

Research Article

Do low-head riverine structures hinder the spread of invasive crayfish? Case study of signal crayfish (*Pacifastacus leniusculus*) movements at a flow gauging weir

Paula J. Rosewarne¹, Adam T. Piper², Rosalind M. Wright³ and Alison M. Dunn^{1*}

¹ School of Biology, University of Leeds, LS2 9JT, UK

² International Centre for Ecohydraulics Research, University of Southampton, SO17 1BJ, UK

³ Environment Agency, Rivers House, Feering, CO5 9SE, UK

E-mail: bspjr@leeds.ac.uk (PJR); atp1g08@soton.ac.uk (ATP); ros.wright@environment-agency.gov.uk (RMW); a.dunn@leeds.ac.uk (AMD)

*Corresponding author

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Abstract

Increasing legislative drivers demand the removal or modification of riverine barriers to enhance habitat connectivity for fish; however there is also concern that greater connectivity will hasten the spread of aquatic invaders such as the signal crayfish (*Pacifastacus leniusculus*). Passive Integrated Transponder (PIT) telemetry was used to assess passage of signal crayfish (n=392) over a typical low-head riverine structure, a flow gauging weir, during a 17 month period. Sixty percent of tagged crayfish were detected, with greatest crayfish activity associated with high water temperatures and long day lengths. The study weir reduced upstream crayfish movements, with 45% less passages than in the control stretch with no weir, but there was no difference in the downstream direction. We found sex and size related differences in crayfish movement patterns with male crayfish more likely to successfully ascend the weir, and larger crayfish to descend the weir. Although increased fluvial connectivity will benefit migratory fish species, we suggest that the removal or modification of even quite minor, low-head structures such as the one investigated could hasten the upstream spread of signal crayfish.

Key words: barrier; invasion; freshwater; weir; barrier removal; connectivity

Introduction

In Europe, the EU Water Framework Directive (WFD), Eel Regulations and, in the UK, proposed forthcoming Fish Passage Regulations (Defra 2013) all require managers to improve habitat connectivity for fish. Accordingly, riverine structures are being assessed for both functional necessity and porosity to fish. Those deemed redundant may be removed and mitigation will be necessary for others (e.g. reducing head drop, modifying surface material, installing fish passes) (Nunn and Cowx 2012). Even relatively minor structures such as culverts and low-head weirs cause habitat fragmentation for fish species (Gibson et al. 2005; McLaughlin et al. 2006; Lucas et al. 2009), and increasing evidence suggests that the physical impediment or altered flow regimes created by such barriers also influence the

dispersal patterns of invasive species (Kerby et al. 2005; Foster and Keller 2011; MacNeil and Platvoet 2013). Hence, there is concern that the removal or modification of structures may hasten invasion rates.

The signal crayfish (*Pacifastacus leniusculus* Dana, 1852) is an invasive decapod native to North America which was introduced to California and then to Europe in the 1960–70s for aquaculture. It subsequently escaped or was released (Rogers and Watson 2011), and has substantially extended its invasive range, now occurring in 27 European territories (Holdich et al. 2009). *P. leniusculus* continues to spread through freshwater systems causing loss of species richness, restructuring of invertebrate communities (Nystrom et al. 2001; Crawford et al. 2006), predation upon fish and emerging fry (Guan and Wiles 1998; Edmonds et al. 2011), loss of river bank integrity due to

burrowing (Holdich et al. 1999), and decimation of native crayfish species through its role as a vector of the crayfish plague pathogen *Aphanomyces astaci* (Schikora, 1903) (Alderman et al. 1990; Edgerton et al. 2004). Crayfish are a much translocated group and many species have become invasive in their introduced range, however, there is currently no effective large-scale means of controlling invasive crayfish populations (Freeman et al. 2010). Localised extirpations of *P. leniusculus* have been reported after treatment with biocide (Peay et al. 2006), and reduced abundances through exhaustive trapping (Dana et al. 2010) and trapping combined with fisheries management (Hein et al. 2007). Many other potential control methods are under investigation including the use of pheromones (Stebbing et al. 2003) and electro-cution (S. Peay, pers. comm.), though direct control, even at smaller scales, is difficult and requires sustained fieldwork. The potential to enhance the upstream movement of invasive crayfish through the removal or modification of barriers is of concern, as native crayfish populations are now largely confined to headwaters (Collas et al. 2007; Weinländer and Füreder 2012).

