Behaviour and Fate of Downstream Migrating Eels at Hydroelectric Power Station Intakes

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ABSTRACT

Longfin eels (Anguilla dieffenbachii) are one of the most common endemic freshwater fish in New Zealand and the top predator in many systems. Strong indications exist that juvenile eel recruitment is declining, as evidenced by the scarcity of large specimens. Similar declines have been noted in Europe, eastern North America and Japan and may be a result of changes in oceanic currents, habitat losses, over-exploitation of adult stocks, migration delays, and mortality experienced by migrants at in-stream barriers. Investigations of downstream-migrant eel behaviour were conducted in the forebay of Arapuni Hydro Power Station, as part of a larger goal to devise means of facilitating downstream passage at hydroelectric projects. Three-dimensional telemetry was used to track six longfin and seven shortfin (A. australis) eels as they approached, encountered and passed downstream of the station. Swimming pathways of individual eels were estimated based on three-dimensional positions recorded approximately every two seconds. Observed eel migration occurred primarily at night and the majority of eels entered the forebay in mid-channel. Forebay residence time varied from several minutes to ten hours, with several eels swimming back upstream before returning and continuing to search, presumably for a suitable downstream passage outlet. The only downstream passage outlet in the forebay of Arapuni is the turbine intakes. Nearly all (11 out of 13) eels eventually passed downstream through the turbines. Based on downstream tag and carcasses recovered, turbine passage resulted in a significant level of mortality for both monitored species. Three-dimensional swimming pathways indicated that migrant longfin eels are initially reluctant to pass through trash screens and spend long periods of time searching the entire forebay prior to eventual passage through these structures. Shortfin eels were observed to either pass into the turbines immediately when they first encountered the trash screens, or to exhibit the searching behaviour indicative of longfin eels. Those demonstrating searching behaviour spent significantly less time in the forebay before selecting a final downstream passage location than did migrant longfin eels. Observations at other hydroelectric power stations have determined that eels will find and use suitably positioned bypass routes, if available. These routes, which include spillways, canals and designed bypass structures are a potential solution to enhance safe downstream passage for these species.

Keywords: Anguilla, longfin eel, A. dieffenbachii, shortfin eel, A. australis, fish passage, three-dimensional acoustic telemetry, behaviour, hydroelectric dam

INTRODUCTION

New Zealand is currently experiencing a decline in adult populations of endemic longfin eels (Anguilla dieffenbachia). There are strong indications that juvenile eel recruitment is also declining. Similar reductions in Anguilla populations have been noted in Europe, eastern North America and Japan. Multiple factors may contribute to these losses, including changes in oceanic currents, habitat losses and over-exploitation of adult stocks. Migration delays and direct mortality at in-stream barriers has also been identified as a significant impact on migrating eel stocks (Castonguay et al. 1994; Haro et al. 2000b; Richkus and Whalen 2000).
Current management practices have been implemented in efforts to reverse the population decline of eels in New Zealand. These have included expansion of un-fished reserves, a quota system, size limits, and increased enforcement of existing upstream and downstream passage requirements at anthropogenic in-stream barriers.

As ocean-bound adult anguillids move downstream, they may encounter in-stream barriers, in particular hydroelectric dams which can affect their migration in three ways. First, eels may experience migration delays in the upstream reservoirs as they search for a downstream outlet (Behrmann-Goel and Eckmann 2003; Haro et al. 2000a; Larinier and Travade 1999; Legault et al. 2003). Second, while eels search for a downstream passage route, they can become impinged and suffocate on intake screens (Adam et al. 1997; Amaral et al. 2003; Boubée et al. 2001; Watene and Boubée 2005). Finally, if eels are entrained into the turbine intakes, they are exposed to turbine-induced injuries or direct turbine mortality (Berg 1986; Haro et al. 2003; Richkus and Dixon 2003).

