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Site-specific selectivity of electric-fishing gear

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S.W Howard,
S.K. Crow,
P.G. Jellyman

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EXECUTIVE SUMMARY

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Electric-fishing is the primary sampling method used to monitor freshwater fish abundance in rivers and streams. This method is used because it samples populations quickly (i.e., does not require a return trip to a site), is non-lethal, and can capture the entire size range of fish present at a location. However, the capture-efficiency of this sampling technique can be influenced by a variety of environmental and technical variables (e.g., netting arrangements and electric settings on the electric fishing machine). Variation in capture-efficiency may lead to different catch-rates between sites that are not associated with population differences but rather are driven by environmental conditions; this can cause problems for researchers wishing to compare abundance between sites. The present project aims to address the objectives of the project EEL2014-02 by identifying factors that influence the capture-efficiency of eels, when sampling using electric-fishing, and explores approaches to standardise eel catch rates between sites.

To explore how variability in capture-efficiency is related to environmental, biological and technical factors an electric-fishing dataset collected from two sites located in each of three rivers in Canterbury (total of six sites) was used. The six sites were sampled with multiple-pass electric-fishing every six weeks over a three-year period (2013–2016) and stop nets were used to block off the top and bottom of the site, which prevented any fish from entering or leaving the sites while sampling was being completed. During each electric-fishing pass, fishes were removed as they were caught, and fish captured in the reach (area between the two stop nets) were kept separate from those captured in the stop-net. Sampled areas were assumed to be closed to migration during sampling because stop-nets were secured across the upstream and downstream ends of the sampled area. Stop-nets close the sampled area to migration, ensuring that the size of the sampled population is unchanged during sampling. Data relating to the number of individuals captured in each pass were then used to examine capture-efficiency and population size estimates. Removal models with both Bayesian and frequentist methods were used to identify the biological, environmental and sampling aspects (use of stop-nets) that influenced capture efficiency.

Complementary experimental work was also conducted in two Canterbury rivers investigating the depths at which shortfin and longfin elvers occur within the river bed (i.e., in the hyporheic zone). In March 2015, 18 layered baskets filled with riverine substrate were buried in the bed of the Ashley River and 15 layered baskets were buried in the bed of the Cust River. Each layered substrate basket was 400 mm deep and contained seven individual layers (about 60 mm each) with 2-cm diameter holes. Each substrate basket was constructed from perforated stainless steel with 2-cm holes to allow elvers to enter any layer; the layers were filled with gravel taken from the river bed. All baskets were left in the river for six weeks to be colonised by elvers and were then removed to examine at what depth the elvers occurred.

Removal models were successfully developed using the multiple-pass electric-fishing data collected from the six Canterbury River sites. These models identified several biological and environmental variables which influenced capture-efficiency in eels to differing degrees. For shortfin eels, fish length was a strong predictor of capture-efficiency as capture success declined sharply with decreasing fish length. A similar trend between capture-efficiency and fish length was found for longfin eels, but this relationship was much less certain. The likely cause for this uncertainty was the low number of longfin eels captured during the surveys, particularly in the smaller size classes. The results also indicated that when stop-nets were used a greater overall number of eels were usually captured, producing a greater number of fish per pass. Data from these additional individuals captured in the stop-nets reduced the uncertainty in population estimates.

In the substrate depth experiment, a total of 240 eels were captured across the two rivers. The eels in the baskets ranged in size from 70–370 mm TL. The total numbers of eels steadily declined with increasing depth/basket level, but dramatically increased by more than 10 times between the deepest two layers. Elvers occupied river substrates down to a depth of at least 400 mm, but most of the eels found were within 200 mm of the substrate surface. Unfortunately, the very high catches from the last layer of the substrate stack suggests that eels migrated down through the substrate layers as they were being separated. This behaviour was observed as the layers were separated (S.K. Crow pers. obs.), but this was unavoidable because there was no other method of separating the layers that would have completely eliminated movement between the levels. It may be possible to examine the level of movement between layers in the laboratory, but this aspect could not be completed within the time and budget constraints of the present study.

The results indicated that if stop nets were not used during a multi-pass electric-fishing survey, the population would be underestimated by 3–40%. The magnitude of the population underestimate was inconsistent between sites, but also within sites over time. The temporal and spatial variability in the stop-net catches suggests that it would be difficult to accurately monitor population changes (within or among sites) over time if stop nets were not used when sampling eel populations using electric-fishing. Furthermore, removal models also identified relationships between site-level habitat variables and the proportion of eels captured in stop nets. For example, stop-net capture rates increased, for both shortfin and longfin eels, with higher stream velocity. This may make stop-net use in fish habitat surveys particularly important where stream velocity or discharge are variables of interest. Consequently, we recommend that stop nets should always be used if accurate estimates of eel abundance are the main goal of the survey work.

Biological and environmental characteristics were found to influence the capture-efficiency of electric fishing for eels. Electric fishing was strongly size-selective in shortfin, and possibly, longfin eels, with efficiency highest in large eels. Stream depth also reduced site-level capture-efficiency while stream velocity influenced the proportion of eels caught in stop-nets (increasing stop-net captures with increasing velocity for both species).

Overall, the substrate depth experiment, stop-net and capture-efficiency modelling studies explored environmental, biological and technical aspects which influence capture-efficiency and population estimation in eel populations. Difficulties in sampling elvers are highlighted from these studies, suggesting that elvers are likely to be underestimated relative to large eels in electric-fishing surveys that do not use stop-nets and only conduct a single pass.

1. INTRODUCTION

Effective management of freshwater fish species relies on monitoring the abundance of the stock. To monitor stock size, populations are sub-sampled and catch-rates are extrapolated over a much larger area than was originally sampled. Therefore, it is critical that the population sub-sampling technique collects abundance data that are representative of the population. Estimates of stock size are usually done by generating indices of catch-rate/abundance at a site, but these indices can vary with a variety of environmental factors (e.g., habitat conditions, water chemistry). Failure to account for these confounding effects when examining trends in abundance indices between sample sites, or from the same site over time, can result in misleading estimates of stock size and lead to ill-advised management decisions.

Electric fishing is one of the most widely used techniques to monitor freshwater fish abundance in rivers and streams because it can capture a large proportion of the population quickly and is non-lethal. However, the capture-efficiency of this sampling technique can be influenced by a variety of biological, environmental and technical variables (Reynolds & Kolz, 2012). Environmental variables influencing capture-efficiency usually relate to chemical and physical aspects of the fish's habitat, which influences the ability of the electric-field to immobilise the fish and/or the ability of the operator to capture the immobilised individuals (Peterson et al. 2004, Hense et al. 2010). Biological variables, such as aspects of the fish's behaviour or population characteristics, dictate how likely the individuals are to evade the electric-field. For example, electric-fishing capture-efficiency increases with fish body size (Peterson et al. 2004, Dauwalter & Fisher, 2007, Hense et al. 2010, Korman et al. 2011, Hedger et al. 2013), but will decrease with increasing population density (Hansen et al. 2004). The different habitats occupied by fishes and differences in their behaviour also means that capture-efficiencies differ between species (Price & Peterson, 2010). Technical aspects that influence electric-fishing capture-efficiency refer to the sampling methodology and equipment used by the operator(s). The variety of methodological and technical combinations available results in different approaches being adopted in the field, which has differing effects on capture-efficiency (Price & Peterson, 2010).

Repeat electric-fishing data can be used to develop abundance estimates that account for differences in capture-efficiency between sites. These multi-pass depletion catch data are used to generate statistical estimates of total fish abundance within the sampling unit. These statistical estimates allow researchers to generate an index of abundance that is minimally influenced by any of the biological, environmental or technical aspects that influence capture-efficiency. The population estimates can then be used to monitor and compare abundance between and within sites over time. Unfortunately, multi-pass catches are not entirely free of sampling bias (Peterson et al. 2004) and they are labour intensive (David et al. 2010). Consequently, electric-fishing sampling is often only done with a single-pass and used to generate an index of abundance or catch-per-unit-effort at a specific site. While these indices of relative abundance can be generated quickly, they do not account for all of the processes that influence capture-efficiency between sites. Moreover, it has previously been suggested that single-pass catches do not accurately estimate the fish assemblage structure at a site (Pusey et al. 1998).

