; Bearlin et al. 2008; Beaumont et al. 2002; Mahoney et al. 1993; Snyder 1992b).

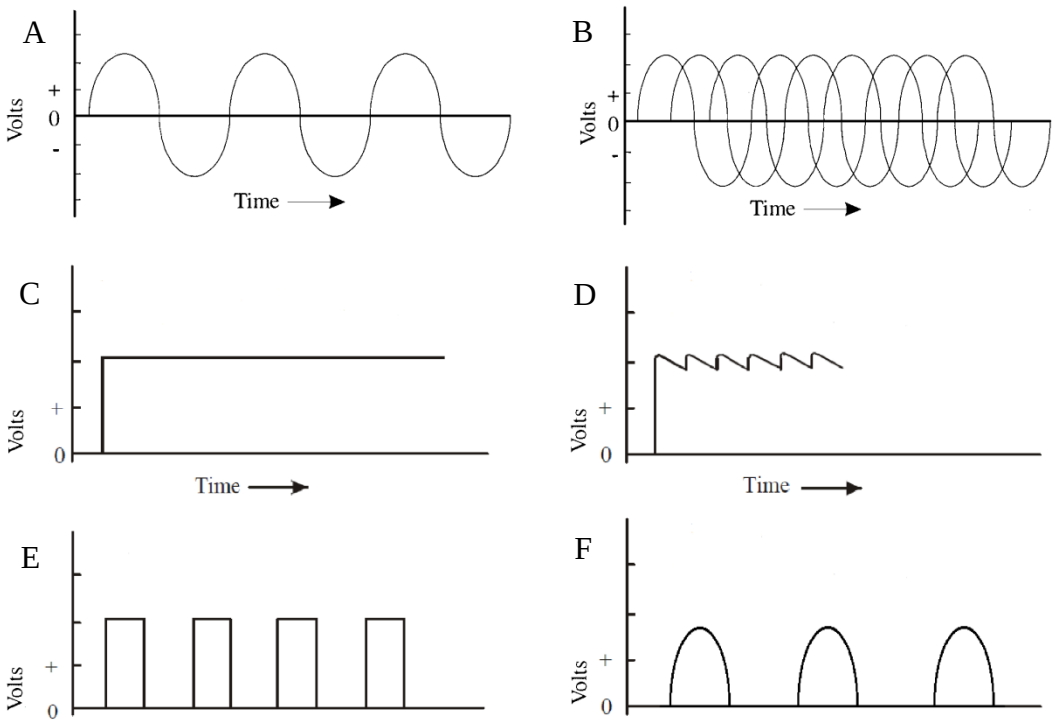

Figure 1.1: Different types of current used for electrofishing, A) AC generated from a single phase generator, B) Multi phase AC generated from a 3 phase generator, C) Smooth CDC generated by a CDC generator, D) Rippled CDC generated by partially filtered full-wave, rectified AC, E) Rectangular PDC generated by interrupting smooth CDC, F) PDC generated by unfiltered, half-wave, rectified AC. Adapted from Beaumont et al. (2002).

The indifference zone is the area where the electric field has no influence on fish behaviour. The perception and repulsion zone occurs on the border of the electrical field where the fish can detect the electrical field but it is not intense enough to physiologically attract the fish towards the anode. Instead the fish reacts to the electrical stimulus; this reaction could include an escape behaviour or the fish may seek refuge from the electrical current by hiding in weed beds or burrowing in the substrate (Brousseau et al. 2005; Halsband & Halsband 1984; Mahoney et al. 1993; Meyer & Miller 1995).

In the attraction zone (DC and PDC fields only), the desirable effect of taxis (forced swimming towards the electrode) occurs. This is the most effective zone in the electrical field for fishing (Brousseau et al. 2005; Mahoney et al. 1993). The tetany (AC, PDC and some CDC fields) or narcosis (DC fields) zone is the region where immobilisation of the fish occurs (Mahoney et al. 1993). If the fish comes too close to the anode; it receives a very high head-to-tail voltage gradient and

may sustain injury; as a result most injuries to fish occur within 0.5 m of the anode (Mahoney et al. 1993; Schill 1994). Due to the potential to cause serious injury, exposure to the zone of tetany or narcosis should be minimised by quickly removing fish (Brousseau et al. 2005; Pratt 1955).

1.3 Behavioural response to electrical current

The aim of electrofishing is to produce an electric field strong enough to elicit behavioural responses that will allow a fish to be captured but not excessively strong to elicit behaviour that will excessive injury or stress to the fish. The behaviour of fish to the different electrical field current intensities varies depending on the current type used for electrofishing (Reynolds 1996).

1.3.1 Fish responses to alternating current

In an AC field, fish are attracted to the electrodes to a much lesser extent than they would be in a CDC or PDC field and forced movement occurs without orientation towards the anode (oscillotaxis) (Reynolds 1996). When the electrical field strength increases, tetany occurs and elicited muscle contraction making the fish rigid. As a result breathing can be impaired by the fixation of the muscles that control the fish's ventilation and death by asphyxia can occur. At high voltage the muscular contractions could be so severe that vertebrae are fractured or the brain damaged, resulting in mortality of fish. Delayed mortality can also occur in fish as a result of prolonged exposure to a high intensity electrical field due to acidosis resulting from the oxygen debt generated by the severe muscles contractions (Brousseau et al. 2005). Fish immobilised by AC take longer to recover than fish captured by PDC or CDC, even when the same power levels were applied (Kolz & Reynolds 1989).

1.3.2 Fish responses to continuous direct current

The response of fish to a CDC field can be categorised into five behaviours; alignment, galvanotaxis, galvanonarcosis, pseudo-forced swimming and tetany. When a fish is first exposed to the electrical current, they align themselves with the direction of the current. If the fish is initially transverse to the anode will undergo anodic curvature that orientates the head in line with the anode

(alignment). Once the fish is aligned with the electrical current, the central nervous system is then stimulated by the field and the fish swims toward the anode (galvanotaxis). Once close enough to the anode the fish are exposed to a sufficient voltage gradient causing their muscles to relax and impairing their ability to swim (galvanonarcosis) (Beaumoint et al. 2000; Brousseau et al. 2005). Although their ability to swim is impaired, fish are still able to ventilate at a reduced rate and when fish are removed from the electric field, they can recover quickly (Mahoney et al. 1993). If the fish gets any closer to the anode, pseudo-forced swimming occurs drawing it in closer to the anode; this is a result of direct stimulation of the fish's muscles (not as a result of central nervous system stimulation). At high CDC voltage, the muscles go into a state of tetany, this can cause skeletal injuries and impair respiration resulting in death by asphyxia if the exposure is sufficiently prolonged (Beaumoint et al. 2000). Direct current has a greater attractive effect than AC and PDC fields, but it is a less effective stimulator and as a result will not narcotise or tetanise the fish as easily because the threshold values required to elicit a response are significantly higher than AC and PDC (Brousseau et al. 2005). Kolz & Reynolds (1986) found the threshold of CDC to achieve narcosis in fish was about 60% higher for CDC than for either AC or PDC. As a result CDC, is generally considered to be the least damaging of the waveforms used (Reynolds 1996).

1.3.3 Fish responses to pulsed direct current

The response of fish to PDC is intermediate to the response of fish to CDC and AC. Electrotaxis occurs as a result of the electrical effect on the fish's muscle which contract with each pulse, rather than its effect on the central nervous system. Each pulse of electrical current in a PDC field causes the fish's body to flex; it then relaxes between each of the pulses. This flexing and straightening action accentuates the involuntary swimming towards the anode (galvanotaxis). As with CDC, tetany and narcosis occurs, but this occurs at a much lower voltage gradient compared to CDC (Brousseau et al. 2005).

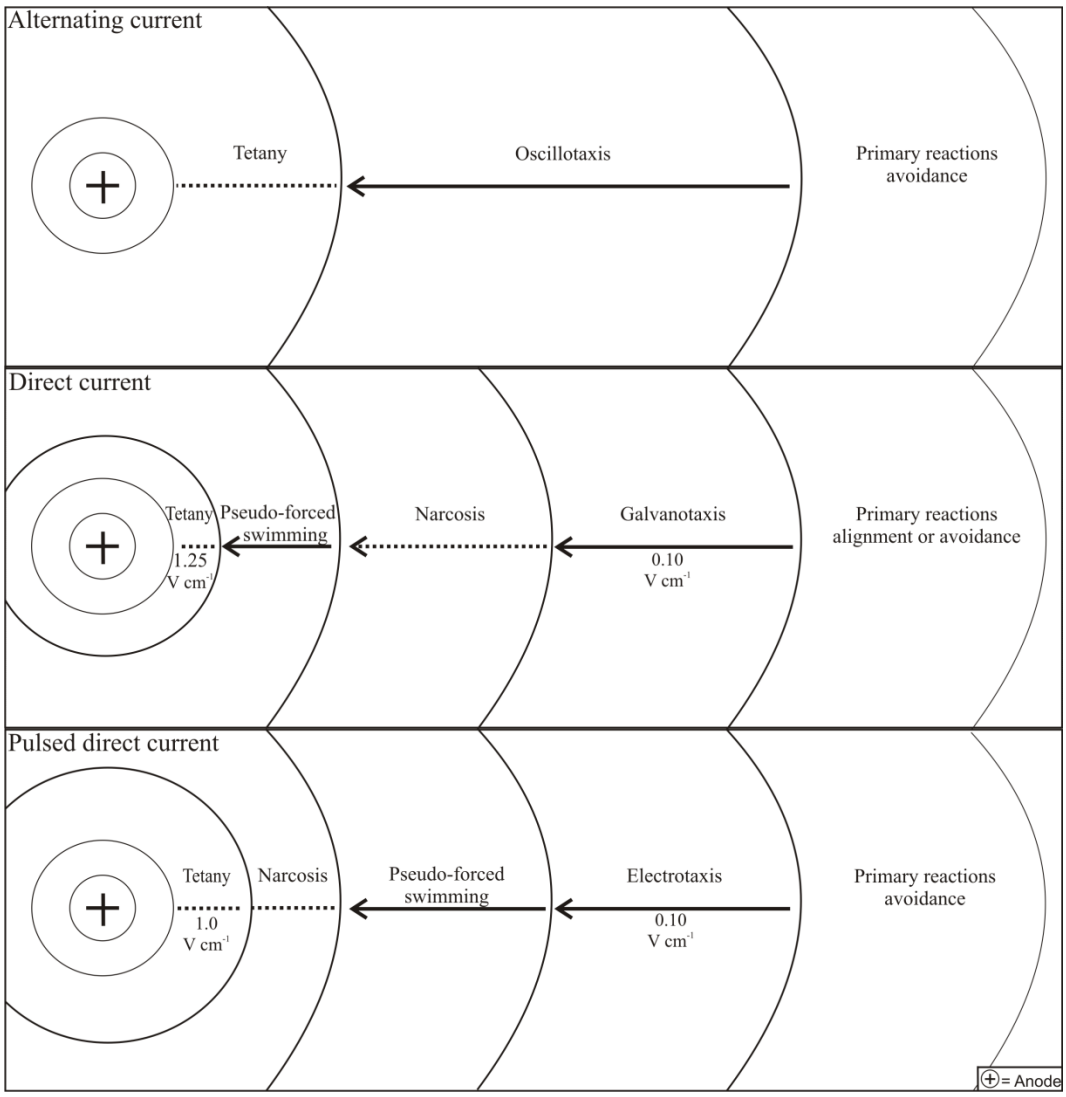

Figure 1.2: Generalised behaviour patterns of fish in alternating current, direct current and pulsed direct current, with approximate voltage gradient thresholds of fish in direct current (Vibert 1963) and pulsed direct current (Lamarque 1967). Adapted from Vibert (1963).

1.4 Electrofishing induced stress and injury

Electrofishing induced injuries can be broadly classified into two categories: physiological stress (a condition in which the fish cannot maintain a normal physiological state because adverse conditions) and physical injury (branding, haemorrhaging and spinal injury) (Lamarque 1967). Both physiological stress and physical injury can cause mortality in fish, particularly if the fish has been over exposed to an electrical field.

1.4.1 Electrofishing induced stress

During normal electrofishing operations fish are exposed to several stressors such as electrical current, handling, confinement, abrupt changes in water temperature and improper stocking densities (Lamarque 1967). Immediate mortality can be attributed to severe stress, presumably through blood ion disturbance (Vibert 1963). Freshwater fish are hypertonic to their environment; under stress adrenalin is released into the blood stream, this increases the loss of ions from the blood, resulting in a disruption of osmoregulation (Lamarque 1967). Delayed mortality can associated with the transport and improper conditioning of fish to a new environment and occur weeks after the initial exposure to the stressor (Lamarque 1967; Vibert 1963).

The stress response in fish can be classified into primary, secondary and tertiary responses. The primary stress response is the release of catecholamines and corticosteroids. This primary response triggers the secondary response, which is characterised by an increase in plasma glucose, haematocrit, lactate, heart rate, metabolic rate and decreases in the plasma chloride, sodium, potassium, liver glycogen, and muscle protein (Whaley et al. 1978). The primary response to stress occurs relatively rapidly (minutes), while the secondary responses generally appear within the first hour. Prolonged stress (day-weeks) may cause tertiary stress responses, which can include reduced growth rates, decreased disease resistance, reduced reproductive capacity, and altered behaviour (Barton & Dwyer 1997; Whaley et al. 1978).

Physiological disturbances as a result of electrofishing induced stress are often unrecognised and under reported, as fish may seem unharmed upon release (Barton & Dwyer 1997). However, the fish may be in an abnormal physiological state, including elevated levels of plasma catecholamines, lactic acid or glucose, resulting in reduced respiratory efficiency that may take hours for the fish to recover to a pre-electrofishing state (Haskell 1939; Haskell & Zilliox 1940; Hicks et al. 2010). In extreme cases death by asphyxiation can occur, it is usually a result of respiratory failure because of a significant increase in blood lactate levels known as lactic acidosis, which critically reduces the oxygen carrying capacity of the blood (Emery 1984; Mahoney et al. 1993; Reynolds 1996).

Schreck et al. (1976) observed changes in lactate levels in the blood of rainbow trout after CDC electroshocking. The lactic acid levels in the blood doubled immediately after fish were shocked and remained high for a period of 1 h, recovery to pre-shock levels taking approximately 3 h. Sternin et al. (1976) examined the oxygen levels in the blood of rainbow trout that were exposed to AC, CDC and PDC for 20 s. The oxygen consumption of trout exposed to an AC electroshock increased to 150% of normal oxygen consumption and took 2 h to recover to pre-shock levels. With CDC, the initial oxygen consumption increased to 130% that of normal and recovered within 80 min. With PDC, the oxygen consumption increased to a 110% that of normal and recovery to pre-shocked consumption occurred in 30 min (Sternin et al. 1976). When exposed to the electrical current, the rapid contractions of the muscle tissue causes lactic acid build up and increase oxygen debt. The rapid increase of respiration rate is a reaction to the oxygen debt in muscle tissues (Emery 1984).

Mitton & McDonald (1994) investigated the physiological consequences of capture with PDC electrofishing with and without the additional stress of air exposure in rainbow trout. There was no mortality and skeletal injuries only occurred in the most severe conditions (large ~600 g fish, 600 V exposed for between 20 and 40 s). Physiological changes induced by electrofishing consisted of lacticacidosis and stimulation of the interrenal stress response. The physiological disturbances caused by PDC were similar to between 2 to 3 min of exhaustive exercise. Mitton & McDonald (1994) results, indicate that PDC electrofishing does not cause physiological stress in rainbow trout above what is normally caused by handling or catch-and-release angling.

1.4.2 Electrofishing induced physical injury

Electrofishing induced physical injuries can be broadly classified into three categories: 1) branding, 2) internal haemorrhaging which occurs in the soft tissues of the fish, and 2) Spinal injuries, which occur principally in the fish's vertebral column (Reynolds 1996; Schill 1994). However, there are a number of different injuries that could occur, damaged ribs, burst blood vessels in the gills or brain, injuries to the swim bladder and ruptured dorsal or haemal arteries (Reynolds 1996; Robb & Roth 2003; Snyder 1992b; Snyder 2003a).

Branding (sometimes referred to as bruises or burn marks) is an externally visible injury caused by electrofishing (Snyder 1992b). Branding usually occurs when a fish comes in direct contact or close proximity to the electrode. However, branding can also occur in fish that have been removed from the electrical field at a significant distance from the electrode (Hartman et al. 1941). Lamarque (1941) noted that some brands observed were "true" burns which occurred as a result of direct contact with the electrode. However, it has been suggested that most branding occurs due to the dilation of skin melanophores, this possibly occurs as a result of sympathetic nerve damage or stimulation (Emery 1984; Fredenberg 1992; Hartman et al. 1941; Sharber & Sharber Black 1999). Reynolds (1996) suggests that some particularly dark marks may be haemorrhages in or under the skin surface caused by the rupturing of capillaries. Branding sites can be evident long after electrofishing has taken place and can offer sites for bacterial or fungal infection. Branding may appear in the vicinity of damaged vertebrae or internal haemorrhages, but fish without branding are not necessarily free of internal injuries (Reynolds 1996). Branding is most prevalent in species that have a fine scale structure, such as salmonids (Allen-Gil 2000).

Internal injuries caused by electrofishing are primarily manifested as haemorrhages or vertebral injury (Allen-Gil 2000; Elle & Schill 2000; McMichael 1993; Northrop 1967). Haemorrhages are blood discharged from broken blood vessels, the severity of this type of injury can range from a minor haemorrhage located in the dorsal white muscle to a large haemorrhage located surrounding the spinal column (Reynolds 1996; Snyder 1992b). Haemorrhages have been shown to heal over time. Holliman et al. (2010) found that the rate of haemorrhages decreased from 65% of the fish examined 1 day after the PDC exposure to significantly, to 9% at the conclusion of the 56 day study. Bleeding of internal organs occurs much less frequently than haemorrhaging in the muscle tissue, this is most likely due to reduced effect of muscle contraction on the organs (Reynolds 1996). Haemorrhages can occur along the spine or in the musculature of the fish without any corresponding spinal damage, and in most cases haemorrhaging is found in greater numbers of fish than vertebral injuries (Fredenberg 1992; Holliman & Reynolds 2002; Holmes et al. 1990; Reynolds & Holliman 2004).

Spinal injuries are caused by electrically induced, violent contractions of the body's musculature (Mahoney et al. 1993; Reynolds 1996). The recovery time from a spinal injury is varied depending on the severity of the injury, but can be long term if not irrecoverable (Mahoney et al. 1993; Snyder 1992b). The degree of spinal injury is largely dependent on several factors, such as electrical current type, water conductivity and exposure time. The use of AC electrofishing tends to cause more vertebrae fracture injuries, while CDC results in more compressions and misalignment of the vertebrae (Mahoney et al. 1993). The combination of spinal injuries and haemorrhaging is indicative of an electrofishing induced injury (Hawkins 2002; Holmes et al. 1990; Meyer & Miller 1990; Sharber & Carothers 1988).

The standardisation of documentation on the presence and severity of spinal injury and internal haemorrhaging occurred following a meeting on electrofishing injuries, held at a meeting of the Western Division of the American Fisheries Society (AFS) (Snyder 2003a). These ratings are used to produce standardised, ranked data (not linear measurements) of fish injury. Since its inception this method for ranking electrofishing induced injury, has been applied to the majority of the publications that address electrofishing injury (Dolan et al. 2002; Elle & Schill 2000; Hollender & Carline 1994; Holliman et al. 2003a; Reynolds 1996; Reynolds & Holliman 2004; Ruppert & Muth 1997; Thompson et al. 1997a).

Vertebral damage is evaluated by the use of radiographic imaging, while haemorrhages are usually evaluated by visual inspection of clean fillets of muscle tissue separated from the spine. Spinal injury and haemorrhages can be ranked from zero to three according to severity (Snyder 2003a). The original procedures only recommended a lateral view x-ray images, but Thompson et al. (1997b) recommended dorsal as well as lateral view x-ray imaging, this allows for increased accuracy in the interpretation of the severity of spinal injuries (Reynolds 1996; Snyder 2003a). Fredenberg (1992) noticed that some of the less severe haemorrhages were often only visible on one side of the spine, and this lead to the suggestion that necropsy procedures should include filleting of both sides of the fish. One major flaw of this method of ranking electrofishing injury, is that the actual relation to fish health is not established, therefore it is unknown how harmful or debilitating each injury class is to the fish (Reynolds 1996).