Recent behavioural studies of downstream migrant anguillids have shown that the majority of eels encountering a hydroelectric dam typically pass downstream through the turbines, which usually pass the majority of total project flow (Brown et al. 2007; Boubée et al. 2001; Haro et al. 2000b; Watene et al. 2003). Turbine mortality at each hydroelectric facility is highly variable and is dependent on the size of the fish and turbine characteristics. These characteristics include turbine runner type (i.e. Francis or Kaplan), size, speed, number of blades, blade spacing and thickness (Boubée et al. 2001; EPRI 1999; Gibson and Myers 2002). The large physical size of downstream-migrant adult eels may result in mortality rates four to five times higher than that estimated for smaller juvenile salmon (Larinier and Travade 1999; 2002). Recent studies conducted in New Zealand on migrant longfin and shortfin eels have indicated that turbine mortality is positively correlated to eel length and can be as high as 100% (Boubée et al. 2001). Eels that select turbine passage routes are exposed to numerous hazards which include: (1) strikes from moving or stationary parts of a turbine runner, such as the runner blades, that can cause internal hemorrhaging, external cuts and abrasions, and severed body parts; (2) sudden acceleration and/or deceleration at the entrance of the turbine and within the turbine casing that can increase the overall stress of turbine passage and risk of damage when strike occurs; (3) unexpected variation in pressure that can cause fatal dissolved gas exposure; and (4) exposure to hydraulic shear that can lead to severed body parts (Larinier and Travade 1999).

Recent evidence suggests that downstream migrant anguillids will readily use alternate lower-mortality passage locations, if these are available to them. The use of a bypass when other routes are limited or unavailable has been reported by Boubée and Williams (2006) and Legault et al. (2003). Boubée and Williams (2006) reported that migrant longfin and shortfin eels used two adjacent 100 mm apertures installed in the forebay to pass downstream through a small hydroelectric facility where narrow trash rack spacing and lack of spill precluded the use of alternate passage routes. Legault et al. (2003) documented silver phase European eels (A. anguilla) migrating downstream through a 75 mm diameter bypass pipe at a small dam in France when it represented the only possible downstream passage location. At the time of passage, the velocity through the bypass pipe was low (0.08 m·s⁻¹).

Devising safer downstream passage alternatives for anguillids is a critical component of ongoing efforts to minimize mortality. Relatively few studies have identified designs to facilitate safer eel passage alternatives through hydroelectric projects where multiple passage routes with varying risks are available (Amaral et al. 2003; Boubée and Williams 2006; Durif et al. 2003; Legault et al. 2003). Dam managers are currently struggling to find solutions allowing them to meet government regulations requiring safer downstream eel passage at anthropogenic in-stream barriers, such as hydroelectric power stations. The purpose of this study was to better understand how eels volitionally select passage routes through power stations, using three-dimensional (3D) acoustic telemetry. The study objectives were to track the 3D movement of eels in the forebay as they approached, encountered and passed downstream of a hydropower station and to assess pre-passage behaviour of longfin and shortfin eels. The pre-passage behaviours investigated included the time, duration, and number (i.e. one or multiple passage attempts) of tagged eel forebay detections. This information was used to define regions of high concentration in the forebay and the location of ultimate downstream passage.
METHODS

Study Site

Research was conducted at Arapuni Hydro Power Station (Arapuni), the second hydroelectric project on the Waikato River that is located 177 river-kilometers (rkm) upstream of Port Waikato (Figure 1). Arapuni, the oldest operating power station on the Waikato River, is equipped with eight vertical Francis turbine runners and has a total generation capacity of 164 MW. Throughout the study, turbine operations and unit generation (on/off) was highly variable.

A diversion canal, constructed in 1929, descends off Lake Arapuni (lake area 9.1 km²) approximately 460 m before reaching the forebay and is contained by 2.5:1 sloped concrete walls. The forebay, the area of interest up to 100 m upstream of the turbine intakes, is 9 m deep. At the entrance of the turbine intakes, water flows through trash racks, a series of flat bar racks (60 mm wide by 10 mm thick) that are spaced 100 mm apart. The trash racks are used to divert large debris from entering the intakes. The approach velocity at the turbine intakes varies between 0.9 and 1.7 m·s⁻¹. The head of the forebay was typically held at 52 m and turbine flow was estimated to be 50 m³·s⁻¹.