New Zealand has a large collection of electric-fishing data that could be used as a fishery independent source of information for monitoring stocks of longfin (*Anguilla dieffenbachii*) and shortfin (*A. australis*) eels. These data include repeatedly sampled sites spanning periods of up to 30 years (NIWA unpublished data) and approximately 1000 single-pass sampling events that are completed each year throughout New Zealand. These data are stored in the New Zealand Freshwater Fish Database (NZFFD). Despite the large amount of data available, few analyses have been made available to fisheries managers because the surveys have not used a consistent methodology. Whilst recent national guidelines now exist that attempt to minimise the effect of technical aspects on capture-efficiency (Joy et al. 2013), these guidelines do not eliminate the need to account for the environmental and biological aspects that influence capture-efficiency. For eels, the factors that influence capture-efficiency are still poorly understood (but see Graynoth et al. 2012). Most of the catch data available in the NZFFD are from single-pass surveys so it is not possible to calculate capture-efficiency and reduce confounding in between-site comparisons. This lack of information on factors influencing capture-efficiency, combined with no available method of accounting for differences in capture-efficiency between sites, has led to the minimal use of these data in eel management decisions. This is because variability in capture-efficiency between- and within-sites compromises any comparisons of catch rates and size/age composition of the catch. This is a valid criticism of these electric-fishing data (Haro et al. 2015) that needs to be addressed before this information can be used to compare abundance between sites and act as an unbiased, robust source of fishery independent information for monitoring stocks.

The present project aims to address the objectives of the project EEL2014-02 by identifying the environmental, biological and technical factors that influence electric-fishing capture-efficiency of eels and explore approaches to standardise catch rates. The specific research objectives of EEL2014-02 are:

Overall Research Objective:

1. To determine factors affecting the site-specific selectivity of electric fishing gear for longfin and shortfin eels.

Specific Research Objectives:

1. To determine the influence of habitat and the biology of shortfin and longfin eels on electric fishing efficiency;
2. To investigate methodological aspects that influence efficiency of electric fishing when targeting longfin and shortfin eels.

We addressed each of the two Specific Research Objectives with a series of field experiments and modelling exercises. For Specific Research Objective 1 we completed two tasks: an electric-fishing model and an elver substrate depth experiment. For Specific Research Objective 2 we completed an analysis that explored the effects of stop nets on catches. Because each of these tasks required different methodologies and analyses, the methods and results sections are separated into three sub-sections that correspond to the three tasks.

2. METHODS

2.1 Electric-fishing model

Electric fishing catch data were collected at two sites from each of three rivers (six sites in total) in Canterbury, New Zealand (Figure 1) over three and a half years between November 2012 and March 2016. For each sampling trip, fishing locations within sites were randomly assigned to two of 15 transects that were spaced at 10 m intervals covering a 150 m stretch of river. The two transects were randomly stratified to include a fast-shallow water habitat (riffle) and a slightly slower and deeper water (run) habitat. Transects used for sampling were alternated between sampling occasions so fishing locations were not re-fished in consecutive sampling rounds. Sampling was completed at approximately six-weekly intervals, although the precise timing of sampling was weather and flow dependent. Sampling was postponed during high rainfall and flows and sampled when flows subsided as close as possible to scheduled sampling.

At each of the selected transects, a 15-m reach (about 7.5 m above and about 7.5 m below the transect) of river was electric-fished across the full width of the river. Stop-nets (4 mm mesh) were installed at the upstream and downstream ends of the reach to prevent immigration/emigration of fish. The blocked reach was fished using a Kainga EFM 300 backpack electric-fishing machine (NIWA Instrument Systems, Christchurch, NZ) by systematically covering the entire area, with at least three passes. Fish were removed from the reach as they were encountered, and fish collected from different passes and from stop-nets were held separately. For each pass, the fish caught in the reach were kept separate from those fish caught in the downstream stop-net.

Habitat variables were measured at each site visit for the two fished reaches, these variables included: substrate, depth, velocity, width, temperature and conductivity. Percentage cover of substrate size classes were visually estimated and summarised as a composite substrate index using the weighted sum of size classes. The index assigns large and small substrates, high and low indices respectively. Depth and velocity were measured at five representative points across each reach and summarised as a mean. Velocity was measured at 0.6 depth using a velocimeter (Marsh-McBirney Flo-Mate 2000, Frederick, MD, U.S.A). Stream width was measured upstream, downstream and in the centre of the reach and summarised as a mean. Conductivity and stream temperature were measured using a handheld meter (TPS WP-81) from the centre of the reach.

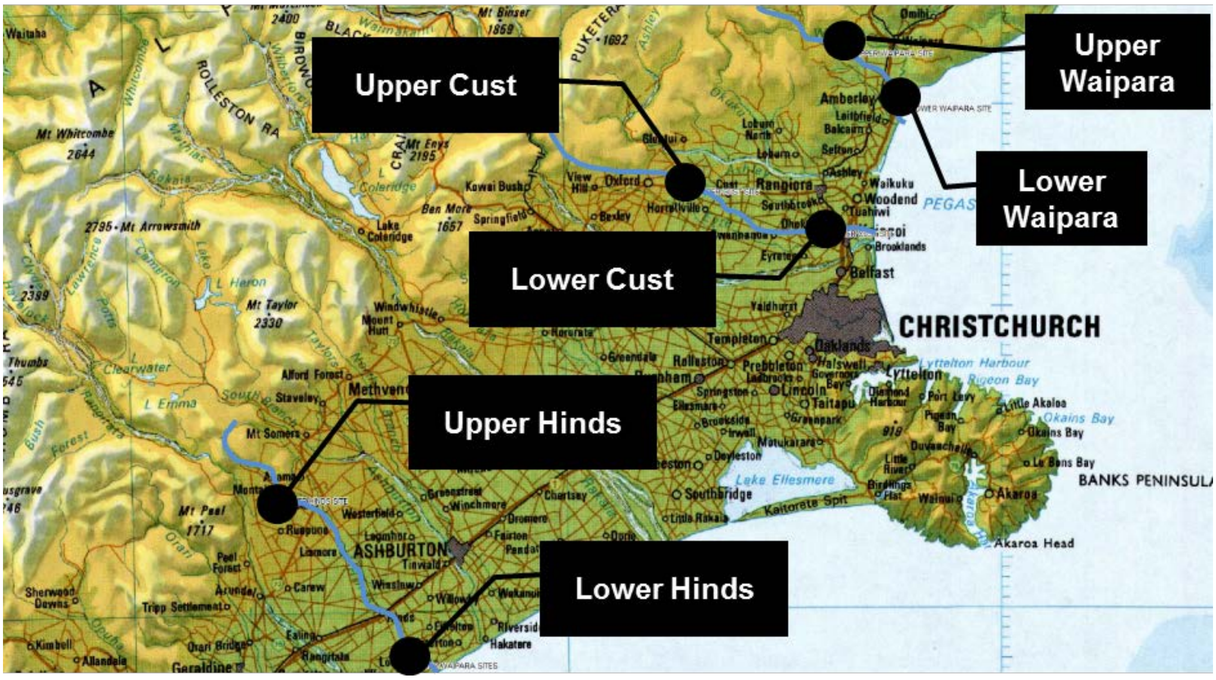

Figure 1: Locations of the six electric-fishing sites that were sampled for the study.

2.1.1 Modelling

Initial electric-fishing models presented to the Eel Working Group (EWG) in 2016 were based on mixed-effects Generalised Linear Models, but an alternative approach using a Bayesian analysis was suggested by the EWG. The following section details the Bayesian analysis only.

Removal models were used to model capture-efficiency using both Bayesian and frequentist methods. To aid in the implementation of these models using a Bayesian framework, we used parameter-expanded data augmentation (PX-DA, Royle & Dorazio, 2012). This technique adds an arbitrarily large number of zero capture observations to the dataset, expanding the potential number of sampled animals well beyond the number of captures. Collectively, actual and augmented capture histories produce a superpopulation of individuals comprising captured and uncaptured individuals, a proportion of which represents the sampled population.

Table 1: Descriptions of capture-type classes within the parameter-expanded data augmentation (PX-DA) framework.

Type	Captured	Missed	Unavailable
Captured	Yes	No	No
Capture history	Observed	Unobserved	Unobserved
Number	Fixed	Variable proportion	Variable proportion
Within sampled population (available for capture)	Yes	Yes	No

An additional inclusion probability parameter (ψ) was then used to capture the process whereby individuals are included or excluded from the sampled transect, a proportion of which are 'true' zeroes (i.e., individuals which were undetected, 'Missed' in Table 1). Models were of the general form:

$$y_i \mid z_i = 1 \sim \mathrm{Bern}(z_i . \pi_i)$$
$$y_i \mid z_i = 0 \sim 0$$
$$z_i \sim \mathrm{Bern}(\psi_j)$$

Where individual captures are a product of a latent parameter z_i which indicates whether an individual is included in the sampled population, and capture probability (π_i). Capture histories (y_i) over multiple passes were expressed as a binary indicator for each individual and when removed from the reach were treated as captured for all remaining passes (i.e., 111, 011 or 001 individuals captured on the first, second or third passes respectively). Capture efficiency and inclusion probability were given vague uniform priors ($\mathrm{Uniform}(0,1)$). The removal structure was induced in the model by setting capture probability for subsequent passes to 1 for previously captured individuals.