Understanding and predicting the future spread of *P. leniusculus* is a crucial step in targeting limited resources for management (Gherardi et al. 2011). Much work has been conducted to this end, ranging from empirical calculation of invasion rates (Peay and Rogers 1998; Bubb et al. 2005; Hudina et al. 2009) and individual dispersal ability (Bubb et al. 2006), to continent-scale modelling (Capinha et al. 2013). In their spread through freshwaters, invasive crayfish may encounter a range of structures of both natural (e.g. waterfalls, rock ramps, rapids) and manmade (e.g. dams, weirs, sluices) origin, yet their influence on dispersal is rarely considered in distribution analyses. In a notable exception, Kerby et al. (2005) found that barriers, both natural and manmade, restricted the movements of the invasive red swamp crayfish (*Procambarus clarkii* Girard, 1852) in California, contributing to a general downstream pattern of spread after colonisation. Remaining in California, Light (2003) similarly found that *P. leniusculus* did not occur in the sites upstream of cross-channel structures. A greater understanding of how river structures affect crayfish dispersal is therefore required to formulate an integrated management approach to both enhance fish migration while protecting native crayfish populations.

Conversely, there is interest around purposefully installing structures that function as migration barriers to prevent the spread of invasive species into highly sensitive areas such as remaining strongholds of natives (Rahel et al. 2008). This approach has been implemented in Southern Spain where field trials revealed that a series of three dams effectively prevented the spread of *P. clarkii* into headwaters over a four period (Dana et al. 2011). Further, Frings et al. (2013) recently proposed design metrics for a fish-passable crayfish barrier based on flume trials. Increasing our understanding of how structures hinder or prevent the spread of crayfish in the field is fundamental to this management approach.

This study investigates the influence of a common riverine structure, a flow gauging weir, on the spread of signal crayfish. Movements of signal crayfish past the weir were tracked over a 17 month period to determine if the structure presented a barrier to crayfish movement, and if so, how this 'barrier effect' was influenced by environmental conditions such as water temperature and flow.

Methods

A Passive integrated Transponder (PIT) telemetry array was used to monitor signal crayfish movements over a flow gauging weir between July 2011 and November 2012. A total of 392 crayfish were captured up- and downstream of the weir, uniquely tagged and released each July. Crayfish movements across the weir were compared with movements across a control stretch of river of equivalent length and analysed in relation to environmental variables (flow, water temperature, day length and moon phase).

Study site

The study was conducted at a concrete trapezoidal flume (weir hereafter) used for flow gauging in the river Glem, Suffolk, UK (52°05'33.14"N, 0°41'34.65"E) (Figure 1A,B). Low-head structures such as this one are estimated 2 – 4 orders of magnitude more numerous than high-head dams (Lucas et al. 2009), with over 700 similar weirs in the UK alone (CEH 2010). The river Glem is a tributary of the river Stour, with mean discharge $0.48 \text{ m}^3 \text{ s}^{-1}$ (10 year average) (CEH 2011). The control and weir stretch were ecologically similar in terms of habitat, refugia and food availability. They ranged in width from 5.56 to 6.62 m and were characterised by a low gradient with a mainly