Figure 1. Arapuni Hydro Power Station (Arapuni) is the second hydro power station located on the Waikato River (rkm 177). All research was conducted in the forebay, the 100 m area immediately upstream of the trash racks.
Telemetry

The HTI Model 290 Acoustic Tag Tracking System was the primary biotelemetry tool used to monitor the movement and passage of downstream migrant eels at Arapuni. The tracking system was composed of an Acoustic Tag Receiver (ATR), hydrophones, acoustic cable, acoustic tags and a personal computer. The ATR operated at 307 kHz, the optimum frequency with respect to detection ranges and resolution at numerous hydropower dams where the system has been used to date. In addition to determining the presence or absence of a tagged fish, the ATR tracked tagged fish in three-dimensions (3D). As a tagged fish approached the hydrophone array, the transmitted signal from the tag was detected and the arrival time was recorded for each hydrophone. The difference in arrival time of signals from an individual tag on each hydrophone was used to calculate the 3D position (Ehrenberg and Steig 2002, 2003). The benefit of using this technology was the ability to estimate the position of tagged fish with sub-meter resolution.

The geometry of the hydrophone array was positioned to detect the movement of telemetered eels within the first 100 m upstream of the powerhouse. Five hydrophones were deployed throughout the forebay; three hydrophones were mounted 1 m below the surface, and two hydrophones were mounted 1 m from the bottom of the canal (Table 1 and Figure 2). We used Model 795X Acoustic Tags (15.7 mm diameter by 47.5 mm length, weight 18 g in air and 13 g in freshwater, 307 kHz, 2.9 to 3.1 s ping rate, 2 ms encoded pulse width); each tag was programmed to emit a unique ping rate. To verify system precision and accuracy, test tags were deployed at known positions in the acoustic array.

Additional presence/absence telemetry methods were used to monitor the movement of telemetered eels outside of the 3D acoustic tag array. The presence of shortfin eels were also monitored using radio telemetry. SIRTRACK radio transmitters (18 mm diameter by 50 mm length with a 250 mm external antenna, weight 17 g in air, 160 MHz 40 ppm) were used in conjunction with ATS R2100 receivers and DCCII loggers to monitor shortfin eels upstream of the Arapuni intakes. The presence of longfin eels were also monitored using fixed, VEMCO acoustic telemetry data loggers. VEMCO transmitters, V16-6H-R256 69 K, (16 mm diameter by 90 mm length, weight 36 g in air, 15-40 random repeat rates) were used in combination with deployed, remote VR1 receivers. A total of six receivers were deployed, two on each bank of the river at 4.2 km upstream of the dam, one 2 km upstream of the dam, one at the dam approximately 1.2 km from the intakes, one at the forebay entrance (0.5 km upstream of the intakes), and one at the powerhouse intakes (Figure 1).

While multiple biotelemetry techniques were employed during the study, the majority of results presented reflect only the acoustic tag data recorded with the HTI Model 290 Acoustic Tag Tracking System.

Table 1. The Cartesian coordinates of each hydrophone in the forebay acoustic array at the Arapuni Hydro Power Station. All coordinates were measured in meters (m).

<table>
<thead>
<tr>
<th>Hydrophone</th>
<th>Cartesian Coordinates (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
</tr>
<tr>
<td>1</td>
<td>156.94</td>
</tr>
<tr>
<td>2</td>
<td>156.77</td>
</tr>
<tr>
<td>3</td>
<td>112.18</td>
</tr>
<tr>
<td>4</td>
<td>49.91</td>
</tr>
<tr>
<td>5</td>
<td>50.12</td>
</tr>
</tbody>
</table>
**Fish Capture, Tagging, Release and Monitoring**

Downstream migrant, silver-phase shortfin and longfin eels were collected by commercial fishermen in the Waikato River watershed. Eels were transported to the release location, Bulmer Landing, and were surgically implanted within 12 hours of capture using methods similar to Baras and Jeandrain (1998) and Brown et al. (2007). Each eel was anesthetized in a 10% clove oil and ethanol solution that was added to a 100 L bath of ambient river water. Eels were held in the anaesthesia bath for 10 to 15 min before tagging.

Once fully sedated, total length (TL) was measured to the nearest 0.01 m and eels were placed in a surgical trough. An additional supply of anaesthesia was circulated through the gills while transmitters were surgically implanted into the abdomen of each eel. The incision was closed with three interrupted sutures. The duration of surgical implantation of transmitters did not exceed two minutes. Eels were released at the site of surgery, approximately 3.8 km upstream of Arapuni. A total of 21 eels (15 shortfin and 6 longfin) were tagged and released.