Exploratory intercept-only models were first fitted to determine the effects of site and season on overall capture-efficiency (Models 1 and 2, Table 2). These exploratory models ignored the effects of fish size on capture-efficiency, primarily to assess whether site and season should be included in more complex covariate models. Individual covariate models included slope terms to model relationships between fish length and capture-efficiency. Capture-efficiency relationships with fish length were expressed as a logit-linear function:

$$\mathrm{logit}(\pi_i) = \alpha + \beta . x_i$$

where individual capture efficiencies (π_i) are a function of fish length (x_i) and a slope parameter (β) with intercept (α). Comparisons between fixed and site-varying slopes and intercepts were compared using Models 3 and 4 (Table 2). Missing fish lengths for captured and uncaptured fish were modelled as a log-normal distribution $x_i \sim \mathrm{Norm}(\mu, \sigma)$ where parameters μ and σ were estimated from the observed lengths and had prior distributions of $\mu \sim \mathrm{Unif}(-10{,}10)$ and $\sigma \sim \mathrm{Unif}(0{,}10)$ respectively.

Table 2: Model number and descriptions.

Model		**Description**
1	$\eta = \alpha_j$	Intercept-only, capture-efficiency varies by site (j)
2	$\eta = \alpha_k$	Intercept-only, capture-efficiency varies by season (k)
3	$\eta = \alpha + \beta x$	Fish length covariate-model, single-intercept (α) and slope (β)
4	$\eta = \alpha_j + \beta_j x$	Fish length covariate-model, intercept (α_j) and slope (β_j) varies by site (j)
5	$\gamma_j = \alpha + \beta_{site} X_{site}$	Hierarchical site- and fish length- covariate model
	$\eta = \gamma_j + \beta_{length} X_{length}$	Site-level capture-efficiency (γ_j) is a function (β_{site}) of site-level covariates (X_{site}) and individual capture-efficiency within sites are a function (β_{length}) of size class (X_{length})

Relationships between site-level covariates and capture-efficiency were modelled using a hierarchical model which separated capture-efficiency associated with sampling occasion from those associated with fish length (Model 5, Table 2). At the top-level, site-level capture probability (γ_j) was a logit-linear function of site covariates (X_{site}, Table 3). Within-site capture probabilities associated with fish length were modelled as frequencies of binned size classes (see Table 7 for size classes) to reduce computational run times. Size-class bins increased with fish length to capture the exponential relationship between length and capture-probability, concentrating the number of bins towards smaller fishes. Size-class categories differed between species and are shown in Table 7. The frequency of captures for each size class was used as a response and class categories were coded as dummy-variables for analysis (X_{length}). Within transects the hierarchical model was of the general form:

$$y_p \sim \mathrm{Bin}(z_p, \pi)$$

$$z_p = n - \sum_{i=0}^{p-1} y_i$$

where the number of captures (y_p) in pass p is a binomial draw from the number of individuals available for capture at the start of the pass (z_p). The individuals available for capture are updated between passes by subtracting the sum of captures in previous passes. This was repeated for each size class and reach and stop-net captures within each transect using capture-efficiency (π) which was a logit-linear function of size-class slopes (β_{length}) and dummy variables identifying factors (X_{length}) for each j transect:

$$\mathrm{logit}(\pi) = \gamma_j + \beta_{length} \cdot X_{length}$$

Site-level capture-efficiency was used as the intercept (γ_j) within each transect and was a logit-linear function of site-covariate slopes (β_{site}) and covariate values X_{site}:

$$\gamma_j = \alpha + \beta_{site} . X_{site}$$

Individuals available for capture within the reach or stop-net captures were treated as separate within each transect. Individuals available within the reach (n_{reach}) were binomially-distributed from the total number of individuals available for capture (N) and reach-capture probability (φ). Remaining individuals were available for stop-net capture (n_{stop}):

$$n_{reach} \sim \text{Bin}(N, \varphi)$$
$$n_{stop} = N - n_{reach}$$

Furthermore, because site-level covariates could also influence stop-net capture a logit-linear relationship between proportion of captures within a reach (φ) was treated as a function of mean-centered and scaled site-level covariates (Table 3) for each transect following:

$$\text{logit}(\varphi) = \alpha + \beta_{\varphi}.X_{site}$$

where β_{φ} is a vector of slopes representing the linear relationship between reach habitat variables and logit-transformed reach capture proportion (φ). The total number of individuals available for capture within a transect (N) was Poisson-distributed and given a log-normal prior $\alpha \sim \text{Norm}(0, 10)$:

$$N \sim \text{Pois}(\lambda)$$
$$\lambda = e^{\propto}$$

Table 3: Reach habitat variables and summary statistics for sampled transects containing shortfin and longfin eels. SD = standard deviation.

Habitat variable	Mean	SD	Range
Substrate index (unitless)	5.2	0.4	3 – 6.5
Depth (cm)	23.9	10.5	1 – 53
Velocity (m/s)	0.5	0.2	0 – 1.2
Stream width (m)	9.8	3.3	2.35 – 24.1
Water temperature (°C)	14.8	3.5	3.8 – 26.2
Conductivity (µS)	217.7	76.6	20.3 – 532

Model fitting

Modelling structures were kept constant, but were fit in two separate modelling programmes, MARK and JAGS in R, primarily to examine consistency between the results. Models were then fit using the JAGS Gibbs sampler (v4.2.0) using the ‘R2jags’ and ‘rjags’ packages (Su & Yajima 2015, Plummer 2016) in R (R Core Team 2017, v3.4.3).

Similarly, structured models were run under ‘Program MARK’ (White & Burnham 1999, v8.2), a frequentist modelling platform for mark-recapture data using the ‘RMark’ R package (Laake 2013). Capture occasions with fewer than five shortfin eel captures were excluded from analysis to reduce the total number of modelled reaches, improving computational run times. However, because longfin eel capture rates were low, all longfin eel sample occasions were included for analysis. Models fit in JAGS were run for 75 000 iterations across three separate chains. The first 25 000 iterations were discarded and a thinning rate of 25 was used on posterior distributions. Model convergence was assessed using visual plots of posterior distributions and the Rubin-Gelman statistic as implemented in JAGS to test for mixing of chains.

Each model fitting method has advantages and disadvantages. MARK for example, requires the same number of recaptures (passes) at each replicate population. However, Bayesian methods are highly adept at fitting models to missing and ragged data structures (Dorazio

2016). Conversely, MARK uses log-likelihood optimisations on capture data, which is much faster than JAGS, which requires both data-augmentation of additional zero-captures, increasing dataset size, and longer run times. A further advantage of Bayesian analyses is a full accounting of uncertainty in estimated parameters. This comes from incorporating all sources of uncertainty into models and allows direct probability statements to be made about model parameters (Dorazio 2016). Differences in the two approaches is reflected in the terminology used to describe uncertainty in estimated parameters. Frequentist approaches express uncertainty in estimated parameters as confidence intervals which represent the expected frequency of population parameter estimates from future samples. Bayesian credible intervals are quantiles of the posterior distribution of the estimated parameter and allow direct probability statements to be made about the parameter. For example, if 950 out of 1000 values for a parameter estimate are greater than a given value, say 0, then the (one-tailed) credible interval would be 0 and a statement like '… the probability of the parameter being greater than zero is 95%' can be made. The equivalent statement for a 5% confidence interval of zero would be '… repeated samples of the population would yield parameter estimates greater than zero for 95% of the samples' and describes the distribution of the population parameter. While credible and confidence intervals represent differing statistical approaches, for most applications the intervals will be similar for large sample sizes (Casper et al. 2018).

2.2 Substrate depth experiment

The aim of this experiment was to examine the substrate depth occupied by elvers and the effective catching distance of an electric-fishing machine for elvers. In March 2015, we buried 18 layered baskets filled with riverine substrate into the bed of the Ashley River and 15 layered baskets into the bed of the Cust River. Each layered substrate basket was 400 mm deep and contained seven individual layers (about 60 mm each) with 2 cm diameter holes (Figure 2). Each substrate basket was constructed from perforated stainless steel with 2-cm holes to allow elvers to enter any layer; the layers were filled with gravel taken from the river bed.