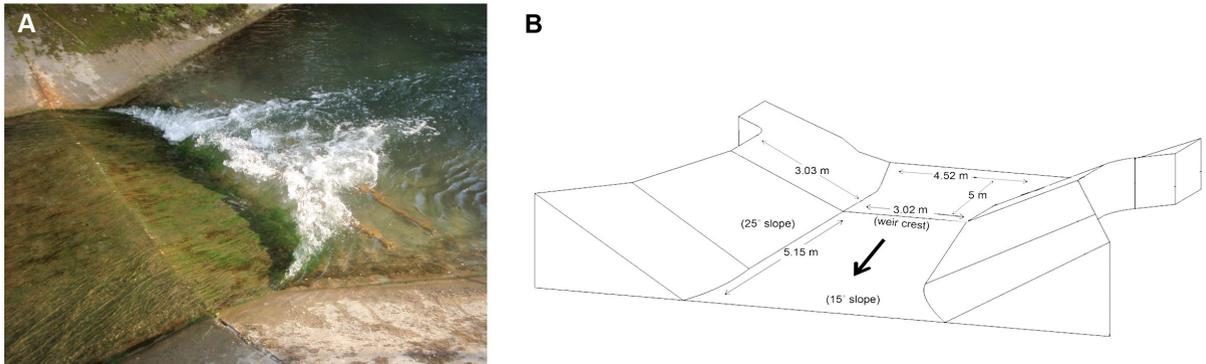


Figure 1. Glensford flow gauging weir, a trapezoidal flume of concrete construction, under low flow conditions (A), and drawn in 3-D with thick arrow denoting the direction of flow (B).

with a mainly silt substrate (approximately 80% coverage), loose cobbles (<20% coverage) and occasional larger flattened rocks, cement blocks or bricks. Undercut banks and alder root bundles provided the majority of crayfish refugia. The predominant within-channel vegetation throughout the study period was filamentous algae (*Cladophora* sp.) which covered much of the silt and cobbles (approximately 35% coverage) and starwort (*Callitriche* sp.) (approximately 5% coverage). Immediately downstream of the weir, the river widens into a pool (2.6 m depth immediately downstream of weir; 21 m maximum width) (Figure 2). Signal crayfish are well established at the study site, both up and downstream of the weir, and are likely to have invaded upstream from the confluence of the two rivers (EECOS 2008), though the possibility of human-mediated introduction(s) upstream of the weir cannot be dismissed.

Telemetry configuration

A half duplex PIT telemetry system (134.2 kHz, 100 ms scan cycle, Wyre Micro Design, Lancashire, UK), comprising an array of 3 equidistantly-spaced antennas and 2 data-logging receivers, was employed to track crayfish through the study reach which comprised a ‘weir stretch’ and an unobstructed ‘control stretch’ (Figure 2). Antenna 1 was a flatbed pass-over rectangular loop (6.1 m long, 0.5 m wide), attached to weir face 2.8 m downstream from the crest and aligned perpendicular to streamwise flow. The loop extended 1.3 m up the sloping weir sides to ensure it would remain within the wetted perimeter under high flows. Antenna 2, a rectangular pass-through loop

(6.32 m long, 0.5 m wide) located immediately upstream of the weir structure was extended up the banks and stretched across the river above the waterline by means of a taut rope. Antenna 3, another pass-over loop (5.72 m long, 0.5 m wide), was placed 7.8 m upstream of antenna 2 and affixed flat onto the channel bed. Time-stamped detection data of tagged crayfish at antennas 1 and 2 were used to establish successful ascent or descent of the weir structure. Similarly, detections of individuals at antennas 2 and 3 were used to deduce directionality of movements through the control stretch (Figure 2).

Antennas 1 and 2, and antenna 3 were connected to two separate receiver and logger systems housed in the onsite gauging hut where they were protected from weather and vandalism. The telemetry system scanned for tags within the detection ranges of antennas every 100 ms, but because crayfish are relatively slow moving animals, a filter was used to reduce the amount of data logged when individuals remained within the detection range of a single antenna for an extended period. Individuals remaining within the detection range were logged only once every 25 s; however movements in and out of the range of detection were always logged. Monthly range testing of the antennas demonstrated consistently greater than 97% detection efficiency at maximum read ranges of 0.45, 0.60 and 0.45 m for antennas 1, 2 and 3 respectively.