All telemetry systems monitored continuously (24 h, 7 d/wk) for the detection of tagged eels. Receiver clocks were synchronized to the nearest second during each data download procedure which occurred every two to five days. Eels were determined to have passed downstream of Arapuni when the final 3D detection was positioned at the trash racks and net upstream movement was not detected. Data collection was terminated on 1 June, two weeks after the last detection (16 May). Water temperature was recorded hourly with a thermocouple sensor placed in the forebay.

Radio and acoustic tags were recovered from the carcasses of eels that were able to be recovered the Karapiro hydro reservoir. Karapiro Dam is the first hydro project on the Waikato River and is 26 rkm downstream of Arapuni.)
Data Analysis

The 3D acoustic telemetry data were compiled and managed in an MS Access database. Records were filtered using HTI proprietary software (AcousticTag and MarkTags) to remove erroneous signals from the data set that were not filtered during data collection (HTI 2000). Erroneous signals caused by excessive noise that exceeded the filter parameters of ambient acoustic noise were excluded from the data set. At Arapuni, this was commonly caused by mechanical and electrical acoustic noise that was associated with the operation of the dam and the high voltage environment. Additional mechanical noise flooded data collection during routine, daily cleaning of the trash racks.

Pre-release data files were collected with deployed test tags in various areas throughout the forebay. The data files were processed to determine the detection boundaries and to analyze the standard error in 3D positioning. The standard error in 3D positioning was determined based on the known position of the test tags and the 3D positions acquired with AcousticTag software. Reflective pinging of the tag along the canal walls, often referred to as multipath, was a secondary source of noise at Arapuni; this source of noise was minimal.

We classified each occurrence of an eel as the period of time from when the eel first entered the acoustic array until the time of passage or movement back upstream, outside of the acoustic array. Detections separated by less than 15 min comprised a single occurrence. The duration of each occurrence, or residence time, was calculated to the nearest second (s) based on the date and time of the first and last 3D detection. The overall detections of eels were also reviewed for diel patterns.

All eel detections were plotted in 3D and swimming pathways were reviewed for trends in downstream movements as they encountered the facility, in particular the location of forebay entrance and exit. Eels were individually assigned a passage route of turbine or net upstream movement based on the last detected location of the eel.

To illustrate the two-dimensional distribution of detections in the forebay, detections were queried into five distinct zones defined by X and Y coordinates (Figure 3). The first three zones were positioned along and the first 20 m directly upstream of the trash racks (zone 1 was located in the northeast corner of the trash racks, directly upstream of Unit 8 intakes and zone 2 and 3 were divided at Unit 5). The remaining two zones, zone 4 and 5, were upstream and parallel to the trash racks (also divided by Unit 5). The distribution of detections by depth was also investigated; all detections were combined and analyzed using the Chi-square test.

Figure 3. Zones of interest analysed for the proportion of detections mapped in the forebay of Arapuni Power Station. The Cartesian coordinates, measured in meters (m), are as follows: zone 1 (>149.7, <=68.2), zone 2 (>121.2 and <=149.7, <=68.2), zone 3 (<=121.2, <=68.2), zone 4 (>121.2 and <=149.7, >68.2) and zone 5 (<=121.2, >68.2).
RESULTS

Telemetry Equipment

The HTI Model 290 Acoustic Tag Tracking System was installed on 24 February 2004. Test tag data were analyzed and we found that 95% of all detections were within 0.16 m horizontally (X dimension) and 0.45 m vertically (Y dimension) of the true, known test tag position. The standard error of the position estimates increased significantly in the third dimension (Z dimension) when the tag remained suspended in the water column for prolonged periods (greater than one minute). The third dimension, depth, had the highest amount of uncertainty in detections; SE typically varied from 0.5 to 1 m.

Acoustic noise did not seem to influence the quality of received signals, but ambient electrical noise intermittently decreased signal detection quality. Recorded tracks of eels were generally continuous, although pings from transmitters were occasionally not detected when tags were in the margins of the forebay or when data collection was interrupted. Data collection was interrupted during various periods throughout the study and occurred under a variety of conditions but was most commonly attributed to loss of power and equipment failure (including ATR and/or PC). Twenty-one percent (16 d) of the total data collection capacity (76 d) was lost. During periods of unexpected power loss, the personal computer and ATR were not set up to restore connection with power. Arapuni personnel or NIWA staff restored the connection manually while on site to retrieve data files. Post-processing of the data files suggested that equipment failed during periods of excessive noise that likely filled and collapsed the ATR processor.