Figure 2: Substrate baskets installed into the Ashley and Cust Rivers.

Substrate baskets were installed into the river so that the top layer was flush with the river bed and only the two metal handles were exposed. After baskets were installed, they were left in-situ for six weeks so that eels could colonise the layers. After six weeks, all substrate baskets were removed, and eels present in each layer were identified to species level and measured for total length. To prevent eels moving between layers when the baskets were extracted, each layer was placed into an individual container immediately after the baskets were removed from the water. Separating the layers was completed by firstly extracting the entire stack and placing this into a container, secondly each layer was removed and placed into an individual container. Three people separated the layers into individual containers while one observer watched each of the layers as they were separated to check for any eels escaping from the sides or moving between layers. The removal of the basket and separation of the layers into individual containers took less than 10 s. Once the baskets were removed, the area adjacent to the baskets were three-pass electric-fished to estimate elver densities.

We then mapped the electric-field density of a Smith-Root LR24 electric-fishing backpack (set to 135 volts, pulse frequency of 60 Hz, pulse width of 3 ms; reading 0.1 amps) by measuring the voltage differential over 10 cm, every 10 cm for 1.8 m. Measurements started from the anode (source of electric-field) and moved away perpendicular to the electric-field. We then electric-fished about 50 m^2 of the Ashley River and watched for any elvers (less than 150 mm total length) that were affected by the electric field. When elvers were spotted being affected by the electric field, the electric-fishing operator stopped moving and attempted to capture the elver. After the fish was captured/escaped, the voltage differential over 10 cm was measured at the point the fish was first seen. The level of response displayed by the fish and the operator's ability to capture the fish was then scored from 1–5 using the behavioural descriptions provided in Table 4.

Table 4: Descriptions of behavioural scores assigned to swimming behaviours and the electric-fishing machine operator's ability to capture elvers.

Behavioural score	Description of capture and swimming behaviour
1	Elvers able to escape capture and displaying full control of all swimming movements
2	Elvers just able to escape capture and displaying partially impaired swimming movements
3	Elvers able to be captured easily and displaying mostly impaired swimming movements
4	Elvers able to be captured easily and displayed only brief movement before all movements were suppressed (tetany)
5	Elvers able to be captured easily and all movements instantly suppressed

2.3 The effects of stop-nets on catches

We used the dataset outlined in Section 2.1 to examine how many fish were captured in stop-nets and what influence using these nets had on population estimates. Stop-nets (or block-nets) are used to completely cover the upstream and downstream end of a sampling site to prevent fish movement in and out of the sampling reach. Installing stop-nets can be labour intensive, which means that surveys often do not utilise these nets to isolate the sampling reach. For each site, catch data were recorded separately from within the site and from the stop-net, for each of the three passes. Population estimates for both eel species and total fish count (all species present) were then calculated with and without stop-net catches. To examine the differences between sites and variability associated with time-of-year, the magnitude of the difference between population estimates with and without stop-net catches included was calculated separately for each site during a sampling trip.

3. RESULTS

3.1 Electric fishing model

Exploratory models showed that capture-efficiency across sites was similar for both shortfin and longfin eels (Figure 3). Capture-efficiency for longfin eels was similar across all sites but could not be estimated for Cust River - upper, Hinds River (lower and upper) and Waipara River - lower sites (Figure 3). This is due to the low number of captured longfin eels at these sites (Table 5). In sites with sufficient captures, Cust River - lower and Waipara River - upper, capture-efficiencies for the two species were similar, with overlapping credible intervals (Figure 3). Capture-efficiencies between sites were broadly similar for shortfin eels and very similar between sites for longfin eels. Similar results were found for seasonal differences, where capture-probability estimates overlapped across seasons for both longfin and shortfin eels informing further models where site and seasonal effects were omitted. Model complexity increased as relationships between capture efficiency and covariates were added to the base model. Relationships between individual and site-level covariates (fish length) were modelled before combining individual covariates into models which also included site-level covariates (stream depth, velocity, width, substrate size, temperature and conductivity).

Table 5: Captured eel numbers for each species and site.

Species	Cust River		Hinds River		Waipara River		Total
	Lower	Upper	Lower	Upper	Lower	Upper	
Shortfin eel	2081	132	17	0	568	208	3006
Longfin eel	130	14	10	0	14	141	309

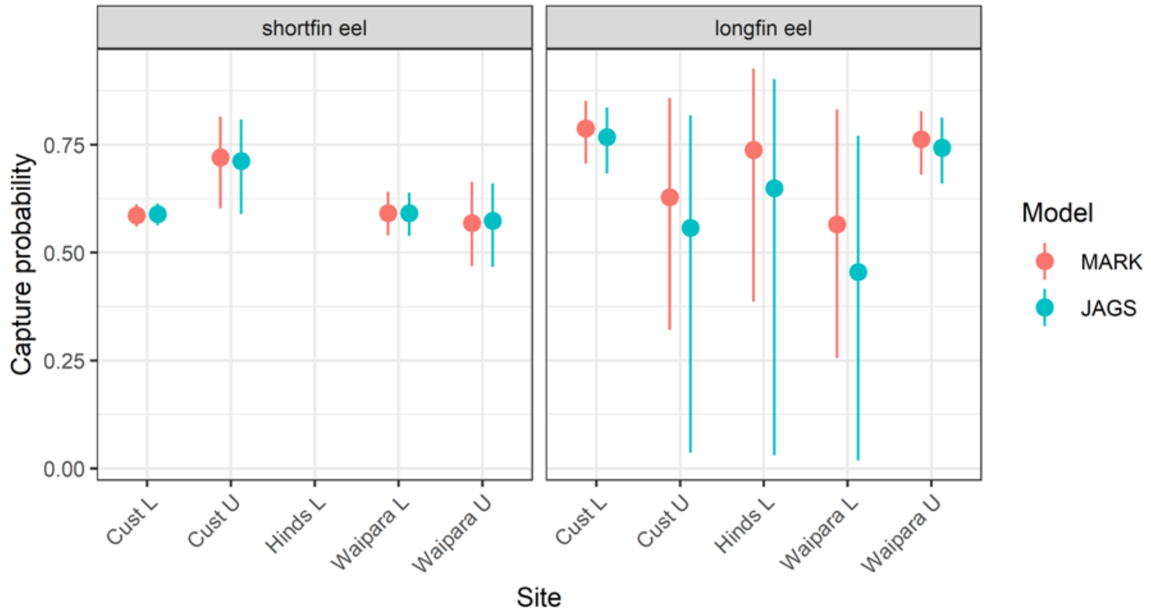

Figure 3: Capture probability estimates by site. Plots are fitted values for the site-only (Model 1). Circles represent model fits from estimated parameters and error bars represent 95% credible and confidence intervals. Note, no data for Hinds River – upper site are shown because no eels were ever captured.

3.1.1 Individual covariates (Models 3 and 4)

Fish length had a positive relationship with capture probability for shortfin eels and a positive relationship for longfin eels was also likely (Figure 4). The slope estimate for the shortfin eel relationship was 0.68, 95% credible intervals for the slope were 0.45 – 0.91 and did not overlap zero providing evidence that fish size influenced capture-efficiency. Differences in the total numbers of captured eels between the two species (Table 5) is likely to account for differences in the certainty of the relationship between capture-efficiency and fish length, with many more captures of shortfin eels allowing a better assessment of the relationship between capture-probability and fish length.

