Enhancing fish passage over large on-stream dams in south-western Australia: a case study

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Instream barriers are known to have major negative impacts on aquatic ecosystems; particularly on migratory fishes. These impacts include exclusion from critical habitats (particularly spawning habitats), reduced colonisation, genetic fragmentation, and increased rates of density dependent mortality below barriers. Construction of fishways can overcome many of the impacts of barriers on migratory fishes by providing passage over, through, or around artificial barriers. In south-western Australia, instream barriers are one of several major stressors on highly endemic (82%) freshwater fishes; many of which are potamodromous and migrate to spawn during the seasonal high flow period. Moreover, climate change has made the allocation of surface water more challenging due to a severe (~50%) reduction in surface flow over the past ~40 years. This study describes the design and construction of the largest fishway system built to date in this region and tests its functionality. The rock-ramp fishway system was located on Rushy Creek (an ephemeral tributary of the Blackwood River) and included a bypass and spillway fishway with an overall lift of 4.5 m. In spring 2010 and 2011, three of the eight native fishes (Western Minnow (*Galaxias occidentalis*), Western Pygmy Perch (*Nannoperca vittata*), and the Blue-spot Goby (*Pseudogobius olorum*)) in Rushy Creek were shown to pass upstream and downstream on the fishway system. Higher and more sustained flows in 2011 likely resulted in greater upstream fish passage in that year compared with 2010; highlighting the flow dependence of successful fish passage through fishways, which will have implications in terms of their functionality in drying climatic regions both in terms of changes in migration cues and fishway passage success. However, hydrological conditions during peak flow in both years also probably exceeded the swimming performance of the Western Pygmy Perch thereby preventing it negotiating the system during the early part of its spawning period, as opposed to the Western Minnow and the Blue-spot Goby both of which successfully negotiated the system during August and September. The findings highlight the importance of understanding species life-histories and swimming abilities, and have implications for future planning and design of fishways in this region to ensure they are appropriate for fish passage under future flow scenarios.

KEYWORDS: fish migration, rock-ramp fishway, swimming performance, surface flow decline, Galaxiidae, Percichthyidae, Gobiidae

INTRODUCTION

Artificial instream barriers such as dams can have severe and broad negative impacts on the structure and functioning of aquatic ecosystems (Bunn & Arthington 2002; Arthington 2012). Many fishes migrate within rivers as part of their life-cycle (often to access spawning habitats) and therefore the impact of instream barriers can be particularly severe on diadromous and potamodromous fishes (e.g. Lucas & Baras 2001; Gehrke *et al.* 2002; Gregory *et al.* 2002). The installation of fishways is a strategy aimed to enhance upstream passage of migratory fishes thereby at least partially overcoming one of the major ecological impacts of barriers. However, they have not always allowed complete passage of all species, particularly smaller-bodied fishes or those with poor swimming abilities (Katopodis & Aadland 2006). For example, in assessing the functionality of Victoria's existing fishways, just over half those assessed provided passage for greater than 70% of fish species (O'Brien *et al.* 2010).

Mediterranean climatic regions are typified by highly seasonal flow regimes due to strong seasonal rainfall patterns. Reductions in flow due to changing climate and water abstraction are recognised as a major threat to freshwater fishes, particularly in Mediterranean regions (Hermoso & Clavero 2011; Maceda-Veiga 2013). In Western Australia, surface water resources are most degraded in the south-west (Halse *et al.* 2002), primarily due to more concentrated human activity. Since the mid-1970s, a reduction of ~15% in annual rainfall and ~50% in surface flows has occurred in south-western Australia (Suppiah *et al.* 2007; Silberstein *et al.* 2012). Global climatic models project this drying trend to continue to 2030 with median rainfall and surface flow declines of ~8% and ~25%, respectively (Silberstein *et al.* 2012). This adds considerable pressure on managers to balance water extraction with environmental water requirements in the region such as ensuring adequate flows to sustain fish populations.

The relative depauperate (11 species) freshwater fish fauna of the region has the highest rate of endemism (82%) of any Australian drainage division (Allen *et al.* 2002; Morgan *et al.* 2011). These fishes have been particularly impacted by anthropogenic stressors, most notably riparian degradation, secondary salinisation (Morgan *et al.* 2003; Beatty *et al.* 2011), and introduced fish species (Morgan *et al.* 2004; Marr *et al.* 2010; Beatty & Morgan 2013). Most are known to undertake some form of migration as part of their life-cycle (Morgan 2003; Chapman *et al.* 2006; Beatty *et al.* 2010) with the numbers of fish migrating upstream positively related to the volume of peak flow discharge (Beatty *et al.* 2014). The combination of ongoing reductions in river flows due to climate change and physical impediments to spawning migration due to numerous instream barriers in the region is undoubtedly having a major impact on their lifecycles (Beatty *et al.* 2014).

Water allocation in Western Australia is administered under the *Rights in Water and Irrigation Act 1914* (RWIA), by the Department of Water, Government of Western Australia (DoW). Under the RWIA, surface water catchments may be proclaimed, which triggers the need for a surface water allocation plan. A key purpose for proclaiming catchments is to protect the water resource from overuse and prevent its degradation. When assessing proposed dams and any take of water the DoW is required to have regard to all matters listed in Schedule 1, clause 7(2) of the RWIA with the primary considerations in applying aquatic passage for a new dam including the flow period, duration of flow, seasonal movements of aquatic fauna, the presence of existing barriers on the tributary and connectivity of riparian vegetation. For example, the Whicher Area Surface Water Allocation Plan (WASWAP) includes a requirement to maintain passage of aquatic fauna through any proposed new dam located on a watercourse, where there is a known population or potential population of migratory aquatic fauna. The applicability of this condition is considered through an environmental assessment of the proposed dam location and the surrounding catchment (Department of Water 2009).

There is considerable literature on fishway design and species usage in eastern Australia (e.g. Mallen-Cooper 1999; Stuart & Mallen-Cooper 1999; Bice & Zampatti 2005; Mallen-Cooper & Brand 2007; Stuart *et al*. 2008; O'Brien *et al.* 2010). However, while the majority of south-western Australian fishes are endemic and are almost exclusively small bodied (i.e. <200 mm total length) (Allen *et al*. 2002; Morgan *et al*. 2011), the applicability of the existing information on fishways designed for eastern Australian fishes to south-west Western Australian species has not been properly assessed (Morgan & Beatty 2006). Moreover, despite barriers representing a major threat to fishes in this region, fishway construction in Western Australia is still in its infancy compared with the eastern states of Australia with most (six of seven fishways) being constructed in the last 12 years for barriers with relatively low lifts (< 2 m) with mixed levels of operating success, and galaxiids found to be the dominant users (Morgan & Beatty 2004 a, b; Morgan & Beatty 2006; Beatty *et al.* 2007).

Fishway design in this region has also been hampered by the lack of information pertaining to the swimming performance of any of the native freshwater fishes. Understanding swimming performance of fishes (including prolonged, sustained and burst swimming performance) is paramount for predicting their ability to negotiate instream barriers (e.g. Starrs *et al.* 2011). Only recently has work begun on determining these swimming performance metrics that will be extremely valuable in designing more effective fishways to facilitate the passage of a larger proportion of native fish species past barriers (Keleher 2011).

Amelioration of larger barriers (>2 m) has not previously been undertaken in Western Australia. Moreover, the efficiency of these fishways has not been assessed in relation to the recently quantified swimming performances of native and introduced fishes. Gathering such hydro-ecological information is of paramount importance to help refine the design of fishways in this region; particularly under the influence of a drying climate.

The current study aimed to describe the design, installation and operational success of by far the largest fishway system yet constructed in south-western Australia and the first constructed under prescription from a surface water allocation plan. Temporal patterns of fish use of the fishway were quantified during the major flow and peak migratory period of several species over two consecutive years. It is hypothesised that fish passage success will be related to the hydrology on the fishway system.

MATERIALS AND METHODS

Study site and resident fish fauna

Rushy Creek is an ephemeral tributary of the lower Blackwood River, the largest river by discharge in south-west Western Australia (Figure 1). Rushy Creek is approximately 44 km long and has a rain catchment of 22 km^2. While there are a number of on-stream soaks and dams, the majority of these are small and would not pose significant barriers to fish migration during winter and spring. There are four relatively large dams, but their location in the upper reaches has limited impact on connectivity throughout most of the catchment.