Pre-implantation trials using radio tracking equipment had shown the use of the equipment would successfully monitor the movement of longfin eels migrating downstream. However, changes in weather patterns from clear/sunny to rain/fog during the downstream migration period created interference by electric fences and high tension power lines in rain and fog created an unreliable system. All radio tracking data for the shortfin eels was therefore discarded. No such problems were encountered with the VEMCO acoustic tracking used with the longfin eels.

Releases and Detection History

Eels were released between 18 March and 29 April 2004. Shortfin eels were released on 18 March and 26 March and all longfin eels were released on 29 April. A total of 21 (15 shortfin and 6 longfin) silver eels were collected, tagged, released, and monitored in the forebay of Arapuni from 18 March to 1 June. The mean TL of shortfin eels was 0.91 m (range 0.83-1.02 m) and of the mean TL of longfin eels was 1.42 m (range 1.14-1.70 m). Water temperatures ranged from 18.3 °C (18 March) to 13.6 °C (1 June) between the first day of release and last detection of downstream movement in the forebay.

Of the 21 tagged eels released upstream of Arapuni, 13 (62%; seven shortfin and five longfin) were detected entering the forebay acoustic array at least once; eight eels were never detected after releases (Table 2). A total of 43,749 detections were logged between 18 March and 1 June (6,996 shortfin detections and 36,753 longfin detections).

The duration of each occurrence was variable; the median residence time was 0.15 h (8.9 min). Longfin eels exhibited a considerably higher residence time than shortfin eels. The median residence time per presence of longfin eels was 0.93 h (55.9 min; range 1 min to 9.96 h) and of shortfin eels was 0.23 h (13.9 min; range 1 min to 4.92 h; Table 3). Sixty-two percent of all eels detected in the forebay (8 out of 13) were detected re-entering the acoustic array on multiple dates, up to 11 times, before passing the station (Table 3). Of the two species, shortfin eels were recorded making fewer attempts to pass Arapuni. Only two shortfin eels were detected re-entering the forebay. All longfin eels that were detected in the forebay made multiple attempts to pass; two to 11 attempts were made (median number of attempts was four; Table 3).

Diel patterns of occurrences in the forebay were examined. Sample size was low and therefore the first hour of all forebay occurrences, including multiple occurrences, were pooled. No diel patterns in shortfin
movement were discovered which may be biased by the low sample size. A bimodal pattern in the attempted downstream passage events by longfin eels was detected (Figure 4). In general, most of the detections occurred during crepuscular periods or at night. Forebay occurrences of longfin eels peaked at 0500 and 1900 (Figure 4).

**Table 2.** 3D track records of eels detected in the Forebay of Arapuni Power Station. Each eel is listed by tag pinging rate, (measured in milliseconds, ms), along with the number of detected occurrences, species (shortfin is SF and longfin is LF), the date (m/d/y) and time of passage and the final detection location (X, Y, Z). All eels exited through the turbines with the exception of 2955 and 3030 which returned upstream (denoted by an asterisk).

<table>
<thead>
<tr>
<th>Tag Number</th>
<th>Number of Occurrences</th>
<th>Species (SF/LF)</th>
<th>Last Detection (Point of Exit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>*2955</td>
<td>2</td>
<td>SF</td>
<td>3/28/04 10:05:48</td>
</tr>
<tr>
<td>2960</td>
<td>1</td>
<td>SF</td>
<td>4/8/04 20:01:15</td>
</tr>
<tr>
<td>2970</td>
<td>2</td>
<td>SF</td>
<td>3/22/04 7:08:27</td>
</tr>
<tr>
<td>2980</td>
<td>1</td>
<td>SF</td>
<td>4/16/04 0:12:27</td>
</tr>
<tr>
<td>2985</td>
<td>1</td>
<td>SF</td>
<td>5/11/04 14:12:27</td>
</tr>
<tr>
<td>2995</td>
<td>1</td>
<td>SF</td>
<td>4/4/04 21:26:01</td>
</tr>
<tr>
<td>3020</td>
<td>1</td>
<td>SF</td>
<td>4/14/04 19:22:41</td>
</tr>
<tr>
<td>3025</td>
<td>4</td>
<td>LF</td>
<td>5/15/04 19:30:27</td>
</tr>
<tr>
<td>*3030</td>
<td>7</td>
<td>LF</td>
<td>5/16/04 21:25:11</td>
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<tr>
<td>3040</td>
<td>2</td>
<td>LF</td>
<td>5/13/04 18:19:29</td>
</tr>
<tr>
<td>3045</td>
<td>7</td>
<td>LF</td>
<td>5/2/04 18:53:33</td>
</tr>
<tr>
<td>3050</td>
<td>2</td>
<td>LF</td>
<td>5/16/04 17:55:11</td>
</tr>
<tr>
<td>3055</td>
<td>11</td>
<td>LF</td>
<td>5/2/04 17:44:44</td>
</tr>
</tbody>
</table>