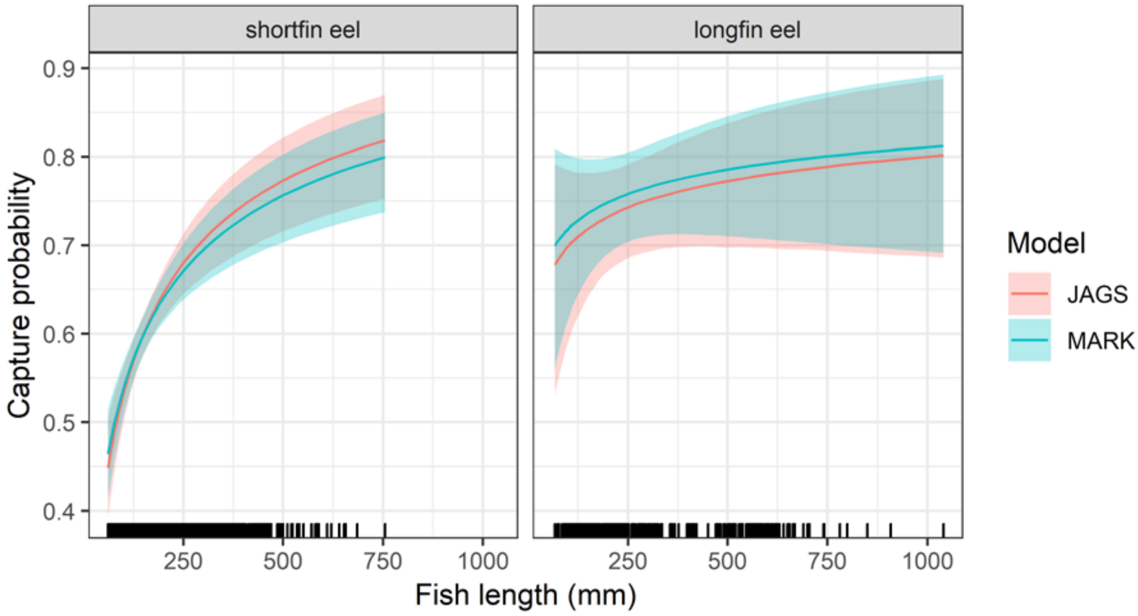

Figure 4: Relationship between eel length and capture probability. Plots are fitted values for the covariate-only (Model 3). Shaded areas represent 95% credible and confidence intervals and lines represent model fits from estimated parameters. Individual lengths of captured fishes are shown as ticks along the horizontal axis.

The length range differed between the two species. Captured shortfin eels ranged between 60 mm and 755 mm, while longfin eels ranged between 67 mm and 1040 mm. Estimated capture probability for the largest captured shortfin eel ($\pi = 0.82$, 755 mm) was almost double that of the smallest ($\pi = 0.45$, 61 mm). The relationship between fish size and capture efficiency is, furthermore, exponential, with log-transformed eel length as the predictor, making declines in capture-efficiency in small eels especially pronounced. For example, the decline in capture-efficiency from a 300 mm to a 60 mm eel is 36%, while declines from large shortfin eels (600 mm) to moderately sized eels (300 mm) were only 11%.

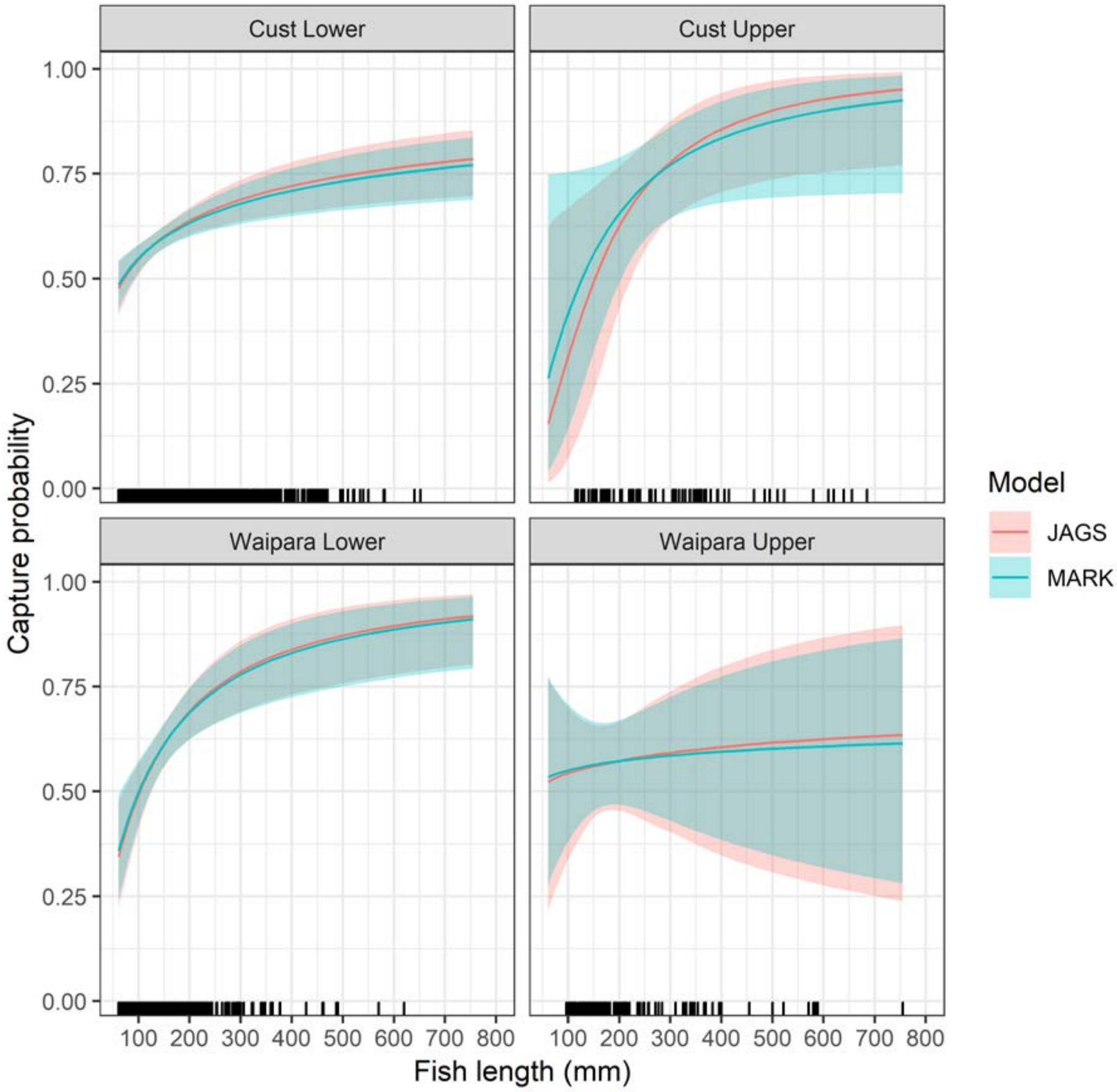

Figure 5: Relationship between shortfin eel capture probability and length for Model 4, where intercepts and slopes of the capture relationship with length are allowed to vary by site. Shaded areas represent 95% credible and confidence intervals and lines represent model fits from estimated parameters. Individual lengths of captured fishes are shown as ticks along the horizontal axis. Note that the fitted relationship is shown across the range of length values for all sites, even where smaller eels were not captured. Note the Hinds river was not included because no shortfins were captured at either of the two sites.

A more flexible covariate model, with varying intercepts and slopes for each site (Model 4), found similar positive relationships between fish length and capture probability (Figure 4, Figure 5). These relationships were strong for Cust River - lower and Waipara River - lower sites while low captures (Table 5) produced uncertain relationships for Cust River - upper and Waipara River - lower. Overall, site relationships from Model 4 (Figure 5) had similar slopes and intercepts to Model 3 (Figure 4). However, Model 3 allowed capture information to be shared across sites, allowing a better assessment of the relationship between capture probability and fish length. Therefore, combined intercept and slopes for all sites were used for more complex models.

3.1.2 Hierarchical model: individual & site covariates (Model 5)

A hierarchical model which included site-scale habitat variables and a process for separating reach capture proportions (Model 5) found that overall capture-efficiency was related to reach habitat variables for both eel species (Table 6). In shortfin eels, the credible intervals for stream velocity did not overlap zero indicating that capture-efficiency increased with velocity for shortfin eels (Table 6). In longfin eels, capture-efficiency increased with water temperature but there was little evidence for relationships between capture-efficiency and the other habitat variables examined (Table 6). However, uncertainty in the relationships for longfin eels was much greater than for shortfin eels, reflecting the reduced catch rates of longfin eels during the study (Table 5).

Table 6: Slopes of capture-efficiency relationships with reach habitat variables for Model 5. Estimates are for the mean values and standard deviation from the posterior distribution and credible intervals (CI) are quantiles from the posterior distribution.

Species	Habitat variable	Mean	SD	$CI_{2.5\%}$	$CI_{97.5}$
Shortfin eels	Substrate index	0.04	0.07	-0.09	0.17
	Depth	-0.09	0.05	-0.20	0.01
	Velocity	**0.15**	**0.06**	**0.04**	**0.26**
	Stream width	-0.04	0.05	-0.15	0.07
	Water temperature	0.11	0.07	-0.03	0.25
	Conductivity	0.04	0.07	-0.09	0.18
Longfin eels	Substrate index	-0.20	0.18	-0.55	0.14
	Depth	-0.36	0.19	-0.74	0.00
	Velocity	-0.37	0.19	-0.75	0.01
	Stream width	-0.23	0.19	-0.62	0.15
	Water temperature	**0.53**	**0.22**	**0.10**	**1.00**
	Conductivity	0.00	0.25	-0.48	0.47

Size-class capture probabilities broadly followed the patterns found in the continuous length covariate models above (Models 3 and 4; Figure 4 and Figure 5) with increasing capture-efficiency for larger size classes (Table 7). Shortfin eel capture efficiencies differed between the smallest and largest size classes (Table 7). In longfin eels, estimates of capture-efficiency contained a high degree of uncertainty and size-class differences in capture-efficiency were unclear because the estimates overlapped for both the smallest and largest size classes (Table 7).