Capture and tagging protocol

Crayfish were collected from a stretch extending 100 m upstream to 100 m downstream of the weir, using a combination of hand-search during

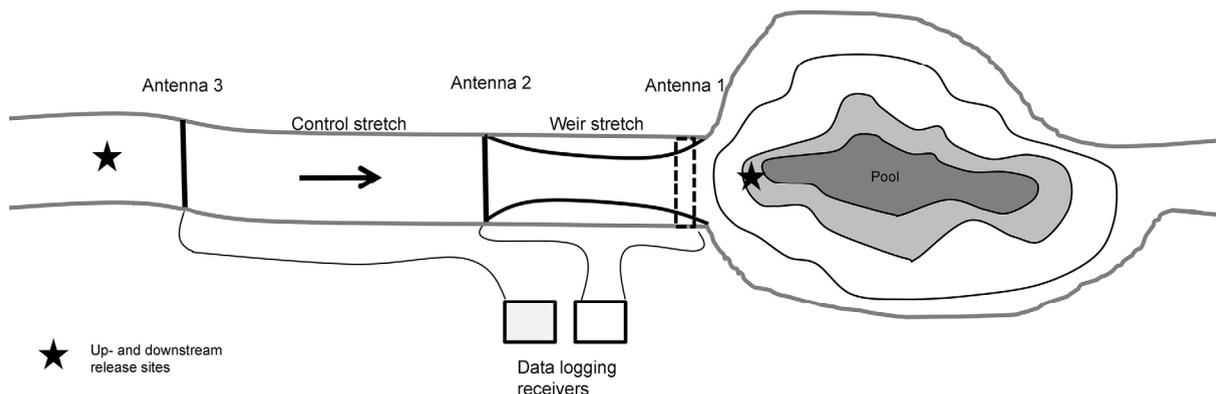


Figure 2. Study site showing the location of control and weir stretches (both 7.8 m length), 3 PIT antennas, data logging receivers and release sites of tagged crayfish (n= 214 in year 1; n= 178 in year 2).



Figure 3. Location of tag insertion.

daylight and baited traps at night. After capture, crayfish were held in aerated tanks of river water (500 L) for a maximum of 2 h prior to tagging. Three separate collections were made in each study year (13th, 18th and 29th July 2011 and 10th,

11th and 19th July 2012). A total of 214 and 178 tagged crayfish were released in year 1 and 2, respectively. Tagged crayfish ranged from 25.9 to 76.9 mm carapace length (CL), measured from tip of the rostrum to posterior end of the cephalothorax, and from 6.0 to 119.2 g wet mass. A total of 74 males and 140 females were tagged and released in year 1, and 92 males and 86 females in year 2. Males and females did not differ in CL ($t = 0.07$, $p=0.94$, 389 d.f.) or mass ($t=1.72$, $p=0.09$, 259 d.f., equal variances not assumed). Only crayfish exceeding 25 mm CL, corresponding to an age of 2 years and older (Guan and Wiles 1999), were tagged as this is considered the minimum size suitable for PIT tagging (Bubb et al. 2002).

A PIT tag (Oregon RFID 12 mm length, 2.1 mm dia., 0.1 g mass in air) was surgically implanted into each crayfish. A 3 mm incision was made on the ventral surface of the crayfish, towards the posterior of the cephalothorax and directly behind the fifth pereopod (fourth walking leg) using a hypodermic needle. The glass encapsulated PIT tag was inserted through the incision, pushing it anteriorly to rest in line with the body and underneath the digestive gland (see Bubb et al. 2002, 2008) (Figure 3). After insertion, the incision was sealed with protective powder (Orashesive^R, ConvaTec, UK) and the crayfish was measured (CL, mm), sexed and the individual tag identification number recorded. Crayfish were transferred to an in-river holding cage for a minimum of 8 hours to recover post-

tagging and acclimate prior to release. Low mortality was experienced at this stage (0.06% over both years combined). After recovery, crayfish were released either up- or downstream of the weir, corresponding to the location of original capture. Release sites were located 5 m down from and 5 m up from antenna 1 and 3 respectively (Figure 2). Releases took place in the evening (20:00 h) to minimise predation on post-release individuals.