1.4.3 Mortality

Mortality as a result of electrofishing has received a large amount of attention, because of its importance from both an ethical and scientific standpoint (Janáč & Jurajda 2011). The rate of mortality following capture by electrofishing varies greatly depending on the study, electrical current type, settings, exposure time, species and many environmental variables (such as conductivity and temperature) (Mahoney et al. 1993). Most investigations on the long-term survival (greater than 7 days) of fish captured by electrofishing show that mortality is seldom significantly affected by electrofishing (Snyder 2003a). Most of the short-term (generally immediately or shortly after capture) mortality attributed to electrofishing being due to asphyxiation or severe physiological stress (Haskell 1939; Sternin et al. 1976).

Maxfield et al. (1971) was one of the first to investigate the effects of electric current on the long term survival of fish. They exposed young of the year (YOY) and yearling rainbow trout to low frequency PDC (as described above). The cumulative mortalities after 3 years for the trout exposed to electrical current as YOY were 9.9% compared to 16% mortality of fish that had not been exposed to electric current. The cumulative mortalities after 2 years for the trout exposed to electric current as yearlings was 7.1% compare to a cumulative mortality of 10.4% for the control fish (Maxfield et al. 1971). Maxfield et al. (1971) concluded that there was no consistent long-term effect of electric shock on survival of rainbow trout.

Ellis (2005) exposed channel catfish (*Ictalurus punctatus*) to 60 s of 60-Hz AC, or 15, 20, or 25-Hz, exponential-wave PDC at 1.5-Vcm^{-1}. The catfish were then confined to cages in a large pond, 133 days post treatment mortality varied between 0 and 25% in fish exposed to the electrical current and in 0 to 23% of fish that were not exposed to electrical current. Ellis (2005) found no significant difference between the treatments and the fish that were not exposed to an electrical current.

Hudy (1985) electroshocked 12 groups of 250 (n = 3000) rainbow trout and brook trout in hatchery raceways using 350, 700 and 760-V AC backpack electrofishing.

The immediate, delayed (15-day) and total mortality were examined, as well as spinal injuries. There was no significant difference between the immediate, delayed, or total mortality all of which were less than 2% (n = 28) in each of the treatments. Radiographic images of surviving trout showed that only a small percentage (<3%) had dislocated or fractured vertebrae, while 21% (n = 6) of the dead trout had fractured or dislocated vertebrae (Hudy 1985).

Barrett & Grossman (1988) captured mottled sculpin (*Cottus bairdii*) that were between 3 and 9 cm standard length (SL) by the use of 600-V CDC electrofishing and a kick seine. In the mottled sculpin captured by electrofishing mortality ranged between 0 to 11%, mortality in mottled sculpin captured by kick seine was between 0 to 15%. There was no significant difference in mortality over a 5 week period between the mottled sculpin captured by electrofishing and the mottled sculpin collected by kick seine. Barrett & Grossman (1988) also reported little or no mortality for largescale stoneroller (*Campostoma oligolepis*), rosyside dace (*Clinostomus funduloides*), warpaint shiner (*Luxilus coccogenis*), Tennessee shiner (*Notropis leuciodus*), longnose dace (Rhinichthys cataractae), creek chub (*Semotilus atromaculatus*) and northern hog sucker (*Hypentelium nigricans*) (Barrett & Grossman 1988).

Roach (1992; as cited in Snyder 2003a) collected adult northern pike between 38 and 77 cm fork length (FL) by gill netting and seine netting from South Dakota and Colorado reservoirs. The fish were then exposed to 5 s of homogeneous 120-Hz PDC (50% duty cycle, 4.2-ms pulse width) at 0.14 to 2.21-Vcm^{-1}. These fish were then placed in ponds and their mortality was monitored for 30 days. At the conclusion of this period, no significant difference was detected between the mortality rates of northern pike exposed to the electric current that had spinal injuries (5% mortality), and shocked fish without spinal injuries (9% mortality) and the control fish (9% mortality).

In contrast to these studies, Taube (1992) and Habera et al. (1996) found increased in mortality rates in rainbow trout exposed to electric current. Habera et al. (1996) found increased mortality rates in rainbow trout as a result of three-pass AC electrofishing (500-V) compared to mortality rates in rainbow trout captured by angling. Half the fish were anesthetised, weighed, measures and fin clipped to

simulate the handling that occurs after capture in most electrofishing operations, the other half were not handled. The mortality rate for than fish captured by electrofishing and then handled was 10%, while the fish captured by electrofishing that were not handled had a mortality of 7%. Both the handled and non-handled rainbow trout captured by angling did not suffer any mortality. All the fish that died during the 7 day holding period as well as 57 fish that survived were X-rayed and dissected to determine the incidence of spinal injuries and haemorrhages. Of the fish captured by electrofishing 3% (n = 2) had spinal injuries and a further 3% (n = 2) had haemorrhages. No injuries were detected in the fish that died during the holding period. Habera et al. (1996) concluded that given that there was no mortality or injury detected in the fish captured by angling, their results do indicate that electrofishing with high-voltage AC does produce some harmful effects in rainbow trout. However, greater than 90% of the fish captured by electrofishing did survive the 7 day holding period.

Taube (2013) found significantly greater mortality over a 203 day period, in fish exposed to an electric field compared to the controls. Rainbow trout (n = 102) were exposed to a homogeneous 60-Hz, 50% duty-cycle PDC at 2.3-Vcm^{-1} for a 5 s duration. The rainbow trout were weighed, measured, X-rayed and held in a raceway for the duration of the holding period. There was 15% mortality in rainbow trout that were exposed to electrical current and 10% mortality in rainbow trout that were not exposed to electrical current. Of the fish exposed to electric current that died during the holding period, 52% had suffered spinal injuries and 29% were uninjured. However, injury evaluation was not possible in some fish (both control and treatment) due to the poor resolution of some radiographic images. The majority (83%) of the total mortality occurred within the first 30 days of the holding.

1.5 Factors effecting electrofishing injury and mortality

Numerous factors effect electrofishing induced injury (haemorrhages and spinal injuries) and mortality. These can be broken down into three categories, electrical field factors, environmental conditions and biological factors. Electrical field factors that affect injury and mortality include the type of current, duration of exposure and pulse frequency. Environmental factors that can affect injury and

mortality include water conductivity, temperature, transparency and substrate type. The biological factors that affect electrofishing induced injury and mortality are species, size, condition and repeated exposure (Mahoney et al. 1993; Snyder 2003a). Often comparisons between different publications are difficult because of differing or inadequately described environmental and electrical parameters (Snyder 2003a).

1.5.1 Electrical field factors

1.5.1.1 Type of current

Generally, it is considered that electrofishing with AC causes the highest rates of injury and mortality to fish. Electrofishing with CDC causes the least amount of fatigue, injuries and mortality, with the rates of both injury and mortality cause by PDC electrofishing being an intermediate between AC and CDC. Comparative studies investigating the electrofishing induced injury and mortality in fish exposed to differing currents generally tend to support this trend. However, there are exceptions to this statement, electrofishing with AC can cause very minimal or no rates of injury (Roth et al. 2003; Spencer 1967; Taylor et al. 1957). Direct current can also cause a substantial number of injuries (Taube 1992) and cause a high percentage of mortality (Holliman et al. 2003a), if the field intensity is significantly strong and exposure duration is long. While reports of PDC electrofishing induced injury and mortality can be low (Ruppert & Muth 1997), nearly as low as those reported for CDC in some occasions. However, the complicating factor is that extent of electrofishing induced injury and mortality caused by the use of different currents can vary considerably as a result of other factors, such as those mentioned above (section 1.5)

Taylor et al. (1957) compared incidences of mortality among fish subjected to AC, PDC or CDC. In laboratory experiments, rainbow trout (20–23 cm) were exposed to fields of 60-Hz AC, 12- to 20-Hz, triangular-wave PDC (with 33–88% duty cycles), and CDC (>0.4-Vcm^{-1}). Rainbow trout (n = 46) exposed to 60-Hz AC electrofishing had a mortality of 4.2% (n = 2), of the rainbow trout exposed to PDC (n =1,641), only 0.3% (n = 5) died and finally in the rainbow trout that were exposed to CDC electrofishing (n = 91), no mortalities were reported. The

mortality rates of rainbow trout exposed to various current types showed that AC caused significantly higher mortality rates compared to PDC or CDC.

The effects of various current types on electrofishing induced spinal injuries and haemorrhages have also been investigated. Spencer (1967) conducted a comparison of AC and CDC induced spinal injuries in 1,575 bluegills with 115-V CDC, 115-V AC and 230-V AC. He reported that the highest injury rates were found in bluegills captured by 230-V AC, which had an average injury rate of 12.2%. Spinal injuries occurred in 4.6% of bluegills captured by 115-V AC electrofishing and in 1.5% of bluegills captured by 115 CDC electrofishing.

In the laboratory, Walker et al. (1989) assessed optimal currents, field intensities, and exposure times for narcosis without causing externally obvious injury using AC (50-Hz, sine-wave AC and 50-Hz, triangular-wave AC) and 50-Hz PDC (36% duty cycle, 0.4–2.1-Vcm^{-1}). Branding was present in 24% of northern pike exposed to sine-wave AC. Branding occurred in 33% of northern pike exposed to triangular wave AC. No obvious external injuries were found in Northern pike as a result of exposure to 50-Hz PDC. However, no radiographic images were taken and the fish were not necropsied to reveal internal injuries.

Hollender and Carline (1994) assessed internal injuries of wild brook trout that were captured with AC (250 to 300-Hz) and PDC (60-Hz) backpack electrofishing in four small, streams. Radiographic images and necropsies were used to assess the injury rates in 579 brook trout (95–237 mm TL) captured by electrofishing. Hollender and Carline (1994) found no significant difference in the injury rates between brook trout captured by AC (26% injury rate) or PDC (22% injury rate) electrofishing.

1.5.1.2 Duration of exposure

The duration of exposure is an important factor in determining electrofishing induced mortality or injury. Increasing mortality occurring as the duration of exposure increases has been well documented (Snyder 2003a). However, the exposure time used in many of these experiments can be significantly longer than the typical exposure time when a fish is captured by electrofishing in a stream or

lake. Under normal electrofishing operating procedures fish will typically be exposed to an electrical current for less than 20 s (Brousseau et al. 2005) but in majority of the literature, exposure times can often be greater than 1 min (Snyder 2003a). Whaley et al. (1994) examined the lethality of 16-Hz PDC electroshock, in fantail darters (*Etheostoma flabellare*) (3–8 cm) and bluegills (9–17 cm), these fish exposed to a homogeneous field at 4-Vcm^{-1} for between 60 and 180 s. Mortality was found to increase significantly with exposure time, with 35% mortality for fish exposed for up to 2 min and greater than 50% mortality rate for fish that were exposed for greater than 3 min (Walker et al. 1994).

Although, authors have found exposure time to be a critical factor in electrofishing mortality, much of the literature has failed to find a correlation between the effects of exposure time and injury rates (Snyder 2003a). Walker et al. (1989) exposed juvenile (13–19 cm SL) northern pike to 50-Hz AC electroshocking in the laboratory for varying exposure times (10, 30, or 60 s). No correlation was found between externally obvious injuries and exposure times. However, no radiographic images or necropsied were conducted to examine internal injuries as a result of the increased exposure time (Mesa & Schreck 1989; Snyder 2003b).

1.5.1.3 Pulse Frequency

Pulse frequency is a major contributing factor effecting electrofishing induced spinal injuries and mortality; this is because most spinal damage and haemorrhaging are caused by the sudden change in electrical potential when currents are switched on and off (Snyder 2003a). Whaley et al. (1978; as described above) also investigated the effects of increased pulse rate of mortality on fantail darters and bluegills. Mortality was found to increase with pulse frequency, from 20% in fantail darters and 69% in bluegills at 2-Hz; to 32% in fantail darters and 77% in bluegills at 9-Hz and finally to 62% in fantail darters to 95% in bluegills at 16-Hz. Whaley et al. (1978) noted that mortality rates were high due to prolonged exposure time (between 60 and 180 s). Sharber et al. (1994) conducted field experiments in the Colorado River, on the effects of pulse frequency on injury rates in rainbow trout using a square-wave PDC, at 15-Hz (4-ms), 30-Hz (4-ms), 60-Hz (4-ms), and at 512-Hz (0.2-ms). Spinal injuries rates

examined by radiographic imaging, showed that the incidence of spinal injuries increased from 3% at 15-Hz, to 24% at 30-Hz to 43% at 60-Hz and finally to 62% at 512-Hz.

1.5.2 Environmental conditions

1.5.2.1 Water conductivity

Water conductivity is the single most important environmental factor effecting electrofishing injury and mortality (Brousseau et al. 2005; Reynolds 1996). The conductivity of streams, lakes and rivers varies depending on the amount of dissolved ions in the water (Brousseau et al. 2005). The conductivity of freshwater can be divided into three categories; low, medium and high. Waters with a conductivity of between 5 and 30 μScm^{-1} are considered to low conductivity. Medium conductivity waters range between 30 and 500 μScm^{-1} and water is considered to have a high conductivity when it exceeds 500 μScm^{-1} (Mahoney et al. 1993). Both extremely high (1000 μScm^{-1}) and extremely low (30 μScm^{-1}) conductivities can exceed the capacity of most generators and reduce injury and mortality. In water high conductivities, fish tend to be less conductive than the water; waters with a low conductivity have a high resistance compared to the fish, this reduces the voltage gradient decreasing injury rates (Brousseau et al. 2005; Hartman et al. 1941; Kelsch & Shields 1996; Mahoney et al. 1993; Reynolds 1996).

1.5.2.2 Water temperature

Water temperature can affect electrofishing injury and mortality by altering the conductivity of the water; it may also affect the fish's response to the field because of the changing conductivity of the fish and the ambient conductivity of the water. In cold conditions, fish become immobilised more easily by the electrical current (Beaumont et al. 2002). However, cold temperatures can decrease floatation rates of fish once they are stunned, resulting in prolonged exposure to the electrical current, increasing the risk of injury and mortality (Beaumont et al. 2002; Reynolds 1996). Scruton & Gibson (1995) found that the behaviour of juvenile salmonids changed once temperatures decreased below 7°C,

juvenile salmonids burrowed into the substrate making them vulnerable to repeated shocking, increasing the risk of injury and mortality.

1.5.2.3 Water transparency

Water transparency effects electrofishing efficiency, but there is little peer-reviewed literature on its effect on electrofishing injury and mortality (Brousseau et al. 2005; Hickey 2003; Reynolds 1996; Snyder 2003b). In waters with low transparency, stunned fish are less visible to the dip net operators and this could result in prolonged exposure to the electrical current increasing the chance of injury and mortality (Brousseau et al. 2005; Reynolds 1996). The use of CDC or PDC waveforms increases the chance of quick capture because fish are attracted to the anode, partially mitigating the effect of turbid water. (Brousseau et al. 2005).

1.5.2.4 Substrate type

Cowx & Lamarque (1991) suggested that different substrates could affect electric field strength in the water. Mud and silt with fine particles and organic matter often reduce the horizontal intensity of the electrical field, because the current is drawn into the substrate. This reduced field strength is likely to decrease the rate of electrofishing induced injury and mortality (Brousseau et al. 2005; Snyder 1992a). A mud or slit substrate can also result in reducing visibility if the stream or lake bed is disturbed (Reynolds 1996). Unfortunately, there is little peer-reviewed literature on the effects of substrate on electrofishing induced injury and mortality (Hickey 2003).

1.5.3 Biological factors

1.5.3.1 Species

The effects of electrofishing varies among species because of differences in their morphology, physiology, behaviour and skeletal and muscular structure (Reynolds 1996). Those with fine scales, for example salmonids or fish that have vestigial scales are generally more vulnerable to electrofishing induced injuries as there is little resistance to the electric current (Allen-Gil 2000; Mahoney et al. 1993;

Reynolds 1996). The proportion of muscle mass is also thought to be a factor that could affect electrofishing induced mortality or injury as a higher proportion of muscle mass may increase the force of muscle contractions caused by the electrical current. Strong swimmers are known to have over 50% muscle mass, for example in salmonids approximately 60% of the body's weight is muscle mass (Allen-Gil 2000).

Reynolds & Holliman (2004) hypothesize that in similar size fish , the underlying risk factor for electrofishing induced injury was the number of vertebrae. Body undulating fish like anguillids, have a high vertebral count which is associated with flexible spines to provide maximum thrust. As a family anguillids have a vertebral count of between 103 and 119 (Reynolds & Holliman 2004). Reynolds & Holliman (2004) suggested that the large number of vertebrae meant that the spine was less likely to remain uninjured during the severe force of muscle contractions experienced in the course of electrofishing.

Investigations into the effects of electrofishing have strongly indicated that salmonids are more susceptible to injury and mortality than many other fish species (Brousseau et al. 2005; Reynolds 1996). For example, a large number of studies have been conducted on rainbow trout exposed to PDC electrofishing and mortality rates have been reported as high as 78% (Meyer & Miller 1995). Spinal injuries have been reported in up to 78% of fish (Meyer & Miller 1995), while the occurrences of haemorrhages have been reported to be up to 91% (Fredenberg 1992). Hudy (1985) reported the relative susceptibility of two species of salmonids to electrofishing induced mortality. He exposed 250 hatchery rainbow and brook trout to 350, 700, and 760-V AC. There was significantly greater mortality in rainbow trout compared to brook trout, but brook trout had a greater number of spinal injuries in surviving fish.

Peer-reviewed literature on electrofishing induced mortality among non-salmonid taxa, is limited. Walker et al. (1989) electroshocked juvenile northern pike for up to 60 s to a homogeneous AC and PDC at 0.4 to 2.1-Vcm^{-1} and reported no mortalities within the first 24 h. Bardygula-Nonn et al. (1995) examined the effects of PDC electrofishing on mortality and injury in largemouth bass, small mouth bass (*Micropterus dolomieu*), bluegills and pumpkinseed sunfish (*Lepomis*

gibbosus). These fish were exposed to 30, 60 and 120-Hz PDC electrofishing and then held in holding pens for 72 h. In largemouth bass (n = 454); 1.3% (n = 6) died during the holding period and one fish suffered external injures. In smallmouth bass (n = 145) only one died during the holding period and 3.4% (n = 5) exhibited external injuries. In bluegills (n = 568), 5.3% died (n = 30) and in the 55 pumpkinseed sunfish examined no injury or mortality was report. These results showed differing susceptibility of species to electrofishing induced injury and mortality.

1.5.3.2 Size

Fish tend to become more sensitive to electric currents as their size increases, because their length spans a greater voltage gradient resulting in greater injury and mortality to large fish (Allen-Gil 2000; Brousseau et al. 2005; Reynolds 1996). However, in published literature, mortality tends to be unaffected by the length of the fish, some studies have reported increased mortality in smaller fish. The relationship between physical injuries and length is supported by some research but not in other research (Reynolds 1996; Snyder 2003a).

Contrary to expectations that mortality would increase as fish size increased, Bardygula-Nonnet al. (1995) found greater electrofishing induced mortality in smaller fish. They reported 5.3% mortality among bluegills (n = 568) electrofished with 30, 60, or 120-Hz PDC but mortality was proportionately greater among fish that were less than 10 cm (TL) than among larger fish (>10 cm TL). Dalbey et al. (1996) found increased incidences of electrofishing induced spinal injury was positively correlated with fish length (r = 0.83, P = 0.01). The incidence of spinal injuries increased from 27% in rainbow trout that were between 15 and 18 cm to 45% in trout that were between 33 and 35 cm. The proportion of fish with vertebral fractures or complete separation of two or more vertebrae (class-3 spinal injuries) was positively correlated with length (r = 0.79, P = 0.02), spinal injuries increased from no injuries in fish ranging between 15 and 18 cm to between 8 and 11% for trout between 25 and 33 cm long.

In non-salmonid species, data supporting the relationship between spinal injuries and fish length is more limited. Roach (1992; as cited in Snyder 2003a) found that

Northern pike captured by electrofishing that had spinal injuries were significantly larger (mean length 57 cm TL) than the average length (mean length 51 cm) that did not suffer any spinal injuries (Lamarque 1990).

1.5.3.3 Condition

Unfortunately, there is little peer-reviewed literature on the effects of physical condition of the fish on electrofishing; most of the reports on this are based mostly on observations rather than experimental data. Thompson et al. (1997b) captured brown trout (*Salmo trutta*) and rainbow trout (>18 cm TL) by electrofishing and calculated the Fulton's condition factor for each fish. Higher incidences of injury were observed in rainbow trout with higher condition factors. These results suggest that rainbow trout in better condition may be more susceptible to electrofishing induced injury and mortality due to more powerful muscular contractions (Thompson et al. 1997b).

1.5.3.4 Repeated exposures

Electrofishing induced injuries and mortality have been documented on numerous occasions, because of this it would be expected that repeated exposure to electrical fields would increase the rate of injury and mortality (Snyder 2003a). However, only a limited number of investigations have been conducted into the effects of repeated exposures on electrofishing induced mortality.