Table 7: Size-class capture probabilities for Model 5. Estimates are for the mean values and standard deviation from the posterior distribution and credible intervals (CI) are quantile values. The number of eels captured in each size class (n) is also shown. Note that the smallest size class for longfin eels combines the two smallest shortfin eel size classes.

Species	Size class	Size range	n	Mean	SD	$CI_{2.5\%}$	$CI_{97.5}$
Shortfin eel	< 90 mm	< 90	339	0.49	0.04	0.41	0.56
	> 90 mm	91–120	911	0.55	0.02	0.51	0.60
	> 120 mm	121–150	496	0.58	0.03	0.52	0.63
	> 150 mm	151–250	765	0.66	0.02	0.62	0.70
	> 250 mm	251 +	331	0.68	0.03	0.62	0.74
Longfin eel	< 120 mm	< 120	41	0.52	0.13	0.23	0.74
	> 120 mm	121–150	52	0.70	0.08	0.52	0.84
	> 150 mm	151–250	69	0.75	0.07	0.60	0.86
	> 250 mm	251 +	147	0.81	0.04	0.72	0.87

Reach capture proportions were high for both shortfin (Mean = 0.85; $CI_{2.5}$ = 0.83, $CI_{97.5}$ = 0.87) and longfin eels (Mean = 0.73, $CI_{2.5}$ = 0.67, $CI_{97.5}$ = 0.78). The proportion of reach captures decreased with increasing velocity for both species (Table 8). Increasing depth and substrate index were associated with increasing reach capture proportions for shortfin eels (Table 8). Reach capture proportions declined sharply with increasing stream width in longfin eels, but a similar relationship was not found for shortfin eels (Table 8).

Table 8: Slopes of reach capture proportion relationships with reach habitat variables for Model 5. Estimates are for the mean values and standard deviation from the posterior distribution and credible intervals (CI) are quantiles from the posterior distribution. Slope estimates with credible intervals which do not overlap zero are shown in bold.

Species	Habitat variable	Mean	SD	$CI_{2.5\%}$	$CI_{97.5}$
Shortfin eels	**Substrate index**	**0.23**	**0.09**	**0.06**	**0.41**
	Depth	**0.50**	**0.08**	**0.35**	**0.67**
	Velocity	**-0.77**	**0.08**	**-0.92**	**-0.61**
	Stream width	-0.05	0.06	-0.18	0.07
	Water temperature	0.15	0.08	-0.01	0.31
	Conductivity	0.10	0.08	-0.07	0.26
Longfin eels	Substrate index	0.13	0.17	-0.20	0.46
	Depth	0.15	0.18	-0.21	0.52
	Velocity	**-0.88**	**0.18**	**-1.24**	**-0.54**
	Stream width	**-0.76**	**0.19**	**-1.14**	**-0.39**
	Water temperature	0.15	0.20	-0.23	0.52
	Conductivity	-0.09	0.20	-0.47	0.31

3.2 Substrate depth experiment

A total of 225 eels were captured from the Ashley River during the substrate depth experiment whereas only 15 eels were captured from the Cust River (Table 9). Given the low numbers of eels found from the Cust River, we do not consider results from this site any further and focus on the Ashley River only. Eels captured from the Ashley River ranged in size between 70–370 mm. The mean ± standard error (SE) depth of substrate occupied by all shortfins (n=196) and longfins (n=29) was 138 ±10 mm and 130 ±10 mm, respectively (Table 10). When only elvers (i.e., eels under 150 mm) are considered, the mean ±SE depth of shortfin elvers (n=152) was 143 ±10 mm compared to a mean depth for longfin elvers (n=6) of 160 ±65 mm.

The highest number of eels (all sizes and species) was found in level 7 (n=87), the deepest of all the layers. This number of eels was more than twice that observed in any of the other layers. Given that the total numbers of eels steadily declined with increasing depth/basket level, but dramatically increased by more than 10 times between layer 6 and layer 7, it appears that the high numbers of eels in level 7 are a result of eels moving down through the layers while they were being separated. If layer 7 catches are ignored, the highest numbers of shortfins was found in layer 1 while the highest number of longfins was found in level 2. This suggests that longfins may utilise slightly deeper substrates than shortfins.

Table 9: Number of eels and elvers found occupying each of the levels in the substrate baskets from the Ashley River.

Basket level	Approximate substrate depth (mm)	All shortfins	All longfins	Shortfin elvers (<150 mm)	Longfin elvers (<150 mm)	All eels
1	0–57	36	2	34	2	38
2	57–114	20	10	11	1	30
3	114–171	22	6	15	1	28
4	171–228	18	3	12	1	21
5	228–285	12	1	8	0	13
6	285–342	8	0	6	0	8
7	342–399	80	7	66	1	87

Table 10: Mean and standard error (SE) of substrate depth occupied by eels in the Ashley River for all baskets combined.

	All shortfins	All longfins	Shortfin elvers (<150 mm)	Longfin elvers (<150 mm)	All eels
Mean depth (mm)	138	130	143	160	137
SE depth (mm)	10	24	12	65	9

The voltage differential on the electric-fishing machine decreased exponentially as distance from the anode increased (Figure 6). Our ability to effectively stun and capture elvers in the Ashley River increased with electric-field density (Figure 7). A response index score of 3 was considered to be the minimum score where an elver was captured consistently, which was observed at a mean electric-field density of 0.34 volts/10 cm (Table 11). The distance away from the anode where this electric-field density could be found was 50 cm, which suggests that the maximum effective catching distance of elvers was up to 50 cm away from the anode. A response index of 4 had an effective catching distance of 40 cm while a response index of 5 had an effective-catching distance of only 18 cm (Table 11).

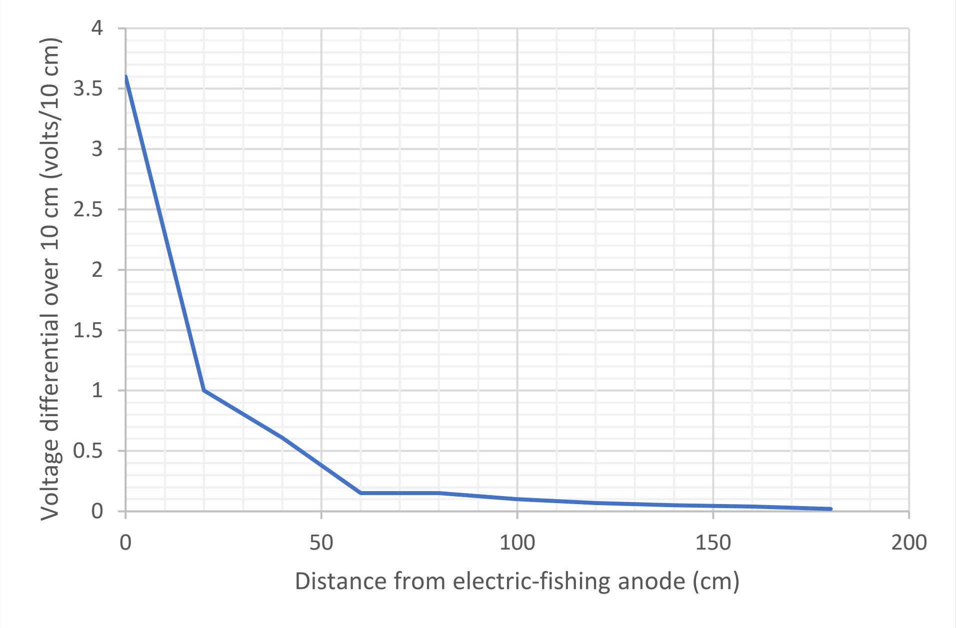

Figure 6: Density of the electric-field for a Smith-Root LR24 electric-fishing backpack.

