Evaluating the impact of hydropower on downstream migrating anguillid eels: catchment-wide and fine-scale approaches to identify cost-effective solutions

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Abstract

Hydropower is an increasingly popular source of renewable and 'green' (in terms of emissions) energy, but reduced longitudinal connectivity and diverting flow through turbines can have negative impacts on catadromous anguillid eel species that have declined globally. There is an urgent need for environmental managers to perform remediation actions, such as protecting flows for migratory fish and providing passage solutions at infrastructure, under increasing legislative pressure. To deliver this, a more comprehensive understanding of eel migration in catchments with hydropower is required. Here, we illustrate the importance of catchment-wide and fine-scale acoustic telemetry, coupled with the influence of eel maturation (i.e. sex steroid levels), to determine the impact of Wairua run-of-river Power Station (WPS) on downstream migrating shortfin eels (*Anguilla australis*; n = 25) in Wairua River, New Zealand. Migration speed through the unregulated reach upstream of WPS was positively correlated with flow, but not eel length or sex steroids. Three eels passed a diversion weir (DW) to follow the natural watercourse and eight entered the WPS canal. Eels predominantly entered (95.2%) and were last detected (85.7%) in WPS forebay during hours of darkness. Eleven (52%) of the 21 eels that entered WPS forebay were impinged or entrained, all when three or four turbines were in operation (power generation >3.04 MW). Ten (48%) passed WPS spillway during significantly higher spill than impinged or entrained eels, with four passing during no turbine operation, after experiencing high flows near the intake (multiple receivers in WPS forebay used to quantify fine-scale behaviour). On average, eels were impinged or entrained at WPS significantly quicker (6.40 ± 11.13 days) than eels that entered the spillway (25.17 ± 15.12 days), but eel length and sex steroids did not significantly influence fate. Of the eels that migrated through the entire 55 km study reach, passage time at DW and WPS equated to between 0.01 – 0.02% and 47.62 – 92.17% of their migration, respectively. Mitigation for WPS (and similar power schemes) should focus on operational or physical changes at DW to minimise eels entering power station forebay(s). Turbine shutdowns, ensuring WPS spillway is available and the provision of a bypass channel in WPS forebay are also discussed as ways to conserve the species with the potential to save costs for water resource managers.

Keywords: Acoustic telemetry, Catadromous, Fish passage, Impingement, Longitudinal connectivity, Renewable energy

Abbreviations:

WPS – Wairua Power Station

DW – Diversion Weir

PG – Power Generation

1 INTRODUCTION

Hydropower contributes 80% of the electricity generated from renewable sources worldwide (World Bank, 2014c). It is viewed as green energy and is becoming increasingly popular as a renewable source globally (Zarfl et al., 2015). That said, due to the scale of development worldwide, river systems and flows are being extensively modified by associated infrastructure, which also creates barriers to up and downstream migrating fish, causing its green status to be questioned (Brink et al., 2018). Further, hydropower plants can impinge downstream migrants onto intake trash screens when the approach velocity exceeds eel swimming speeds, or they can pass through turbines (also known as entrainment) if the screen bar spacing is large enough to allow entry. High mortality of migratory eels after passage through turbines, partly due to their elongate body shape, has been widely reported since the 1980s (see Lucas & Baras, 2001) and has received increasing attention in recent years due to the decline of freshwater eel stocks worldwide (Dekker & Casselman, 2014). Finding cost-effective passage solutions is of global interest in order to conserve species whilst ensuring required ecosystem services are achieved in managed water bodies, and requires a more comprehensive understanding of eel migratory behaviour in catchments with hydropower.

In New Zealand, hydropower produces >50% of the electricity (MBIE, 2018). Native shortfin (*Anguilla australis*) and longfin (*A. dieffenbachii*) eels are commercially, ecologically and culturally significant species (McDowall, 2013). Both have a complex catadromous life cycle and are susceptible to the same anthropogenic disturbances proposed for the European eel (*A. anguilla)* and other temperate eels (see Feunteun, 2002; Lokman, 2016). These include degradation of habitat, especially in lowland areas – wetland areas have been reduced by up to 90% in some areas – and barriers to both up and downstream migration (FNZ, 2018; Dunn et al., 2018). Increased temperatures related to climate change affect recruitment of glass eels (Gollock et al., 2018). Further, overexploitation of females causes a skewed sex ratio, as males escape before they reach the minimum catch size – but both species have strict Quota Management Systems and Total Allowable Commercial Catch limits to protect them from foreseeable issues that other eel stocks have faced (MPI, 2020). As these species are larger than other catadromous eels, they are particularly vulnerable to risks associated with turbine passage (Beentjes et al., 2005) due to greater likelihood of collision with internal structures. Mortality or damage caused by turbines can have long-lasting negative effects on eel populations, particularly on long-lived species such as shortfin and longfin eels that can inhabit freshwater for more than 60 years before reaching maturity (Boubée et al*.,* 2008). For all these reasons, longfins are classified as at risk – declining while shortfins are not threatened according to the most recent official Conservation status of New Zealand freshwater fishes, 2017 (Dunn et al., 2018).

The risks posed to New Zealand eel species when attempting to exit the freshwater catchment are recognised amongst traditional and commercial eel fishers and dam operators, with trap and transfer programmes being implemented at numerous sites (MPI, 2016). Nonetheless, there is no programme for monitoring escapement of migrant eels in New Zealand (Haro et al., 2015). Moreover, although the New Zealand Freshwater Fisheries Regulations 1983 require fish passage to be provided at barriers, this came into effect after many barriers were already installed so conflict arises around when and where the protective measures need be implemented (Boubée & Williams, 2006).

As the decline of many eel species has occurred relatively fast (e.g. Dekker & Casselman, 2014), comprehensive studies on the impact of water resource infrastructure in the context of catchment-wide migration to identify if / where remediation measures are required are rare. The timing of downstream silver eel migration has previously been documented using fisheries catch data (e.g. Durif & Elie, 2008), but this approach does not account for inter-individual variation in movement or impact of impediments on migration delays. More recent research has provided answers to important questions by focusing on certain aspects of eel migration using telemetry techniques. For example, catchment-wide migration studies have been performed to elucidate migration triggers and processes (e.g. Drouineau et al., 2017) or the impact of impediments (e.g. Winter et al., 2006; Monteiro et al., 2020), but not fine-scale behaviour. Others have focused on fine-scale behaviour of individual eels upstream of specific structures (e.g. Trancart et al., 2019, Deleau et al., 2019), but not catchment-wide migration. Likewise, despite studies to understand the influence of hormones on maturation of eels (e.g. Nguyen et al., 2019) and downstream migration (e.g. Sudo et al., 2011; Hagihara et al., 2012), they have been performed in unregulated systems, and thus the interaction between sexual maturity and passage at impediments and harmful intakes remains unquantified. Consequently, the aim of this multi-faceted study was to achieve a complete understanding of downstream migrant silver eel behaviour in a regulated river, incorporating catchment-wide migration, fine-scale behaviour and the influence of hormones, in order to fully understand the impact of hydropower and identify remediation measures.

Acoustic telemetry was employed to quantify the catchment-wide migration and fine-scale behaviour of downstream migrating shortfin eels upon reaching Wairua Power Station (hereon referred to as WPS) on Wairua River, New Zealand. WPS is a high-head, run-of-river hydropower station with an associated diversion weir and spillway. In addition, environmental variables (i.e. flow in the catchment, time of day and lunar cycle), anthropogenic influences (i.e. sluice gate opening, power generation (hereon referred to as PG), spillway flow) and eel maturation (i.e. reproductive hormone levels (Lokman, 2016)) were quantified to understand extrinsic and intrinsic influences on migration. This multidisciplinary study investigated the influence of WPS on three different phases of shortfin eel migration:

1. Movements through the unregulated reach upstream of WPS, including timing of arrival, migration delay and passage route at the DW, i.e. continue along the natural watercourse or entering the WPS canal leading to WPS forebay.
2. Movements into and through WPS forebay, including timing of arrival, migration delay, locations occupied (within 10 m of WPS intake chamber) and route taken, i.e. whether eels passed over the spillway in the forebay or were impinged/entrained.
3. The onward migration in the reach downstream of WPS, including the speed and timing of migration.

2 Materials and Methods

2.1 Study catchment

The Wairua River drains the north-eastern part of the northern Wairoa catchment (sixth largest in New Zealand, approx. 567 km^2) through the Hikurangi Swamp and flows out to sea via the Wairoa River and upper Kaipara Harbour (Figure 1). In the early 1970s, the Hikurangi Swamp Land Drainage and Flood Protection Scheme was constructed by the Northland Catchment Commission to control floodwaters within the Hikurangi valley and to increase production from farmland in the Hikurangi floodplain. It is recognised that flow regulation in this catchment poses the greatest risks to downstream migrating eels due to non-friendly pump stations and aforementioned risks posed by power station operation (Williams et al*.,* 2013). Eels are distributed throughout the entire Wairoa catchment, including into the headwaters ~200 km from the tidal limit (New Zealand freshwater fish data base, 2020), which is located in one of the most productive eel fishery subareas on the North island of New Zealand (New Zealand Fisheries, 2019).