A fish survey was undertaken in December 2007 (Beatty *et al.* 2008a) in the McLeod Creek catchment, including two sites in Rushy Creek. Four native estuarine species (South-western Goby (*Afurcagobius suppositus*), Blue-spot Goby (*Pseudogobius olorum*), Western Hardyhead (*Leptatherina wallacei*) and Black Bream (*Acanthopagrus butcheri*)), four native freshwater species (Western Minnow (*Galaxias occidentalis*), Western Mud Minnow (*Galaxiella munda*), Nightfish (*Bostockia porosa*) and Western Pygmy Perch (*Nannoperca vittata*)), and one introduced species (Eastern Gambusia (*Gambusia holbrooki*)) were identified in the survey. Rushy Creek was shown to house all of those native freshwater fishes (aside from *G. munda*) that were in the McLeod system, along with one estuarine species (i.e., South-western Goby), and the introduced species (i.e., Eastern Gambusia) (Beatty *et al.* 2008a). As most of the native freshwater species recorded in the Rushy Creek system are known to undertake spawning migrations (Beatty *et al.* 2014), it was concluded that they would likely be impacted by major instream barriers.

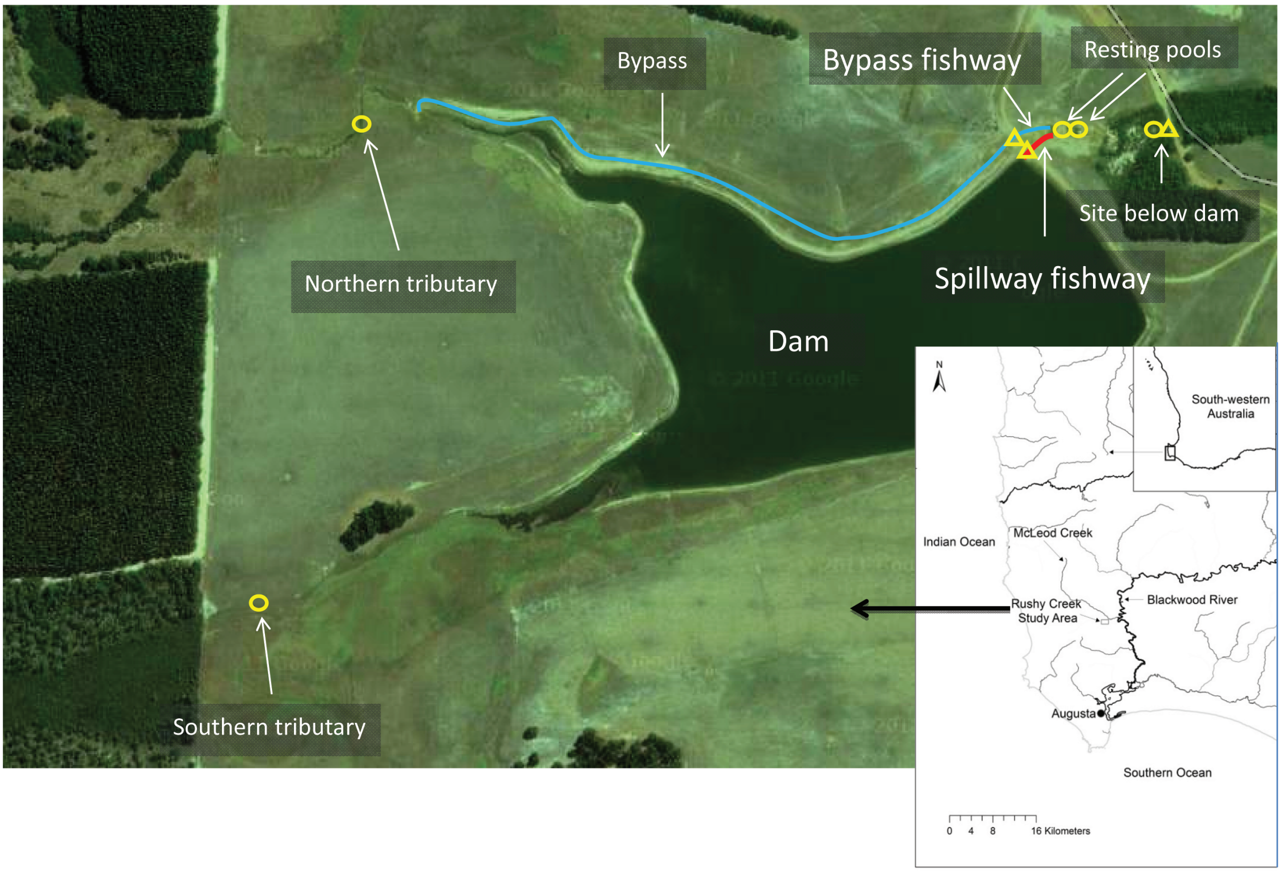


Figure 1 Location of Rushy Creek, south-western Australia. The aerial photo shows the location of the Rushy Creek Dam and the bypass and spillway fishways along with other key habitats that were sampled as part of the current study. N.B. blue line indicates the passage of the bypass around the Dam, the yellow triangles indicate fyke netting sampling sites and the yellow circles indicate those sites sampled for densities.

Design and construction of the fish passage system

In 2008, through the WASWAP, a condition to provide aquatic passage was placed on an application for a proposed dam located in the lower reaches of Rushy Creek; 0.5 km upstream of the confluence with McLeod Creek and 1.8 km upstream of the confluence with the Blackwood River (Figure 1). The proposed reservoir was to intercept three tributaries of the Rushy Creek system, two entering the reservoir from the south and one from the north. Its location would therefore stop any upstream migration into Rushy Creek and impact on the recruitment and reduce the availability of habitat for freshwater species (i.e., ~42 km upstream).

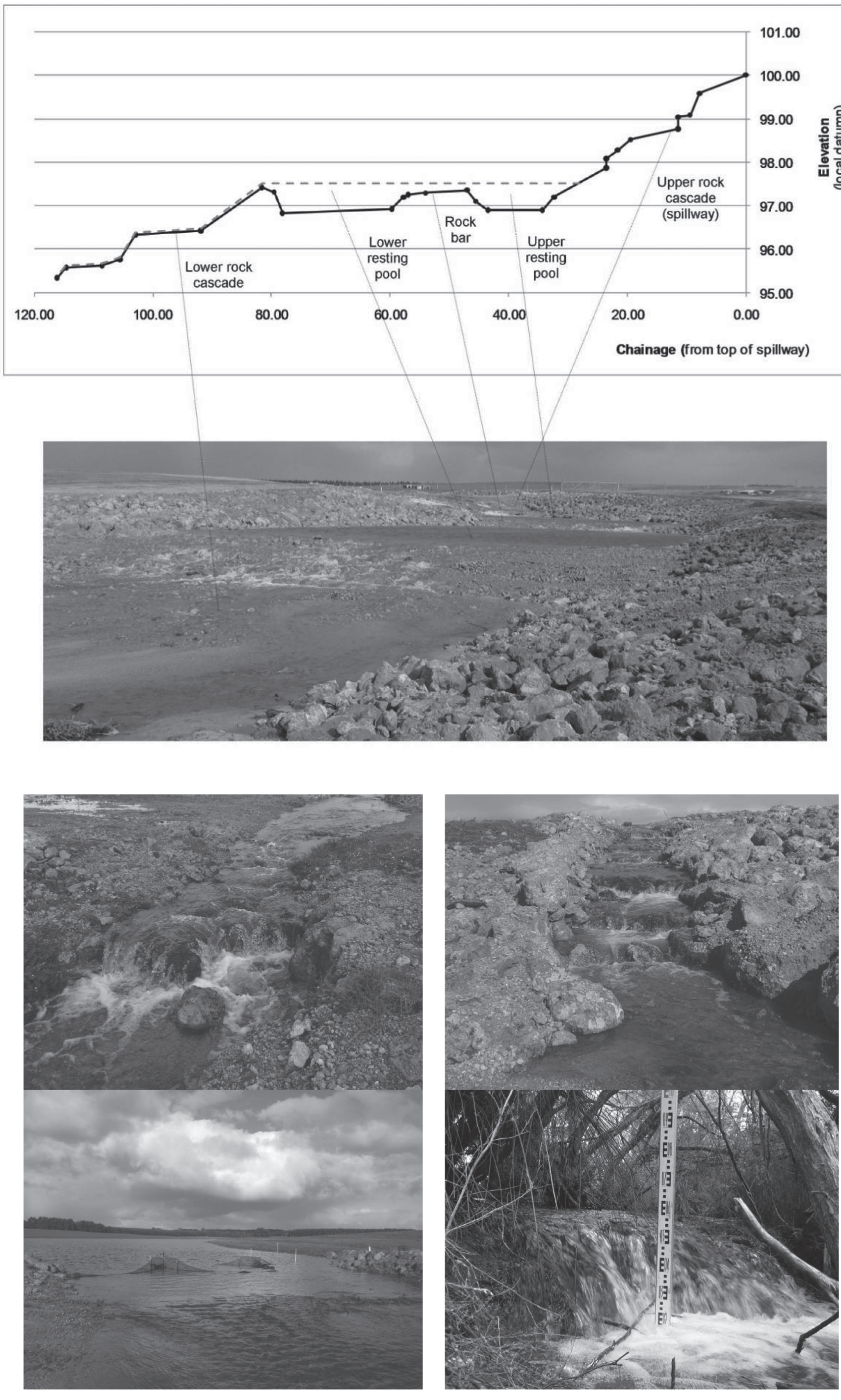
As several fish species were known from Rushy Creek, a range of possible migration periods had to be considered. Being an ephemeral tributary, this required ensuring that early and late low flow events were able to bypass the reservoir. Therefore, a condition was applied that would result in the creation of an open-channel, low-flow bypass connecting the aquatic passage system with the northern tributary upstream of the reservoir; which comprised ~63% of both the stream length (27.7 km) and catchment area (13.7 km^2) of Rushy Creek.