**Table 3.** The median and range (minimum and maximum) of detected occurrences and residence times of migrant eel detected in the forebay of Arapuni Hydro Power Station.

<table>
<thead>
<tr>
<th>Species</th>
<th>No. of Occurrences</th>
<th>Residence Times (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median  Min  Max</td>
<td>Median  Min  Max</td>
</tr>
<tr>
<td>Shortfin</td>
<td>7       1     2</td>
<td>0.23     0.01 4.92</td>
</tr>
<tr>
<td>Longfin</td>
<td>6       4     11</td>
<td>0.93     0.01 9.96</td>
</tr>
</tbody>
</table>

Most eels entered the forebay in the center of the power canal, where the dominant flow pattern existed, near the surface. Eels were detected entering the forebay throughout the entire water column; eels were detected near the bottom at 0.01 m and the surface at 8.9 m of the canal. Due to the high level of standard error in the depth component of the calculated test tag positions, the depth of detections throughout the array was split between the upper and lower portions of the water column (4.5 m increments) for further analysis. There were no significant differences in depth of detections by either species when analyzed by depth throughout the entire forebay or within the first 20 m of the trash racks (Chi-square test).

To further quantify where eels were spending the majority of time within the acoustic array, the forebay detections were separated into five distinct zones (Figure 3). All zones were reviewed by species (Table 4). Shortfin eels were detected in the highest proportions in zone 2 (46.4 %), zone 1 (23.7 %) and zone 4 (18.0 %). Longfin eels were detected in the highest proportions in zone 2 (40.2 %), zone 3 (20.5 %) and zone 5 (19.64 %).
Figure 4. Diel patterns of eels detected by hour as they entered the forebay acoustic array at Arapuni Hydro Power Station. Sample size was limited and multiple occurrences were included (9 shortfin and 33 longfin forebay entrance detections).

Table 4. Two-dimensional positions of migrant eels tracked in the forebay of Arapuni Hydro Power Station. Refer to Figure 3 for position of the zone of interest. The detections are represented by the total number the relative percent of detections per zone of interest. (SF = shortfin, LF = longfin).

<table>
<thead>
<tr>
<th>Species (SF/LF)</th>
<th>Zone of Interest</th>
<th>Detections</th>
<th>n</th>
<th>%</th>
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<tr>
<td>SF</td>
<td>1</td>
<td>1470</td>
<td>21.8</td>
<td></td>
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<td>SF</td>
<td>2</td>
<td>2882</td>
<td>41.7</td>
<td></td>
</tr>
<tr>
<td>SF</td>
<td>3</td>
<td>739</td>
<td>10.7</td>
<td></td>
</tr>
<tr>
<td>SF</td>
<td>4</td>
<td>1116</td>
<td>16.2</td>
<td></td>
</tr>
<tr>
<td>SF</td>
<td>5</td>
<td>702</td>
<td>10.2</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>6909</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LF</td>
<td>1</td>
<td>2982</td>
<td>8.3</td>
<td></td>
</tr>
<tr>
<td>LF</td>
<td>2</td>
<td>14546</td>
<td>40.2</td>
<td></td>
</tr>
<tr>
<td>LF</td>
<td>3</td>
<td>7393</td>
<td>20.5</td>
<td></td>
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<tr>
<td>LF</td>
<td>4</td>
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<td>11.4</td>
<td></td>
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<tr>
<td>LF</td>
<td>5</td>
<td>7100</td>
<td>19.6</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>36148</td>
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Downstream Passage Behaviour