2.1.1 Wairua Power Station (WPS)

Wairua run-of-river hydropower station (WPS) was commissioned in 1915 and utilises the natural head over the Omiru Falls to generate up to 4 MW (Figure 1). The station has four Francis turbines, three with 18 blades, 840 mm (n = 2) and 760 mm (n = 1) and one 880 mm with 13 blades. The turbines are protected by a vertical trash screen with 23-25 mm bar spacing which impinges eels, though some of the bars are bent so eels can also become entrained. Upstream of WPS (2.5 km) the river can either flow through or over a diversion weir (hereon referred to as DW) with a series of gates (gate 1; vertical gate and gates 2 and 3, tip gates; referred to hereon as gate 1, 2 and 3, respectively) and follow the natural watercourse or be diverted to WPS through vertical, bottom opening canal gates (Figure 1). Gate 2 was not open when tagged eels were detected upstream so will not be discussed further.

2.2 Tagging and tracking methods

2.2.1 Animal collection, tagging and blood sampling

A total of 13 eels were captured by station staff in a trap set in the spillway gate of WPS during a forebay and canal dewatering event for maintenance between 4 and 13 April 2016, tagged and released at the head of the WPS Canal (hereon referred to as Site C). Additionally, eels were collected from the intake screen trash pile (*n* = 2) or caught in fyke nets elsewhere in the catchment (see Table A1; *n* = 10) and released 33 km upstream at 'River' release site (hereon referred to as R). The timing of eel capture was informed by studies of eel migration in New Zealand (Todd et al., 1981b), the local Maori community that harvest eels in this catchment for consumption and anecdotal records of impingement at the WPS. Prior to tagging in the field, the maturity status of migrant eels (*n* = 25) was visually determined as described by Todd, (1981a). Eels were then anaesthetised using an aqueous solution of AQUI-S® at a dose rate of 15-20 mg/L for 10 – 15 minutes before they were weighed (780 - 2960 g) and total length (775 – 1033 mm), horizontal (7.3 – 10.6 mm) and vertical (7.2 – 11.8 mm) eye diameters were recorded. A 10 – 15 mm long, ventro-lateral incision was made and an acoustic transmitter implanted into the body cavity. The incision was closed with absorbable sutures. A total of 23 x V13 (36-mm long x 13-mm diameter, 11-g weight in air, 198 days expected life) and 2 x V9 (21-mm long x 9-mm diameter, 4.7-g weight in air, 271 days expected life) acoustic transmitters were implanted (Vemco, Halifax, Canada; https://vemco.com/). Transmitters had a 15 – 45 second coded ping delay, emitted at 69 kHz. A blood sample (maximum 0.1% of eel body weight) was taken from the caudal vein using a hypodermic needle, distributed into a labelled tube (5 ml) containing 50 μl of 200 mg/ml ethylenediamine tetracetic acid and stored on ice to prevent blood clotting until the sampling process was finished. Samples were transported to a laboratory where they were centrifuged at 4°C for 10 minutes for plasma collection. Plasma was aspirated and stored at -80°C until sex steroid (11-ketotestosterone and estradiol-17β) levels were assayed using radioimmunoassay, exactly as described previously (Lokman et al., 1998). Eels were held in aerated tanks until visual observation confirmed full recovery (swimming around, alert) and then were released. During the study, WPS was visited monthly to check equipment; during these visits two tagged eels (one live and one dead) were found on the trash pile after being impinged onto intake trash screens. These eels were found within two weeks after surgery and showed little to no scarring where the acoustic transmitter had been implanted, nor did any suture remain. It is possible that eels impinged at other times may not have been observed and members of the public may have harvested them from the trash screen or trash pile, as this is a common occurrence at this site.

2.2.2 Tracking methods

Acoustic transmissions were recorded using 16 x VR2W receivers (69 KHz; Vemco, Halifax, Canada; https://vemco.com/) strategically located throughout the catchment from 1 April to 16 June 2016, each with an individual code from receiver (R)1 (first receiver downstream from R release, 173 km upstream of the tidal limit) to R16 (most downstream receiver, 119 km upstream of the tidal limit) (Figure 1). River width ranged from 14.8 m at R1 to 44.5 m at R16. Receivers were mounted approximately 1 m from the bottom, facing upwards. Of these, four (R11-R14) were installed in an autonomous underwater acoustic telemetry array system ((Vemco Positioning System (VPS), Vemco, Halifax, Canada)) in the immediate vicinity of WPS forebay during the aforementioned dewatering event. R13 malfunctioned early into the study; hence the array only contained three receivers. Receivers were arranged in a formation that maximised coverage of the required study area as they had known overlapping detection ranges. Each VPS receiver (R11-R14) had a co-located synchronization or 'sync' tag (V8, 69 kHz transmitter, 386 days expected life) secured approximately 30 cm from the top of the receiver. The data were offloaded from each receiver at the end of the study and Vemco conducted initial processing. VPS provides position data for individual tagged eels in the acoustic receiver array, and a relative, unitless estimate of the accuracy of this position; this is referred to as horizontal position error (HPE) (Smith, 2013). Spatial assessment of sync and animal tag HPE in the array was performed, as described by Smedbol et al*.,* (2014) (see Figure A1 for full details). It was determined that all eel positions within 10 m of WPS turbine intake (analysed in ArcGIS) were retained if a HPE filter of 5 or less was applied. The number of eel detections (HPE <5) in 1 m zones within 10 m of the intake were analysed in relation to PG (i.e. categorized by those during 0 – 0.1, 0.1 – 1, 1 – 2, 2 – 3, 3 – 4 and 4 – 5 MW).

2.3 Flows in the catchment and power generation (PG)

Flow data for the Wairua River was recorded at Purua (provided by the Northland Regional Council), 20 km upstream of the DW; mean river flow during the study period was 19.9 m^3/s (range = 5.9 – 96.16 m^3/s). PG data (MW at 30-minute intervals) during the study period (mean = 2.78 MW (range = 0 – 4.75 MW)) were provided by Northpower, owners of WPS. There was a strong positive correlation between canal flow and PG (Pearson Product-Moment correlation, t = 155.62, df = 3104, P < 0.001, cor = 0.94), so PG data were used for analysis when comparing conditions experienced with eel passage. Forebay level (MV) throughout the period eels were detected in the array (13/04/2016 – 15/06/2016) was used as a measure of spill-over (hereon referred to as 'spill level'). A flow exceedance curve (Q values; referred to hereon as Q) was calculated for both river flow (when eels passed over the DW) and PG (when eels passed through WPS during the study period (release date to final eel detection)).

2.4 Data analysis

Timing of all eel movements were cross-compared to sunrise and sunset hours for Auckland (~160 km distance) for the relevant dates (https://www.timeanddate.com/sun/new-zealand/auckland) to determine whether movements occurred during daylight or darkness. For statistical comparisons between two variables, data were first tested for normality of variance using a Shapiro-Wilk normality test and a T-test was used (referred to as t-test) if found to be parametric or a Wilcoxon Signed-Rank test was used (referred to as Wilcox-test) for non-parametric data. For small non-parametric sample sizes, independence permutation tests were used (referred to as independence-test) (see Hothorn et al., 2006). To test for correlations between two factors, a Pearson Product-Moment correlation was used (referred to as cor-test). To compare the distribution of eel detections in the area upstream of WPS intake, Komolgorov – Smirnov tests were used (referred to as KS-test) Significance levels are given to three decimal places. The distance between receivers was calculated using Google Earth measure tool, taking into account river morphology, and used to calculate migration speed. For assessment of eel movement and passage at WPS, eels released at R that entered WPS canal and C (in the WPS canal) were combined because release location did not significantly influence fate (i.e. impinged or passed spillway; two – proportions *Z* test with a Yate's continuity correction ((as the total sample was less than 40 (Gianinni, 2005)) $X^2 = 0.078$, $df = 1$, $P = 0.781$, 95% confidence interval = -0.696 and 0.369). Further, passage time was comparable between release locations for both impinged eels (t-tests; $t = -0.621$, $df = 4.826$, $P = 0.563$) and those that passed the spillway ($t = 0.539$, $df = 4.809$, $P = 0.614$). All statistical analyses (see Table 1) were carried out in R studio v 3.3.0 including the use of packages data.table (Dowle & Srinivasan., 2018), ggplot2 (Wickham, 2016), coin (Hothorn et al., 2006) and gridExtra (Baptiste, 2017).