To assess long-term post tagging survival, a group of 40 individuals were captured, tagged and measured. Individuals were transferred to a 2000 L recirculation holding tank with filter, provided with PVC pipe refugia, and maintained for 6 months on a diet of crab pellets (Hinari) and soaked beech and alder leaves. Overall mortality rate at the end of the holding period was 5%.

Environmental variables

Flow data ($\text{m}^3 \text{s}^{-1}$) recorded at 15 minute intervals were obtained from the Environment Agency for the entire study period (13th July 2011 - 20th November 2012). Water temperature data were collected every hour using a data logger (Tinytag Aquatic T-2100, Gemini Data Loggers, Chichester, UK) secured near the channel bed immediately upstream of the weir. Moon phase predictions (as % illuminated) were obtained for each day (NASA/GSFC 2012), along with day lengths (Time and Date AS 2013).

Data analysis

Crayfish frequently remained in the vicinity of an antenna for long periods (> 6 h) producing near-continuous detection records. To obtain a measure of crayfish activity levels, it was necessary to determine when they moved either in or out of a single detection zone, or between different zones (antennas). These movements were sub-divided into discrete 'detection events' which were defined as periods of continual detection whereby consecutive detections were separated by time intervals of less than 20 minutes. Further, to breakdown longer periods of large-scale movements into discrete events, only one movement between consecutive antennas was included in each 'detection event'. If, for example, a crayfish moved from antenna 1 to antenna 2, and then back to antenna 1, the moment when it was detected at antenna 1 for the second time was considered as the start of a

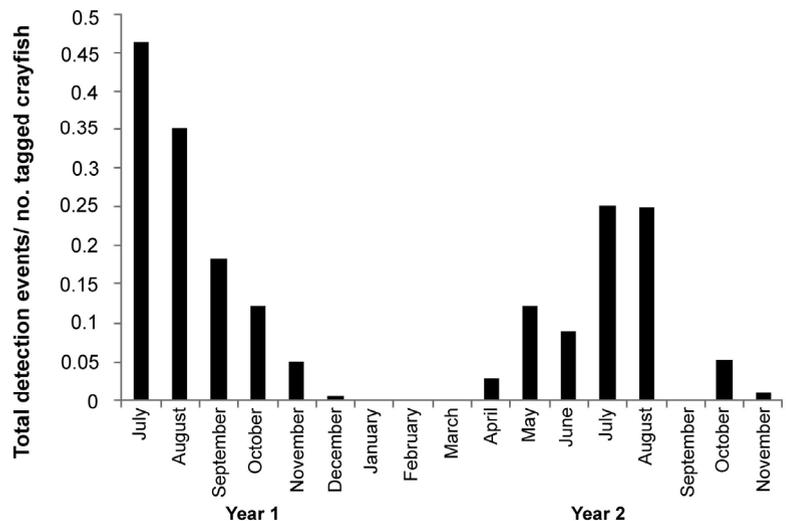
new detection event. Detection events within the first 24 h after a crayfish was released were considered to denote flight responses (Barbaresi et al. 2004) and were removed from datasets (47% of detection events) because we were primarily interested in the 'typical' movement patterns of crayfish i.e. those not induced by the stress of handling and subsequent release. The activity level of each crayfish was calculated as the total number of detection events during the study period and compared between sexes using Wilcoxon rank-sum test at 0.05 significance level.

To determine predictors of daily activity level (excluding a period of downtime in the telemetry system, see below), the total number of detection events per 24 hr period was modelled as function of mean daily flow, mean daily temperature, moon phase (% illumination), number of daylight hours and all first order interactions. Due to the zero-inflated negative binomial distribution of the data, a two-part 'hurdle' model with zero-altered negative binomial error distribution was used. First, a maximum model with all terms was fitted, and then terms were stepwise-deleted to reach the Minimum Adequate Model (MAM) according to the outcomes of likelihood ratio chi-squared tests between alternate models. Model fit was assessed using plots of Pearson residuals against fitted values and comparison of observed and fitted values using linear regression (Zuur 2009). We fitted extended hurdle models with the *p*scl library (Jackman 2012).