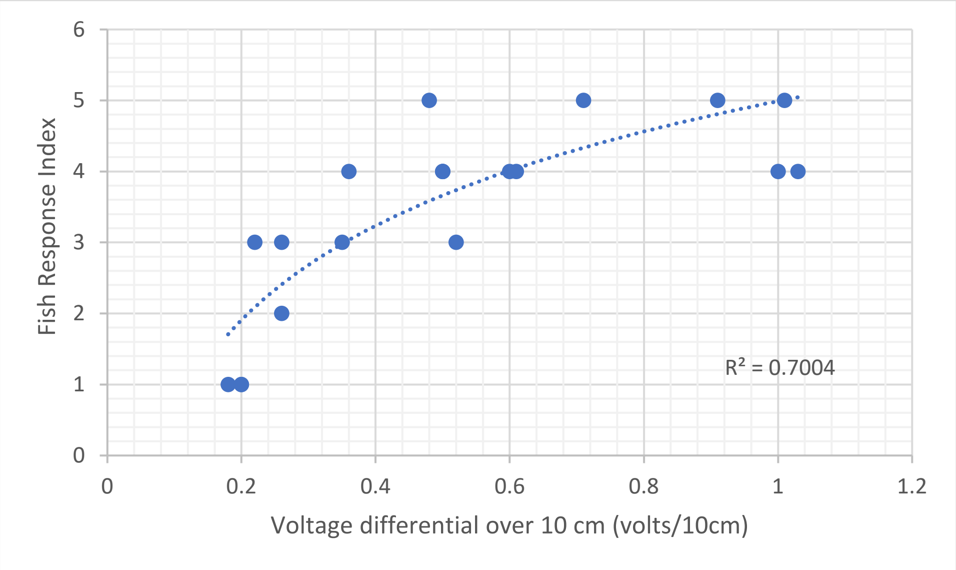

Figure 7: Relationship between fish response index (see Table 2) and electric-field density.

Table 11: Summary of mean electric-field density that generated each category of fish response, and the corresponding distance from the anode this electric-field density was found (calculated from the relationship in Figure 6).

Fish response	Mean electric-field density (v/10 cm)	Distance away from the anode (cm)
1	0.19	80
2	0.26	55
3	0.34	50
4	0.64	40
5	1.24	18

3.3 The effect of stop-nets on electric-fishing catches

The difference between population estimates (for all fish species and for eels only) calculated with and without stop-net catches varied between sites and within sites over time (Figure 8 and Figure 9). For total fish catch, the magnitude of the difference between population estimates for each sampling trip varied between 10–30%, on average, across all sites (Figure 8). For total eel catch (both species combined), the magnitude of the difference between population estimates for each sampling trip varied between 3–40%, on average, across all sites (Figure 9).

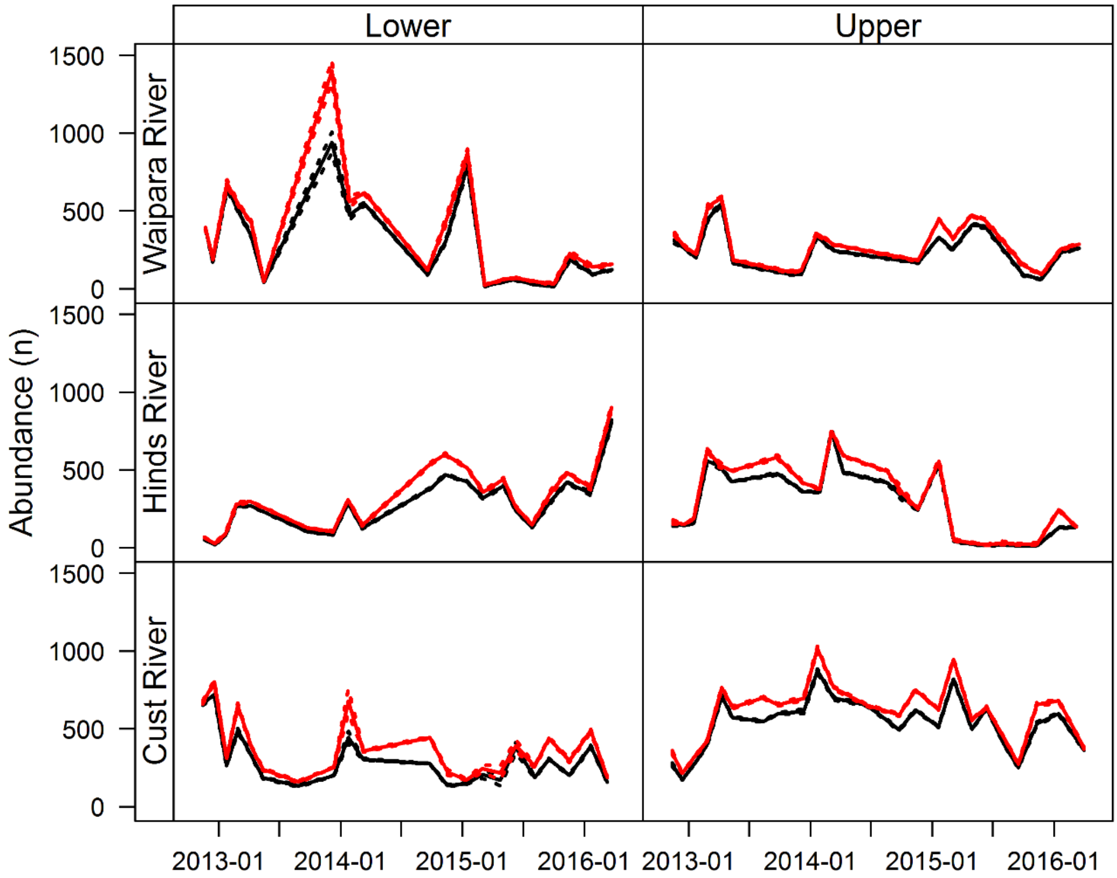

Figure 8: Population estimates (all species) for the six sites when stop-net catches are included (red) and excluded (black). Solid lines represent the population estimates and dashed lines are the standard errors of the estimates.

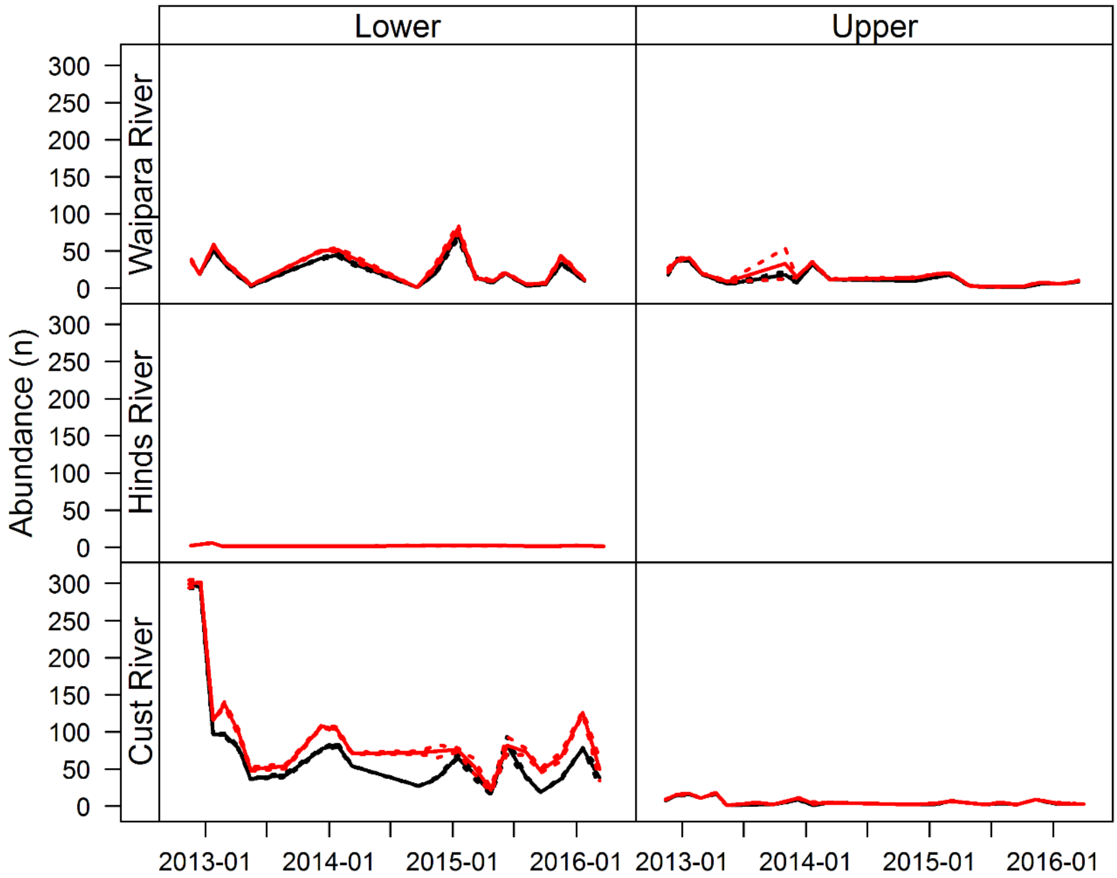

Figure 9: Eel (both species combined) population estimates for the six sites when stop-net catches are included (red) and excluded (black). Solid lines represent the population estimates and dashed lines are the standard errors of the estimates.