3 Results

3.1 Passage at the DW or entry into WPS canal

Eleven of 12 tagged migrant eels released at R were detected upstream of DW (33 km from R) between 2 – 38 days after release, the other eel was last detected at R4 (12.6 km from R). Eels arrived at DW at river flows of 5.9 – 44.0 m^3/s ($Q_{5.4}$ – $Q_{99.7}$), with 63.6% arriving in hours of darkness (18:19 – 07:04) and 36.4% during daylight (07:35 – 16:45) (Table 2), on all states of the lunar cycle. The mean ± S.D. migration speed from R to DW was 0.19 ± 0.14 bls^{-1} (min – max = 0.01 – 0.37) and was positively correlated with flow (cor-test; t = 2.118, df = 9, P = 0.063, r = 0.576) (Figure 2). Estradiol-17β levels ranged from 0.46 – 1.21 and 11-ketotestosterone from 10.01 - 20.62 ng/mL and were not correlated with speed of migration, eel length, eye diameter or eel total length (cor-tests; P > 0.05; see Table A2 for full stats).

Three eels (27.2%; flow = $Q_{38.4}$ – $Q_{5.4}$; PG = 3.2 - 4.7 MW/day) passed downstream over gates at the DW and eight (72.7%; $Q_{99.7}$ – $Q_{18.6}$; 1.1 - 4.7 MW/day) entered the WPS canal (Table 2). During passage at the DW, flow (independence-tests; Z = -1.575, n = 11, P > 0.05) and PG (Z = 1.0311, n = 11, P > 0.05) were not significantly different between each of these routes. Nine of the 11 eels (81.8%) passed over DW gates or entered WPS canal in less than 16 minutes; of the remaining two eels one took 36 minutes and the other just over 16 hours (Table 2) to enter the canal. Three eels (33888, 33898 and 33889) passed over the DW when Gate 3 was 61%, 46% and 1% open, Gate 1 was 22 cm, 22 cm and 19 cm open, and PG was 4.6 MW/day, 4.7 MW/day and 3.2 MW/day, respectively. Two eels entered WPS canal when only DW Gate 3 was open 14% (33899) and 35% (33884), and the other two passed when only DW Gate 1 was open 11 cm (33883) and 14cm (33907). Four eels entered WPS canal when all DW gates were closed, i.e. all river water was being diverted to WPS, which included the eel that took over 16 hours to pass.

3.2 Passage at WPS

All eels that entered (n = 8) or were released in (n = 13) the WPS canal entered WPS forebay, predominantly during hours of darkness (95.2%) except for one eel that arrived at 09:59 (33887). PG upon forebay entry ranged from 0.0 to 4.7 MW (Q_{100} – $Q_{4.0}$) and spill level ranged from -10.3 to 109.4 MV (Figure 3). One eel (33905) was detected on two occasions on the receiver at the head of the canal (2 km upstream) after being detected in WPS forebay, but subsequently returned to the forebay.

Based on tag detections by receivers upstream and downstream of WPS, eleven tagged eels were impinged or entrained (52.4%), all when three or four turbines were in operation (turbine flow = $Q_{54.1}$ – $Q_{3.9}$) with the minimum turbine flow that an eel was impinged on being 3.04 MW; (Figure 3) and ten passed downstream over WPS spillway (47.6%). All but three (21549, 33895 and 33896) of the 21 eels detected in WPS forebay were last detected in the forebay during hours of darkness (85.7%). During last detection in WPS forebay, PG did not differ between eels that were impinged/entrained (n = 11; 3.7 ± 0.6 MW; $Q_{54.1}$ – $Q_{3.9}$) and those that passed downstream over WPS spillway, including four eels that passed when turbines were not operational (n = 10; 2.3 ± 2.0 MW; Q_{100} – $Q_{2.4}$) (Wilcox-test; W = 69, n = 21, P > 0.05). Eels that passed WPS spillway experienced significantly higher spill level at this time (n = 10, 113.4 ± 61.0 MV) than eels that were impinged/entrained (n = 11, 46.1 ± 43.6 MV) (t-test; t = -2.928, df = 18.055, P = 0.009).

Average PG while tagged eels were in the WPS canal also did not differ between eels that were impinged/entrained (3.2 ± 0.9 MW) and those that passed WPS spillway (3.3 ± 0.9 MW) (t-test; t = -0.279, df = 18.572, P > 0.05). Similarly, there was no significant difference in average spill level between eels that were impinged/entrained (31.9 ± 32.2 MV) and those that passed WPS spillway (15.1 ± 10.2 MV) (Wilcox-test; $W = 75$, $n = 21$, $P > 0.05$) though one eel was impinged/entrained when no water was passing over the spillway and one when spill level was low (1.9 MV), and hence was not considered to be providing a downstream passage route. Further, PG during last detection of individual eels in WPS forebay relative to the maximum PG each eel experienced prior to passing was significantly larger for impinged/entrained eels (96.4 ± 5.5%) than for eels that passed WPS spillway (49.8 ± 44.4%) (Wilcox-test; $W = 93$, $n = 21$, $P = 0.008$). Also, spill level during last detection relative to maximum spill level experienced prior to passage was also comparable for impinged/entrained eels (46.3 ± 44.2 MV) and eels that passed WPS spillway (66.5 ± 29.3 MV) (Wilcox-test; $W = 40$, $n = 21$, $P > 0.05$) (see Figure A2). There was no significant difference in eel total length between those that were impinged/entrained (mean ± SD = 918.4 ± 70.8 mm) and those that passed WPS spillway (884.8 ± 80.5 mm) (t-test; $t = 1.2911$, $df = 17.569$, $P > 0.05$). Two tagged eels impinged on the trash screen were removed by automated mechanical cleaners and were found in trash during visits to service equipment; one (33880*) was last detected in WPS forebay two days earlier and was dead, whereas the other (33895) was last detected on the same day it was found alive and was released in WPS tailrace.

Three eels (33888, 33889 and 33898) released at R passed downstream over DW gates and travelled to R15 at WPS tailrace (2.50 km downstream of DW via the river) at a migration speed of 1.30 ± 0.39 bls^{-1} (min – max = 0.99 – 1.74). This migration speed was significantly faster (t-test; $t = 5.824$, $df = 2$, $P = 0.028$) than two eels also released at R (33880 and 33884; 0.002 ± 0.001 bls^{-1} (min – max = 0.002 – 0.001)) that entered WPS canal and passed the spillway (R15 = 2.48 km downstream of DW via the WPS). On average, eels were impinged/entrained at WPS after 6.40 ± 11.13 days (min – max = 0.002 – 37.35) which was significantly less time delayed than that of eels to pass WPS spillway (25.17 ± 15.12

(1.25 – 46.75)) (Wilcox-test; W = 14, *n* = 21, *P* = 0.003). Indeed, 82% of eels were impinged/entrained in less than 5.32 days whereas for eels that passed WPS spillway, 90% remained in the forebay for between 12.77 – 46.75 days (Figure 4 top).

There was a negative correlation between mean PG and passage time at WPS (Figure 4 bottom); which was significant for eels that passed over WPS spillway (cor-tests; *t* = -2.418, *df* = 8, *P* = 0.042, *r* = -0.64) but not for impinged/entrained eels (t = -1.629, *df* = 9, P = 0.138, *r* = -0.48). There was also a significant negative correlation between mean spill level and passage time at WPS for eels that passed WPS spillway (cor-tests; *t* = -3.055, *df* = 9, *P* = 0.014, *r* = -0.71) but not for impinged/entrained eels (*t* = -1.626, *df* = 9, *P* = 0.138, *r* = -0.48). Likewise, there was no significant correlation in passage time at WPS and levels of reproductive hormones, estradiol (0.12 – 1.04 ng/mL) or 11-ketotestosterone (10.96 – 95.41 ng/mL) for impinged/entrained eels or eels that passed WPS spillway, respectively (cor-tests; *P* >0.05, see Table A2). Nor was there a significant difference in levels of either hormone between impinged/entrained eels (estradiol; 0.29 – 0.91 ng/mL and 11-ketotestosterone; 14.24 – 48.94 ng/mL) and eels that passed WPS spillway (estradiol; 0.12 – 1.04 ng/mL and 11-ketotestosterone; 10.96 – 95.41 ng/mL) (t-tests; estradiol; *t* = -0.020, *df* = 6.794, *P* > 0.05 and 11-ketotestosterone; *t* = -1.301, *df* = 5.342, *P* > 0.05).

3.2.1 Behaviour upstream of WPS intake chamber

Relatively few eel positions (<12%) recorded in WPS forebay were immediately upstream (within 1 m) of WPS intake chamber for eels that were impinged/entrained. For these eels, the majority of positions from PG 1 – 2 MW and higher were from 6 – 8 m away (1 – 2 MW = at 7 m distance (19.0%), 2 – 3 MW = 7 m (15.0%), 3 – 4 MW = 6 m (17.0%) and 4 – 5 MW = 6 m (17.4%). In contrast, for eels that passed WPS spillway, at 2 – 3 MW and higher, there was a large proportion of detections within 1 m of the intake chamber (2 – 3 MW = 70%; 3 – 4 and 4 – 5 = 60% of eels) (Figure 5), i.e. a number of eels that did get close to WPS intake chamber escaped and passed downstream. Overall, there was no significant difference in eel positions upstream of WPS intake between impinged/entrained eels and those that passed downstream over the spillway (Wilcox-test; W = 1466, n = 21, P > 0.05) nor was there any significant difference in eel positions between the six levels of PG examined (KS-tests; P > 0.05, Figure 5).