Barrett and Grossman (1988) examined the effects of repeated electrofishing events on the survival of mottled sculpin (4–9 cm SL) in tank trials. Mottled sculpin were exposed for 30 s to CDC fields five times over a 4-week period, with controls collected by kick-seining and both treatment and control fish were handled after each electrofishing event. There was no significant difference in mortality rates between the two treatments; and the authors concluded that repeated electrofishing does not adversely affect the short-term survival of these fish.

Unlike mortality, an increased incidence of electrofishing induced injury as a result of repeated exposure to electrical current has been demonstrated in the

literature. Kocovsky et al. (1997) examined the long-term (8 years) effects of intensive annual backpack electrofishing on rates of spinal injury in brook trout, rainbow trout, brown trout and longnose suckers (*Catostomus catostomus*) in three small northern Colorado streams. In two streams three-pass electrofishing study was conducted and in the final stream a single-pass electrofishing was conducted (control). Electrofishing was conducted by backpack electrofishing units using 100-Hz, square-wave PDC with a 50% duty cycle. Fish (n > 8000) were examined visually and by touch for externally evident injuries. The incidence of injuries from three-pass electrofishing increased progressively, from an average of 4.5% in the first study year, 11.5 % in the second year and 18.5% in the third year. The incidence of injuries from single-pass electrofishing was much lower compared to the incidence of injuries from three-pass electrofishing. No externally evident injuries were found in the first year, an average of 1% of fish was injured in the second year and an average of 2% had externally evident injuries in the third year. A significant difference in the occurrence of externally detectable injuries between three-pass study and single-pass control reaches was found.

1.6 Subjectivity of injury assessments

The standardisation of methods to evaluate electrofishing induced injuries occurred following a meeting of the Western Division of the American Fisheries Society. Prior to this (especially in injury analysis conducted before 1996), some authors only used externally visible spinal deformities to indicate electrofishing induced vertebral damage. Dalbey et al. (1996) reported that only 3% of rainbow trout captured by CDC electrofishing had externally visible spinal deformities, subsequent radiographic imaging revealed that that 53% of fish had vertebral damage. Kocovsky (1997) concluded that external examination for spinal deformities may have underestimated the occurrence of vertebral damage because more that 30% of spinal injuries detected by X-ray imaging were compressed vertebrae, which could not be detected by external examination. Moreover, Kocovsky (1997) found during external examinations the only healed injuries caused by previous electrofishing operations were detected not fresh injuries. This lead Kocovsky (1997) to conclude that assessment of spinal injuries without the use of X-ray imaging will greatly underestimate the occurrence of spinal injury

rates. Following the standardisation of methods to evaluate spinal injury, the need for radiographic imaging in both the dorsal and lateral views to increase the accuracy of vertebral damage detection and ranking was highlighted by Thompson et al. (1997b). Following this, Carline (2001) concluded that the frequency of spinal injury reported that only assessed injury from the lateral perspective should be considered conservative estimates because of the likelihood that some spinal injuries may go unrecognised.

Some authors have failed to include an assessment of an un-shocked control group (Hawkins 2002; Mahoney 1997; Pratt & Threader 2011), such as fish captured by angling or netting, which is necessary to confidently distinguish electrofishing induced injuries from congenital deformities (Carline 2001; Clément & Cunjak 2010; Hawkins 2002; Thompson et al. 1997b). This could lead to a potential overestimation of the effects of electrofishing as the occurrence of spinal injuries in fish capture by control methods is well documented. Carline (2001) documented a high rate (15.5%) of spinal injuries in brown trout captured by angling, McMichael et al. (1998) reported the occurrence of spinal injuries in 12% of brook trout and in 9% of rainbow trout angling and netting. Thompson et al. (1997b) found that in-between 3% and 16% of rainbow trout captured by angling, or that were hatchery-reared trout had spinal injuries.

Schill & Elle (2000) suggested that injury ratings could differ between observers, in many of the haemorrhages that they classified as a class-2 wounds because they extending from myomeres up or down to the edge of the spine; may have been classified as a class-1 haemorrhage by other authors because the injury's did not occur on the spine. Dwyer et al. (2001) conducted an assessment of spinal injuries as a result of exposure to three different current types, the X-ray were evaluated by four people independently. The number of spinal injuries reported by the investigators for each current type varied greatly. The number of spinal reported in fish exposed to PDC varied between 20 and 35 with a mean of 26 injuries, in CDC the number of injuries varied between 12 and 20 with a mean of 17 and finally the number of spinal injuries ranged between 26 and 36 with a mean of 30 in a complex pulse system (CPS).

1.7 Evaluation of electrofishing on New Zealand native fish

To date, there have been no investigations into the effects of electrofishing on any New Zealand native species. The effects of electrofishing been conducted on American eels (*Anguilla rostrata*) (Pratt & Threader 2011; Reynolds & Holliman 2004), which are not found in New Zealand, but they are closely related to the New Zealand native anguillids longfin eel (*Anguilla dieffenbachii*) and shortfin eel (*Anguilla australis*).

Reynolds & Holliman (2004) compared the occurrence of spinal injuries and haemorrhaging in adult American eels captured by trap-netting (n = 20) and by 30-Hz, PDC electrofishing (square wave, 5–6-ms pulse width, 15–18% duty cycle) (n = 18) in the St. Lawrence River, New York. The eels had an average length of 917 mm (± 81 mm SD) and an average weight of 1,633 g (± 533 g SD). Of the eels that were captured by trap netting, 15% (n = 3) had spinal injuries and no haemorrhages were reported. However, 60% (n = 10) of the eels captured by electrofishing had sustained spinal injuries and 30% (n = 5) had sustained haemorrhages. The occurrence of both spinal injuries and haemorrhages was significantly higher in eels captured by electrofishing compared to the trap-netted eels (spinal damage P = 0.016, haemorrhage P = 0.017). However, it is not known what effect these injuries would have had on the health and survival of eels had been released back into the water (Reynolds & Holliman 2004). As a secondary objective to their original study, Pratt & Threader (2011) (prompted by the results of Reynolds & Holliman 2004), also investigated spinal injury in American eels captured by 60-Hz PDC. The percent of range was adjusted (usually 0-10%) to standardise the output at 3 A. Radiographs of American eels (n = 10) with an average length of 254 mm (SE = 31 mm) revealed no for spinal injuries (Pratt & Threader 2011).

1.8 Aims and objectives

As discussed earlier, there have been no investigations into electrofishing induce injury or survival on any New Zealand native species or any closely related species, with the exception of the investigations into the effects of electrofishing of American eels. Thus, it is important to gain greater understanding into the potential effects of electrofishing on our native fish species. Particularly because

of the frequent use of boat electrofishing, bank mounted and backpack electrofishing surveys to conduct population estimates and pest fish removals (Avise et al. 1990; Fredenberg 1992; Hicks & Tempero 2011; Hopkins & Cech 1992; Schill & Beland 1995).

The overall aim of this research was to investigate the incidence and severity of boat electrofishing injury and mortality in shortfin eel, grey mullet (*Mugil cephalus*) and common smelt (*Retropinna retropinna*) and to compare this to injury and mortality of fish captured by trap netting. These fish were captured using standard boat electrofishing (60-Hz PDC) and trap netting methods in the Waikato River and surrounding lakes. The trap netting methods selected are the conventional methods of capturing each species; eels were captured by fyke netting, grey mullet by gill netting and smelt by beach seine netting.

Injury was evaluated by external and internal examinations. External examinations were conducted to reveal branding or external abnormalities. Internal examinations were conducted by necropsies that revealed haemorrhages and radiographic mages that revealed spinal injuries. Survival of eels and smelt was examined by a 30-day holding period in eels and a 30 min holding period for smelt. Physiological stress was evaluated in eels and grey mullet by analysis of haemoglobin, haematocrit, sodium, potassium, magnesium and calcium.

2 Methodology

2.1 The boat-mounted electrofisher

In 2003 the University of Waikato built an electrofishing boat from a locally made aluminium pontoon hull fitted with fishing platform (Orca Engineering & Marine Ltd, Rotorua, New Zealand) and Smith-Root electrofishing equipment. This equipment included a Model 5.0 gas powered pulsator (GPP) as the electrical control unit powered with a 6-kW custom-wound Honda generator (Smith-Root Inc, Vancouver Washington, USA). Two anode poles, each with an array of six electrode droppers are suspended from bow-mounted booms, with the aluminium hull of the boat acting as the cathode (Hicks et al. 2006). Electrical conductivity and temperature are routinely measured with an YSI 3200 conductivity meter; these were used to calculate and select a range on the GPP.

2.2 Collection methods

2.2.1 Shortfin eels

Shortfin eels greater than 400 mm TL were captured from Lake Rotongaro (37°29’14.04”S, 175°07’11.23”E) and Lake Areare (37°40’06.42”S, 175°12’02.71”E), New Zealand. These lakes were selected because no previous electrofishing operations had been conducted in them, thus reducing the chance of sampling eels that had been injured by previous electrofishing operations. While the original study design included only one comparison (Lake Rotongaro eels), the experiment was repeated in Lake Areare because of unexpectedly greater spinal injury rates in eels held for 30 days.

In lake Rotongaro, eels were captured using standard fyke netting (n = 51) and boat electrofishing (n = 51) techniques (Hicks & Tempero 2011) in November, 2011. Fyke nets were set perpendicular to the shoreline in water less than 2 m deep, the fyke nets measured 3 m long and had an opening 0.65 m wide, the fyke nets had a mesh size of 4 mm and had a leader of 5 m long and 0.6 m high. Once removed from the fyke nets, the eels were held onshore in continually aerated 50-L transfer tanks, until processing. PDC electrofishing from the boat, was conducted at a low range (machine settings 0-500-V; 45-50% of range) at 60-Hz with an output of 3.5-4 Amps (A), root mean square (RMS) output. Electrofishing

was conducted in 20-min intervals, along the shoreline, in waters 1-2 m deep, with an ambient conductivity of 153.6 μScm^{-1} (specific conductivity of 174.6 μScm^{-1}) and a water temperature of 18.7ºC. Water clarity in the lake was poor with a vertical Secchi depth of 30 cm.

In Lake Areare, 50 eels were caught using fyke nets (with identical techniques as mentioned above) set in water less than 1 m deep. A further 50 eels were then captured using standard boat electrofishing techniques, in November, 2012. Electrofishing, conducted at a low range (machine settings 0-500-V; 60% of range) at 60-Hz with an output of 3.5 A RMS output. Electrofishing was conducted along the shoreline, in water < 1 m deep with an ambient conductivity of 136.5 μScm^{-1} (specific conductivity of 148.4 μScm^{-1}) and a water temperature of 20.8ºC. Water clarity was extremely poor with a vertical Secchi depth of 22 cm. During electrofishing in both lakes, fish were removed from the electric field as quickly as possible to minimise the effects of electrical stimulation. The fish were then held in a continuously aerated 50-L holding tank on board the boat, for a short period (< 40 min) before processing.

2.2.2 Grey mullet

Grey mullet were captured using standard gill netting (*n* = 25) and boat electrofishing (*n* = 29) in December 2011, from the Waikato River (37°32’31.89”S, 175°09’15.14”E) and Lake Whangape (37°28’33.63”S, 175°03’21.58”E), New Zealand.

Twenty five grey mullet were collected using 12 m long gill nets (mesh size 85 mm) set in Lake Whangape in water less than 3 m deep for a 45 min period. Once grey mullet were removed from the gill net they were place into a continually aerated 50-L transfer tank and transported back to the shore for immediate processing. Grey mullet were captured using 60-Hz, PDC boat electrofishing conducted at a low range (60% of range), with an output of 3.5 A RSM. Electrofishing was conducted in 20 min shock intervals, along the banks of the Waikato River in waters between 1 and 5 m deep. At the time of electrofishing the Waikato River had an ambient conductivity of 139.4 μScm^{-1} (specific conductivity of 151.5 μScm^{-1}), a temperature of 20.9ºC and a vertical Secchi

depth of 80 cm. During electrofishing grey mullet were removed from the electric field as quickly as possible to minimise the effects of electrical stimulation. They were then held in a continuously aerated 50-L holding tank on board the boat, for a short period (< 40 min) before processing.

2.2.3 Common smelt

Common smelt were captured using standard boat electrofishing techniques and beach seining between January and March, 2012 Seine netting was conducted at two locations along the shoreline of the Waikato River; Wellington Street beach (37°47'53.09"S, 175°17'20.04"E) and the Grantham Street boat ramp (37°47'39.31"S, 175°17'25.61"E). At each of these locations seine netting hauls were conducted weekly, for five consecutive weeks. The seine net used was 9.8 m long x 2.1 m tall net with a 75 cm pocket located in the middle of the net and a mesh size of 4 mm. Beach seining was performed along a stretch of shoreline approximately 15 m long in water less than 1.5 m deep. The net was then hauled onto the beach and the smelt were promptly transferred by hand into a continuously aerated 50-L holding tank for the 30 min survival analysis.

Boat electrofishing conducted at a low range (60% of range) at 60-Hz, PDC with an output of 3.5 A RMS output, was then used to capture smelt along the banks of the Waikato River. Electrofishing was conducted in 10 min intervals, until a total of ten intervals had been completed. Electrofishing was performed in waters less than 1-2 m deep with a vertical Secchi depth of 78 cm, an ambient conductivity of 132.6 μScm^{-1} (specific conductivity of 142.6 μScm^{-1}), and a temperature of 18.1ºC. During electrofishing smelt were removed from the electric field as quickly as possible to minimise the effects of electrical stimulation. The smelt were then held in a continuously aerated 50-L holding tank on board the boat, for a short period (< 10 min) before a survival analysis was conducted.

2.3 Onshore processing methods

2.3.1 Shortfin eels and grey mullet

After capture, shortfin eels and grey mullet were weighed (± 1 g) and measured (± 1 mm TL). The eels that were used for the survival analysis were then returned

to continuously aerated 50-L holding tanks for transport back to the laboratory (see section 2.5.1). The remaining eels (captured from Lake Rotongaro only) and the grey mullet, had blood drawn from the caudal vein (see section 2.4.1). The fish were then euthanised with an overdose of AQUI-S (20 mg L^{-1}), placed on ice and transported back to the laboratory at the University of Waikato. Handling was kept to a minimum at all times to reduce any further injury beyond what the fish may have sustained during capture.

2.4 Blood extraction method

2.4.1 Shortfin eels and grey mullet

Blood was extracted from shortfin eels (n = 51; only those captured in from Lake Rotongaro) and grey mullet (n = 54). Approximately 1 mL of blood was drawn from the caudal vein into a heparinised syringe (lithium heparin, Sigma, New Zealand; 5000 i.u. mL^{-1}) and then placed on ice. Within 30 min of extraction, blood samples were analysed for haematocrit (HCT) and total haemoglobin (HB) using the cyanohaemoglobin described by Dacie & Lewis (1975). Blood plasma was extracted by centrifugation of whole blood samples at 5000 rpm for 5 min followed by pipetting of the supernatant plasma. Plasma was kept on ice and then frozen at -20°C until further analysis could be performed. Blood plasma analysis was conducted by mixing 0.25 mL of blood plasma along with 0.25 mL of 12% Trichloroacetic acid. The sample was then centrifuged at 15000 rpm for 3 min and 0.25 mL of the supernatant was pipetted into a mixture of 9.55 mL Milli-Q water with 0.2 mL nitric acid. The samples were then analysed for sodium (Na), potassium (K), calcium (Ca) and magnesium (Mg) by inductively coupled plasma mass spectrometry (ICP-MS).

2.5 Survival analysis methods

A survival analysis was conducted on shortfin eels and common smelt to quantify potential mortality caused by the capture methodologies. A survival analysis was not conducted on grey mullet because of the difficulties in holding these fish in artificial conditions for prolonged periods.

2.5.1 Shortfin eels

Following onshore processing, 25 shortfin eels collected by fyke netting and 25 eels collected by boat electrofishing from Lake Rotongaro and Lake Areare in the following year, were held for a 30-day period. The eels were marked with a T-bar tag in the epaxial musculature and a pectoral fin clip. Eels were housed outdoors under natural light conditions and ambient water temperature in a covered (90% shade cloth dome) 10,000 L circular holding tank with flow-through dechlorinated municipal water supplied to the holding tank at a rate of 10 L min^{-1}. During the first holding period with eels captured from Lake Rotongaro the average water temperature was 18.6°C (November – December, 2011), during the second holding period with eels captured from Lake Areare the average water temperature was 18.9°C (November – December, 2012). During the holding periods the tank was monitored daily, any eels that died during this period were removed, photographed, weighed, measured (TL), examined for external injuries and frozen for injury analysis (see section 2.6.1). At the completion of the holding period, the remaining eels were removed from the holding tank, photographed, weighed, measured (TL), examined for external injuries, euthanised with an overdose of AQUI-S and then frozen on flat racks pending internal injury evaluation (see section 2.6.1).

2.5.2 Common smelt

Directly after capture by either fishing method, common smelt were held for a period of 30 min in a continuously aerated 50-L holding tank that was approximately 75% filled with Waikato River water, the average temperature of the water during the holding period was 19.8ºC, with an average dissolved oxygen (DO) concentration of 78%. The temperature and dissolved oxygen concentration did not change significantly during the holding period. At the completion of the holding period, any dead smelt were removed and the surviving smelt were euthanised with an overdose of benzocaine. The smelt were then frozen on flat trays, pending injury evaluation.

2.6 Injury evaluation method

2.6.1 Shortfin eel and grey mullet

The frozen fish were then radiographed in the lateral and dorsal perspectives, at Cambridge Veterinary Services (Cambridge, New Zealand). Radiographic images were taken with a Shimadzu (China) MC125L-30 set to 43 kV, 3 mAs. The position of every affected vertebra was recorded (head-to-tail vertebral count), the apparent severity of the spinal injuries in each eel was then rated according to methods described by Reynolds (1996) (0 = no spinal injury apparent, 1 = compression or distortion of vertebrae only, 2 = misalignment of vertebrae, including compression, 3 = fracture of one or more vertebrae or complete separation of two or more vertebrae).

Fish were then filleted on both sides from just behind the head to the caudal peduncle to expose the axial skeleton and lateral musculature. The spinal column and fillets were then visually examined for internal haemorrhages. Haemorrhages were photographed and evaluated based on the apparent severity of the worst haemorrhage as described by Reynolds (1996) (0 = no haemorrhage apparent, 1 = one or more wounds isolated in the muscle, 2 = one or more small wounds equal in width to two or fewer vertebrae, 3 = one or more large wounds greater in width than two vertebrae).

2.6.2 Common smelt

A subsample (n = 80) of all the common smelt that were captured for the survival analysis were used for injury analysis. This subsample was comprised of 40 smelt captured by electrofishing, of these 20 died the holding period and 20 survived the holding period. As well as 40 smelt captured by seine netting, of these 20 died the holding period and 20 survived the holding period. These smelt randomly selected from the total number of smelt caught in each of the groups using a random number generator.

The smelt were examined for external injuries, such as tail damage (indicated by bleeding on the tail fin) or externally visible spinal damage near the tail of the smelt (indicated by visible internal haemorrhaging). The smelt were then

weighed (g), measured (TL), individually numbered and frozen at −20°C on glass panels in preparation for radiographic imaging. Smelt were radiographed at Hamilton Radiology with Siemens Mammomat machine 3000 Nova set to 28 kV, 8 mAs, processed by a Philips PCR image reader. The apparent severity of spinal injuries in each smelt was rated according to Reynolds (1996) (as described above). The smelt were then filleted on both sides, from just behind the head to the caudal peduncle. The exposed fillets were then visually examined for haemorrhages (as described above).

2.7 Statistical analysis

A Student's *t* test was used to test if the differences between the means for length, weight, blood plasma attributes were significant; the *P*-value was tested against a significance level of 0.05.

To test if a significant difference existed between the pre-determined injury classes of spinal injury and haemorrhaging, as defined by Reynolds (1996), a *G*-test, or multinomial log-likelihood ratio test was used (Venables & Ripley 2002). The proportions of haemorrhage and spinal damage were analysed and reported separately.

Each fishing method was presumed to produce a set of data from a multinomial distribution. That is, for a set of two trials, each trial results in a particular outcome (*i)* with constant probability (p_i). The null hypothesis, that the two variables were independent, i.e., the probability of a fish being in any injury category would be the same for both methods of fishing. The alternative hypothesis is that the distributions of the responses are different for each level of one of the variables, i.e., the variables are dependent on the fishing method.