Nearly all eels tracked in the forebay eventually passed downstream of Arapuni through the turbines; two eels, one of each species, were last detected moving back upstream (Table 2). The shortfin eel was believed to have passed downstream through the intakes during a period when data collection failed because the carcass was recovered in the tailrace of Arapuni; this fish (shortfin eel with tag period 2955)
was last detected on 28 March at 10:00 with net upstream movement and there were no data files collected from 28 March at 10:09 through 30 March at 10:00. Data collection did not fail at any time following the recorded upstream movement of the longfin eel mentioned above and therefore this eel most likely returned upstream.

There were no evident trends in the final location of passage; the last detected location for eels that passed at the turbine intakes did so at multiple locations across the trash racks. Five shortfin eels were detected passing through the trash racks immediately after contact with the trash racks. The remaining six eels that were detected passing the station (one shortfin and five longfin) were recorded passing through the trash racks following more than one occurrence in the acoustic array. Eels that passed directly through the turbine intakes upon their first encounter had significantly lower residence times. The median residence time of this group of eels was 1.5 min (range 1-14 min). In contrast, the median residence time of the first occurrence of the remaining eels that exhibited searching behaviour was 2.4 h (range 2.8 min to 5.7 h).

Combinations of the following searching behaviours were observed before each eel committed to a downstream passage route through the turbines. These searching behaviours included: 1) quick, sprint-like upstream movement once they encountered the trash racks, 2) vertical searching movements, swimming up and down within the water column at or near the trash racks, (3) horizontal searching movements, swimming along the trash racks in a guided movement of the forebay when they encountered the trash racks, and (4) circling movement in small upstream movements at the trash racks and/or throughout the entire forebay (Figures 5 & 6).

Upon first encounter of the trash racks, eels that did not pass either moved back upstream of the trash racks or displayed vertical sounding and/or swam horizontally along the trash racks. Circling movement at or near the trash racks (within the first 20 m directly upstream), along with larger scale looping throughout the entire forebay, was also detected of all eels that did not pass when they first encountered the trash racks. Circling movements were typically associated with vertical, horizontal or a combination of both searching behaviours along the trash racks. The authors believe that these patterns of movement indicated that eels were searching for an alternate downstream passage route.

A total of 17 eel carcasses were identified in the tailraces of Arapuni Dam and in Karapiro Reservoir. During the period of 14 April to 20 May 2004, the transmitters of one shortfin and five longfin eels were repeatedly detected in the tailrace of Arapuni Dam and the transmitters of eleven shortfin eels in Karapiro Reservoir (four recovered). Lack of movement recorded of these transmitters implied that all these eels had died.
Figure 5. Example three-dimensional swimming pathways of two shortfin eels in the forebay of Arapuni Hydro Power Station. Tag 2980 presented in figure A represents the behaviour of eels that passed directly through the trash racks upon first encounter. Tag 2970 (second occurrence) presented in figure B is more representative of searching behaviours which included vertical and horizontal excursions with circular, looping movement at or near the trash racks.
Figure 6. Example three-dimensional swimming pathways of two longfin eels are displayed in the forebay of Arapuni Hydro Power Station. Tag 3030 (sixth occurrence) is presented in figure A and tag 3045 (fourth occurrence) is presented in figure B. Both swimming pathways are representative of longfin searching movements detected at Arapuni Hydro Power Station before committing to a passage route via turbine intakes.
DISCUSSION

Two factors affected the resolution of eel detections in the forebay of Arapuni using the Acoustic Tag Tracking System. 3D positioning of targets in the depth domain was observed to be variable. A single source responsible for this variability was not identified. Probable causes included several compounding factors that included hydrophone array geometry, data processing parameters, and unknown hydraulic conditions that may have altered the test tag position during calibration tests. Upon completion of the study, it was apparent that a revised hydrophone deployment geometry including the addition of hydrophones would have significantly decreased the standard error in target positioning, particularly in the depth (Z-axis) dimension.