3.3 Onward migration

Fifty percent (n = 6) of eels released at R (n = 12) were detected on the most downstream receiver (R16); three of these had passed over the DW and three over WPS spillway. Passage time at the DW was between 2 and 36 minutes and passage time at WPS was 12 to 36 days, which equated to 0.01 – 0.02% and 47.62 – 92.17%, respectively of the total time individuals were detected in the river. Despite delays, eels that passed WPS spillway were detected on R16 (08/05/2016 – 23/05/2016) during the same period as eels that passed over DW (30/04/2016 – 25/05/2016) (Figure 6 top). One eel arrived at R16 on a third quarter moon, two on a new moon and three on a full moon. Further, both groups of eels migrated through the unobstructed reach downstream of WPS at a comparable speed (WPS eels = 0.14 ± 0.25 bls^{-1} and DW eels = 0.46 ± 0.35 bls^{-1}; t-test; t = -1.377, df = 3.471, P > 0.05). However, the flow when these eels passed R16 was higher for eels that passed over WPS spillway ($Q_{42.7}$ – $Q_{26.6}$) compared with eels that passed over the DW ($Q_{85.2}$ – $Q_{68.9}$) (independence-test; Z = -2.130, n = 6, P = 0.033) (Figure 6 bottom). In addition, the seven eels released at C that passed WPS spillway were all detected on R16 in between 0.36 and 6.01 days after last detection at WPS, but the eel (33895) found in trash removed from the screen and released downstream of WPS was never detected again.

4 Discussion

This study demonstrated how catchment-wide and fine-scale acoustic telemetry (rather than one in isolation), coupled with environmental and biotic data (including the influence of hormones), enabled a comprehensive understanding of the impact of hydropower on downstream migrating anguillid eels. Indeed, the influence of WPS on three different phases of shortfin eel migration were investigated, i.e. through the unregulated reach upstream of WPS, into and through WPS forebay and the onward migration in the reach downstream. The findings from all three phases of their migration have been used to recommend a combination of measures to remediate the impact of WPS on the downstream migration of shortfin eels. The findings and recommendations are transferrable to water managers attempting to identify and implement cost-effective, evidence-based management and policy for remediating the impact of hydropower generation on the downstream migration of anguillid eels globally.

Eels were caught, tagged and released during a period of elevated river discharge which probably triggered their downstream migration, as reported by Boubée et al., (2001) and Jansen et al., (2007). Eel movements in an unregulated reach of the Wairua River were quicker during higher river flow but arrival at the first barrier (DW) occurred across a wide range of flows ($Q_{5.4}$ – $Q_{99.7}$), both during the day (36.4%) and at night (63.6%) and on all phases of the lunar cycle. A high proportion of eels (73%; $Q_{99.7}$ – $Q_{18.6}$) entered WPS intake canal leading to the forebay, including two when DW gates were partially open and allowing access to the natural river channel (Q_{39} and Q_{46}). Tracking eels in the reach upstream of the WPS revealed that under the current operational regime, 73% of eels that reached the DW entered WPS intake canal and 81% of these entered within 16 minutes. It is strongly recommended that minimising the proportion of migrants that enter WPS intake canal and maximising the proportion that pass through DW gates is the preferred option for minimising the impact of hydropower generation on shortfin eel stocks in the Wairua River. Elsewhere, operational shutdowns when environmental conditions, such as elevated discharge and a new moon, prompt silver eels to migrate have been proposed as mitigation (e.g. Eyler et al., 2016; Haro, 2003). Unfortunately, such a tailored approach is unlikely to be economically acceptable at this site given the broad range of flows, times of day and lunar cycle that eels approached the DW. Therefore, based on the observations made at this site, gates at the DW could be kept open by the minimum amount eels were observed passing (i.e. gate 1; >19 cm; Gate 3; >46 %) throughout the autumn shortfin eel migration period, i.e. February – June. This is further supported by four eels entering WPS canal when DW gates were closed and four more when DW gates were open less than when eels were observed to pass. In addition, deterring eels from entering WPS canal, most likely through physical screening (e.g. Gosset et al., 2005) or possibly behavioural deterrents (e.g. Patrick et al., 2001) is likely to be the most effective method to protect downstream migrating eels at this site. Sweeping flows from the main river will also be beneficial for physical screens at WPS canal gate in terms of minimising impingement of debris and fish on the screen.

Over half (52.4%) of the eels that entered WPS were deemed to have been impinged/entrained at WPS and died, including two when the spillway was not available for downstream passage (i.e. spill level <1.9 MV), while the remaining eels (47.6%) passed over the spillway and continued their onward migration. Tagged eels were only impinged/entrained when three or four turbines were in operation (turbine flow > 3.04 MW; $Q_{54.1}$ – $Q_{3.9}$) which is consistent with other studies that report impingement/entrainment typically occurs when intake flows exceed fish swimming capabilities (Calles et al., 2010; Russon et al., 2010). Published turbine mortality rates vary widely worldwide but as the risk increases with eel size and intake head height (see Beentjes et al., 2005) mortality may reach 100% for large shortfins in New Zealand (Mitchell & Boubée, 1992). Consequently, measures to reduce the mortality rate at the WPS intake and increase downstream passage via the spillway are required, if an effective screen cannot be installed at WPS canal entrance. Turbine shutdowns have been successful in the U.S. to allow eel passage via spillways or through bypass chutes (Smith et al., 2017) while Haro et al., (2003) predicted that hydropower shutdown on days of rainfall could reduce mortality from 10.7 to 3.9%. Based on the findings of this study, rather than full shutdown or during periods of high flow, a more tailored approach is recommended with WPS turbine operating capacity not exceeding 3.04 MW (i.e. the lowest PG an eel was impinged on) during the silver shortfin eel migration period.

To reduce the impact of impingement, Turnpenny (2011) proposed a fish recovery and return (FRR) system that collects impinged eels and transports them downstream. Such remediation could be implemented at WPS and may help reduce impingement mortality. However, two eels retrieved from the WPS trash pile that appeared to be in good condition and were tagged early in the study both migrated through the catchment after release at R, but were subsequently impinged onto WPS intake screens, potentially because of indiscernible reduced fitness. Further, an impinged eel recovered from trash at WPS and released downstream the same day failed to complete its onward migration, suggesting impingement had caused reduced fitness. Calles et al., (2010) and Pederson et al., (2012) also reported that all impinged eels examined in their studies were either dead or severely damaged. Further, it is known that members of the public enter WPS (despite the fencing, signage and extensive consultation) to retrieve eels from the trash pile for consumption, and thus an efficient FRR system must prevent human access to prove effective. An alternative may be to have openings in the racks that lead fish to a route outside the turbines via a flushing channel, as reported by Økland et al., (2019), who found that 24% and 27% of eels used such a route at a hydropower site on the River Rhine.

Ten eels (47.6%) passed the WPS spillway during significantly higher spill level, whereas turbine flow did not influence route choice. Haro et al., (2003) simulated that mortality of the eel run (based on 6 years of data) for American eel (*A. rostrata*) decreased with increasing spill flow. During this study, only four eels passed the spillway when turbines were not operational, which occurred for 43.8% of the time. The remaining six eels passed the spillway despite it only being open for 52.8% of the time turbines were operational, and did so during almost the entire range of turbine flows (Q_{100} – $Q_{2.4}$). This indicated that the spillway was either hard to find (i.e. low attraction efficiency) or eels were reluctant to pass over it (i.e. low entrance efficiency); both factors are important for bypass efficiency (Baker et al., 2018) but it was not possible to distinguish between the two in this study. A low spillway attraction efficiency could be attributed to its location in a corner of the forebay downstream of the WPS intake and / or due to it having a surface entrance, as eels are known to be bottom – oriented when navigating forebays (Brown et al., 2009; Haro et al., 2000a). A low spillway entrance efficiency could be attributed to depth and / or velocity of water passing over the spillway, with European eels known to avoid constricted, accelerating flows (Piper et al., 2015), while bypass avoidance rates for American eels were lower at higher entrance velocities (Haro et al., 2016). The lowest spill when eels passed during this study was 33.9 MV and thus is recommended as a minimum spill level during silver shortfin eel migration to increase downstream passage via the spillway. Given 95.2% of tagged eels first approached and 85.7% passed WPS spillway during hours of darkness, it is possible the minimum spill level needs only to be maintained at night. Selective opening of hydroelectric dam spillway gates has been proven to provide safe downstream passage for migrant eels in New Zealand (Watene & Boubée, 2005). Alternatively, a bypass channel with a bottom-orientated entrance and attractive flows (e.g. Conte airlift or siphon bypass, Baker et al., 2018) could be installed in WPS forebay. Crucially, from a hydropower generation perspective, such an approach may demand less water than ensuring certain flows pass over the existing spillway.