The multinomial distribution function is:

$$f(n_1,...,n_r, p_1,..., p_r) = \frac{n!}{n_1!\times...\times n_r!} p_1^{n_1} \times...\times p_r^{n_r}$$

Where there are *r* injury classes and *n* is the total number of observations for a particular fishing type. As there were two sets of data, one for each fishing type,

the two likelihood values were multiplied together, one for each fishing type. The value of the likelihood-product under the null hypothesis divided by the value under the alternative hypothesis to give a likelihood ratio was then calculated. The counts (i.e. *n* values) were the same under both hypotheses, so the terms involving factorials cancel.

Taking the natural log of the likelihood ratio and multiplying by two, we get a test statistic:

$$D = 2\ln\left[\frac{\left(\hat{p}_{01}^{n_{11}} \times \ldots \times \hat{p}_{0r}^{n_{1r}}\right)\left(\hat{p}_{01}^{n_{21}} \times \ldots \times \hat{p}_{0r}^{n_{2r}}\right)}{\left(\hat{p}_{11}^{n_{11}} \times \ldots \times \hat{p}_{1r}^{n_{1r}}\right)\left(\hat{p}_{21}^{n_{21}} \times \ldots \times \hat{p}_{2r}^{n_{2r}}\right)}\right]$$
$$= 2\left[n_{11}\ln\left(\frac{\hat{p}_{01}}{\hat{p}_{11}}\right) + \ldots + n_{1r}\ln\left(\frac{\hat{p}_{0r}}{\hat{p}_{1r}}\right) + n_{21}\ln\left(\frac{\hat{p}_{01}}{\hat{p}_{21}}\right) + \ldots + n_{2r}\ln\left(\frac{\hat{p}_{0r}}{\hat{p}_{2r}}\right)\right]$$

Where $\hat{p}_{0i}$ is the maximum likelihood estimate of p_i under the null hypothesis (the sum of responses for category *i* in both samples divided by the total number of counts over both samples), $\hat{p}_{1i}$ is the maximum likelihood estimate of p_i for fishing method 1 under the alternative hypothesis (the sum of responses for category *i* from method 1 only divided by the total number of counts from method 1 only), and $\hat{p}_{2i}$ is the maximum likelihood estimate of p_i for fishing method 2 under the alternative hypothesis (the sum of responses for category *i* from method 2 only divided by the total number of counts from method 2 only).

This is then expressed as log-likelihood ratio in term of the expected counts calculated in the previous section:

$$D = 2\left[n_{11}\ln\left(\frac{n_{11}}{E_{11}}\right) + \ldots + n_{1r}\ln\left(\frac{n_{1r}}{E_{1r}}\right) + n_{21}\ln\left(\frac{n_{21}}{E_{21}}\right) + \ldots + n_{2r}\ln\left(\frac{n_{2r}}{E_{2r}}\right)\right]$$

If the null hypothesis is true, this test statistic also is assumed to come from a chi-square distribution, with degrees of freedom equal to the number of fishing methods − 1 times the number of injury classes – 1, i.e., (2-1) (3-1) = 2.

Instances where the observed count for a cell is 0, and possibly the count for that whole injury class (i.e. the column total) is 0 were accounted as follows. In the first instance, for a particular cell we might get the equation $0\ln\left(\frac{0}{E_{ij}}\right)$, i.e. 0ln(0). Although this number doesn't strictly exist, it can be shown mathematically that it approaches the value 0 in the limit, so we can just say this is 0. In the second instance, we get $0\ln\left(\frac{0}{0}\right)$, which can be rewritten 0ln(0)-0ln(0), and using the previous result, we have also called this 0. That is, for any cell where the observed count is 0, the contribution to the test statistic is 0 (Venables & Ripley 2002).

2.8 Animal ethics approval

All work conducted was approved by the University of Waikato Animal Ethics Committee protocol 838. Anaesthetic and tagging techniques were conducted as per University of Waikato Animal Ethics Committee Standard Operating Procedure 6.

3 Results

3.1 Shortfin eels

Shortfin eels captured from Lake Rotongaro (n = 102) and Lake Areare (n = 100) were analysed for injury. There was no significant difference in the mean length (t = -0.642, P = 0.524) or weight (t = -0.069, P = 0.945) of eels that were euthanised immediately captured by either fyke netting or electrofishing from Lake Rotongaro. There was also no significant difference between the mean length (t = -1.876, P = 0.066) or weight (t = 1.379, P = 0.174) of eels captured by the two different methods that were used in the 30-day survival trial (Table 3.1).

In the eels captured from Lake Areare, there was a significant difference in the mean length (t = -4.087, P = 0.001) and weight (t = -3.491, P = 0.001) of eels that were euthanised immediately captured by either fyke netting or electrofishing. However, there was no significant difference between the mean length (t = -0.189, P = 0.851) or weight (t = -0.362, P = 0.718) of eels captured by the two different methods and used in the 30-day survival trial (Table 3.1).

Eels captured in Lake Areare were significantly longer (t = 7.426, P = 0.001) and significantly heavier (t = 5.124, P = 0.001) than those captured from Lake Rotongaro.

Table 3.1: The mean length and weight of shortfin eels captured by electrofishing or fyke netting, which were either euthanised immediately or held for 30-day after capture from Lake Rotongaro and Lake Areare.

Location	Capture method	Treatment	n	Mean length ± SD (mm)	Mean weight ± SD (g)
Lake Rotongaro	Electrofishing	No holding	25	500 ± 96	321 ± 240
		Holding	26	450 ± 50	211 ± 91
	Fyke netting	No holding	26	516 ± 83	325 ± 189
		Holding	25	477 ± 51	247 ± 94
Lake Areare	Electrofishing	No holding	25	524 ± 78	328 ± 173
		Holding	25	576 ± 98	424 ± 290
	Fyke netting	No holding	25	617 ± 83	543 ± 253
		Holding	25	581 ± 90	454 ± 291

3.1.1 Survival

Survival of shortfin eels captured by electrofishing from both lakes was high (94%) as was that of eels captured by fyke netting (90%). Of the eels captured from Lake Rotongaro, one (4%) eel captured by electrofishing died during the holding period (day 25) and three (12%) eels that were captured by fyke netting died during the holding period. One of these died on day 8 and the remaining two eels died on day 11. No haemorrhaging or spinal injuries were detected in any of these eels, but fungal infections were observed on two of the eels that died and four eels that survived the holding period. Two eels (8%) captured from Lake Areare by electrofishing died during the holding period; these deaths occurred on the day 1 and on day 27. Two eels (8%) captured by fyke netting also died during the holding period, with both deaths occurring on the first day of holding. No physical injuries or fungal infections were detected on any of the eels from Lake Areare that died during the holding period.

3.1.2 External injuries

No branding was observed on shortfin eels captured by electrofishing from either Lake Rotongaro or Lake Areare. However, small abrasions were noticed in the tail regions of 16% (n = 8) of the eels captured by fyke nets in Lake Rotongaro and in 24% (n = 12) of the eels captured in Lake Areare. These abrasions were caused by eels of rubbing against the mesh of the fyke nets.

3.1.3 Internal haemorrhages

Internal haemorrhaging was observed in shortfin eels captured by both electrofishing and fyke netting from Lake Rotongaro. Haemorrhaging occurred in 28% (n = 7) of the eels that were captured by electrofishing and euthanised immediately. These haemorrhages were generally severe with one class-2 wound and six class-3 wounds (Figure 3.1). Haemorrhaging was also found in 8% (n = 2) of the eels captured by fyke netting in Lake Rotongaro, these wounds comprised of one class-1 wound and one class-2 wound. Electrofishing caused significantly more haemorrhages in eels than capture by fyke net (G = 4.278, P = 0.039; Figure 3.2). Only one haemorrhage, a class-1 wound, was found in the eels that were held

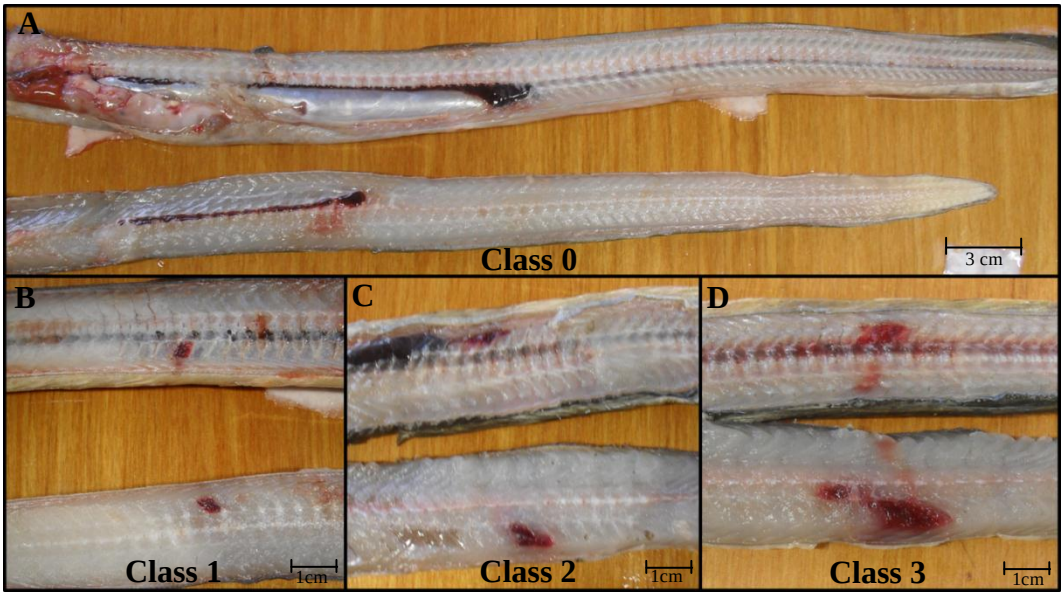

Figure 3.1: The severity of haemorrhaging in shortfin eels, A) class-0: no haemorrhage, B) class-1: mild haemorrhaging, C) class-2: moderate haemorrhaging, D) class-3: severe haemorrhaging.

for 30 days. No haemorrhages were found in any of the eels captured from Lake Areare by either electrofishing or fyke netting. In the eels captured by electrofishing in Lake Rotongaro, there was no difference in the mean length (t = -1.859, P = 0.075) or weight (t = -1.647, P = 0.112) of eels that sustained haemorrhages or that were uninjured. Of the eels captured by fyke netting in Lake Rotongaro, there was no difference in the mean length (t = -0.507, P = 0.616) or weight (t = -0.499, P = 0.621) between eels that sustained haemorrhages and the uninjured eels (Table 3.2).

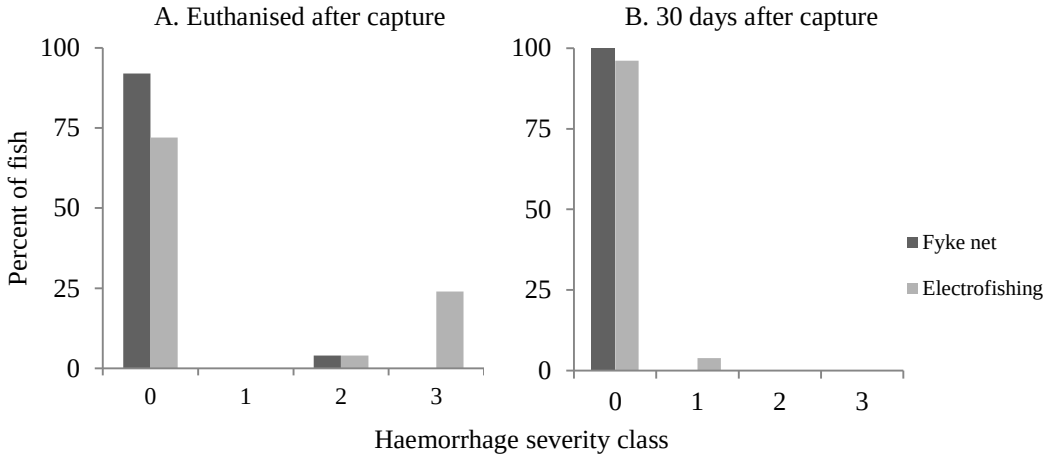

Figure 3.2: The severity of haemorrhaging in shortfin eels captured by electrofishing and fyke netting that were A) euthanised immediately post capture (n = 51) and B) that were held 30 days after capture (n = 51).

Table 3.2: The mean length and weight of shortfin eels that either sustained haemorrhages or were unharmed captured by electrofishing or fyke netting in Lake Rotongaro and Lake Areare (* only one data point so standard deviation could not be calculated).

Location	Capture method	Treatment	Injury status	Injuries		Mean length ± SD (mm)	Mean weight ± SD (g)
				N	%		
Lake Rotongaro	Electrofishing	0 days	Haemorrhage	7	28	445 ± 52	199 ± 72
			Uninjured	18	72	521 ± 102	369 ± 266
		30 days	Haemorrhage	1	4	442 *	170*
			Uninjured	25	96	451 ± 51	213 ± 93
	Fyke netting	0 days	Haemorrhage	2	8	487 ± 81	260 ± 113
			Uninjured	24	92	519 ± 85	331 ± 195
		30 days	Haemorrhage	0	0	0	0
			Uninjured	0	100	477 ± 50	248 ± 94
Lake Areare	Electrofishing	0 days	Haemorrhage	0	0	0	0
			Uninjured	25	100	524 ± 78	328 ± 173
		30 days	Haemorrhage	0	0	0	0
			Uninjured	25	100	576 ± 99	424 ± 290
	Fyke netting	0 days	Haemorrhage	0	0	0	0
			Uninjured	25	100	617 ± 83	543 ± 253
		30 days	Haemorrhage	0	0	0	0
			Uninjured	25	100	581 ± 90	454 ± 292

3.1.4 Spinal injuries

Low frequencies of spinal injuries were found in shortfin eels captured by electrofishing in Lake Rotongaro and Lake Areare. In eels that were captured in Lake Rotongaro by electrofishing and euthanised immediately, 8% (n = 2) had spinal injuries and in the eels that were held for 30 days after capture 27% (n = 7) had spinal injuries. Spinal injuries were found in 4% (n = 1) of eels captured by fyke netting that were euthanised immediately and in 8% (n = 2) of eels that were held for 30 days. There was no significant difference between the number of spinal injuries sustained by either of the capture methodologies in eels that were euthanized immediately after capture (G = 0.333, P = 0.564) or held for a 30-day period (G = 1.366, P = 0.242; Figure 3.3). In eels captured by electrofishing that were euthanized immediately, one spinal injury (class-2) occurred in conjunction with a class-3 haemorrhage. The other spinal injury (class-1) was not found in conjunction with a haemorrhage. Only one spinal injury (class-1) was found in eels captured by fyke netting and no haemorrhaging was found in conjunction with this injury.

Of the eels captured in Lake Areare by electrofishing and euthanised immediately, 12% (n = 3) had spinal injuries and in those that were held for 30 days, 20% (n = 5) had spinal injuries. No spinal injuries were found in any eels captured by fyke netting. As a result, there was a significantly greater number of spinal injuries in eels caught by electrofishing that were both euthanised immediately after capture (G = 4.351, P = 0.037) and in the eels that were held for 30 days (G = 7.488, P = 0.006; Figure 3.3).

In eels captured from both Lake Rotongaro and Lake Areare by electrofishing, class-2 spinal injuries were the most frequently reported (n = 15). In the eels captured by fyke netting the frequency of class-1 and class-2 spinal injuries was equal (n = 2). In eels captured by electrofishing, the majority of the injuries were located between vertebra 40 and 59 (n = 20; Table 3.3; Appendix 2).

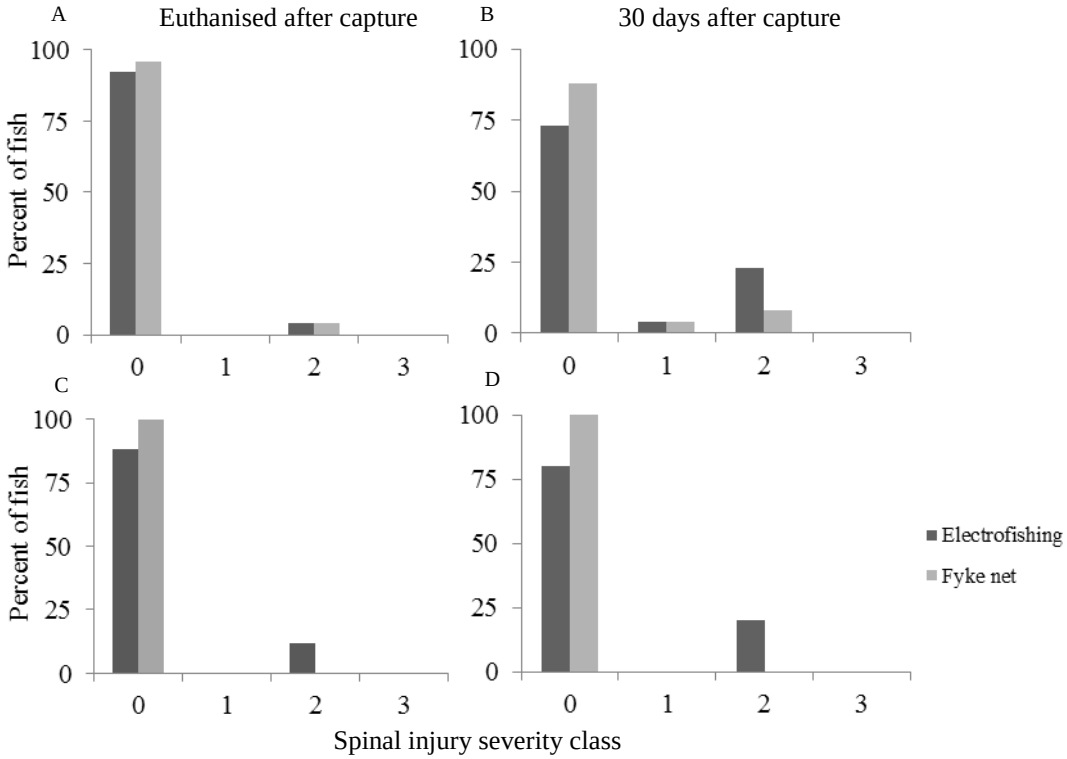

Figure 3.3: The severity of spinal injuries in shortfin eels captured in Lake Rotongaro (A & B) and Lake Areare (C & D) by electrofishing and fyke netting that were euthanised immediately post capture (A & C) and that were held post capture (B & D) with class-0 (no spinal damage apparent), class-1 (compression or distortion of vertebrae), class-2 (misalignment of vertebrae), class-3 (fracture or complete separation of vertebrae).

Table 3.3: Number of spinal injuries found within sections of 20 vertebra along the spine, irrespective of severity, in shortfin eels captured by electrofishing or fyke netting in Lake Rotongaro and Lake Areare. The number of injuries exceeds the number of eels because some fish had multiple injuries.

Capture method	Injured fish (*n*)	Location of the injury by vertebral number (head to tail)					
		1-19	20-39	40-59	60-79	80-99	100 +
Electrofishing	16	-	-	20	7	1	-
Fyke netting	4	-	-	2	2	-	-

Table 3.4: Mean length and weight of shortfin eels that either sustained spinal injuries or were unharmed captured by electrofishing or fyke netting in Lake Rotongaro and Lake Areare (* only one data point so standard deviation could not be calculated).

Location	Capture method	Treatment	Injury status	Injuries		Mean length ± SD (mm)	Mean weight ± SD (g)
				n	%		
Lake Rotongaro	Electrofishing	0 days	Spinal injury	2	28	570 ± 231	530 ± 551
			Uninjured	23	72	494 ± 66	303 ± 190
		30 days	Spinal injury	8	4	465 ± 75	238 ± 164
			Uninjured	17	96	446 ± 76	204 ± 61
	Fyke netting	0 days	Spinal injury	1	8	412*	150*
			Uninjured	25	92	521 ± 91	332 ± 178
		30 days	Spinal injury	2	0	422 ± 24	245 ± 162
			Uninjured	23	100	482 ± 49	248 ± 92
Lake Areare	Electrofishing	0 days	Spinal injury	3	0	519 ± 75	297 ± 154
			Uninjured	22	100	524 ± 81	332 ± 179
		30 days	Spinal injury	5	0	549 ± 53	346 ± 91
			Uninjured	20	100	583 ± 107	444 ± 320
	Fyke netting	0 days	Spinal injury	0	0	0	0
			Uninjured	25	100	617 ± 83	543 ± 254
		30 days	Spinal injury	0	0	0	0
			Uninjured	25	100	581 ± 91	454 ± 320

In the eels captured by electrofishing in Lake Rotongaro, there was no difference in length (t = 0.516, P = 0. 608) or weight (t = 0.609, P = 0.544) of eels that sustained spinal injuries and the uninjured eels. The eels captured by fyke netting in Lake Rotongaro that sustained spinal injuries had a mean length less than the mean length of the uninjured eels (t = -2.028, P = 0.047). There was no difference between the mean weight of eels that sustained spinal injuries and the uninjured eels (t = -0.859, P = 0.394). In the eels captured by electrofishing in Lake Areare, there was no difference in length (t = -1.180, P = 0.241) or weight (t = -1.227, P = 0.222) of eels that sustained spinal injuries and the uninjured eels (Table 3.4).