In addition, periodic high acoustic noise levels resulted in ATR shutdowns that interrupted data collection. These interruptions resulted in periods when eel behaviour were not recorded in the forebay and instances where tagged individuals were not detected following release. The reliability of the tag receivers and associated software has been significantly improved since this study, such that high acoustic noise levels should not significantly limit potential future monitoring efforts. These improvements include improved noise level filtering parameters in the AcousticTag software and advances in remote data collection methodologies. Recent similar studies use satellite technology to monitor and download data files remotely, allowing confirmation of continuous system operation. The uses of battery backup power systems and power loss censoring equipment have also demonstrated to greatly improve monitoring system reliability. These advances should be incorporated in future studies.

Based on the recorded patterns of eel movement in the forebay, two types of behavioural responses were observed when eels encountered the power station intake trash racks. Eels either passed directly through the trash racks or into the intakes on their first encounter or they rejected immediate entrainment and began searching for an alternative passage route in the forebay or upstream of the detection zone. Shortfin eels were the only species that passed through the trash racks during their first encounter, suggesting potential species-specific behavioural differences in passage route selection. Longfin eels made a significantly greater number of attempts to pass downstream via the turbines which corresponded with significantly longer residence times in the forebay presumably searching for alternate passage locations. Relatively few shortfin eels displayed forebay searching behaviours or long residence times upstream of the dam. Longfin eels appeared to be more reluctant to pass through the turbine intakes, but eventually did so when provided with no other passage alternative.

The recorded 3D behavioural movement illustrated an increase in vertical movement at or near the trash racks. Previous radio telemetry studies conducted by Durif et al. (2003) have shown that both species will seek deep passage outlets at a higher frequency than those located near the surface. Additional studies monitoring downstream anguilid movement past hydropower stations have shown that American eels (A. rostrata) are bottom-oriented, with the exception of searching behaviours observed directly upstream of the trash racks and intake structures (Brown et al. 2007; Haro et al. 2000b).

The pre-passage behaviour of shortfin and longfin eels recorded in the forebay of Arapuni is similar to anguilid recorded behaviours in other geographic locations. The passage behaviour of American and European eels at hydro power stations has also ranged from direct passage to extensive horizontal and vertical milling and looping behaviours that occur directly upstream of hydro projects (Behrmann-Goel and Eckmann 2003; Brown et al. 2007; Haro et al. 2000b). While it is unclear how the hydraulics of a given forebay affects the choice of downstream passage location at a specific hydro power station, it is apparent that eels will typically select a passage route based on dominant flow and lack of attractive alternatives. The effects of conditions and turbine configuration (on/off) experienced by individual eels and species-specific differences are unknown, yet may have influenced the behaviour of eels in this study. In future studies, it would be prudent to further investigate the pre-passage behaviour of eels with respect to the hydraulic environments they experience.

The large size of longfin eels makes them highly susceptible to turbine related mortality when passing through intakes. Previous studies have shown that the mortality of longfin eels can be as high as 100%,
compared to the 37% mortality rates recorded of American and European eels (EPRI 2001). The fate of all eels that passed downstream of Arapuni is unclear; however over several days six transmitters were detected at the same location of the Arapuni Dam tailrace and a further eleven (four of which were subsequently extracted from eel carcases) in Karapiro Dam. It is evident that the mortality rate of migrant eels that are passing through the powerhouse of Arapuni is very high.

Safer downstream passage alternatives must be employed to ensure the population shortfin and longfin eels are no longer threatened by the existing hydro power stations of New Zealand. While our sample size is low, other studies have recorded similar behaviour; some eels will search for non-turbine alternative passage locations. Bypass alternatives, such as the installation of small bypass pipes, have proven to be effective (Boubée and Williams 2006) but only when it is the only option of bypassing an impoundment. In addition to attractive bypass alternatives, altered operations conditions at hydro projects during peak passage events may be necessary to attract eels to non-turbine passage routes. Alternative operations may include temporary shutdown coinciding with the operation of a bypass system or inadvertent spill where spill bays exist or tapered operations that would attract eels to location of an alternate passage route such as a bypass system. Decreased searching behaviour will also decrease the overall transit time of eels moving through each impoundment and will likely decrease the stress and increase the rate of survival during downstream passage. Without alternative, non-turbine passage routes, with the increasing number of hydro dams being contemplated and excessive fishing pressure affecting eel populations in non impounded waterways it is likely that the number of large adult eels that successfully migrate out to sea to spawn will continue to decline.

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