4. DISCUSSION

4.1 Effects of stop-nets of population estimates

Total fish abundance and eel abundance will be underestimated on average by 10–30% and 3–40% respectively if stop-nets are not used during multi-pass electric-fishing surveys. Including the standard error estimates shown in Figure 8, population estimates of total eel numbers could be underestimated by up to 60% if stop nets are not used.

These biases are well documented and arise directly because only a proportion (remaining fish) are sampled. All population estimates are then negatively-biased (estimating lower-than-observed population densities). These biases can also be species- and size-class-specific. Large fish, for example, are able to flee further from sampling activities and thus are more likely to escape sampled areas. Furthermore, escape behaviours can also interact with habitat conditions within the reach. Escape rates may depend on available cover, stream depth and substrate (Peterson et al. 2004, Peterson et al. 2005).

The magnitude of the difference between these population estimates was inconsistent between sites, but also within sites over time. There was temporal and spatial variability in the population estimates suggesting that it may be difficult to accurately monitor population changes (within or among sites) over small timescales if stop-nets were not used during the sampling. Overall trends in relative abundance from single-pass catches may be consistent with population estimates over long-time scales (i.e. larger than 10 years), but this requires further exploration. Multi-pass models (Model 5) also identified relationships between site-level habitat variables and the proportion of eels captures in stop-nets. Stop-net capture rates in both shortfin and longfin eels increased with stream velocity. This may make stop-net use in fish habitat surveys where stream velocity, or discharge, are variables of interest especially critical. Consequently, we recommend that stop-nets should always be used if accurate estimates of eel abundance are the main goal of the survey work.

4.2 Substrate depth experiment

Results from the burrowing experiment suggest that elvers occupy river substrates down to a depth of at least 400 mm, but most of the eels were found within 200 mm of the substrate surface. The mean substrate depths occupied by both species were very similar, regardless of fish size (elvers vs. all size classes). Unfortunately, the very high catches from the last layer of the substrate stack suggest that eels migrated down through the substrate layers as they were being separated. This behaviour was observed as the layers were separated (S.K. Crow pers. obs.), but this was unavoidable because there was no method of separating the layers that would have completely eliminated movement between the layers. It may be possible to examine the level of movement between layers in the laboratory, but this aspect could not be completed within the time and budget constraints of the present study. Regardless of problems with elver movement between layers, results do suggest that elvers and small eels can occupy the substrate down to considerable depth. The subterranean behaviour seen in the present study is consistent with burrowing behaviour seen in *Anguilla rostrata*. In the USA, *A. rostrata* have been shown to forcefully burrow into fine substrates and also swim into substrates with larger interstitial spaces (Tomie et al. 2013). While *A. rostrata* are generally located within 35 mm of the substrate surface, eels (all species and size) in the present study were found about 100 mm deeper in the substrate (at an average depth of 137 mm).

4.3 Electric-fishing model

Removal models identified biological and environmental variables which influenced capture probabilities in eels. Capture-efficiency in shortfin eels was positively related to fish length, with capture-efficiency of the largest eels (755 mm) being greater than 80%, but capture probability was reduced to approximately 45% for the smallest eels (60 mm). An assumption made during the present study is that the population estimates generated from the three-pass depletion catches was an accurate estimate of the density of eels at the site. The present study did not collect data to verify this assumption, which means capture efficiency may be underestimated. We are exploring this assumption in an upcoming study that aims to compare three-pass depletion population estimates with population estimates generated with a mark-recapture experiment. The relationship between size and capture-efficiency in the present study was was much less certain for longfin eels, which prevented any comparisons of capture-efficiency between the two species. Differences in the total number and size ranges of fish sampled is likely to have caused these differences in the certainty of the relationships between capture-efficiency and length for the eel species. This study suggests that the efficacy of electric fishing survey methods for eels is strongly size dependent, with much less survey effort required to capture large eels compared to small eels. This is consistent with overseas research

(Peterson et al. 2004, Dauwalter & Fisher, 2007, Hense et al. 2010, Korman et al. 2011, Reynolds & Kolz, 2012, Hedger et al. 2013). Increasing capture-efficiency with increased size has also previously been shown in eels from Canterbury, where large eels were shown to be more vulnerable to capture than small eels (Graynoth et al. 2012). Capture probability was also influenced at a site-level by site habitat conditions. Site-specific capture-efficiency increased with reach stream velocity in shortfin eels. Similar relationships between capture efficiency and stream velocity were not found for longfin eels, however, water temperature was positively related to capture-efficiency. Certainty in the relationships differed between eel species, with much greater uncertainty in habitat-capture-efficiency relationships in longfin eels. Relationships with environmental variables are common in other fish species varying with conductivity, substrate coarseness and stream width (Peterson et al. 2004, Hense et al. 2010, Speas David et al. 2011).

Population estimates based on total numbers of captured eels, which do not account for capture-efficiency differences across size ranges, may be biased and underestimate population sizes because this approach would fail to account for uncaptured small eels. The inclusion of fish length information in mark-recapture models accounts for this bias by incorporating size differences in capture-efficiency. Length information can be included as a continuous variable in the models presented in the present study or capture frequencies for size classes can be passed as a categorical variable, producing a population estimate for each size class. The total size-adjusted population estimate can then be prepared by summing population estimates for each size class.

Single pass surveys are commonly used to estimate catch per unit effort as a measure of relative abundance. Utilising the size differences in capture-efficiency outlined in the present study should improve these estimates by taking into account the large differences in capture-efficiency between large and small eels. For example, average eel size is likely to be over-estimated in spot surveys as large eels are more likely to be captured than small eels. Furthermore, eel size may influence abundance estimates based on captures from single pass surveys. For example, across sites with identical eel densities, but unequal eel size structure, in sites with larger eels, the number of captures would be expected to be greater. The difference in numbers captured would reflect fish size-related differences in capture-efficiency between sites and be unrelated to density differences. However, captures from single pass surveys should be able to be adjusted using the known relationships with capture-efficiency outlined in the present study if eel size and abundance data are available (Wyatt 2002, Mitro et al. 2003).

Whether the relationship between capture-efficiency and size is the same for both eel species is unclear. Large differences in the total number of each species captured across the size ranges make comparisons difficult. For shortfin eels, the declining relationship of capture-efficiency with decreasing length was relatively certain. However, for longfin eels, the low number of captured eels was associated with reduced certainty in the capture-efficiency relationship with fish length. It’s also important to note that from the fitted models the mechanisms for capture-efficiency differences are unclear. The surveys are useful to identify relationships between capture-efficiency and measured variables but are not suitable for establishing mechanisms for those relationships. Therefore, fish length may influence capture-efficiency in eels via a combination of biological, environmental or technical mechanisms.

Summary

This study showed that both biological and environmental characteristics influence the efficiency of electric fishing in eels. Electric fishing was strongly size-selective in shortfin, and possibly, longfin eels, with efficiency highest in large eels. Stream depth also reduced site-level capture-efficiency while stream velocity influenced the proportion of eels caught in stop-nets (increasing stop-net captures found with increasing velocity for both species).

Fine-scale experiments investigating burrowing and electric field responses in elvers found that elvers can burrow to depths of at least 400 mm but are typically found within 200 mm of the stream substrate surface. Measurement of electric field density and elver capture success also found that the effective catching distance for elver capture is 50 cm or less.

The positive relationship between capture-efficiency and size suggests that catches will be biased towards larger fish and population estimates must be size adjusted to ensure that they are accurate. This size bias suggests that models like those outlined in the present study should be used to estimate population sizes because they incorporate fish length data. Failure to utilise these size-adjusted population estimates will underestimate potentially large numbers of uncaptured small eels. Single-pass electric fishing, should also be interpreted as potentially missing a large uncaptured proportion of small eels. These problems are compounded if stop-nets were not used to survey a site because the catchable eels would be underestimated by up to 40%. In size-class assessments based on electric fishing catches, usually shown only for captured fishes, the absence of small eels should be interpreted as an under-representation of small eels as opposed to true absence. Overall, understanding these relationships in capture-efficiency should allow more precise and less biased estimates of eel populations and guide future survey designs.

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