3.1.5 Blood plasma analysis

The blood plasma constitutes of the shortfin eels showed no significant differences between the mean concentrations of sodium, potassium, magnesium and calcium (Table 3.5). There was also no significant difference between the haematocrit and haemoglobin in eels captured by electrofishing and fyke netting (Figure 3.6).

Table 3.5: The mean (± SD) blood plasma concentrations of sodium, potassium, magnesium and calcium of shortfin eels captured by electrofishing (n = 25) or fyke netting (n = 25).

	Elemental concentration (mM)			
	Electrofishing	Fyke netting	*t* value	*P* value
Na	150.91 ± 6.25	146.94 ± 13.56	1.07	0.28
K	3.22 ± 0.51	3.53 ± 1.07	-1.29	0.20
Mg	1.00 ± 0.15	0.99 ± 0.18	0.16	0.86
Ca	2.10 ± 0.26	2.09 ± 0.31	0.11	0.90

Table 3.6: The mean (± SD) blood plasma concentrations of haematocrit (HCT) and haemoglobin (HB) of shortfin eels captured by electrofishing or fyke netting.

	Electrofishing (n = 25)	Fyke netting (n = 25)	*t* value	*P* value
HCT (%)	28.50 ± 3.98	27.72 ± 3.36	-0.75	0.45
HB (g L^{-1})	74.67 ± 9.75	77.89 ± 12.78	-1.01	0.31

There was no significant difference between the blood plasma concentrations of sodium, potassium, magnesium and calcium in uninjured and injured eels captured by either capture method (Table 3.7). There was also no significant difference between haematocrit and haemoglobin in uninjured and injured eels captured by either capture method (Table 3.8).

Table 3.7: The mean (± SD) blood plasma concentrations of sodium, potassium, magnesium and calcium of injured and uninjured shortfin eels captured by electrofishing or fyke netting.

	Elemental concentration (mM)			
	Na	K	Mg	Ca
Electrofishing				
Injured (*n* = 10)	150.23 ± 6.74	3.13 ± 0.47	1.01 ± 0.17	2.05 ± 0.25
Uninjured (*n* = 15)	151.39 ± 5.54	3.27 ± 0.53	0.98 ± 0.15	2.12 ± 0.27
t value	-0.46	-0.68	0.25	-0.66
P value	0.64	0.50	0.80	0.51
Fyke netting				
Injured (*n* = 2)	140.41 ± 5.87	2.57 ± 0.26	0.91 ± 0.14	2.03 ± 0.23
Uninjured (*n* = 24)	147.50 ± 13.75	3.61 ± 1.07	0.99 ± 0.19	2.09 ± 0.31
t value	-0.71	-1.33	-0.54	-0.23
P value	0.48	0.19	0.59	0.81

Table 3.8: The mean (± SD) blood plasma concentrations of haematocrit (HCT) and haemoglobin (HB) of injured and uninjured shortfin eels captured by electrofishing and fyke netting (*n* = 25).

	Electrofishing			
	Injured (*n* = 10)	Uninjured (*n* = 15)	*t* value	*P* value
HCT (%)	28.75 ± 3.35	27.01 ± 3.29	1.26	0.21
HB (g L^{-1})	76.17 ± 10.70	73.67 ± 9.31	0.62	0.54
	Gill netting			
	Injured (*n* = 2)	Uninjured (*n* = 23)	*t* value	*P* value
HCT (%)	36.75 ± 3.18	27.81 ± 3.23	0.72	0.44
HB (g L^{-1})	106.59 ± 9.98	75.51 ± 9.78	0.24	0.80

3.2 Grey mullet

Grey mullet (*n* = 54) captured by boat electrofishing and gill netting were analysed for injury. The mean length (t = 2.007, P = 0.050) and weight (t = 1.014, P = 0.315) of grey mullet were not significantly different between fish captured by electrofishing or gill netting (Table 3.9)

Table 3.9: The mean length and weight of grey mullet captured by electrofishing or fyke netting.

Location	Capture method	*n*	Mean length ± SD (mm)	Mean weight ± SD (g)
Waikato River	Electrofishing	29	356 ± 41	688 ± 220
Lake Whangape	Gill netting	25	376 ± 30	744 ± 173

3.2.1 External injuries

External injuries were observed in grey mullet captured by both electrofishing and gill netting. Branding as a result of exposure to an electric current was observed in 7% (n = 2) of grey mullet, on both occasions the branding ranged from the lateral to the dorsal side of the fish with 3–4 brands present in each specimen. The width of the brands ranged between 20–35 mm in diameter (Figure 3.4). Minor net injuries on the bodies of the fish were observed in 68% (n = 17) and severe damage around the gills or body occurred in 12% (n = 3) of grey mullet captured by gill netting. This damage included deep wounds around the site of capture, gill damage, loss of scales and damaged fins.

Figure 3.4: Branding in grey mullet (400 mm TL) captured from the Waikato River by 60-Hz electrofishing.

3.2.2 Internal haemorrhages

In grey mullet captured by electrofishing, there was haemorrhaging in 24% (n = 7) of fish, these injuries were generally severe with three class-2 wounds and four class-3 wounds. Gill netting caused haemorrhaging in 8% (n = 2) of grey mullet. These two haemorrhages were comprised of one class-2 wound and one class-3 wound. There was no significant difference between the number of haemorrhages sustained in grey mullet by either capture method (G = 2.696, P = 0.101; Figure 3.5).

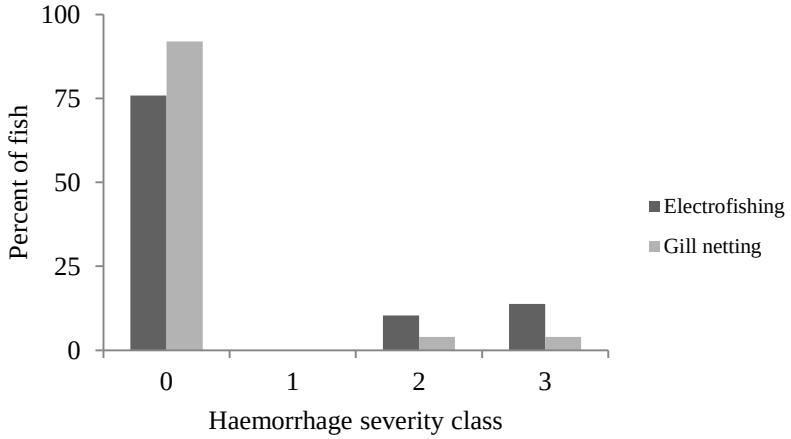

Figure 3.5: The percentage of grey mullet captured by electrofishing and gill netting in each of the haemorrhage classes.

In grey mullet captured by electrofishing, there was no statistical difference in length (t = 0.603, P = 0.551) or weight (t = 0.588, P = 0.561) of grey mullet that sustained haemorrhages and the uninjured grey mullet. In the grey mullet captured by gill netting, there was no statistical difference in length (t = 1.538, P = 0.137) or weight (t = 0.891, P = 0.382) in fish that sustained haemorrhages and the uninjured grey mullet (Table 3.10).

Table 3.10: Mean length and weights of grey mullet that either sustained haemorrhages or were unharmed captured by electrofishing or gill netting.

Location	Capture method	Haemorrhages	*n*	Mean length ± SD (mm)	Mean weight ± SD (g)
Waikato River	Electrofishing	Injured	7	364 ± 45	731 ± 155
		Uninjured	22	353 ± 45	674 ± 239
Lake Whangape	Gill netting	Injured	2	408 ± 39	849 ± 176
		Uninjured	23	373 ± 29	734 ± 174

3.2.3 Spinal injuries

Of the grey mullet captured by electrofishing, 14% (n = 4) had spinal injuries (Figure 3.6). These were generally severe, with two class-2 spinal injuries (vertebrae 9 and vertebrae 13) and two class-3 spinal injuries (vertebrae 11-12 and vertebrae 10; Figure 3.7). Spinal injuries occurred in 12% (n = 3) of grey mullet captured by gill netting, these consisted of one class-2 spinal injury (vertebrae 8) and two class-3 spinal injuries (vertebrae 11 and vertebrae 4). There was no significant between the number of spinal injuries in grey mullet captured by either electrofishing or gill netting (G = 0.027, P = 0.869). The spinal injuries in grey

mullet captured by electrofishing occurred mid-body (vertebrae 10–13); at the region of the greatest body girth. Spinal injuries in grey mullet captured by gill netting were less localised, with vertebral damage ranging between vertebrae 4 and 14.

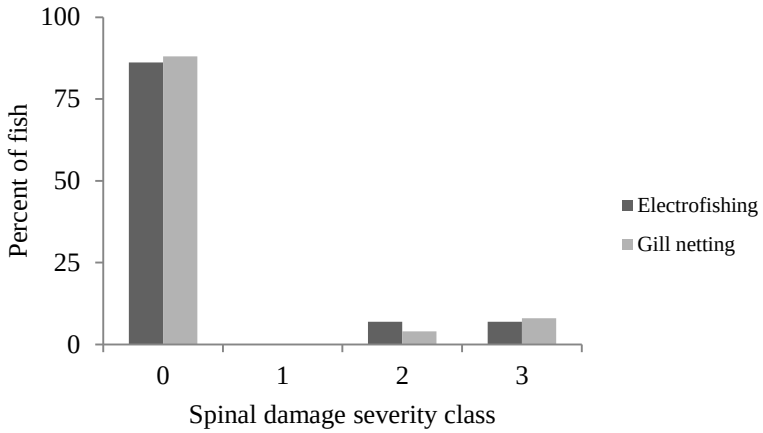

Figure 3.6: Percentage of grey mullet captured by electrofishing and gill netting in each of the spinal injury classes.

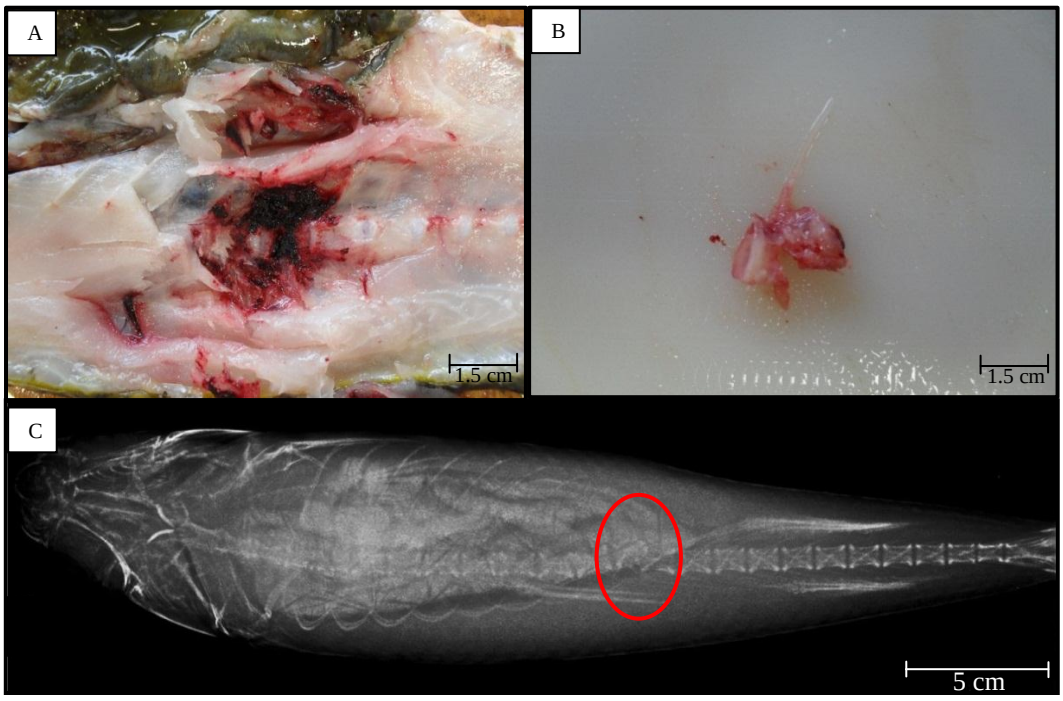

Figure 3.7: Electrofishing injury in a single grey mullet, A) necropsy showing a class-3 haemorrhage, B) fractured vertebrae and C) radiographic image, red circle indicating a class-3 spinal injury with a complete separation and fracture of the vertebrae.

In the grey mullet that were captured by electrofishing there was no significant difference in mean length (t = 1.259, P = 0. 218) or weight (t = -0.212, P = 0.833) between fish that sustained spinal injuries and uninjured grey mullet. There was also no significant difference in the mean length (t = -0.093, P = 0.926) or weight (t = 1.363, P = 0. 183) of grey mullet captured by gill netting that sustained spinal injuries and those that were uninjured (Table 3.11).

Table 3.11: Mean length and weight of grey mullet that either sustained spinal injuries or were unharmed captured by electrofishing in the Waikato River or gill netting in Lake Whangape.

Location	Capture method	Spinal injuries	*n*	Mean length ± SD (mm)	Mean weight ± SD (g)
Waikato River	Electrofishing	Injured	4	380 ± 16	826 ± 112
		Uninjured	25	352 ± 42	666 ± 227
Lake Whangape	Gill netting	Injured	3	375 ± 40	723 ± 239
		Uninjured	22	376 ± 30	746 ± 170

Spinal injuries and haemorrhaging in grey mullet captured by electrofishing were usually in the same position on the spinal column (between vertebra 9 and 13). In grey mullet captured by gill netting, 6% (n = 2) had a spinal injuries but this vertebral damage occurred with no apparent associated haemorrhaging. In one fish, both a spinal injury and a haemorrhage were found, but these injuries were found in separate sections of the spinal column. The spinal injury was located on vertebrae 11 while the haemorrhaging was located in the muscle tissue surrounding vertebrae 23 to 25.

3.2.1 Blood plasma analysis

In grey mullet captured by electrofishing the mean sodium blood plasma level was 139.4 mM this was significantly lower (t = 2.38, P = 0. 021) than in grey mullet captured by gill netting (149.1 mM). There was no significant difference between the mean blood plasma concentrations of potassium, magnesium and calcium (Table 3.12). There was a significant decrease (t = 0.24, P = 0. 001) in the in the haemoglobin concentration in grey mullet captured by electrofishing compared to that of grey mullet captured by electrofishing, but there was also no significant difference in the percent of haematocrit between either capture method (Table 3.13).

Table 3.12: The mean (± SD) blood plasma concentrations of sodium, potassium, magnesium and calcium of grey mullet captured by electrofishing (n = 29) or gill netting (n = 25; * denotes significant difference).

	Elemental concentration (mM)			
	Electrofishing	Gill netting	*t* value	*P* value
Na	139.38 ± 13.24	149.06 ± 15.58	2.37	0.02*
K	4.58 ± 1.65	4.92 ± 1.05	-0.90	0.36
Mg	1.22 ± 0.28	1.14 ± 0.23	1.15	0.25
Ca	2.69 ± 0.49	2.66 ± 0.42	0.24	0.80

Table 3.13: The mean (± SD) of haematocrit (HTC) and haemoglobin (HB) of grey mullet captured by electrofishing or gill netting (* denotes significant difference).

	Electrofishing (n = 29)	Gill netting (n = 25)	*t* value	*P* value
HTC (%)	43.89 ± 6.14	44.68 ± 10.99	0.32	0.74
HB (g L^{-1})	86.55 ± 9.21	108.81 ± 23.86	4.64	0.001*

There was no difference in the blood plasma concentrations of sodium, potassium, magnesium, calcium and haematocrit between injured and uninjured grey mullet captured by electrofishing and gill netting (Table 3.14). There was also no significant difference between the haematocrit and haemoglobin between injured and uninjured grey mullet captured by electrofishing and gill netting (Table 3.15)

Table 3.14: The mean (± SD) blood plasma concentrations of sodium, potassium, magnesium and calcium of injured and uninjured grey mullet captured by electrofishing or gill netting.

	Elemental concentration (mM)			
	Na	K	Mg	Ca
Electrofishing				
Injured (n = 7)	131.76 ± 12.24	4.85 ± 1.42	1.15 ± 0.21	2.72 ± 0.57
Uninjured (n = 22)	142.04 ± 22.06	4.95 ± 0.92	1.13 ± 0.31	2.64 ± 0.36
t value	1.54	0.21	-0.23	-0.39
P value	0.13	0.84	0.81	0.71
Gill netting				
Injured (n = 3)	150.13 ± 14.37	3.03 ± 0.51	0.97 ± 0.13	2.21 ± 0.46
Uninjured (n = 22)	141.61 ± 13.09	4.75 ± 1.68	1.25 ± 0.28	2.76 ± 0.52
t value	1.04	1.45	1.69	1.93
P value	0.31	0.15	0.11	0.07

Table 3.15: The mean (± SD) blood plasma concentrations of haematocrit (HTC) and haemoglobin (HB) of injured and uninjured grey mullet captured by electrofishing or gill netting.

	Electrofishing			
	Injured (n = 7)	Uninjured (n = 22)	t value	P value
HTC (%)	44.51 ± 5.92	43.70 ± 6.32	0.29	0.77
HB (g L^{-1})	85.56 ± 7.40	86.87 ± 9.86	-0.32	0.75
	Gill netting			
	Injured (n = 3)	Uninjured (n = 22)	t value	P value
HTC (%)	37.00 ± 6.48	43.70 ± 11.17	-1.57	0.74
HB (g L^{-1})	106.96 ± 26.70	109.17 ± 23.99	-0.16	0.86

3.3 Common smelt

A survival analysis was conducted on 2,502 smelt, of these 1,224 were captured by electrofishing and 1,278 were captured by seine netting. The mean lengths and weights between seine netted and electrofished smelt were significantly different (length; t = -9.925, P < 0.001) (weight; t = -7.29, P < 0.001; Table 3.16).

Table 3.16: The mean length and weight of common smelt used for the survival analysis and for the injury analysis captured by electrofishing or seine netting.

Capture method	n	Smelt mortality	Mean length ± SD (mm)	Mean weight ± SD (g)
Electrofishing	1,224	5.2% (n = 63)	64 ± 11.86	2.32 ± 1.73
Seine netting	1,278	7.1% (n = 94)	60 ± 9.76	1.892 ± 1.15

From the smelt captured for survival analysis, a subsample of 80 smelt was randomly selected and used to conduct an injury analysis. This subsample was comprised of four groups; 20 smelt that survived and did not survive the holding period, for each of the capture methods (Table 3.17).

Table 3.17: The mean length and weight of common smelt selected for injury analysis, captured by electrofishing or seine netting that either survived or died during the holding period.

Capture method	Survival analysis	n	Mean length ± SD (mm)	Mean weight ± SD (g)
Electrofishing	Survived	20	62.5 ± 10.7	2.3 ± 1.7
	Died	20	64.9 ± 11.9	2.0 ± 1.2
Seine netting	Survived	20	61.1 ± 9.7	1.9 ± 1.2
	Died	20	54.2± 7.8	1.3 ± 0.9

3.3.1 Survival

On average the survival of common smelt captured by electrofishing (94.8%), was not significantly different (t = -1.021, P = 0.320; Figure 3.8) from the average survival of smelt captured seine netting (92.8%).

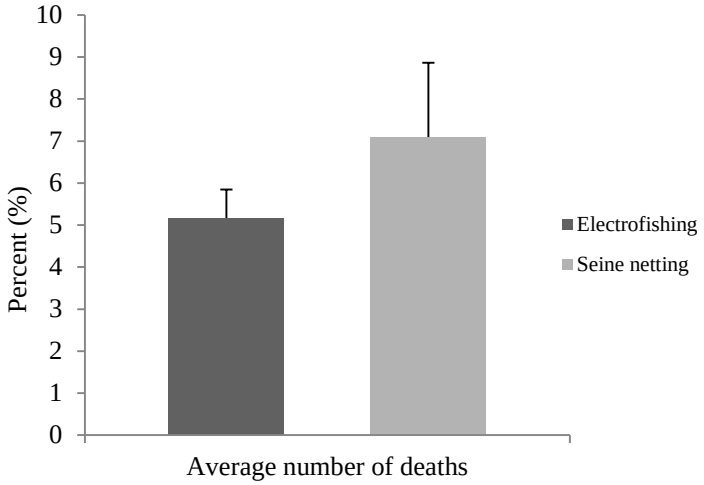

Figure 3.8: The average mortality during the post capture holding period in common smelt captured by electrofishing and seine netting.