During this study, eels passed the WPS spillway after delays of up to 47 days. Delays in downstream migrating silver eels have been reported upstream of other hydropower, water abstraction and pump stations, ranging from 8 to 157 days (e.g. Behrmann-Godel & Eckmann, 2003, Piper et al., 2013, Eyler et al., 2016). Migration delays can influence time of arrival at spawning grounds (Eyler et al., 2016), deplete energy reserves of eels that cease feeding during their spawning migration (e.g. Dainys et al., 2017) and/or increase the risk of diseases due to stress and increase predation risk (Garcia De Leaniz, 2008). Despite delays, eels passing WPS spillway were detected in the estuary (R16) at a comparable time to eels that passed the DW. Five of six (83.3%) eels arrived on either new (n = 3) or full (n = 2) moons, which corresponds to when tide would be highest as the catchment is tidal below WPS. Therefore, route choice, despite affecting delay length, did not affect time to escape from the catchment (onward migration) possibly because eels that passed the DW paused their migration during either sub-optimal conditions, earlier stages of maturity or because of stress (e.g. Aoyama et al., 2002; Tesch, 2003; Watene & Boubée, 2003). Although silver eels generally perform directional movements during their migration, both silver and yellow eels have been found to seek refuge during the day in areas with rocks or debris for hiding or soft mud for burrowing (Aoyama et al., 2002). As forebays to intakes generally have reduced habitat and flow diversity (SEPA, 2008), eels that were delayed by WPS may have expended considerable energy avoiding impingement/entrainment and finding a safe downstream passage route. Further, eels delayed at WPS migrated faster, which would be more energetically costly. While providing an attractive safe downstream passage route for eels would reduce delays, artificial refuges could be installed in forebays, to minimise indirect impacts of hydropower on eels. These could also be used to catch migrant eels for safe manual transfer downstream of hydropower stations.

The onset of the eel spawning migration coincides with onset of puberty and an associated increase in sex steroid levels, principally estradiol-17β and 11-ketotestosterone (Lokman et al., 1998). Moreover, experimental exposure of yellow eels to 11-ketotestosterone results in many of the changes that are seen during the silvering transformation (Rohr et al., 2001), prompting the hypothesis that levels of both sex hormones could be indicative of migratory readiness. However, whilst morphology was indicative of, and biochemical criteria (sex steroid levels) were within the range typical for migrant female shortfins (c.f., Lokman et al., 1998), there was no correlation between speed of eel movement or passage time at WPS in the present study. Therefore, the inter-individual variation in movement between tagged silver eels and the impact of WPS (e.g. migration delays) could not be attributed to level of sexual maturity, emphasizing the importance of extrinsic influences on migration.

4.1 Conclusions and summary of remediation measures

In catchments with obstructions to longitudinal connectivity and around potentially hazardous intakes, understanding the downstream spawning migration of eels is essential for water resource managers to identify whether eel passage solutions are required. Ultimately this information will help meet environmental legislation to conserve ecologically and economically important species by improving access to spawning grounds. During this study, a high proportion of downstream migrating eels entered the WPS forebay, approximately half of which were unable to continue their seaward journey and those that passed over WPS spillway experienced long delays before passage, which could not be attributed to sexual maturity. This knowledge led to the identification of the following potential remedial measures that could be implemented singly or in parallel during the eel migration period

(February – June in New Zealand), including whether each measure has been proven (denoted by an *), or is recommended based on findings (denoted by a +):

(1) To improve passage at the DW;
    (a) Ensure that a gate is always open by a minimum amount (i.e. gate 1; >19 cm; Gate 3; >46 %) *
    (b) Install a physical screen or behavioural deterrent on WPS canal intake +
(2) To reduce the risk of impingement or entrainment;
    (a) Generate no more than 3.04 MW at any one time *
(3) To increase the attractiveness of the spillway;
    (a) Always maintain flow over the spillway a minimum of 33.9 MV* at night +
(4) To improve safe passage, provide an additional bypass channel in the forebay tailored to eel behaviour +
    (a) Flow refuges could be provided in the forebay to reduce energy expenditure and reduce risk of impingement and entrainment +

While operational changes (i.e. measures 1, 2 and 3) and installing additional bypass channel (i.e. measure 4) are relatively inexpensive in comparison to engineered solutions, such as physical screening (fine-mesh and low through-screen velocities) and retrofitting fish-friendly turbines, they will potentially reduce the amount of power generation and thus will incur indirect costs throughout the period of implementation. Such generation losses would certainly impact hydropower generation, which is a dilemma for New Zealand water resource managers (see Beentjes et al., 2005). However, the increasing pressure on water resources worldwide calls for reassessment of legislative requirements. Utilising the natural conditions of the river and adapting management regimes (Haro et al., 2003) reduces the necessity for expensive structural changes to provide safe alternative routes. Therefore, a combination of approaches that demand the least amount of water could potentially be explored if it is not possible to implement all recommendations. These findings should be transferrable globally to water managers that are attempting to identify cost-effective solutions for remediating the widespread issue of the impact of water intakes on the downstream migration of anguillid eels.

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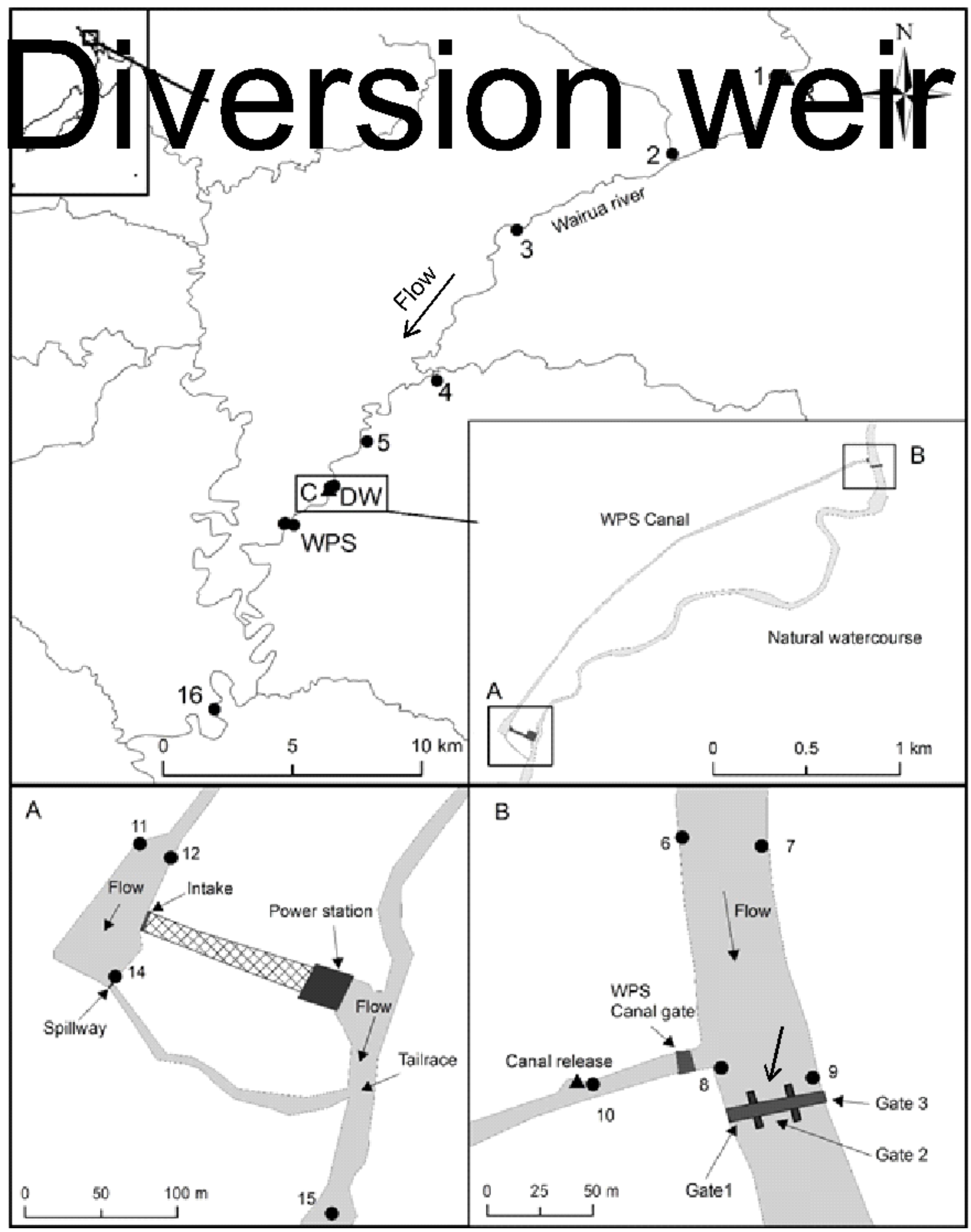
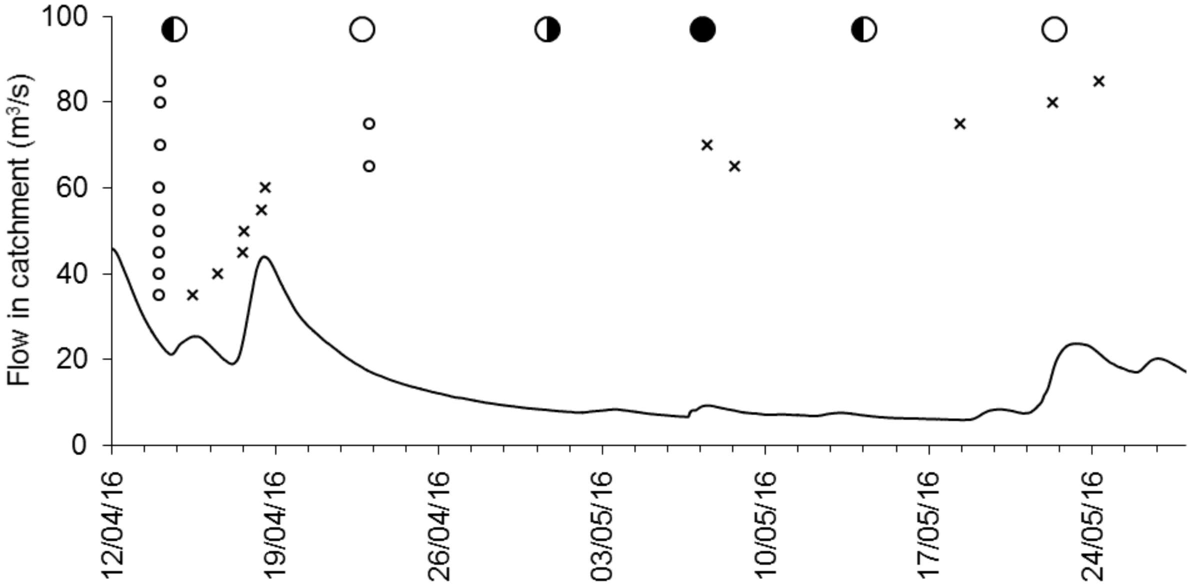