Design and installation of the low flow bypass and fish passage systems was the responsibility of the proponent, however, the DoW provided advice and outlined key design criteria. The cost of a vertical slot system for the 4.5 m lift required was deemed unacceptable at the time and as rock-ramp systems were known to be successful in facilitating the passage of a range of small fish species in eastern Australia (O'Brien *et al.* 2010) and to a lesser extent in south-western Australia (Morgan & Beatty 2004a, b; 2005; Beatty *et al.* 2007), a rock-ramp fish passage system was proposed as the most cost effective option.

The original concept comprised diverting low flows from the northern tributary into an open channel constructed along the northern edge of the reservoir. At the spillway a rock-ramp system would then enable the water from both the open channel and reservoir to discharge into a resting/stilling pool. In low flow conditions the water would continue down a rock-ramp system into a second resting pool at the base of the spillway on the original stream. The advised criteria for the rock-ramps were the commonly adopted specifications of a maximum overall slope of 1:20 comprising 100 mm steps at 2 m intervals (Thorncraft & Marsden 2000). Inclusion of resting pools was also advised, in accordance with literature that recommended a series of rock-ramps with resting pools be used for larger lifts (Water and Rivers Commission 2002; Kapitzke 2010).

During construction in 2009, contractor delays led to complications, and emergency works on the spillway were required during significant high flow periods. This resulted in a spillway and fish passage configuration that deviated from the recommended design criteria. The final spillway configuration comprised two major resting pools connected by cascade rock-ramps (Figure 2). The ramps varied in length from 10 to 30 m with overall slopes varying from 1:10 to 1:66, resulting in individual lifts of up to 2.5 m. The top ramp comprised a cascade connecting to the spillway crest and a separate channel connecting to the bypass system, both of these had an overall slope of 1:11 but the separate channel also included a sequence of significant steps (100, 290 and 340 mm) within a 3 m length. Being a confined and steep channel, these steps do not drown out in higher flows (Figure 2).

The final structure was further complicated due to its connection to an old soak adjacent to the stream rather than the stream itself. Water from the spillway entered the soak and overflowed the downstream clay bund that created a 400 mm step at the bottom of the system (Figure 2). This step partially drowned out in higher flows providing alternative paths for fish movements. Documented specifications for cascade rock-ramp



A

B

Figure 2 A) Cross sectional profile and image of the spillway fishway identifying the rock cascades, bar and resting pools. B) (Clockwise from top left) significant steps located at the top (left image) and bottom (right image) of the bypass fishway, significant step located downstream of the spillway where water spills over the clay bund wall of the soak before entering the original stream, fyke nets established to monitor up and downstream movements on the spillway.

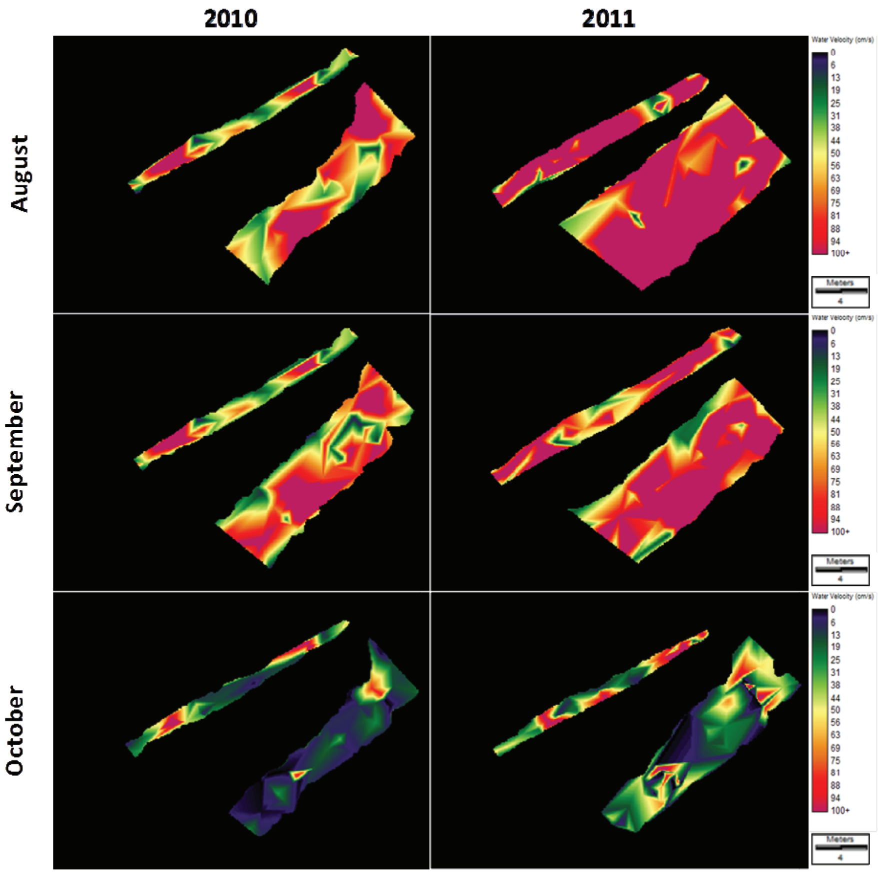


Figure 3 The flow profiles of the bypass (left) and spillway (right) fishways in August (top), September (middle) and October (bottom) 2010 and 2011. N.B. the clear reductions in flow rates between the sampling months in each year and the greater area of low flow on the spillway compared to the bypass in October.

systems suggest an overall slope of 1:9 and maximum lift per cascade of 0.4 m (Kapitzke 2010). These specifications were therefore exceeded in the system that was constructed. To assess the functionality of the fishway system, fish movement and density surveys were undertaken between late winter and early spring in both 2010 and 2011.

Assessing fish passage

A total of six monthly sampling events were undertaken in August, September and October 2010 and 2011 during the major high flow period of rivers in this region. An assessment of the upstream and downstream movement patterns of fishes and their ability to traverse the two fishways was made in each month. On each sampling occasion, fyke nets (11.2 m in total width, consisting of two 5 m wings and a 1.2 m wide mouth fishing to a depth of 0.8 m, 5 m long pocket with two funnels all comprised of 2 mm woven mesh) were set facing upstream and downstream above both the bypass fishway and the spillway fishway (Figure 1). Fyke nets were checked every 24 hrs for three consecutive 24 hr periods during each sampling month. In order to compare species movements in the unimpeded section of Rushy Creek downstream of the dam with those on the fishways, a downstream site in Rushy Creek was also monitored for upstream movements in 2011 (Figure 1). The latter downstream site was monitored following the fyke netting on the fishways in each month so as not to bias the captures on the fishways. Prior to the fyke nets being set on the fishways in 2011, resident fish (that would otherwise bias the fishway catch) were removed from shallow water habitats (<~20 cm maximum depth) of both the spillway crest and bypass using a back-pack electrofisher (Smith Root Model LR20). This was undertaken as the fyke nets were unable to be set precisely at the upstream end of the fishway structures due to lack of depth and excessive flow.