The smelt captured by electrofishing that survived the holding period, had a mean length (t = -1.529, P = 0.126) and weight (t = 1.325, P = 0.185) that was not significantly different those that died during holding. There was a significant difference in the length (t = -6.642, P < 0. 001) and weight (t = -5.029, P < 0. 001) of smelt captured by seine netting that survived the holding period and those that did not survive.

3.3.2 External injuries

External injuries were observed in smelt captured by both electrofishing and seine netting. Injuries observed included jaws being splayed open, bleeding around the gill plates and noticeable bleeding at the junction of the spine and the tail. One smelt (2.5%) captured by electrofishing that did not die during the holding period had external injuries, while 12.5% (n = 5) of the smelt that died during the holding period suffered visible external injuries. Two smelt (5%) that were captured by seine netting that survived the holding period had visible external injuries, while 15% (n = 6) of the smelt captured by seine netting that did not survive the holding period had visible external injuries (Table 3.18).

Table 3.18: Description of injuries sustained in common smelt captured by each of the capture methodologies that survived or died during the holding period.

Treatment	Mortality	*n*	Description of injury
Electrofishing	Survived	1 (2.5%)	Jaw splayed open
	Died	1 (2.5%)	Jaw splayed open
		2 (5%)	Bleeding around the gill plates
		2 (5%)	Bleeding at the junction of the spine and the tail
Seine netting	Survived	2 (5%)	Bleeding around the gill plates
	Died	1 (2.5%)	Jaw splayed open
		2 (5%)	Bleeding around the gill plates
		2 (5%)	Bleeding at the junction of the spine and the tail
		1 (2.5%)	Jaw being splayed open and bleeding around the gill plates

3.3.3 Haemorrhages

Neither of the capture methodologies caused haemorrhages to be found in the smelt, despite the observation of externally visible injuries such as bleeding at the base of the spine in several smelt.

3.3.4 Spinal injuries

Spinal injuries were observed in smelt captured by both electrofishing and seine netting. Of the smelt captured by electrofishing 10% (n = 4) had spinal damage, one of these smelt survived the 30 min holding period and the other three died during the holding period. The smelt that survived the holding period had one class-2 spinal injury and the three smelt that did not survive the holding period all had class-2 spinal injuries (Figure 3.9; Appendix 2). In smelt captured by seine 5% (n = 2) had spinal injuries, there was no significant difference (G = 0.215, P = 0.642) between the number of spinal injuries between smelt captured by electrofishing and seine netting (Figure 3.10).

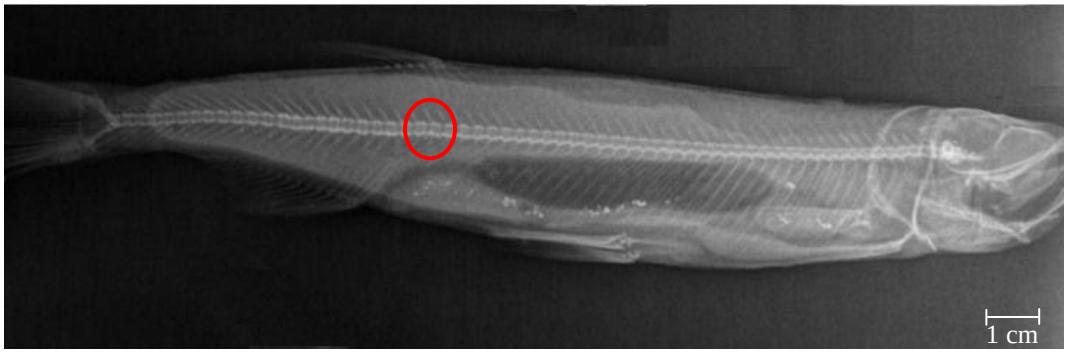

Figure 3.9: Radiographic image of a common smelt showing misalignment of the vertebrae, a class-2 spinal injury.

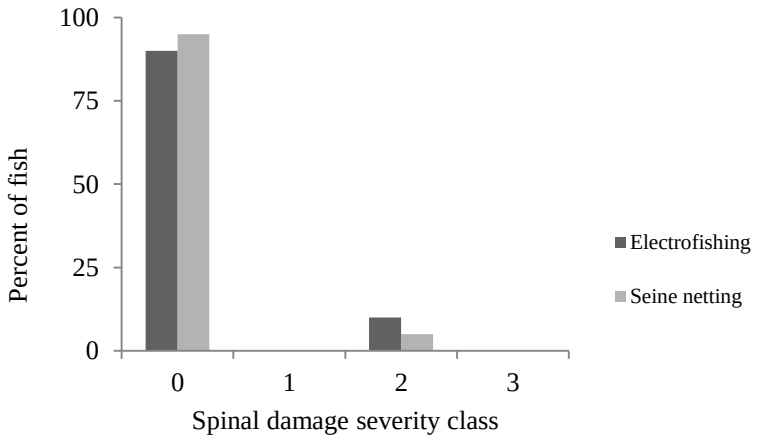

Figure 3.10: The percentage of common smelt captured by electrofishing and seine netting in each of the spinal injury classes.

In the smelt that were captured by electrofishing, there was no significant difference in length (t = -1.132, P = 0.264) or weight (t = -1.045, P = 0.302) of smelt that sustained spinal injuries and the uninjured smelt. There was also no significant difference in the mean length (t = 0.111, P = 0.912) or weight (t = 0.061, P = 0.951) of smelt captured by seine netting that sustained spinal injuries and those that were uninjured (Table 3.19).

Table 3.19: Mean length and weight of common smelt that either sustained spinal injuries or were unharmed, that were either captured by electrofishing or seine netting in the Waikato River.

Capture method	Spinal injuries	*n*	Mean length ± SD (mm)	Mean weight ± SD (g)
Electrofishing	Injured	3	56.3 ± 4.1	1.29 ± 0.35
	Uninjured	37	66.6 ± 16.0	2.88 ± 0.41
Seine netting	Injured	2	57.0 ± 1.4	1.52 ± 0.05
	Uninjured	38	56.4 ± 6.6	1.48 ± 0.27

4 Discussion

4.1 Shortfin eels

4.1.1 Significance of results

Survival for 30 days of shortfin eels captured by electrofishing (92% for Lake Areare eels and 96% for Lake Rotongaro eels) was similar to that for fyke netting (92% for Lake Areare and 88% for Lake Rotongaro). Rates of internal haemorrhaging immediately after electrofishing were inconsistent (0% in Lake Areare and 28% in Lake Rotongaro); in Lake Rotongaro, this was significantly greater than those captured by fyke netting, in which only 8% had haemorrhages. No haemorrhaging was observed in eels after 30 days from Lake Areare. Haemorrhages from electrofishing in our study appeared to heal within the 30-day holding period, as the incidence of haemorrhaging in Rotongaro eels reduced from 28% at capture to only 4% after 30 days in captivity. Rates of spinal injury in eels captured by electrofishing were also variable (12% in Lake Areare eels and 8% in Lake Rotongaro eels), compared to the rate of spinal injury in eels captured by fyke netting (0% in Lake Areare eels and 4% in Lake Rotongaro eels). Electrofishing caused no more physiological stress to eels than fyke netting, as there was no significant difference between any of the blood plasma constitutes that were evaluated. Electrofishing should be considered as a potentially harmful sampling technique, because injury was found in shortfin eels. However, the results have also shown that fyke netting will also harm eels and fyke netting is used far more frequently used compared to boat electrofishing.

4.1.2 Survival

Electrofishing mortality rates from field studies are often difficult to interpret because the exposure duration and the voltage gradient experienced by the fish are often unknown. During electrofishing, the voltage gradients vary spatially and the fish's position relative to the electrode can change, which can have a large influence on electrofishing mortality (Henry et al. 2004). One of the major short comings of the injury severity scale described by Reynolds (1996), which is used in this study and in the majority of literature that has investigated electrofishing induced injury, is that it is not known what effect these injuries would have had on the health and survival if the fish had been released.

What is clear is that haemorrhage injury scores and fish health cannot be directly correlated to mortality. To provide a better indication of the effects of electrofishing on shortfin eels, a survival analysis was conducted over a 30-day period; over this time mortality was observed to be less than 5% of eels captured by electrofishing. Low mortality rates in eels captured by electrofishing suggest that, standardised boat electrofishing techniques (60-Hz PDC, 3-4 A RMS) had a negligible effect on the survival of shortfin eels. However, the holding was conducted in an artificial environment, without natural selection pressures such as predation or competition. In a natural environment, spinal injuries could have a greater influence on swimming and foraging efficiency, but the extent of these effects cannot be estimated without further research (Dalbey et al. 1996; Holliman et al. 2010).

Fungal infections were found in 16% (n = 8) of eels captured from Lake Rotongaro, these infections originally formed on sites of skin abrasions. Disruptions to the dermis may have been caused by rubbing on the mesh of the fyke nets, bite marks or handling. Cooke et al. (1998) reported similar abrasion related injuries in greenside darters (*Etheostoma blennioides*) captured in Gee minnow traps and attributed the mortality to water mould (hyphomycete fungi) developing at the sites of abrasions. Abrasion injuries can remove the mucus covering of the fish that normally acts as a barrier to infection and thus abrasions may predispose fish to fungal-induced mortality (Cooke et al. 1998).

Electrofishing has been shown to cause an increased physiological stress response in fish (Barton & Dwyer 1997; Lamarque 1967; Vibert 1963; Whaley et al. 1978). However, environmental stressors and handling also have a significant role in the post capture survival of fish. For example extreme temperature changes may occur when fish are transferred from water into a live-well, which may increase water temperature by several degrees in summer (Hawkins 2002), at a time when water temperatures are already high. Clément & Cunjak (2010) recommend that electrofishing in waters with a high temperature (> 20ºC) be avoided to minimise stress. Mortality of shortfin and longfin eels has been caused by handling stress in water temperatures in excess of 24°C (A. Daniel personal communication, February 13, 2013)

On the first day of holding, two eels (8%) captured from Lake Areare died, probably as a result of capture, handling or transport stress, as no physical injuries were observed. The water temperate and dissolved oxygen (DO) during the holding of eels prior to the survival analysis was not monitored, but the water temperature of Lake Areare at the start of electrofishing (20.8ºC) was higher than recommended for electrofishing by Clément & Cunjak (2010). As this temperature was recorded at approximately 10:00 am it is highly likely that the water temperature would have increased further during the day. The holding tanks were aerated so low DO concentrations were unlikely to have caused stress. The eels were then transported back to the laboratory and released into the 10,000-L holding tank, which had an average temperature of 18.9ºC over the holding period. Failure to properly acclimate the eels to differences in water temperatures could have increased the stress levels of eels in this study.

There was a large biomass of eels found in most of the fyke nets (>35 eels per fyke net), likely causing some degree of stress. The stress may have been further compounded by handling, anaesthetic and close confinement with other eels during transportation back to the laboratory (Lamarque 1967). However, no physiological indicators of stress were monitored in eels captured in Lake Areare, so it cannot be conclusively said that the observed cases of short term mortality were a result of physiological stress. An advantage of using electrofishing over fyke netting is a shorter duration of holding, fyke nets will often be set over night and this means fish can be exposed to stressful conditions at least 12 hours. Exposure to stressful conditions during capture by electrofishing is often much shorter (10 min to 1-2 h depending on handling procedures and number of fish caught).

4.1.3 Internal haemorrhages

The injury rates of shortfin eels in our study varied widely between the two lakes sampled (0-28%). Electrofishing caused significantly more haemorrhages than fyke netting, but healing of these injuries occurred over time, as only 4% of fish were found to have haemorrhages after 30 days in captivity. The rate of haemorrhaging observed in Lake Rotongaro, was similar to the rate reported (30%) by Reynolds & Holliman (2004). The apparent severity of haemorrhages observed

in this study were generally severe with the majority (85%) rated as class-3 wounds. Similarly, Reynolds & Holliman (2004) reported that the majority (80%) of the haemorrhages they found were severe (class-3 haemorrhages).

Holliman et al. (2010) assessed the effects of time on injury detection in juvenile (age-1) Chinook salmon. The fish were exposed to 60-Hz PDC and dual-frequency PDC (DFPDC) (568 and 15-Hz) on day 0 and then injuries were evaluated on a sub sample of fish on days 1, 7, 14, 28, and 56. Holliman et al. (2010), found that the occurrence of haemorrhages in fish exposed to PDC significantly reduced from 65% of the fish examined on day 1 to 9% at the conclusion of the 56 day experiment ($P < 0.007$). In salmon exposed to dual-frequency PDC the occurrence of haemorrhages decreased significantly from 85% at capture to 5% after 56 days ($P < 0.001$).

Schill and Elle (2000) exposed 502 rainbow trout to CDC (375-V) and PDC (325-V, 60-Hz 25% duty cycle) at 7.5 A. The voltage gradients (1.7-Vcm^{-1} for CDC and 1.9 Vcm^{-1} for PDC) and the exposure times used were selected because they were suspected to produce high injury rates in muscle tissue. One day after exposure, in a subsample of the rainbow trout exposed to CDC, 86.1% of the fish had haemorrhaging and 81.6% of those exposed to PDC had haemorrhaging. The severity of haemorrhages initially increased throughout the first 15 days and then decreased at each successive subsampling occasion through the remaining duration of the experiment. At the conclusion of the holding period, haemorrhages had declined by 78% in rainbow trout exposed to CDC (36 days after shocking), The occurrence of haemorrhages in rainbow trout had declined by 92% 57 days after initial exposure to PDC electroshocking. This initial increase in severity was thought to be due class-2 haemorrhages spreading to class-3 wound as the blood diffused outward into the myomeres and away from the spinal column following initial injury (Schill & Elle 2000).

In the current study, one class-1 haemorrhage was observed in eels held for 30 days, meaning there was an 85% reduction in the occurrence of haemorrhages observed in the eels that were held compared to the eels that were euthanised immediately after capture. This suggests healing occurred over the 30-day period. The results of the present study as well as the results of Holliman et al. (2010) and

Schill and Elle (2000) show that the high rate of haemorrhages reported by Reynolds & Holliman (2004) could heal over time.

Many researchers have documented a relationship between increasing fish size and physical injuries (Dalbey et al. 1996; Snyder 2003a). However, there was no difference in length or weight of eels that sustained haemorrhages or the uninjured eels. The failure to detect difference is possibly due to the low sample size of injured fish (n = 8) and the relatively uniform size of the eels captured.

No haemorrhaging was observed in any eels captured from Lake Areare. The difference in frequencies of haemorrhages in the two lakes sampled could be simply due to differences in the severity of spinal injuries. Even though in both lakes class-2 spinal injuries were the only injuries observed, the misalignment of some vertebrae could have been more significant in Lake Rotongaro resulting is an increased chance of rupturing blood vessels. The difference between the frequencies of haemorrhages in the two lakes sampled could be due to the differences in the environmental conditions of the lakes. The water temperature was colder in Lake Rotongaro (18.7ºC) compared to the water temperature in Lake Areare (20.8ºC). Apart from temperature the environmental conditions were fairly similar. The specific conductivity of Lake Rotongaro was 174.6 µS cm^{-1} compared to that of Lake Areare which was148.4 µScm^{-1}. The clarity of the waters in both lakes was poor, the vertical Secchi depth of 30 cm in Lake Rotongaro and 22 cm in Lake Areare.

Differences in depth of the water in which eels were capture between Lake Rotongaro (1-2 m deep) and Lake Areare (< 1 m deep) may have caused the lower rate of haemorrhaging in Lake Areare. The anode wires touched the bottom during fishing in Lake Areare, which may have dissipated power into the lake bed, reducing the effect on the eels.

4.1.4 Spinal injuries

All the spinal injuries observed were caused by recent capture or handling, as they were unhealed (indicated by lack of calcium deposition) and none resembled congenital deformities (which would be indicated by misshapen vertebrae or extra

spines attached to vertebrae) (Reynolds & Holliman 2004). In eels captured from Lake Rotongaro by electrofishing and euthanised immediately after capture, 8% (n = 2) had spinal injuries, while those that were held for 30 days after capture 27% (n = 7) had spinal injuries. There was no significant difference between the number of spinal injuries sustained during capture with electrofishing or fyke netting in Lake Rotongaro. In the eels captured in Lake Areare by electrofishing and euthanised immediately after capture, 12% (n = 3) had spinal injuries, while in those held for 30 days after capture, 20% (n = 5) had spinal injuries. However, there were no spinal injuries were detected in eels captured by fyke netting in Lake Areare, meaning that there was a significant difference in the number of spinal injuries sustained in eels captured by boat electrofishing. The observation of spinal injuries in 60% of American eels reported by Reynolds & Holliman (2004), was substantially higher than the number of spinal injuries found in this study. While, Pratt & Threader (2011), did not find any spinal injuries in the American eels (n = 10; 254 ± 31 mm SE) they examined by X-ray imaging.

In both trials conducted during this study, eels that were held for 30 days had a higher rate of spinal injury than eels that did not have a holding period after capture. It is unlikely that the holding alone would cause spinal injuries and handling at the completion of the experiment was minimal and it was not severe enough to cause spinal injuries. Holliman et al. (2010) reported a significant increasing trend in spinal injury detection (40% on day 1, 78% on day 56; P = 0.025) was evident for age-1 fish over a 56 day experiment in small (17 cm TL) Chinook salmon exposed to dual-frequency PDC (as reported above). However, this significant trend in spinal injury detection was because of increasing visibility of spinal injuries on the X-rays. This increased visibility was due to healing of the spinal injuries causing increased bone density and calcium deposition.

In eels captured from both Lake Rotongaro and Lake Areare by electrofishing, class-2 spinal injuries were the most frequently reported (93%). While Reynolds & Holliman (2004), reported that Class-3 were the most frequent (50%) followed by class-2 spinal injuries (30%). In eels captured by fyke netting Class-3 spinal injuries were found by Reynolds & Holliman (2004), to be the most commonly (66%) reported spinal injuries. In the results of this study we did not find any

class-3 spinal injuries in eels captured by fyke netting but class-1 and class-2 spinal injuries were present in equal numbers (n = 2).

The majority of vertebral injuries (71%) found in our study were located between vertebra 40 and 59. Reynolds & Holliman (2004), reported that spinal injuries were more widely distributed compared to the results of our study. They found that the majority (47%) of spinal injured occurred between vertebra 20 and 39 and 37% of injuries occurred between vertebra 40 and 59. In both this report and reported by Reynolds & Holliman (2004), spinal injuries tended to occur at about one third to half of the body length from the head; this is the area of greatest body girth in anguillids.

Reynolds & Holliman (2004) hypothesize that in similar size fish , the underlying risk factor for electrofishing induced injury was the number of vertebrae. Body undulating fish like anguillids, have a high vertebral count which is associated with flexible spines to provide maximum thrust. As a family anguillids have a vertebral count of between 103 and 119 (Reynolds & Holliman 2004); more specifically American eels have a mean vertebral count of 107.2 (Avise et al. 1990), shortfin eels have a mean vertebral count of 111.64 (Schmidt 1928) and longfin eels have a mean vertebral count of 112.66 (Griffin 1936; Schmidt 1928). Reynolds & Holliman (2004) suggested that the large number of vertebrae meant that the spine was less likely to remain uninjured during the severe force of muscle contractions experienced in the course of electrofishing. However, our results and the results of Pratt & Threader (2011) suggest that vertebral count is not as important to injury as Reynolds & Holliman (2004) suggested.

4.1.5 Blood plasma analysis

Physiological stress not physical injury may cause mortality in fish exposed to an electrical current. Dolan & Miranda (2004) found that mortality was not related to the occurrence of haemorrhage and spinal injury because injury rates were similar in fish that survived electrofishing and those that died, Spencer (1997) also report a lack of correlation between mortality and injury in bluegills. The effects of electroshock on stress levels in salmonids has been documented on several occasions (Barton & Dwyer 1997; Haskell 1939; Haskell & Zilliox 1940; Sternin

et al. 1976; VanderKooi et al. 2000; VanderKooi et al. 2001). Barton and Dwyer (1997) measured the effects of physiological stress of electrofishing. They found that in juvenile bull trout, plasma cortisol and glucose significantly increased within 15 min of a 10 s 60-Hz PDC electroshock exposed to electric current and that this stress response may reduce survival. However, in non-salmonids studies on the impact of electrofishing induced stress are very limited, and even fewer have examined these effects on American native species (Bracewell et al. 2004).