Generalised linear mixed models (GLMMs) with binomial error distributions and random factor (individual crayfish ID) were used to investigate the effect of environmental factors (mean daily flow and mean daily temperature) and morphometric variables (CL, mass, sex) on successful passage of crayfish across the weir and the control stretches. The dataset was split into four and modelled separately: 1) upstream movements in the weir stretch; 2) upstream movements in the control stretch; 3) downstream movements in the weir stretch, and 4) downstream movements in the control stretch. For the first dataset, the outcome of movements of crayfish detected at antenna 1 at the start of each detection period were modelled in terms of binary response i.e. 1 = successful passage over the weir by the end of the detection period, or 0 = no weir passage. Similarly, for the second dataset, the outcome of movements of crayfish detected at downstream end of the control stretch (antenna 2) at the beginning of a detection period was modelled in terms of binary response i.e. 1 =

Table 1. Summary statistics for environmental variables measured at Glemsford flow gauging weir, Suffolk, UK, over the period 13th July 2011 - 20th November 2012.

Environmental variable	Minimum	Maximum	Average
Mean daily water temperature (°C)	2.4 (February 2012)	16.6 (August 2012)	11.07 ± 3.36 (mean ± S.D.)
Flow (m ³ s ⁻¹)	0.05	5.53	3.24 ± 2.66 (mean ± S.D.)
Water depth at weir crest	0.05	1.06	0.53 ± 0.29 (mean ± S.D.)

Figure 4. Number of detection events per month during the two study years (1 and 2) expressed as a function of the cumulative number of tagged crayfish released, excluding detections within the first 24 h post-release. Absence of detection events during September in year 2 reflects a period of downtime in the telemetry system.

successful passage through the control stretch to antenna 3 by the end of the detection period, or 0 = no passage. Model fit and simplification was performed as previously described then repeated using stepwise addition; the MAM was arrived at as the most parsimonious model with lowest AIC value. Binomial GLMMs were fitted using lmer in the lme4 library (Bates et al. 2008) and all statistical analyses were performed in R v3.0.0 (R Core Team 2013).

Results

Activity level

The overall detection rate for the study was 57.9%, with 227 crayfish detected at least once over the two year period. Of the crayfish released in year 1, 22 (10%) were also detected in year 2. Detection rate did not vary between males and females (59.7% and 55.4% respectively, $X^2=0.16$, $p=0.69$, 1 d.f.). The total number of detection events per crayfish, which may be

considered as a surrogate measure of activity, ranged from 1 to 72, with a median of 2 events (interquartile range, 1 to 4) and did not vary between sexes ($W=6094$, $p=0.81$). A total of 81 crayfish (21%) were associated with just one detection event. The duration of detection events ranged 1 second to 21 h 44 min 20 s, with median 4 min 8 s (interquartile range, 51 s to 15 min 29 s).

Activity levels were highest in July, followed by August (Figure 4). An absence of detection events during September in year 2 reflects a period of downtime in the telemetry system due to a large piece of woody debris lodged in antenna 1 and damage to the wires of antenna 2 during groundworks at the site. The system was fully restored by October 4th.

Environmental factors

Variations in water temperature and flow over the course of the study are presented in Table 1. Mean daily water temperature ($X^2=69.9$, $p<0.01$,

2 d.f.) and day length ($X^2=6.25$, $p<0.05$, 2 d.f.) were identified as significant predictors of daily activity level (no. of detections per day) in the MAM. In this two part model, the occurrence of a detection event within a 24 h period (zero hurdle part of model) was most likely when temperatures were highest (estimate = 0.50, 0.06 S.E.). In the count part of the model, most activity was associated with long day lengths (estimate = 0.12, 0.06 S.E.).