All fishes captured were identified and measured to the nearest 1 mm total length (TL), and evidence of spawning activity recorded in larger (>60 mm TL) Western Minnow (i.e. obvious presence of eggs or exudence of sperm), before being released. Captures on the spillway and in the Creek downstream of the fishway system were scaled to 100% as the fyke nets did not permit the channel to be fully blocked (~90% and 60% blockage for the spillway and Rushy Creek, respectively).

Mean upstream and downstream movement was determined for each species in each month at each site. Spatial and temporal patterns of species densities were determined on each monthly sampling period in the stream below the resting pools, in the resting pools, and the streamlines upstream of the dam and bypass channel. Density sampling was undertaken upon cessation of fyke net sampling each month using a combination of replicate seine netting (10 m seine, 2 mm mesh width) in the spillway resting pools and a back-pack electrofisher at the other sites. Three replicate samples for each technique were taken from randomly chosen stream habitats within each location and all fish captured were identified and measured to the nearest 1 mm TL, and mean density of fish (fish.m^{-2}) was determined for each species, at each site, in each sampling month. Temperature, pH, salinity, conductivity and dissolved oxygen were measured at three sites in Rushy Creek on each sampling month and a mean (±1S.E.) calculated.

Flow modelling

Depth-flow profiling was undertaken on the bypass fishway, spillway fishway, and riffle sections downstream of the fishway to characterise the hydrological conditions present on the fishway system during each sampling occasion. Depth and velocity measurements were made (flow measured with Global Water FP101 and Hontzsch HFA probes, and channel widths measured using Bosch DLE 70) at up to 15 points along transects positioned perpendicular (i.e. cross section) or parallel (i.e. longitudinal section) to the flow. Depth-flow profiling was also undertaken on the two largest steps located near the top and bottom of the bypass fishway with three measurements being taken during each sampling period.

Hydraulic modelling to describe flow characteristics in each area in each month sampled was undertaken using the program IDRISI Taiga. This allowed comparison of flow characteristics against laboratory derived swimming performance metrics (Keleher 2011). Flow data was entered into the program IDRISI Taiga as vector points. Interpolations between vector points were then created using the TIN (triangulated irregular network) model to generate a triangulated irregular network model. The TIN first divides the set of input data points into sections, and then each section is triangulated. The resulting 'mini-TINs' are then merged and a local optimisation routine is run during the merge process to ensure that Delaunay criteria are met in the final TIN (i.e., ensures that maximisation of the minimum angles of all of the triangles contained within the final triangulation occurs). The previous TIN images were reclassified and the pixel values were stored in each image. This process resulted in composite flow profiles being generated of the bypass and spillway fishways on each sampling occasion. The RECLASS module was also used to determine the percentage of area on the fishway and bypass greater or less than 65 cm.sec^{-1} (i.e. the U_{sprint} value (Starrs *et al.* 2011) of the Western Pygmy Perch determined by Keleher (2011)).

Statistical analysis

Differences in the mean upstream and downstream passage among the three species that utilised the fishways (i.e. Western Minnow, Western Pygmy Perch and the Blue-spot Goby; see results), between the bypass and spillway fishways, and between years sampled were tested using a full factorial general linear model, where: $N_{movement} = \mu + S_i + F_j + Y_k + S_i x F_j + S_i x Y_k + F_j x Y_k + S_i x F_j x Y_k + e$, where μ is the overall average upstream or downstream fish movement of fish through the fishway system, S_i the fixed effect of the ith species, F_j the fixed effect of the jth fishway, Y_k the fixed effect of the $_k$th year, and $S_i x F_j$, $S_i x Y_k$, $F_j x Y_k$, $S_i x F_j x Y_k$ are the various interactions between the factors, and e the residual error. All data were log+1 transformed prior to analysis and tests were undertaken in the SPSS (v21) statistical program.

RESULTS

Environmental variables and flow profiles

Water quality in Rushy Creek was fresh (<650 µS.cm^{-1}), highly oxygenated (>92 % DO), and near neutral (pH 6.9-7.8) throughout the sampling period (Table 1). There was a considerably greater average water velocity on both the bypass and spillway fishways in all months sampled in 2011 compared with 2010. The increase in velocities between 2010 and 2011 was proportionally greatest on the bypass in August (70% increase) and September (82% increase) compared to the spillway in those months (55 and 16% increase, respectively) (Table 2). Average flow velocities were greater on the spillway compared to the bypass in August and September in both 2010 and 2011, but were greater on the bypass compared to the spillway in October of both years (Table 2).

The composite spatial flow profiles of the two fishways revealed that both the bypass and spillway fishways were dominated by areas of high flow (>65 cm.sec^{-1}) in August and September in both years.

Table 1 Mean (±1S.E.) physicochemical variables in Rushy Creek in the months sampled in 2010 and 2011.

Year	Month	Temp. (° C)	pH	Cond. (µS.cm^{-1})	NaCl (ppm)	TDS (ppm)	DO (mg.l^{-1})	DO (%)
2010	**August**	11.3 (0.03)	6.93 (0.04)	532.6 (4.56)	155.6 (0.13)	84.6 (0.07)	10.4 (0.14)	92.2 (2.69)
	September	14.5 (0.12)	6.90 (0.07)	535.3 (3.28)	157.3 (1.01)	99.76 (0.68)	9.49 (0.06)	93.1 (0.09)
	October	18.23 (0.09)	7.38 (0.08)	647.7 (18.31)	186.4 (4.18)	145.2 (4.82)	9.79 (0.10)	101.1 (1.23)
2011	**August**	14.9 (0.07)	–	252.9 (0.59)	126.8 (0.19)	121.0 (1.03)	9.9 (0.04)	98.7 (0.47)
	September	15.9 (0.1)	7.8 (0)	233.1 (0.15)	116.3 (0.2)	111.2 (0.85)	9.4 (0.04)	92.5 (0.43)
	October	23.3 (0.09)	7.4 (0.06)	186.8 (0.07)	93.4 (0.13)	91.2 (0.07)	8.5 (0.15)	101.9 (0.87)

Table 2 Mean (±1S.E.) water velocity (cm.sec^{-1}) on the bypass and spillway fishways on Rushy Creek in each month sampled in 2010 and 2011.

	Bypass (cm.sec^{-1})		**Spillway (cm.sec^{-1})**	
	2010	**2011**	**2010**	**2011**
August	55.23 (6.02)	93.77 (9.54)	62.57 (6.04)	96.89 (7.74)
September	37.83 (4.08)	68.86 (6.81)	60.95 (4.78)	70.50 (4.84)
October	23.16 (2.88)	31.10 (3.35)	12.64 (1.64)	23.33 (2.29)

Table 3 The percentage (%) of the total wetted area on the bypass and spillway fishways on Rushy Creek that had water velocities < 65 cm.sec^{-1} (i.e. below the U_{sprint} value of the Western Pygmy Perch (Keleher 2011)) in each month sampled in 2010 and 2011.

	Bypass (% of area <65 cm.s^{-1})		**Spillway (% of area <65 cm.s^{-1})**	
Month	**2010**	**2011**	**2010**	**2011**
August	71.51	18.36	40.50	11.19
September	68.98	36.01	48.17	23.76
October	84.86	71.55	96.14	94.44

There was a larger reduction in flow rates between September and October on the spillway compared to the bypass in both years with ~96% and ~94% of the spillway area having a velocity <65 cm.sec^{-1} in October 2010 and 2011, respectively, compared with ~85% and ~72% of the bypass during those corresponding months (Table 3, Figure 3). This was also reflected in the average velocity on the spillway being less than that on the bypass in October in 2010 and 2011 (Table 2).