The results of the blood plasma analysis of the shortfin eels captured by either method showed no significant differences between the mean concentrations of sodium, potassium, magnesium, calcium, haematocrit and haemoglobin. There was also no significant difference between any of the blood plasma constitutes in eels that were uninjured or injured eels captured by either capture method. Based on the blood plasma results electrofishing appeared to be no more physiologically stressful to eels than fyke netting despite the increased occurrence of haemorrhages.

It is likely that any capture technique will cause some level of stress from confinement, aesthetic or handling (Lamarque 1967; Vibert 1963). It was not possible to establish baseline concentrations of these blood constitutes in this study because prior to the extraction of the blood all eels were handled in some way. There are no published baseline concentrations for any anguillids blood constitutes to compare the result of either treatment.

4.1.6 Considerations with comparisons

There are several considerations that need to be taken into account when making comparisons between the results found in this study and other investigations conducted. Reynolds & Holliman (2004) failed to report significant environmental variables such as conductivity and temperature and Pratt & Threader (2011) only reported temperature. These of which are known to affect electrofishing induced injury. Moreover, both of these studies had relatively small sample sizes. Reynolds & Holliman (2004), only examined 18 American eels captured by electrofishing and 20 eels captured by trap netting. While, Pratt & Threader (2011) only sampled 10 American eels captured by electrofishing and they did not

examine any eels captured by an alternative fishing method. The small sample sizes used greatly increase the risk of overrepresentation or underrepresentation of injury rates.

Another consideration is the difference in the average size of eels sampled, as many researchers have documented increased incidences of electrofishing induced spinal injury with increasing fish length (Dalbey et al. 1996; Lamarque 1990; Snyder 2003a). The average size of eels captured by electrofishing in Lake Rotongaro was 483 mm (± 76 SD) with a range of between 400 mm and 734 mm. The average size of eels captured by electrofishing in Lake Areare 550 mm (± 91 SD) with a range of between 415 mm and 755 mm. The average size and the size range of eels sampled were generally consistent with other lakes in the Waikato region. For example the range size of eels captured from Lake Ohinewai was between 39 mm and 855 mm, with 90% of eels captured being between 300 mm and 700 mm. The disparity between the lower ranges of sound class is due to experimental because any eels smaller than 400 mm were immediately returned to the lake, due to size limit restraints. But overall the ranges of eels found in Lake Rotongaro, Lake Areare and Lake Ohinewai were similar.

The average size of American eels captured by Reynolds & Holliman (2004) was large (917 mm ± 81 mm SD). While, the average size of American eels captured by Pratt & Threader (2011) was smaller (254 ± 31 mm SE) than those captured by Reynolds & Holliman (2004). While, no size range eels captured by either author was reported, the average size range of American eels is between 22 mm (Pratt & Threader 2011) and 1250 mm (Labar & Facey 1983). This suggest the only the upper end of the size range of American eels was sampled by Reynolds & Holliman (2004) and because of their length these eels may have been more susceptible to injury. While the injury evaluations conducted by Pratt & Threader (2011) were at the lower end of the size distribution of American eels, because of their small size the fish may have been less susceptible to electrofishing induced injury.

4.2 Grey mullet

4.2.1 Significance of results

In most boat electrofishing operations conducted in the main stem of the lower Waikato River, the greatest biomass of any native species observed is comprised of grey mullet (Hicks et al. 2005). Mullet are often a non-target species and entire schools can be accidently exposed to electric current during boat electrofishing operations. Analyses of injury and physiological stress grey mullet captured by standard boat electrofishing techniques revealed that physiological stress from electrofishing caused a significant reduction of the sodium ion concentration compared to that in grey mullet captured by gill netting. Physiological stress from electrofishing also caused a significant reduction in the concentration of haemoglobin. Despite the physiological stress response caused by capture with electrofishing there was no difference in rates of internal injuries between grey mullet captured by electrofishing and gill netting. However, gillnets, are the most common technique for harvesting and collecting grey mullet, as a result the use of gill nets is far more likely to injury or mortality to grey mullet.

4.2.2 External injuries

Branding is an externally visible injury caused by electrofishing, they are thought to be a result of erratic stimulation of chromatophores when nerve fibres are damaged by sever spinal damage or by haemorrhaging of capillaries near the skin (Hartman et al. 1941; Reynolds 1996). Published reports of the frequency of branding greatly vary with species and electrical waveforms, from 0% in pumpkinseeds exposed to 60-Hz PDC (Bardygula-Nonn et al. 1995) to 38% in rainbow trout exposed to 250-V AC (Habera et al. 1999).

Branding occurred in 7% (n = 2) of grey mullet, 3–4 brands were found on each specimen with branding. It is highly likely that these fish were in close proximity or came in direct contact with the electrode (Hartman et al. 1941; Snyder 1992b; Snyder 2003a). Generally, the published reports on electrofishing induced branding revealed that brands are often found in association with the severe spinal damage, but severe spinal injuries can still be found in fish that do not exhibit branding (Ainslie et al. 1998; Fredenberg 1992). We found that in both cases

branding was found in association with severe spinal injuries and in one case complete vertebral fracture. As a result of capture and removal of fish from the gill net, net injuries around the gills or body occurred in 80% (n = 20) of grey mullet. The occurrence of external injuries as a result of capture by gill netting occurred far more frequently than the occurrence (7%; n = 2) of external injuries in grey mullet captured by electrofishing. Rulifson (1983) documented a similar rate of external injuries in spiny dogfish (*Squalus acanthias*) captured by gill netting. He found that 88% of fish had net marks their head and 41.2% had net marks on their body.

4.2.3 Internal haemorrhages

The frequency and severity of haemorrhages reported in the literature varies greatly from in 0% to 90% of fish (Appendix 1), electrical current, settings, environmental conditions and biological factors all attribute to this variation (Reynolds 1996; Reynolds 2000; Schill & Elle 2000; Snyder 2003a). The results of this report showed haemorrhaging in 24% (n = 7) of grey mullet captured by electrofishing, these injuries were generally severe (the majority were comprised of class-2 and class-3 wounds). Although haemorrhages may be considered less important compared to spinal injuries in regard to long-term survival, it is likely that energy would be diverted to heal wounds and this may reduce the growth rate of injured fish (Ainslie et al. 1998; Dalbey et al. 1996; Habera et al. 1999; Holliman & Reynolds 2002).

Many researchers have documented a relationship between increasing fish size and haemorrhages due to differences in muscle mass and muscle composition (Dalbey et al. 1996; Snyder 2003a). Larger fish such as grey mullet often have a larger muscle mass; this means that the muscles contract with greater force and which may severely compress the vertebrae resulting in rupture of the dorsal aorta or other blood vessels from the mid-dorsal fin to the caudal area (Bardygula-Nonn et al. 1995; Hartman et al. 1941). Furthermore large fish may have a greater proportion of white muscle fibres which tend to contract more powerfully than red muscle fibres (Hartman et al. 1941). Our study found no relationship between the length or weight and injury in grey mullet captured by either method. The failure

to detect a difference, is likely because of the low sample size of injured fish (n = 7).

4.2.4 Spinal injuries

In grey mullet captured by electrofishing, 14% (n = 4) had spinal injuries, consistent with a low to moderate rate of spinal injury when compared to literature on other fish species which ranged between 0% and 75% (Appendix 1). The spinal injuries in grey mullet captured by electrofishing occurred mid-body (vertebrae 10–13); at the region of the greatest body girth, this is consistent with published reports of the location of spinal injuries (Reynolds & Holliman 2004). Spinal injuries occurred in 12% (n = 3) of grey mullet captured by gill netting, these injuries were less localised, with vertebral damage ranging between vertebrae 4 and 14. It is likely that these injuries occurred when the fish were removed from the gill net.

Spinal injuries have often been associated with increased length (Dalbey et al. 1996; Dolan & Miranda 2004; Snyder 2003a). The majority of this work has been conducted in salmonids, while data supporting this relationship in non-salmonid fishes is limited. Among northern pike 36 to 74 cm FL that were subjected to similar electric fields, h (1990) found that those fish experiencing spinal injuries were significantly larger (~ 57 cm FL) than those that were not injured (~ 51 cm FL). In our study, we failed to detect a significant difference in the length or weight of grey mullet that sustained spinal injuries and the uninjured grey mullet.

4.2.5 Blood plasma analysis

The mean sodium blood plasma concentration of grey mullet captured by electrofishing was significantly lower than that of fish captured by gill netting. An ion imbalance occurs as a result of increased water permeability and ionic transfers across the gills are often accompanied by an increase in catecholamines which is released in response to stress. The decrease of sodium levels suggest that there was some electrofishing induced stress caused in grey mullet. However, there was no significant difference between the mean blood plasma concentrations of potassium, magnesium, calcium and haematocrit. Furthermore injury (spinal

damage of haemorrhaging) did not have an effect on the concentrations of the blood constitutes either.

Hopkins & Cech (2002) captured striped bass (*Morone saxatilis*) in gill nets with a 20-40 min set time and fyke nets with 24-48 hour set times. Their results showed that fish captured by gill net were generally more stressed that fish captured by fyke net, they had a significantly lower blood pH, which is associated with a greater lactate concentration and PCO_2. The fish also had significant erthrocytic swelling and hypoglycaemia, as well as an increased haematocrits and plasma glucose levels which is indicative of a stress response. No difference was found between gill and fyke net captured fish for haemoglobin, plasma HCO_3^-, osmolality (Na and Cl) and total protein. Hopkins & Cech (2002) found that handling and air exposure on the deck while removing the fish from gill nets impairs to significantly impair gas exchange leading to hypoxia and hypercapnia. Hopkins & Cech (2002) found that overall fyke net capture induced less physiological stress than gill netting. The results of Hopkins & Cech (1992) show that gill netting also causes an increase in blood plasma constitutes (haemoglobin, plasma HCO_3^-, Na, Cl and total protein) suggesting gill netting should not be treated as a control instead as a method of fish capture that also causes stress in fish. In this study gill netting was used as a control because it is the only other effective method of capturing mullet.

4.3 Smelt

4.3.1 Significance of results

Common smelt are often the most numerous species observed when electrofishing in the Waikato River, resulting in significant number of smelt could be effected by boat electrofishing (Hopkins & Cech 1992). Analyses of injury and survival rates of common smelt captured by standard boat electrofishing techniques and beach seining found that injuries and mortalities were detected in smelt captured by electrofishing. However, there was no significant difference in the survival or the rate of spinal injuries in smelt captured by electrofishing or seine netting. Suggesting that boat electrofishing was no more injurious to smelt than seine netting.

4.3.2 Survival

On average the survival of common smelt captured by electrofishing was high (94.8%) and was not significantly different from the average survival of smelt captured via seine netting (92.8%). The short duration (30 min) of the holding period was probably insufficient to reveal the effect of injuries. However, a longer holding period may have shown mortality as a result of physiological stress of holding rather than the capture method. Smelt are easily stressed and not well suited to holding of any kind often resulting in mortality (McQueen 2010). As mentioned above environmental stressors may also have a significant role in the post capture survival of fish such as temperature. It is recommend that electrofishing in waters with a high temperature (> 20ºC) should be avoided to minimize stress in fish (Cunjak 2010). It is not thought that the water temperate (mean = 18.1ºC) or DO during the live-well and survival analysis would have had a physiological effect during the capture and holding of smelt as the temperature did not significantly change during the holding time. However, no physiological indicators of stress were monitored in smelt, so it cannot be conclusively said that the short term mortality was a result of physiological stress.

In fish of a similar size (4.3–8.2 cm TL) exposed to the similar electrofishing conditions (60-Hz PDC at 0.9-Vcm^{-1} for 6 s) to the smelt used for the survival analysis, Holliman et al. (2003b) reported 10% mortality in Cape Fear shiners. Barrett & Grossman (1988) documented a mortality of between 0–11% in similar sized (3–9 cm SL) mottled sculpin captured by 600-V CDC.

The probability of survival of smelt captured by electrofishing was not affected by the length or weight of the smelt. However, the size and weight of smelt captured by seine netting did effect survival, with the smaller and lighter smelt having an increased chance of post capture mortality. The smaller and lighter fish are probably more delicate and as a result the most probable cause of injury in seine net captures smelt was either the pressure from the current or handling. Smelt were removed from the seine net by hand as quickly as possible to minimise air exposure, but this process may have damaged or stressed some fish. Handling has been shown to induce a physiological stress response, this could add additional stressors to an already injured fish; possibly effecting survival (Barrett &

Grossman 1988; Habera et al. 1999; Haskell & Zilliox 1940; Janáč & Jurajda 2011). Barrett & Grossman (1988) documented that the effects of handling stress were the most important factor in determining mortality of mottled sculpins collected by 600-V CDC electrofishing. While, Habera et al. (1996) found that there was no significant difference between mortality in brown trout that were handled and those that were not handled.

4.3.3 External injuries

External injuries were observed in 15% (n = 6) of smelt captured by electrofishing, and in 20% (n = 8) of smelt captured by seine netting. Bleeding around the gill plates was a commonly observed injury in smelt captured by both methods. This type of injury has been noted by other researchers such as in Colorado pikeminnow following electrofishing (Hawkins 2002). Snyder (1992) suggested that gill bleeding was not associated with spinal injuries or tetany, also that the effects of gill bleeding on survival was not known, Hawkins (2002) also found no correlation between bleeding around the gill plates and spinal injuries in Colorado pikeminnow.

4.3.4 Internal haemorrhaging

Neither of the capture methodologies caused haemorrhages in the smelt, despite the observations of externally visible injuries such as bleeding at the base of the spine in several smelt, no injuries were detected during necropsies. Although smelt are small fish necropsies were conducted successfully and we are confident that if injuries were present they would have been detected. As necropsies have been used by both Holliman et al. (2003a, 2003b) and Clément & Cunjak (2010) to successively identify and quantify haemorrhaging in small fish (2.5-15 cm FL).

4.3.5 Spinal injuries

Spinal injuries were observed in 10% (n = 4) of smelt captured by electrofishing and in 5% (n = 2) of smelt captured by seine netting; there was no significant difference found between the two capture methods. Spinal injuries were apparent in smelt despite their size, although two fish were X-rayed for a second time due to poor resolution in the first image. Radiographic images were conducted using

mammography radiographic equipment to increase the resolution for smaller fish. The small size of some fish species or juveniles of larger fish species may be a limiting factor for an accurate injury evaluation. Fredenberg (1992) found that their radiographic equipment was too crude to allow for adequate identification and assessment of spinal injuries in small fish (~20 cm TL). Holliman et al. (2003a, 2003b) examined electrofishing-induced spinal injuries in spotfin chub (*Cyprinella monacha*) (3.5–5.7 cm TL) and Cape Fear shiners (*Notropis mekistocholas*) (2.5–8.2 cm TL) using a mammography radiographic equipment. This allowed for greater image quality in the X-ray images, which allowed for a more accurate analysis of spinal injury in these fish. However, even with this increased X-ray definition, spinal injuries could not be identified injury to the level of individual vertebrae (Holliman et al. 2003a; Holliman et al. 2003b). Mahoney (1997) also found that spinal compression in the smallest (< 8 cm TL) bull trout could not be identified and may have been overlooked. Clément & Cunjak (2010) evaluated injury in juvenile Atlantic salmon using a Torrex 120D radiography machine (Scanray Corporation, Hawthorne, California) with a Kodak X-Omat TL film, with X-ray machine set to 50 kV, 4 mA, 8 s for small fish (3.0-5.9 cm FL). They concluded that their X-ray techniques were inadequate to detect individual vertebral injuries in small (< 6.0 cm FL) Atlantic salmon, but the X-ray images could be used to estimate if spinal injuries had occurred. However, some injuries may not have been detected.

5 Management implications

The results of this study indicate that boat electrofishing does cause injury and stress in all three species studied. However, commonly used methods of capture (fyke net, gill netting and seine netting) also had similar impacts on shortfin eels grey mullet and smelt. Considering that these techniques are used far more frequently in commercial and recreational fishing the use of boat electrofishing is largely benign.

For common species, some mortality or injury from electrofishing may be acceptable given the advantages that electrofishing provides (i.e. higher catch rates) over other methods of fish capture such as gill nets. Some degree of electrofishing induced injury to individual fish is acceptable, as long as the resulting injuries do not result in effects at the population level. For rare or endangered species the same theory is applicable, but harm to fewer individual may cause population level effects, so caution is required when electrofishing these fish species (Nielsen 1998; Schill & Beland 1995). With these considerations in mind and despite the risk of injury and mortality associated with electrofishing, it is an efficient and effective sampling tool for fisheries management.

Generally, electrofishing induced injury and mortality are considered to have minimal effects on fish populations (Ainslie et al. 1998; Elle & Schill 2000; Habera et al. 1999; Holliman & Reynolds 2002; McMichael et al. 1998; Schill & Beland 1995). Despite this injuries to individual fish are important; as public perception of electrofishing induced injuries could override studies documenting low population level impacts (Elle & Schill 2000) and this could result in major restrictions in electrofishing operations in New Zealand. There are currently no guidelines on acceptable levels of electrofishing induced injuries or mortality in common or endangered species in New Zealand. The finding of this study would suggest that such guidelines would only be useful for endangered species and would also need to restrict the use of other capture methods (fyke net, gill netting and seine netting). Additionally the Animal Welfare Act (1999) provides no protection for wild fish, endangered or otherwise.

The present study adds to the developing body of research documenting the effects of electrofishing on non-salmonid fish, providing the first reports on electrofishing induced injuries on New Zealand native fish species. Further research is needed to explore on the effects of boat electrofishing and backpack on New Zealand native species to determine if population level effects occur in fish that are exposed to repeated electrofishing.

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7 Appendices

Appendix 1: Compilation of published electrofishing induced mortalities, spinal injuries, haemorrhaging and branding and by fish species (ordered alphabetically by family name) and electrical current type (AC, CDC and PDC). Empty fields mean no data available.