All passages through site

A total of 100 and 124 passages were made across the weir and control reaches, respectively. There were significantly more weir passages in the downstream direction than the upstream direction for both years 1 and 2 ($X^2 = 4.67$, $p=0.03$, 1 d.f. and $X^2 = 4.41$, $p=0.036$, 1 d.f., respectively). Conversely, for the control reach, there was no significant difference in the number of upstream and downstream passages in year 1 ($X^2 = 0.10$, $p=0.75$, 1 d.f.) or year 2 ($X^2 = 0.05$, $p=0.83$, 1 d.f.) (Figure 5). Overall, there were 45% fewer passages across the weir than the control reach in the upstream direction ($X^2 = 8.49$, $p<0.01$, 1 d.f.), but there was no difference for the downstream direction ($X^2 = 0.20$, $p=0.65$, 1 d.f.). The maximum number of weir passages, in either direction, made by a crayfish was 7, and the maximum for the control reach was 14.

Weir passage

Of the 215 detection events that commenced on the lower weir (antenna 1), 16% resulted in successful ascent of the weir. Crayfish sex was the only significant predictor of weir ascent with 22% success rate for males compared to 12% for females (estimate = 0.80, 0.37 S.E., $X^2=4.6$, 1 d.f., $p= 0.03$). For crayfish moving in a downstream direction, 24% of the 272 detection events that commenced at the upper weir (antenna 2) resulted in successful descent of the weir. There were two significant predictors of downstream passage; both higher water temperature (estimate = 0.13, 0.11 S.E., $X^2=8.3$, 1 d.f., $p< 0.01$) and greater crayfish mass (estimate = 0.03, 0.01 S.E., $X^2=71.2$, 1 d.f., $p< 0.01$) increased the probability of weir descent.

Control passage

Passage through the control stretch in the upstream direction occurred during 20% of detection events that commenced at the upper

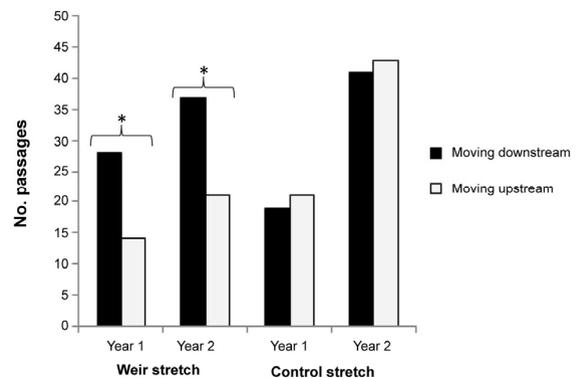


Figure 5. Summary of passages by crayfish through the weir and control stretches in both up- and downstream directions during year 1 and year 2. * indicates a significant difference at the 0.05 level, Chi-square test, 1 df.

weir (antenna 2). Temperature was the only significant predictor of passage with greatest probability of passing upstream when water temperatures were high (estimate = 0.41, 0.12 S.E., $X^2=14.7$, 1 d.f., $p< 0.01$). In the downstream direction, successful passage through the control stretch occurred during 39% of detection events that commenced at antenna 3. None of the measured variables were significant predictors of passage through the control reach in the downstream direction.

Discussion

This study demonstrated that the presence of a low head weir reduced crayfish upstream movements by 45% compared to an unobstructed reach, suggesting that the weir is a partial barrier to invasive *P. leniusculus*, at this site. The structure did not reduce downstream movements. Surprisingly, the porosity of the weir ‘barrier’ for crayfish did not vary with flow. In contrast to fish, crayfish can both walk and swim, hence they may pass a barrier in walking mode where water velocities exceed critical swimming velocity and vice versa where steep slopes forfeit walking (Frings et al. 2013). An effective invasion barrier must therefore combine both flows above the critical swimming velocity and steep slopes ($> 25^\circ$). The gradient of the downstream weir face was 15° which, based on flume trials (Frings et al. 2013), would be expected to be impassable only at flow velocities exceeding 0.7 m s^{-1} ($< 10\%$ of the study period) which may explain the absence of a relationship

between flow and passage rates. Further, an alternative means by which crayfish may have passed the weir during higher flow periods is by leaving the water and traversing the weir sides; thereby decoupling the expected relationship between flow and barrier passability. Unfortunately, we were unable to detect this behaviour with the telemetry set-up, hence it was not possible to measure the degree to which this occurred, or determine concurrent flow conditions.