Overall captures and fishway utilisation

A total of seven and nine fish species were recorded during 2010 and 2011, respectively (Tables 4 and 5; Figures 4 and 5). In 2010, a total of 1760 individual fish were recorded of which 533 (30.3%) were captured on the bypass and 1227 (69.7%) on the spillway. In 2011, a total of 4183 fish were recorded utilising the fishways (a 138% increase from 2010). Of these 2275 (54.4%) were captured on the bypass and 1908 (45.6%) on the spillway. The Western Minnow and Western Pygmy Perch dominated captures on the fishways in both years with the native Blue-spot Goby also captured on the spillway (Figures 5–7). There was a significant effect of species (F = 29.191, p = 0.00), fishway (F = 14.038, p = 0.001), and

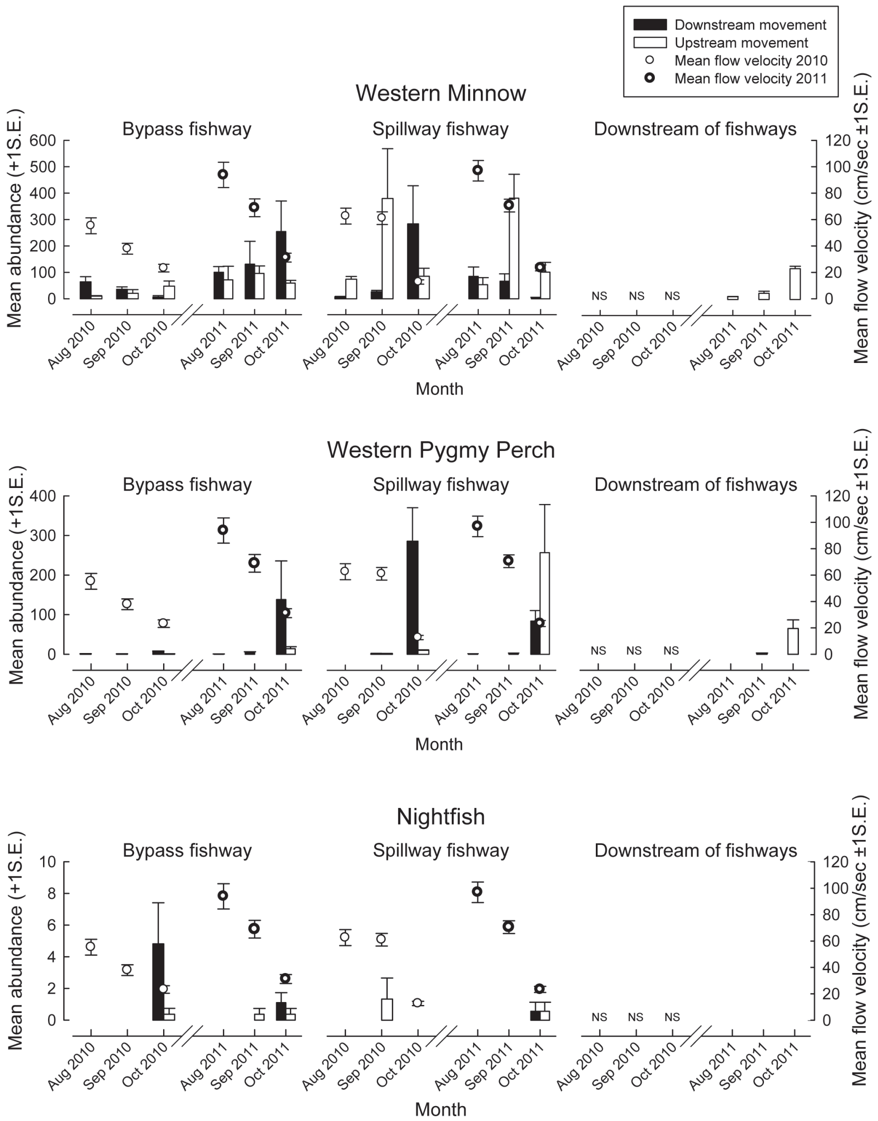


Figure 4 Mean (+1 S.E.) upstream and downstream movement of Western Minnow, Western Pygmy Perch and Nightfish recorded on the bypass fishway, spillway fishway and in Rushy Creek downstream of the dam (upstream movement only in 2011) during each sampling month in 2010 and 2011.

Table 4 Species densities (fish.m^{-2}) at the sites sampled in 2010 in the Rushy Creek system. N.B. A = August, S = September, O = October, ±1 S.E. in parentheses.

	Native freshwater fishes				**Native estuarine fishes**			**Introduced fishes**		**Freshwater crayfish**		
Site	Western Pygmy Perch	Western Minnow	Nightfish	Freshwater Cobbler	Blue-spot Goby	South-western Goby	Western Hardyhead	Eastern Gambusia	Goldfish	Marron	Gilgie	Yabby
Rushy Creek below fishways	A=0.39 (0.19) S=1.30 (0.2) O=0.17 (0.17)	A=0.35 (0.15) S=1.53 (1.16) O=0.66 (0.29)	O=0.03 (0.03)		A=0.01 (0.01) S=0.03 (0.03) O=0.02 (0.02)	A=0.05 (0.03) S=0.42 (0.16)		A=0.13 (0.13) S=0.33 (0.26) O=0.17 (0.08)		S=0.01 (0.01)		S=0.02 (0.02)
Lower resting pools	S=0.02 (0.02) O=0.07 (0.04)	A=1.63 (0.35) S=2.56 (1.07) O=5.33 (1.78)								S=0.02 (0.02)		
Upper resting pool	O=0.31 (0.28)	A= 3.13 (2.94) S=3.6 (3.2) O= 12.6 (9.82)			O=0.04 (0.04)			O=0.56 (0.56)		A=0.01 (0.01)	O=0.02 (0.02)	
Northern tributary above fishway: farmland	A=0.04 (0.02) S=0.01 (0) O=0.01 (0.01)	A=0.08 (0.03) S=0.25 (0.1) O=0.16 (0.07)	S=0.01 (0.01)					S=0.01 (0.01) O=0.01 (0.01)				A=0.02 (0.01) S=0.03 (0.01) O=0.25 (0.03)

Table 5 Species densities (fish.m^{-2}) at the sites sampled in 2011 in the Rushy Creek system. N.B. A = August, S = September, O = October, ±1 S.E. in parentheses.

	Native freshwater fishes				**Native estuarine fishes**			**Introduced fishes**		**Freshwater crayfish**		
Site	Western Pygmy Perch	Western Minnow	Nightfish	Freshwater Cobbler	Blue-spot Goby	South-western Goby	Western Hardyhead	Eastern Gambusia	Goldfish	Marron	Gilgie	Yabby
Rushy Creek below fishways	A=0.8 (0.24) S=0.59 (0.12) O=1.2 (0.65)	A=1.47 (0.79) S=1.84 (1.32) O=0.26 (0.17)	A=0.16 (0.13) O=0.03 (0.03)	S=0.04 (0.04) O=0.03 (0.03)	A=0.32 (0.18) S=0.44 (0.26) O=0.52 (0.23)	S=0.56 (0.29)	A=0.1 (0.1) S=0.03 (0.03)	A=0.58 (0.43) S=0.74 (0.74) O=3.33 (2.4)	A=0.12 (0.06)			A=0.03 (0.03) S=0.12 (0.07) O=0.45 (0.38)
Lower resting pools	A=0.02 (0.02) S=0.16 (0.07) O=3 (1.26)	A=0.72 (0.28) S=1.85 (0.7) O=3.42 (1.85)		S=0.01 (0.01)	S=0.18 (0.05) O=0.14 (0.1)			A=0.4 (0.3)				
Upper resting pool	A=0.02 (0.02) S=0.25 (0.11) O=0.22 (0.22)	A=2.3 (0.8) S=3.2 (1.31) O=5.5 (4.21)			A=0.01 (0.01) S=0.52 (0.2) O=0.21 (0.21)			S=0.02 (0.02)				O=0.02 (0.02)
Upstream crest of spillway	O=0.09	A=0.01 O=0.09			A=0.06 S=0.08 O=0.19			S=0.05				A=0.03 S=0.01 O=0.03
Upstream crest of bypass	O=0.55	O=0.25	O=0.05		A=0.04						S=0.04	A=0.04
Northern tributary above fishway: farmland	A=0.2 (0.08) S=0.06 (0.03) O=2.98 (2.65)	A=0.05 (0.03) S=0.14 (0.02) O=1.72 (0.84)	A=0.01 (0.01) S=0.02 (0.02) O=0.08 (0.01)							N=0.01 (0.01)	A=0.02 (0.01) O=0.06 (0.02)	A=0.06 (0.01) S=0.08 (0.01) O=0.07 (0.05)
Southern tributary above fishway: bushland		S=0.07 (0.07) O=0.17 (0.17)									S=0.21 (0.1) O=0.26 (0.08)	S=0.02 (0.02) O=0.04 (0.04)
Southern tributary above fishway: farmland	S=0.06 (0.02) O=2.97 (2.52)	A=1.01 (0.75) S=0.51 (0.34) O=0.44 (0.28)	O=0.01 (0.01)		A=0.1 (0.03) S=0.07 (0.01) O=0.09 (0.06)			A=0.01 (0.01)			A=0.01 (0.01) S=0.01 (0.01) O=0.09 (0.04)	A=0.14 (0.07) S=0.02 (0.01) O=0.11 (0.06)