Species		Injury				Electric Field and Current			Source
Common name (scientific name)	Size (cm)	Mortality (%) and duration	Spinal injury (%)	Haemorrhaging (%)	Branding (%)	Current type / Volatage / Wave form	Frequency / Voltage gradient	Pulse width (ms) / duration(s)	
Acipenserdae									
White sturgeon (*Acipenser transmontanus*)	24-33 cm FL			10		CDC, 150-V		3 s	Holliman & Reynolds (2002)
	37-54 cm FL			10		CDC, 150-V		3 s	Holliman & Reynolds (2002)
	Average of 39.9 cm FL	7 (short-term)	0	0		PDC	30-Hz		Ostrand et al. (2009)
	24-33 cm FL			75		PDC, 150-V (square-wave)	60-Hz	6-ms, 3 s	Holliman & Reynolds (2002)
	37-54 cm FL			60		PDC, 150-V (square-wave)	60-Hz	6-ms, 3 s	Holliman & Reynolds (2002)
Anguillidae									
American eels (*Anguilla rostrata*)	Average of 91.7 cm TL		60	30		PDC	30-Hz	6-ms	Reynolds & Holliman (2004)
	Average of 25.4 cm TL		0			PDC	60-Hz		Pratt & Threader (2011)

Common name	Size	Mortality (%) and duration	Spinal injury (%)	Haemorrhaging (%)	Branding (%)	Current type / Volatage / Wave form	Frequency / Voltage gradient	Pulse width (ms) / duration(s)	Source
Centrarchidae									
Pumpkinseeds (*Lepomis Gibbosus*)	6-20 cm TL	0-1 (short-term)				AC, 115-V (3-phase)	180-Hz		Schneider (1992)
	7 – 12 cm TL	9 (short-term)				AC, 230-V (3-phase)	180-Hz		Schneider (1992)
	20-67 cm TL	2-12 (short-term)				DC, 115-V (3-phase)	180-Hz		Schneider (1992)
	Average of 11 cm TL	0 (3 d)			0	PDC	60-Hz		Bardygula-Nonn et al. (1995)
Bluegills (*L. macrochirus*)	8-10 cm		4.6			AC, 115-V (3-phase)	180-Hz		Spencer (1967)
	8-10 cm		12.2			AC, 230-V (3-phase)	180-Hz		Spencer (1967)
	8-10 cm		1.5			DC, 115-V (3-phase)	180-Hz		Spencer (1967)
	9-17 cm TL	35 (short-term)				PDC	16-Hz, 4-Vcm^{-1}	120 s	Whaley et al. (1994)
	9-17 cm TL	50 (short-term)				PDC	16-Hz, 4-Vcm^{-1}	180 s	Whaley et al. (1994)
	Average of 13 cm TL	5.3% (short-term)			5	PDC	60-Hz		Bardygula-Nonn et al. (1995)
Largemouth bass (*Micropterus salmoides*)	13-25 cm TL		0			AC, 230-V (3-phase)	180-Hz		Spencer (1967)

Common name	Size	Mortality (%) and duration	Spinal injury (%)	Haemorrhaging (%)	Branding (%)	Current type / Volatage / Wave form	Frequency / Voltage gradient	Pulse width (ms) / duration(s)	Source
Largemouth bass continued	Average of 21 cm TL	1.3 (3 d)			0.2	PDC	60-Hz		Bardygula-Nonn et al. (1995)
Small mouth bass (*M. dolomieu*)	Average of 21 cm TL	0.6 (3 d)			3.4	PDC	60-Hz		Bardygula-Nonn et al. (1995)
Black crappie (*Pomoxis nigromaculatus*)	12-20 cm TL	0 (18 h)	9	0		DC			Dolan et al. (2002)
	12-20 cm TL	0 (18 h)	27	7		PDC	15-Hz	1-ms	Dolan et al. (2002)
	12-20 cm TL	15 (18 h)	20	15		PDC	15-Hz	4-ms	Dolan et al. (2002)
	12-20 cm TL	7 (18 h)	20	14		PDC	15-Hz	6-ms	Dolan et al. (2002)
	12-20 cm TL	0 (18 h)	10	33		PDC	60-Hz	1-ms	Dolan et al. (2002)
	12-20 cm TL	0 (18 h)	45	50		PDC	110-Hz	1-ms	Dolan et al. (2002)
	12-20 cm TL	0 (18 h)	20	43		PDC	110-Hz	6-ms	Dolan et al. (2002)
Clupeidae									
Atlantic Herring (*Clupea harengus*)	Average of 29 cm TL		60			AC [A] (sine wave)	50-Hz		Nordgreen et al. (2008)
Cottidae									
Mottled sculpin (*Cottus bairdii*)	3-9 cm (SL)	0-11 (35 d)				CDC, 600-V		30 s	Barrett & Grossman (1988)

Common name	Size	Mortality (%) and duration	Spinal injury (%)	Haemorrhaging (%)	Branding (%)	Current type / Volatage / Wave form	Frequency / Voltage gradient	Pulse width (ms) / duration(s)	Source
Slimy sculpin (C. cognatus)	Average of 6.3 cm FL		6	0	0	PDC, 300-V	60-Hz		Clément & Cunjak (2010)
Cyprinidae									
Spotfin chub (*Cyprinella monacha*)	3.5-5.7 cm TL	10 (1 h)	0 [B]	0		AC	60-Hz, 3.3-Vcm^{-1}	3 s	Holliman et al. (2003)
	3.5-5.7 cm TL	0 (1 h)	0 [B]	0		PDC	60-Hz, 2.5-Vcm^{-1}	3 s	Holliman et al. (2003)
	3.5-5.7 cm TL	25 (1 h)	0 [B]	0		PDC	60-Hz, 5.0-Vcm^{-1}	3 s	Holliman et al. (2003)
Humpback chubs (*Gila cypha*)	4.9-9.6 cm TL	0 (98 d)	0	0	20	PDC (square-wave)	80-Hz		Ruppert & Muth (1997)
Bonytails (*G. elegans*)	32-487 g		17			CDC, 200-V			Dwyer et al. (2001)
	4.6-7.9 cm TL	0 (98 d)	0	0	3-20	PDC (square-wave)	30-Hz	4-ms	Ruppert & Muth (1997)
	4.6-7.9 cm TL	0 (98 d)	0	0	7-27	PDC (square-wave)	60-Hz	4-ms	Ruppert & Muth (1997)
	4.6-7.9 cm TL	0 (98 d)	0	0	13-23	PDC (square-wave)	80-Hz	5-ms	Ruppert & Muth (1997)
	4.6-7.9 cm TL	0 (98 d)	0	0	7-10	CPS [C] (square-wave)	240/15-Hz	2.6/11-ms	Ruppert & Muth (1997)
	32-487 g		30.5			CPS [C]	15-Hz	3 x 2-ms	Dwyer et al. (2001)
Cape Fear shiners (*Notropis mekistocholas*)	4.3–8.2 cm TL	38 (1 h)	0	0		CDC			Holliman et al. (2003b)

Common name	Size	Mortality (%) and duration	Spinal injury (%)	Haemorrhaging (%)	Branding (%)	Current type / Volatage / Wave form	Frequency / Voltage gradient	Pulse width (ms) / duration(s)	Source
Cape Fear shiners continued	4.3–8.2 cm TL	0 (1 h)	0	0		PDC (square-wave)	60-Hz	4-ms	Holliman et al. (2003b)
	4.3–8.2 cm TL	25 (1 h)	0	0		PDC (square-wave)	120-Hz	4-ms	Holliman et al. (2003b)
Colorado pikeminnow (*Ptychocheilus Lucius*)	36 to 77cm TL		26		2	PDC, 150-390-V	60-Hz		Hawkins (2002)
Blacknose dace (*Rhinichthys atratulus*)	Average of 6.82cm TL		6	0		PDC, 300-V	60-Hz		Clément & Cunjak (2010)
Esocidae									
Northern pike (*Esox lucius*)	13-19 cm SL	0 (24 h)			24	AC (sine-wave)	50-Hz		Walker et al. (1994)
	13-19 cm SL	0 (24 h)			33	AC (triangular-wave)	50-Hz		Walker et al. (1994)
	52-68 cm FL		11	0		PDC	30-Hz	16-ms	Roach (1992)
	36-74 cm FL		5			PDC 100-V	30-Hz	16-ms	Roach (1992)
	36-74 cm FL		10			PDC 400-V	30-Hz	16-ms	Roach (1992)
	13-19 cm SL	0 (24 h)			0	PDC	50-Hz, 0.4-2.1-Vcm $^{-1}$	7-ms	Walker et al. (1994)
	13-19 cm SL	0 (24 h)			0	PDC	50-Hz, 0.4-2.1-Vcm $^{-1}$	7-ms	Walker et al. (1994)
	40-80 cm FL		16	19		PDC	60	8-ms	Holmes et al. (1990)
	52-68 cm FL	5-9 (30 d)	8			PDC	60-Hz	8-ms	Roach (1992)

Common name	Size	Mortality (%) and duration	Spinal injury (%)	Haemorrhaging (%)	Branding (%)	Current type / Volatage / Wave form	Frequency / Voltage gradient	Pulse width (ms) / duration(s)	Source
Northern pike continued	36-74 cm FL		12			PDC 100-V	60-Hz	8-ms	Roach (1992)
	36-74 cm FL		33	15		PDC 400-V	60-Hz	8-ms	Roach (1992)
	38-77 cm FL		28			PDC	120-hz	4.2-ms	Roach (1992)
Gadidae									
Pollock (*Pollachius virens*)	Average of 46 cm TL		60			AC [A] (sine wave)	50-Hz	12 s	Roth et al. (2003)
	Average of 46 cm TL		60			AC [A] (sine wave)	200-Hz	12 s	Roth et al. (2003)
	Average of 46 cm TL		75			AC [A] (sine wave)	500-Hz	12 s	Roth et al. (2003)
	Average of 46 cm TL		30			AC [A] (sine wave)	1000-Hz	12 s	Roth et al. (2003)
Ictaluridae									
Channel catfish (*Ictalurus punctatus*)	[D]	0- 23 (133 d)				AC	60-Hz		Ellis (1975)
Salmonidae									
Cutthroat trout (*Oncorhynchus clarki lewisi*)	45-315 g [E]		17			CDC, 200-V	1.4-Vcm $^{-1}$	5 s	Dwyer et al. (2001)
	32-479 g [E]		26.8			PDC, 100-V	50-Hz, 0.75-1.5-Vcm $^{-1}$	2-ms / 5 s	Dwyer et al. (2001)
	62-487 g [E]		30.5			CPS [C], 125-V	15-Hz	3 x 2-ms / 5 s	Dwyer et al. (2001)

Common name	Size	Mortality (%) and duration	Spinal injury (%)	Haemorrhaging (%)	Branding (%)	Current type / Volatage / Wave form	Frequency / Voltage gradient	Pulse width (ms) / duration(s)	Source
Rainbow trout (*O. mykiss*)	18-31 cm TL	0 (48 h)	5	90		AC	60-Hz		Walsh et al. (2004)
	4–36 cm SL	4.2 (short-term)				AC	60-Hz		Taylor et al. (1957)
	0.7- 2.3 kg [F]	26 (2-5 d)				AC 80-90-V (square wave)	60-Hz		Hauck (1949)
	32-47 cm FL		58	25		AC, 100-V (sine-wave)	60-Hz		Taube (1992)
	33–52 cm TL		38	54	31	AC, 250-V	60-Hz		Habera et al. (1999)
	64 cm TL		0	0	0	AC, 250-V	60-Hz		Habera et al. (1999)
	29–51 cm TL		58	67	38	AC, 250-V	60-Hz		Habera et al. (1999)
	16–26 cm TL	1 (15 d)	1		2	AC 350-V	250-300-Hz		Hudy (1985)
	32-47 cm FL		75	58		AC, 400-V (sine-wave)	60-Hz		Taube (1992)
	26–65 cm TL		40	70	40	AC, 400-V	60-Hz		Habera et al. (1999)
	35–50 cm TL		14	71	43	AC, 500-V	60-Hz		Habera et al. (1999)
	5-9.9 cm TL	15-23 (7 d)	0	3		AC 500-V	60-Hz		Habera et al. (1996)

Common name	Size	Mortality (%) and duration	Spinal injury (%)	Haemorrhaging (%)	Branding (%)	Current type / Volatage / Wave form	Frequency / Voltage gradient	Pulse width (ms) / duration(s)	Source
Rainbow trout continued	10-23 cm TL	2-9 (7 d)	3-10	0-6		AC 500-V	60-Hz		Habera et al. (1996)
	30–65 cm TL		17	67	17	AC, 600-V	60-Hz		Habera et al. (1999)
	26–48 cm TL		25	38	25	AC, 600-V	60-Hz		Habera et al. (1999)
	16–26 cm TL	2 (15 d)	2.5		2	AC 700-V	300-Hz		Hudy (1985)
	16–26 cm TL	3 (15 d)	2.5		2	AC 760-V	300-Hz		Hudy (1985)
	4–36 cm SL	0% (short-term)				CDC	>0.4-Vcm^{-1}		Taylor et al. (1957)
	32-47 cm FL	11 (30 d)	47	33	28	DC, 100-V			Taube (1992)
	Average of 13.3 FL	0 (short-term)	15			DC, 300-V	120-Hz	4-ms	Ainslie et al. (1998)
	15-18 cm TL	46 (335 d)	12			DC, 350-400-V			Dalbey et al. (1996)
	Average of 26 cm TL			86.1		CDC, 375-V	1.7-Vcm^{-1}	5 s	Schill & Elle (2000)
	Average of 19 cm TL	7.1 (2 y)				PDC	5-Hz	60-ms	Maxfield et al. (1971)
	Average of 5 cm TL	9.9 (3 y)				PDC	8-Hz	40-ms	Maxfield et al. (1971)

Common name	Size	Mortality (%) and duration	Spinal injury (%)	Haemorrhaging (%)	Branding (%)	Current type / Volatage / Wave form	Frequency / Voltage gradient	Pulse width (ms) / duration(s)	Source
Rainbow trout continued	4–36 cm SL	0.3 (short-term)				PDC (triangular-wave)	12-20-Hz		Taylor et al. (1957)
	>30 cm TL		3			PDC (square-wave)	15-Hz	4-ms	Sharber et al. (1994)
	>30 cm TL		24			PDC (square-wave)	30-Hz	4-ms	Sharber et al. (1994)
	11–23 cm TL		10.7	56.1		PDC, 300-V	30-Hz		McMichael (1998)
	6.2-9 cm TL	12.9 (1 h)				PDC (square-wave)	30-Hz, 4 Vcm^{-1}	20 s	Grizzle et al. (2003)
	Average of 13.3 FL	0 (short-term)	39		26	PDC	30-Hz, 0.1-1 Vcm^{-1}	4-ms	Ainslie et al. (1998)
	32-47 cm FL	10 (30 d)	52			PDC (square wave)	60-Hz	8.3-ms	Taube (1992)
	30-56 cm TL		44			PDC (exponential pulse)	60-Hz	4.2-ms	Sharber & Carothers (1988)
	30-56 cm TL		67			PDC (1/4 sine wave pulse)	60-Hz	4.2-ms	Sharber & Carothers (1988)
	30-56 cm TL		43			PDC (square wave)	60-Hz	4.2-ms	Sharber & Carothers (1988)
	>30 cm TL		43			PDC (square-wave)	60-Hz	4-ms	Sharber et al. (1994)
	33-35 cm TL	40 (335 d)	54			PDC, 0-400-V	60-Hz		Dalbey et al. (1996)

Common name	Size	Mortality (%) and duration	Spinal injury (%)	Haemorrhaging (%)	Branding (%)	Current type / Volatage / Wave form	Frequency / Voltage gradient	Pulse width (ms) / duration(s)	Source
Rainbow trout continued	20-47 cm TL		18	28		PDC (half sine-wave)	60-Hz	8-ms	Thompson et al. (1997a)
	21-48 cm TL		55	65		PDC (half sine-wave)	60-Hz	8-ms	Thompson et al. (1997a)
	13-51 cm TL		64	43		PDC (half sine-wave)	60-Hz	8-ms	Thompson et al. (1997a)
	14-45 cm TL		6	13		PDC (half sine-wave)	60-Hz	8-ms	Thompson et al. (1997a)
	22-50 cm TL		40	49		PDC (half sine-wave)	60-Hz	8-ms	Thompson et al. (1997a)
	14-43 cm TL		22	40		PDC (half sine-wave)	60-Hz	8-ms	Thompson et al. (1997a)
	Average of 28 cm TL			81.6		PDC, 325-V (square-wave)	60-Hz	5 s	Schill & Elle (2000)
	>30 cm TL		62			PDC (square-wave)	512-Hz	0.2-ms	Sharber et al. (1994)
Chinook salmon (*O. tshawytscha*)	10-14 cm FL		2			PDC, 300-V	30-Hz		McMichael (1998)
	Average of 19 cm	16 (56 d)	80		22	PDC	60-Hz	6-ms	Holliman et al. (2010)
	Average of 19 cm	9 (56 d)	40		12	DFPDC [G]	568 and 15-Hz		Holliman et al. (2010)
Atlantic salmon (*Salmo salar*)	50.8-67.2 cm		0			AC [A] (sine wave)	50-Hz	1 s	Roth et al. (2003)

Common name	Size	Mortality (%) and duration	Spinal injury (%)	Haemorrhaging (%)	Branding (%)	Current type / Volatage / Wave form	Frequency / Voltage gradient	Pulse width (ms) / duration(s)	Source
Atlantic salmon continued	50.8-67.2 cm		0			AC [A] (sine wave)	50-Hz	1.5 s	Roth et al. (2003)
	50.8-67.2 cm		27			AC [A] (sine wave)	50-Hz	2 s	Roth et al. (2003)
	50.8-67.2 cm		20			AC [A] (sine wave)	50-Hz	3 s	Roth et al. (2003)
	50.8-67.2 cm		40			AC [A] (sine wave)	50-Hz	6 s	Roth et al. (2003)
	7.4-11.7 cm FL		46	48		PDC	60-Hz		Clément (1996)
	3.3-15 cm FL		46	48		PDC, 300-V	60-Hz		Clément & Cunjak (2010)
Brown trout (*Salmo trutta*)	17-39 cm TL		25	30		PDC (half sine-wave)	60-Hz	8-ms	Thompson et al. (1997a)
	20-39 cm TL		18	24		PDC (half sine-wave)	60-Hz	8-ms	Thompson et al. (1997a)
	17-49 cm TL		52	45		PDC (half sine-wave)	60-Hz	8-ms	Thompson et al. (1997a)
	10-43 cm TL		27	30		PDC (half sine-wave)	60-Hz	8-ms	Thompson et al. (1997a)
	10-40 cm TL		31	13		PDC (half sine-wave)	60-Hz	8-ms	Thompson et al. (1997a)
	14-42 cm TL		38	28		PDC (half sine-wave)	60-Hz	8-ms	Thompson et al. (1997a)

Common name	Size	Mortality (%) and duration	Spinal injury (%)	Haemorrhaging (%)	Branding (%)	Current type / Volatage / Wave form	Frequency / Voltage gradient	Pulse width (ms) / duration(s)	Source
Brown trout continued	Age-1		6.9 [H]			PDC (square-wave)	100-Hz	5-ms	Kocovsky et al. (1997)
Bull trout (*Salvelinus confluentus*)	Average of 18 cm	0				CDC, 130-V			Barton & Dwyer (1997)
	Average of 18 cm	0			0	PDC	60-Hz		Barton & Dwyer (1997)
Brook trout (*S. fontinalis*)	12-24 cm TL	2 (15 d)	3		1	AC, 350-V	300-Hz		Hudy (1985)
	12-24 cm TL	2 (15 d)			2	AC, 700-V	300-Hz		Hudy (1985)
	12-24 cm TL	5 (15 d)			2	AC, 760-V	250-300-Hz		Hudy (1985)
	9.5-23.7 cm TL		13	6		AC, 125-V	250-300-Hz		Hollender & Carline (1994)
	9.5-23.7 cm TL		28	19		AC, 350-V	250-300-Hz		Hollender & Carline (1994)
	9.5-23.7 cm TL		9	8		AC, 350-V	250-300-Hz		Hollender & Carline (1994)
	9.5-23.7 cm TL		21	18		AC, 400-V	250-300-Hz		Hollender & Carline (1994)
	9.5-23.7 cm TL		3	7		PDC, 200-V (square-wave)	60-Hz		Hollender & Carline (1994)

Common name	Size	Mortality (%) and duration	Spinal injury (%)	Haemorrhaging (%)	Branding (%)	Current type / Volatage / Wave form	Frequency / Voltage gradient	Pulse width (ms) / duration(s)	Source
Brook trout continued	9.5-23.7 cm TL		26	21		PDC, 400-V (square-wave)	60-Hz		Hollender & Carline (1994)
	9.5-23.7 cm TL		8	10		PDC, 500-V (square-wave)	60-Hz		Hollender & Carline (1994)
	9.5-23.7 cm TL		11	10		PDC, 500-V (square-wave)	60-Hz		Hollender & Carline (1994)
	Age-1	0.5 (short-term)				PDC (square-wave)	100-Hz	5-ms	Riley at al. (2004)
	Age-1		5-14 [H]			PDC (square-wave)	100-Hz	5-ms	Kocovsky et al. (1997)

[A] fish were exposed to AC in seawater with a salinity of between 30–34‰. [B] The spotfin chub vertebrae were too small to allow use of X-rays for identifying injury to individual vertebrae. [C] Complex pulse system. [D] No data on size available. [E] No data on length available, so weight (g) was presented. [F] No data on length available, so weight (kg) was presented. [G] Dual-frequency PDC. [H] Spinal injury assessment conducted by external observations of spinal injuries only no X-rays or necropsies conducted; X-rays were capable of identifying gross misalignment in the spinal column.

SL: Standard length; FL: Fork length; TL: Total Length

Appendix 2: The classification and location of the spinal injury on the spine of shortfin eels that were captured by electrofishing and fyke netting which were either euthanised immediately post capture or held for 30 days after capture in Lake Rotongaro and Lake Areare

Treatment	Holding	Site	Spinal injury classification	Location of the spinal injury
Electrofishing	No holding	Lake Rotongaro	Class-2	Vertebrae 42
		Lake Areare	Class-2	Vertebrae 50
		Lake Areare	Class-2	Vertebrae 58
		Lake Areare	Class-2	Vertebrae 57 & 64
Fyke netting	No holding	Lake Rotongaro	Class-1	Vertebrae 78
Electrofishing	30 day holding	Lake Rotongaro	Class-1	Vertebrae 55
		Lake Rotongaro	Class-2	Vertebrae 55
		Lake Rotongaro	Class-2	Vertebrae 68
		Lake Rotongaro	Class-2	Vertebrae 48 & 54
		Lake Rotongaro	Class-2	Vertebrae 52 & 60
		Lake Rotongaro	Class-2	Vertebrae 44 & 95
		Lake Rotongaro	Class-2	Vertebrae 48, 50 & 67
		Lake Areare	Class-2	Vertebrae 54
		Lake Areare	Class-2	Vertebrae 47 & 50
		Lake Areare	Class-2	Vertebrae 48 & 60
		Lake Areare	Class-2	Vertebrae 52 & 57
		Lake Areare	Class-2	Vertebrae 46, 52 & 61
Fyke netting	30 day holding	Lake Rotongaro	Class-1	Vertebrae 40
		Lake Rotongaro	Class-2	Vertebrae 56
		Lake Rotongaro	Class-2	Vertebrae 63