More generally, we found no evidence that flow influenced activity levels or crayfish movements in either direction throughout the study area. In contrast, Kerby (2005) identified flow as an important predictor of crayfish spread in streams in the Santa Monica mountains. However, mountainous regions are characterised by 'flashy' flow regimes with rapid rises in water level and high flows, whereas the lowland location of the present study meant changes in flow occurred more gradually with lower peaks. Indeed, flow in the study site exceeded $1 \text{ m}^3 \text{ s}^{-1}$ for only 6% of the time, much of which occurred during the winter months when crayfish were largely inactive in response to short day lengths and low water temperatures. Water temperature was found to be a much stronger predictor of both general activity levels and passage across the weir. Movement distances of *P. leniusculus* have previously been found to be positively related to temperature (Bubb et al. 2004), likely reflecting higher metabolic rate at higher temperatures (Armitage and Wall 1982).

We found evidence for differences in crayfish movement patterns based on sex and size with male crayfish more likely to successfully pass the weir in the upstream direction, and larger crayfish to move over the weir in the downstream direction. No such patterns were evident in the control reach. In mark-recapture studies, Moorhouse and Macdonald (2011a, 2011b) found migration distances increased with crayfish size, though they found no relationship with sex. Our results may reflect a greater physical capability among larger and male crayfish to pass the weir structure, lower vagility among female crayfish (for example when ovigerous; Gherardi et al. 1998), or other common behavioural traits that favoured passage among larger males. There has been much recent research interest surrounding the role of individual traits within invasion dynamics (Holway and Suarez 1999; Duckworth and Badyaev 2007; Sih et al. 2012). One salient hypothesis is that individuals at an invasion front will display behavioural characteristics that facilitate

colonisation (Cote et al. 2010), as was demonstrated for western bluebirds, with the most aggressive individuals associated with range expansion and displacement of native conspecifics (Duckworth and Badyaev 2007). In crayfish, large males tend to be bolder and more aggressive than other components of the population (Bovbjerg 1956), and exhibit larger nearest-neighbour distances than less dominant crayfish (Fero and Moore 2008). If aggressiveness and/or size are similarly favourable traits for crayfish with regards to range expansion, one may expect, as we observed, this portion of the population to be more likely to move past a 'barrier', potentially expanding into new areas. Based on this finding, it may be hypothesized that obstructions such as weirs will modify crayfish population structure in the immediately vicinity causing, in the case of upstream population expansion, an accumulation of juveniles and females below the weir and larger male crayfish above it. This may have implications for potential control methods to prevent or slow population expansion. For example, trapping is biased towards the capture of larger males (Matthews and Reynolds 1992; Demers et al. 2003), therefore intensive trapping effort at the margins of populations and immediately upstream of structures such as flow gauging weirs may prove the most efficient means of applying this control method.

While legislation is driving increased habitat connectivity for fish, invasive species are recognised as a significant pressure that may cause waterbodies to fail to achieve 'good ecological status' by 2015 as required under the WFD (Cardoso and Free 2008). Our study demonstrated that even relatively minor structures, such as that investigated, may hinder upstream movement of invasive crayfish, thus highlighting the potential conflict between barrier removal or modification to enhance habitat connectivity and invasive species management. The current study addressed a single crayfish population and weir, therefore further investigation of invasive species movements at a range of weir types, gradients and flow regimes would provide the porosity metrics necessary to make informed risk-based decisions. Such information could be integrated within the standard regulatory planning and consent process for the installation or modification of riverine structures. Further, the apparent efficacy of any barrier in limiting crayfish spread must also be evaluated against the risk of human-mediated introductions of invasive crayfish within and between catchments.

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