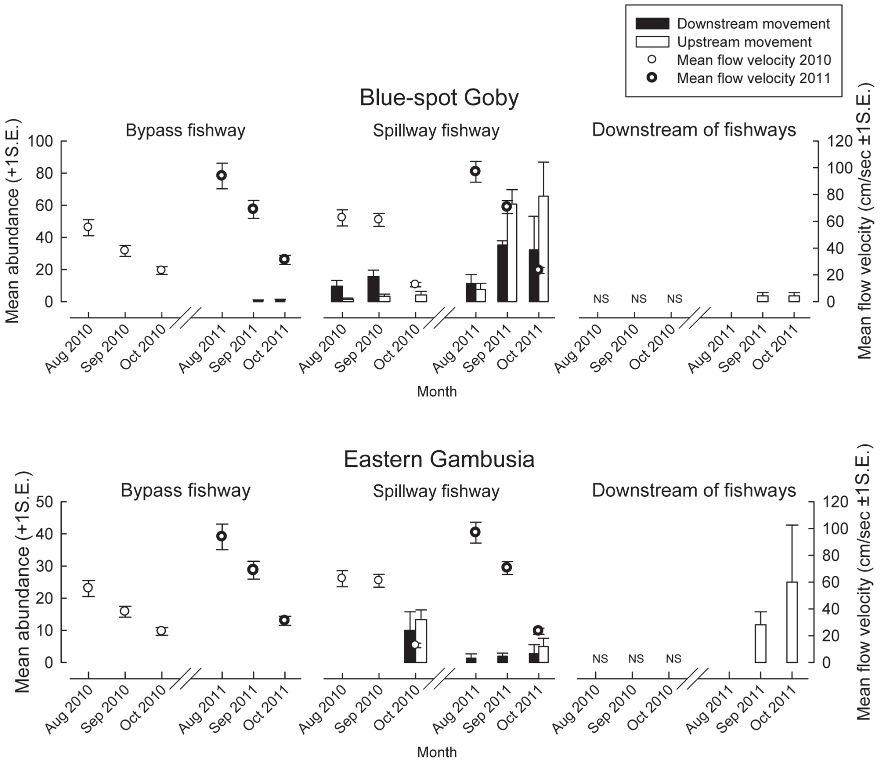


Figure 5 Mean (+1 S.E.) upstream and downstream movement of the Blue-spot Goby and introduced Eastern Gambusia recorded on the bypass fishway and spillway fishway, and in Rushy Creek downstream of the dam (upstream movement only in 2011) on Rushy Creek during each sampling month in 2010 and 2011.

year (F = 4.88, p = 0.037) but none of the possible interactions between the factors on the mean numbers of fish moving upstream over the fishway system. There was a significant effect of species (F = 9.380, p = 0.01) but not fishway (F = 2.133, p = 0.157), year (F = 1.14, p = 0.296) nor any interactions between the factors on the mean numbers of fish moving downstream over the fishway system.

In 2010 in the bypass channel, 213 (40.0%) fish were moving upstream and 320 (60.0%) downstream. All upstream captures in the bypass channel were freshwater endemic fishes comprising 210 (98.6% of total) Western Minnows, two (0.9%) Western Pygmy Perch and one (0.5%) Nightfish (Figure 4). On the spillway in 2010, 1003 (81.7%) fishes were moving upstream and 224 (18.3%) downstream. Upstream captures of fishes comprised 928 (92.5%) Western Minnows, 23 (2.2%) Western Pygmy Perch, 18 (1.8%) Blue-spot Gobies, 2 (0.2%) Nightfish, and the introduced Eastern Gambusia 32 (3.2%).

Downstream movement in the bypass in 2010 consisted of 285 (89.1%) Western Minnows, 21 (6.6%) Western Pygmy Perch, 13 (4.1%) Nightfish, and a single Western Mud Minnow. Downstream movement on the spillway consisted of 119 (53.1%) Western Minnows, 76 (33.9%) Western Pygmy Perch, 26 (11.6%) Blue-spot Gobies, and 3 (1.3%) Eastern Gambusia (Figure 5).

In 2011 in the bypass channel 575 (25.6%) fish were moving upstream and 1700 (74.7 %) downstream. Of the upstream moving captures, 533 (92.7%) were Western Minnows, and 38 (6.6%) were Western Pygmy Perch (Figure 4). On the spillway moving upstream, 765 (55.3%) Western Minnows were captured, 400 (28.9%) Western Pygmy Perch, and 211 (15.3%) Blue-spot Gobies (Figures 4 and 5). There was therefore an increase in the proportion of Western Pygmy Perch moving upstream over the bypass from 2.2% in 2010 to 28.9% in 2011. Similarly, an increase in the proportion of Blue-spot Goby moving upstream on the spillway occurred between 2010 (1.8%) and 2011 (15.2%).

Downstream captures on the bypass in 2011 consisted mostly of the Western Minnow (1311, 77.1%) and Western Pygmy Perch (384, 22.6%). There was therefore an increase in the proportion of Western Pygmy Perch moving downstream over the bypass from the 6.6% recorded in 2010. There was also a reduction in the proportion of Nightfish moving downstream from the 4.1% in 2010 to just 0.2% in 2011 (Figure 4). Downstream movements on the spillway in 2011 largely consisted of the Western Minnow (272, 51.9%), Western Pygmy Perch (113, 21.6%), and Blue-spot Goby (127, 24.2%) (Figures 4 and 5).

Expansion of the fyke netting program in 2011 to include a site on Rushy Creek below the dam resulted in the recording of the Freshwater Cobbler (*Tandanus bostocki*) that was not recorded during the density estimate sampling. The introduced Goldfish (*Carassius auratus*) was also recorded below the dam in 2011 and had not been previously recorded in McLeod or Rushy Creek. The Freshwater Cobbler and Western Mud Minnow (the latter recorded in 2010), were not recorded on either the bypass or spillway, or either branch of Rushy Creek in 2011.

Spatial and temporal patterns in movements and population structures

Upstream passage of the Western Minnow was recorded on the bypass and spillway fishways in all months in both years (Figure 4). There was a clear peak in upstream

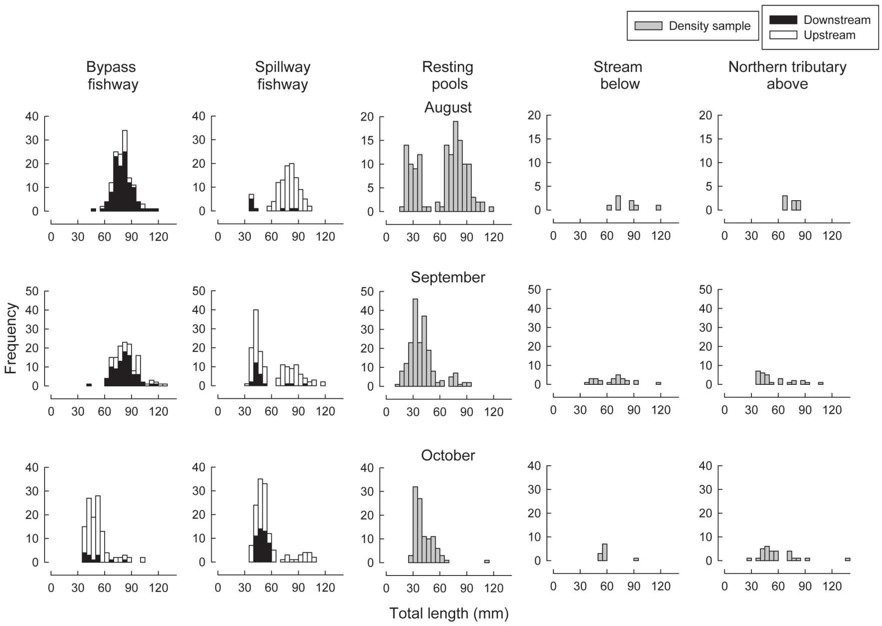


Figure 6 Length-frequency distributions of the Western Minnow in Rushy Creek at the sites and months sampled in 2010.