Diversion weir
N
1
2
Wairua river
3
Flow
4
5
C
DW
WPS
16
0
5
10 km
B
WPS Canal
Natural watercourse
A
0
0.5
1 km
A
11
12
Flow
Intake
Power station
14
Spillway
Flow
Tailrace
0
50
100 m
15
B
6
7
Flow
WPS
Canal gate
Canal release
8
9
10
Gate 3
Gate 2
Gate1
0
25
50 m

Figure 1. Map of study catchment showing receiver locations, river (R) and canal (C) release site locations and location of arrays of receivers at the diversion weir (DW, 4 receivers) and Wairua Power Station (WPS,3 receivers); Schematic of the WPS, showing receivers (6 – 9) and gate locations (1, 2 and 3) at the DW that lead to Wairua falls, and the canal gate that leads down the canal to WPS; receiver locations in the WPS forebay area (11 – 13), location of intake, spillway, WPS and receiver 15 in the tailrace. Natural watercourse and power station canal and tailrace are indicated.



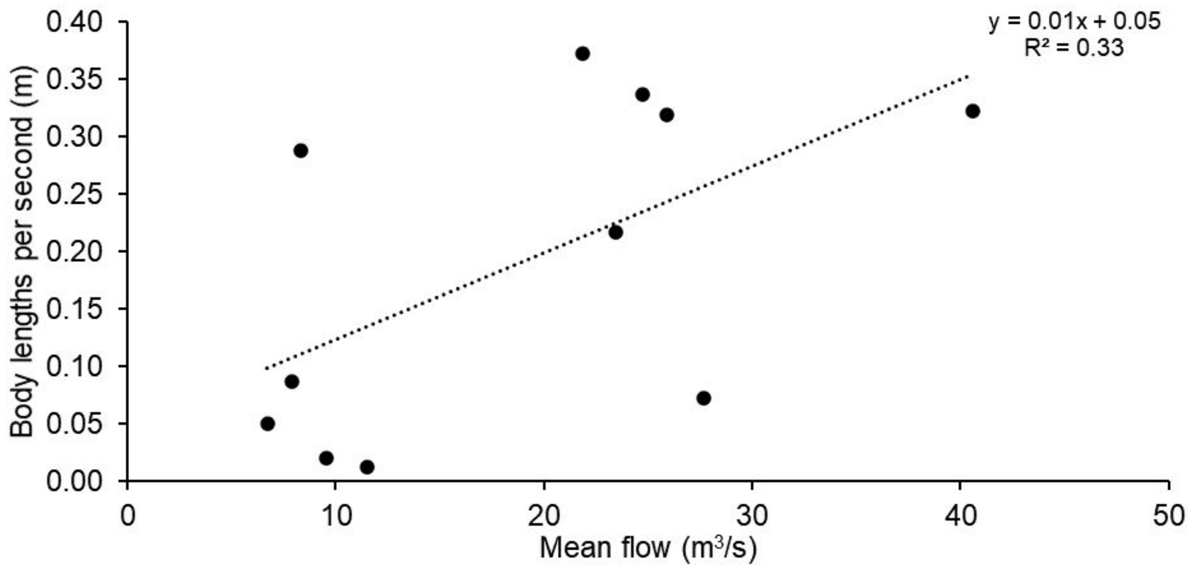


Figure 2. Timing of eel released at R (circle) and first detection at DW (cross), flow in the catchment (m^3/s) and lunar cycle (top), and speed (bls^{-1}) and mean flow (m^3/s) during each eel's downstream movement from release to the DW (bottom).

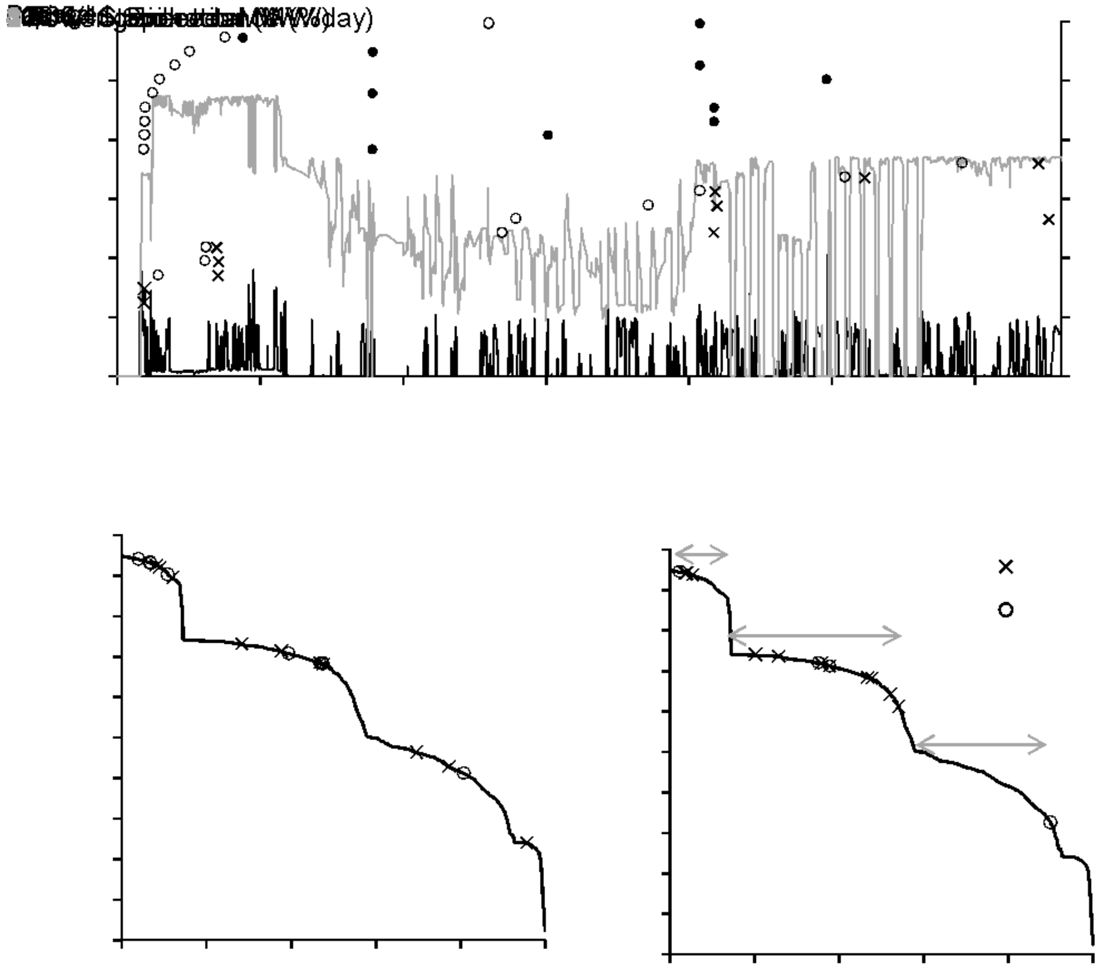


Figure 3. Top: Power generation (grey line) and spill level (black line) at WPS during the study showing eels first (white circle) and last detection in the array for eels that passed WPS spillway (black circles) and those that impinged (crosses); (Note: crosses only indicate eel was impinged shortly after first detection). First (bottom left) and last detection (bottom right) in WPS forebay for eels that were impinged/entrained (cross) and passed (circle) in relation to PG exceedance curve during the study period, grey numbers and arrows indicating number of turbines in operation (note: nil PG not plotted).