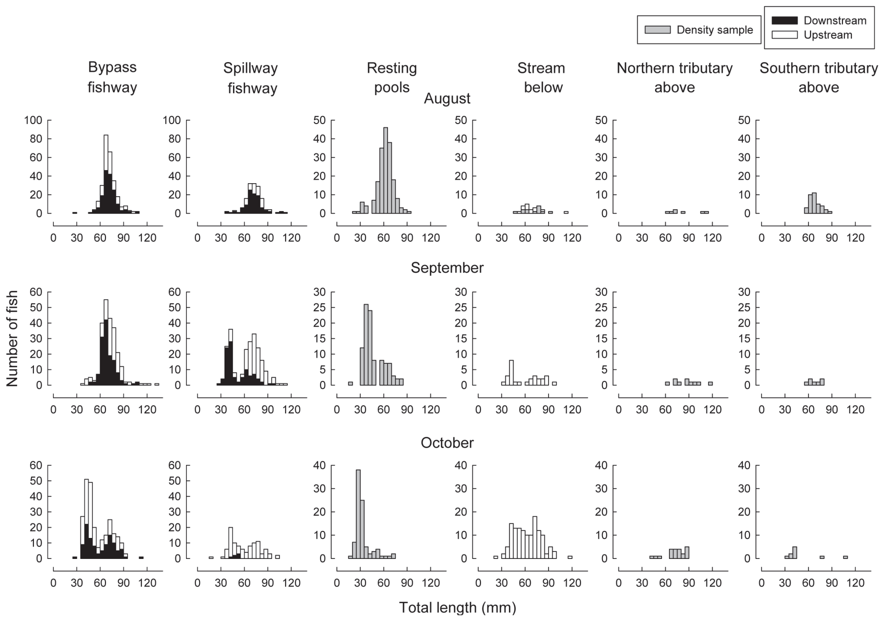


Figure 7 Length-frequency distributions of the Western Minnow in Rushy Creek at the sites and months sampled in 2011.

movement on the spillway fishway in September in each year with a less distinct peak occurring on the bypass in October and September in 2010 and 2011, respectively (Figure 4). Upstream movement of the species was recorded below the dam during all months sampled in 2011 peaking in October (Figure 4). Downstream passage of the species also occurred in all months on both fishways in both years. On the spillway fishway, a clear peak in downstream movement occurred in October 2010 *cf* a decline in movement occurring in that month in 2011 (Figure 4). On the bypass, a gradual decline in downstream movement occurred monthly in 2010 with the opposite trend occurring in 2011 (Figure 4).

Length frequency distributions of the Western Minnow in 2010 and 2011 confirmed the population was self-maintaining with multiple size cohorts being present in all months (that would likely correspond to age cohorts) (Figures 6 and 7). The length-frequency distributions in the resting pools were generally similar to those recorded passaging upstream on the spillway suggesting that a broad size range could move over the structure under most flow conditions (Figures 6 and 7). However, very few smaller fish (<50 mm TL, that were present in the resting pools) were recorded moving upstream over either structure in August 2010 or 2011, nor September 2010 on the bypass. Similar patterns generally existed in length-frequency distributions between the years with smaller fish (<50 mm TL) being recorded utilising the bypass and spillway fishways mostly in September (particularly the spillway) and

October. The length-frequency distributions on the bypass fishway were generally similar between those fish moving upstream and downstream. However, on the spillway, larger fish (>50 mm TL) were mostly recorded passaging upstream versus downstream in all months sampled aside from August 2011.

As highlighted by the length-frequency distributions (Figures 6 and 7) and the density estimates (Tables 4 and 5), the Western Minnow was recorded utilising both upstream branches of Rushy Creek. Juveniles were recorded in upstream tributary habitats in September and October in 2010, and in October 2011.

The Western Pygmy Perch was captured in far greater numbers moving upstream over the bypass and the spillway in 2011 compared to 2010, particularly in October (Figure 4). Movement of the species on the bypass was generally in a downstream direction in all three months in both 2010 and 2011 with a notable large downstream movement occurring over the spillway in October 2010 and 2011, and the bypass in October 2011 (Figure 4). Negligible upstream movement of the Western Pygmy Perch on the bypass was recorded in 2010, whereas there was upstream movement on the spillway in October 2010 and upstream movements over both the bypass and spillway in October 2011.

The length-frequency analysis demonstrated that juvenile and adult Western Pygmy Perch were present in October 2010 and 2011 (Figures 8 and 9). A large upstream movement of the Western Pygmy Perch was recorded below the fishway in October 2011, which

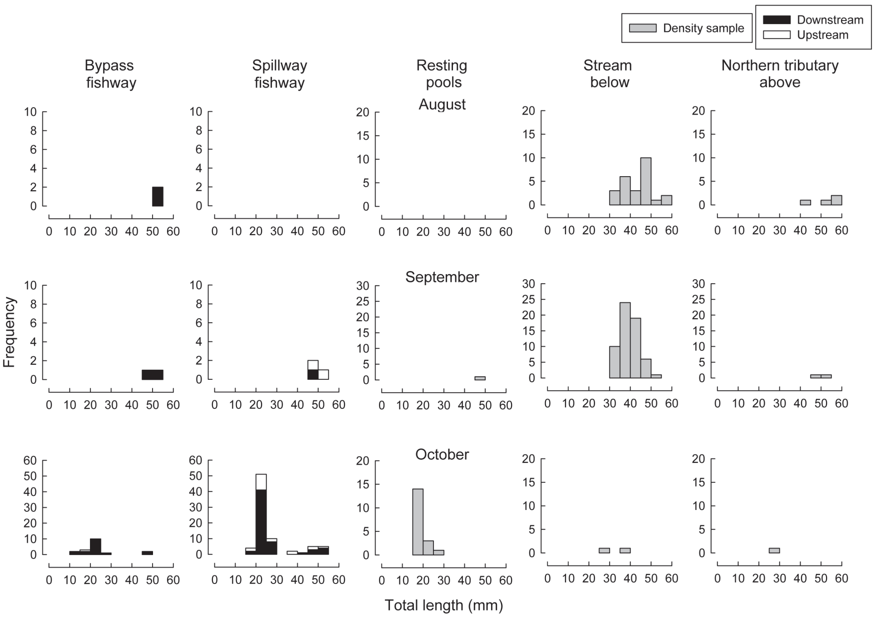


Figure 8 Length-frequency distributions of the Western Pygmy Perch in Rushy Creek at the sites and months sampled in 2010.

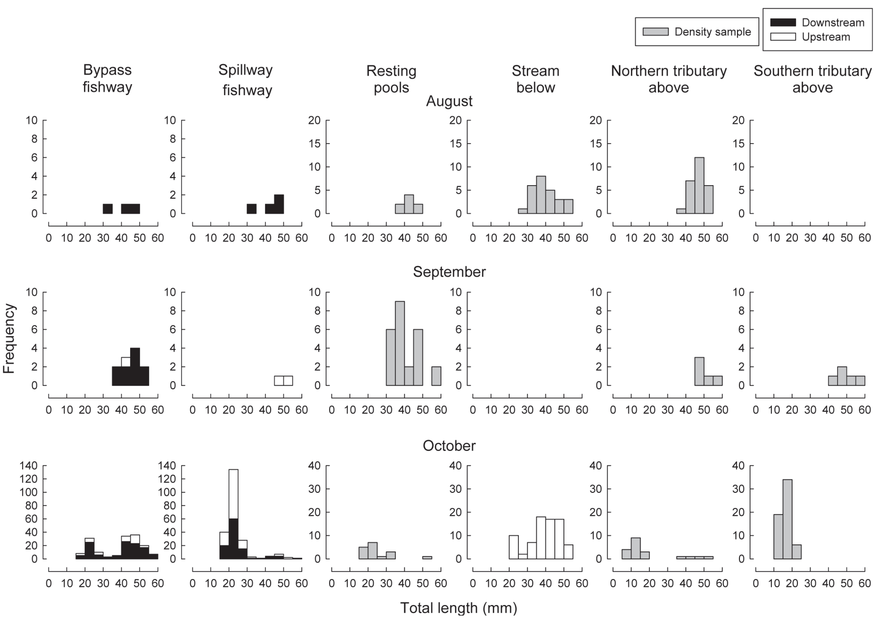


Figure 9 Length-frequency distributions of the Western Pygmy Perch in Rushy Creek at the sites and months sampled in 2011.