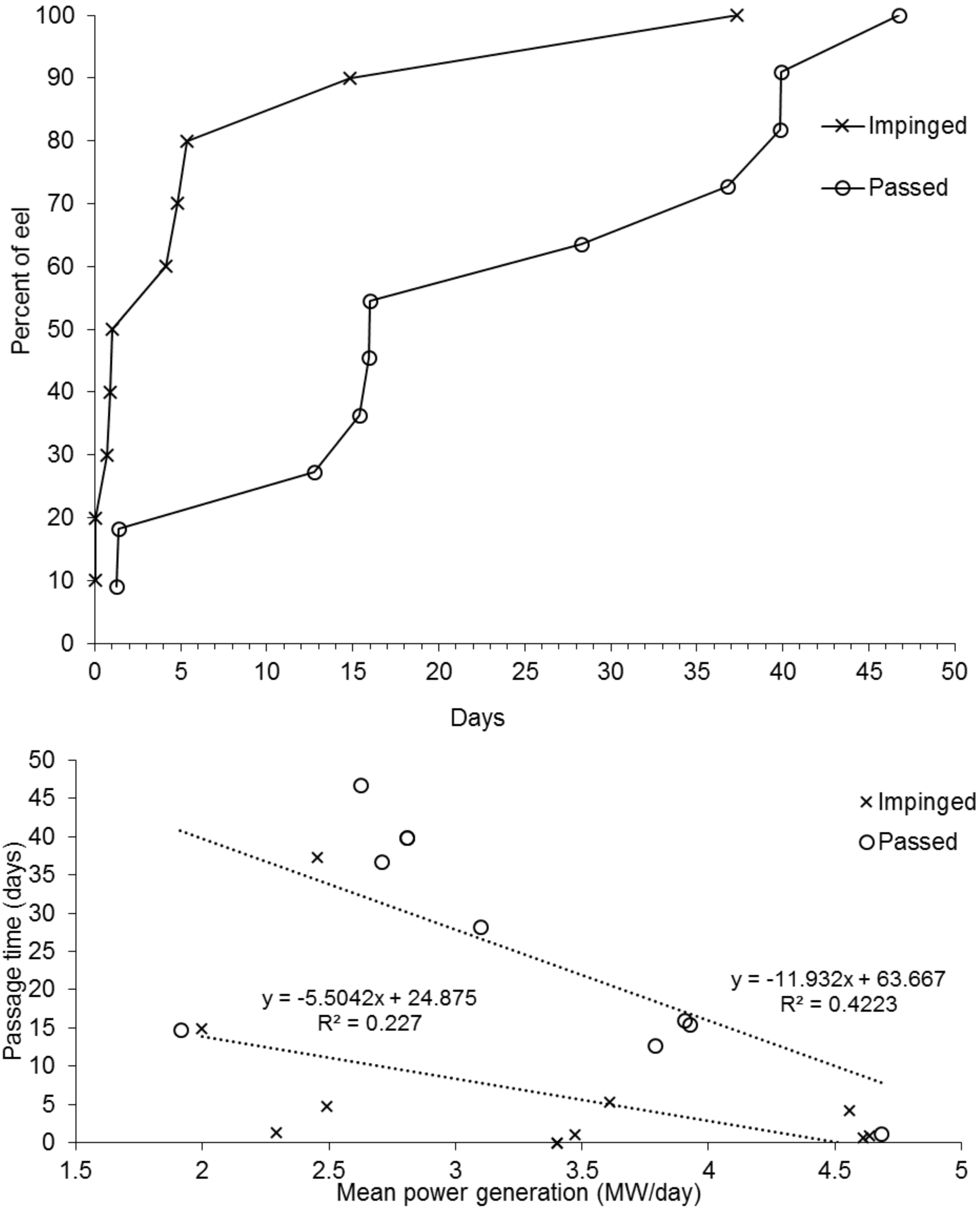


Figure 4. Cumulative proportions (%) (top) and mean power generation (MW/day) (bottom) for time (days) between first approach to WPS and subsequent impingement/entrainment (crosses) or spillway passage (circles).

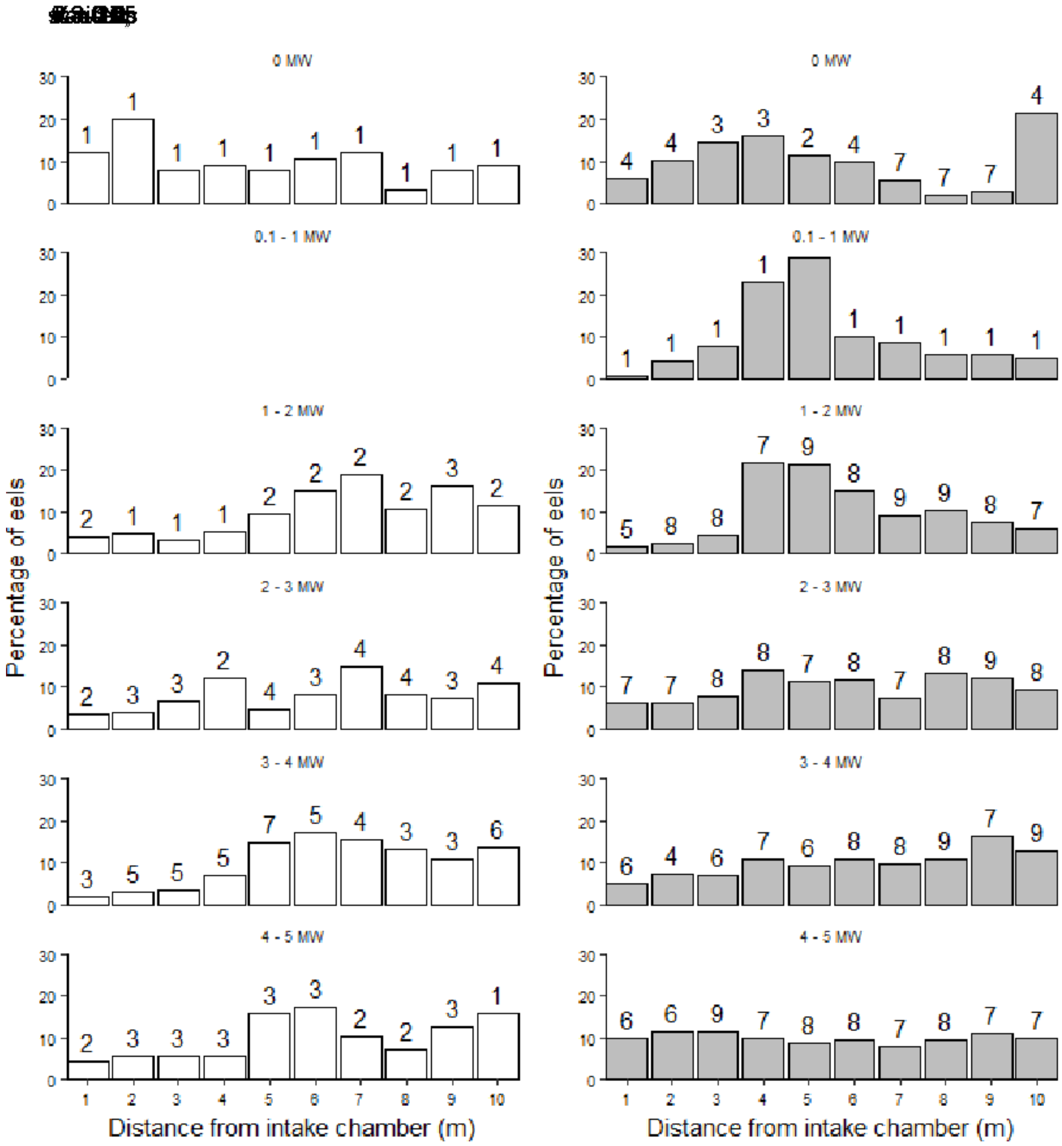


Figure 5. Percentage of detections within 1m zones upstream of the intake chamber, for impinged/entrained eels (left) and eels that passed WPS spillway (right) at differing power generation. Data labels = number of different eels.

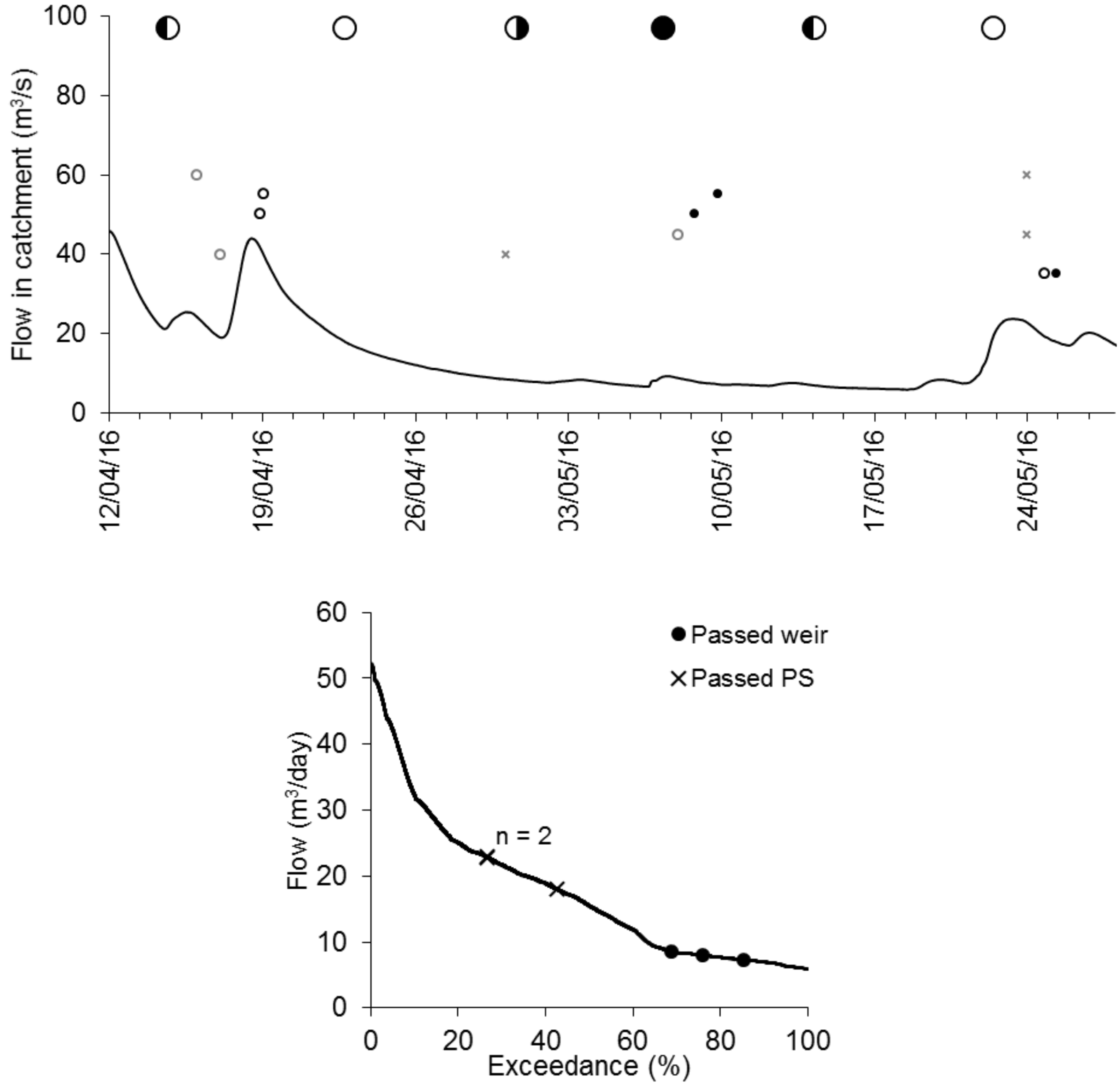


Figure 6. (top) Timing of eels arriving at R16 (last receiver in the catchment) after either passing through gates at the DW (black symbols) or over the WPS spillway (grey symbols). River flow in the catchment (m^3/s) and lunar phase also shown. (bottom) timing of last detection on Receiver 16 (last receiver in the catchment) in relation to flow exceedance curve of the catchment flow data. All records are for eels released at R1 that travelled via the weir (n = 3) and power station spillway (PS; n = 3).

Table 1. Statistical tests carried out on data collected during the study

Factor	Test used
Proportion of eels impinged or passed from each release location (R or C)	Two – proportions *Z* test with a Yate's continuity correction
Time to be impinged or pass the spillway at WPS between eel release locations (R and C)	T-tests
Speed of eel migration through unobstructed reach 33 km upstream of DW, final detection on R2 to first detection at the DW (all speed units given in body lengths per second (bls^{-1}).	Cor-test with: ● Flow ● Levels of reproductive hormones
Flow (m^3/s) and PG (MW/day) at the time of passage at DW	Independence-tests between eels (released at R) that passed over a) DW and b) WPS spillway
Time between first and last detection of individual eels at a) DW and b) WPS (referred to as 'passage time').	Cor-tests with average WPS PG and spill level for a) impinged/entrained and b) eels that passed downstream over the spillway in the forebay of WPS (hereon referred to as eels that passed WPS spillway)
Conditions experienced when eels passed over DW (n = 3) to those that entered WPS canal (n = 8)	Independence-test between the two groups
Conditions experienced during final detection (PG and spill level)	Wilcox-tests; between impinged/ entrained eels and eels that passed WPS spillway
Proportion of maximum generation/spill level experienced per eel (for analysis of conditions when eels left relative to that experienced)	Wilcox-tests; between impinged/entrained eels and those that passed WPS spillway.
Average PG and spill level when in WPS canal	t-tests between impinged/ entrained eels and eels that passed WPS spillway
Proportion of detections in in 1 m zones extending to 10-m upstream of WPS intake under different PG, to assess whether power generation affected eel distribution in this area	Wilcox-tests; between impinged/entrained eels and those that passed WPS spillway.
The distribution of eel detections in the area upstream of WPS intake	KS-test; between impinged/entrained eels and those that passed WPS spillway under aforementioned different PG categories (0 – 0.1, 0.1 – 1, 1 – 2, 2 – 3, 3 – 4 and 4 – 5 MW/day.
Speed of eel migration from last detection at DW to WPS tailrace (first detection on R15) Last detection on R15 to most downstream receiver (R16)	t-tests between eels (released at R) that passed over a) DW and b) WPS spillway

Speed of eels released at R from receiver downstream of WPS (R15) to final receiver (R16)	Independence-test between eels that passed spillway at WPS; *n* = 3 and DW; *n* = 3
Flow in catchment when last detected	Independence-test between eels that passed spillway at WPS; *n* = 3 and DW; *n* = 3
Size of eels	t-test between impinged/ entrained eels and eels that passed WPS spillway Cor-tests between eel length/ eye diameter and levels of reproductive hormones
Passage time of eels	Wilcox-test between impinged/ entrained eels and eels that passed WPS spillway
Reproductive hormone levels	t-tests between impinged/ entrained eels and eels that passed WPS spillway
Day length and hormone levels	Cor-tests between impinged/ entrained eels and eels that passed WPS spillway

Table 2. Time and flow (Q) on arrival at DW, passage route (DW = diversion weir; WPSC = WPS canal), time of passage, passage time, position Gates 1 and 2, and WPS power generation (PG) at time of passage for eels released at R.

Eel	Time of arrival	Q on arrival	Passage route	Time of passage	Passage time (hh:mm:ss)	Gate 1 (cm)	Gate 3 (%)	PG (MW/day)
33888	21:10	5.4	DW	21:12	00:02:13	22	61	4.6
33898	01:08	6.3	DW	01:17	00:08:19	22	46	4.7
33889	18:19	38.4	DW	18:29	00:09:35	19	1	3.2
33880	23:57	67.3	WPSC	00:13	00:16:23	2	1	2.0
33883	15:26	5.4	WPSC	15:28	00:01:42	11	1	4.2
33884	22:34	21.4	WPSC	23:10	00:36:33	1	35	4.5
33899	00:47	39.2	WPSC	00:55	00:07:46	2	14	4.7
33901	07:35	99.7	WPSC	07:49	00:13:12	1	1	1.1
33905	16:45	74.6	WPSC	08:47	16:01:52	2	1	2.5
33906	07:04	46.0	WPSC	07:17	00:12:37	1	1	2.7
33907	13:50	23.1	WPSC	13:51	00:00:47	14	1	4.5