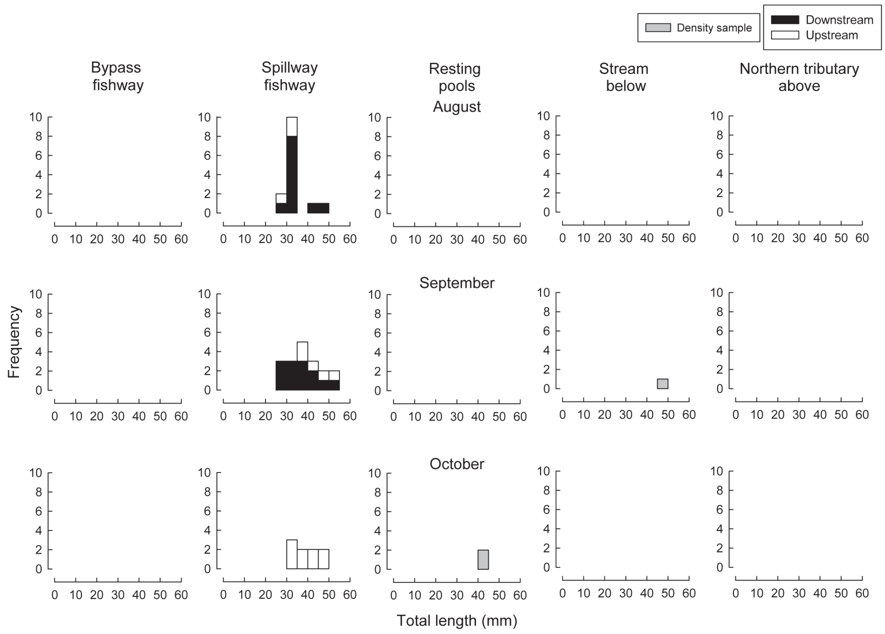


Figure 10 Length-frequency distributions of the Blue-spot Goby in Rushy Creek at the sites and months sampled in 2010.

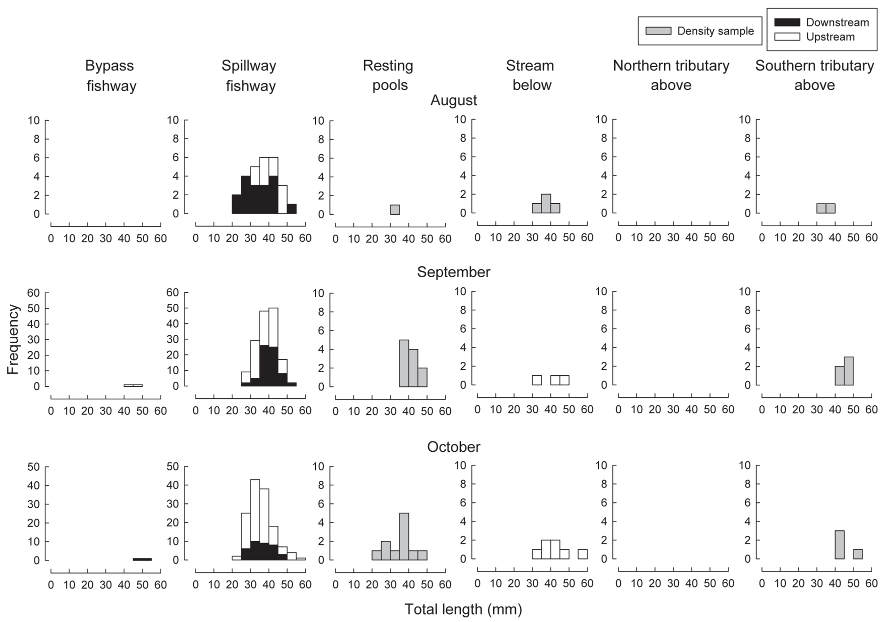


Figure 11 Length-frequency distributions of the Blue-spot Goby in Rushy Creek at the sites and months sampled in 2011.

corresponded to the large upstream movement of a wide size range over the spillway and to a lesser extent the bypass at that time (Figures 4 and 9). The modal length of juvenile Western Pygmy Perch was consistent between the 2010 and 2011 sampling periods being between 20–25 mm TL and there were no overall obvious differences in the length-frequency distributions between fish moving upstream and downstream on the fishways (Figures 8 and 9). Above the dam in the northern tributary in 2010 captures comprised of adult Western Pygmy Perch exclusively (Figure 8). However, in 2011 juvenile cohorts were present having modal lengths 10–15 and 15–20 mm TL in the northern and southern tributaries, respectively (Figures 8 and 9). Examination of the changes in density of the Western Pygmy Perch in both the northern and southern tributaries of Rushy Creek in October 2011 also showed a substantial increase between September and October (i.e. from 0.06 to 2.98 fish.m^{-2} in the northern tributary and from 0.06 to 2.97 fish.m^{-2} in the southern tributary (Table 5)). No such increase in the density of the species was recorded in the northern tributary in the 2010 sampling (Table 4). However, the upstream passage over the fishway system (mostly or exclusively over the spillway fishway) by the Western Pygmy Perch in October 2010 coincided with a considerable reduction in its density in the stream below the dam that occurred between September and October (Figure 8).

Nightfish were recorded in very low numbers moving upstream over the spillway in September 2010, and the bypass in October 2010 (Figure 4); however these captures are probably attributable to resident fish in the small section of habitat below the nets, rather than evidence of passage through the fishways. Negligible movement of the species was again recorded in those months in 2011. Additional sampling for upstream movement in Rushy Creek below the dam in 2011 also failed to detect the species; however, it was recorded in low abundance above and below the dam in both years (Tables 4 and 5).

The Freshwater Cobbler was recorded for the first time in the McLeod Creek system during the 2011 sampling (Table 5). It was recorded moving in an upstream direction below the fishways in October 2011 and was also recorded in Rushy Creek below the fishways in September and October 2011, and the lower resting pool in September 2011 (Table 5). Although captured in relatively low abundance (n = 14), the size range (i.e., 182–323 mm TL) of captured specimens represented multiple age classes and the population was therefore likely to be self-maintaining.

Blue-spot Goby was rarely recorded on the bypass (Figure 5). Captures of the species on the spillway in 2010 were dominated by downstream movements in August and September with only limited upstream movement (i.e. <5 individuals per month) being recorded in that year (Figure 5). However, similar to the Western Pygmy Perch, the species had a much greater upstream passage over the spillway in 2011 compared to 2010 (Figure 5). Upstream movement was consistently high in September and October 2011 with those months also having the greatest numbers of downstream movement over the spillway (Figure 5). The species was also recorded in relatively low numbers moving upstream in Rushy Creek below the dam in September and October 2011 (Figure 5). A relatively wide size range of the Blue-spot Goby was recorded moving upstream and downstream over the spillway, although in October 2010 and 2011 captures were dominated by upstream moving individuals (Figures 10 and 11). The Blue-spot Goby was recorded in Rushy Creek below the dam during all sampling events in both 2010 and 2011, and in the resting pools in both years (Tables 4 and 5). The species had not previously been recorded in the northern tributary above the dam but was recorded in the southern tributary in all months in 2011 (Tables 4 and 5, Figure 11).

The South-western Goby was only recorded below the dam in 2010 (September) and 2011 (September) (Table 5). Like the Western Hardyhead, the South-western Goby appears restricted in distribution to the lower reaches of Rushy Creek and McLeod Creek.

The Eastern Gambusia was found to move upstream and downstream on the spillway in very low numbers in October 2010 and 2011 (Figure 5). The Eastern Gambusia was recorded in both 2010 and 2011 on a number of occasions at a number of other sites in Rushy Creek including: below the dam, within the resting pools, and in low abundance in both the northern tributary (September and October 2010) and southern tributary (August 2011) (Tables 4 and 5). Goldfish *Carassius auratus* was also recorded below the fishways in August 2011 (Table 5).

DISCUSSION

The abundance of a number of south-western Australian freshwater fish undertaking upstream spawning migrations are positively related to amount of discharge during the peak flow periods (Beatty *et al.* 2014). The Rushy Creek fishway system was found to facilitate the upstream and downstream passage of three of the eight native fishes known to occur in the system, including the Western Minnow, Western Pygmy Perch and Blue-spot Goby. Native species that were known from the system that effectively did not passage upstream over the fishway included the Nightfish, Western Mud Minnow, Freshwater Cobbler, South-west Goby, and Western Hardyhead.

Higher rainfall and corresponding higher and more sustained stream flow occurred in 2011 *cf* 2010 (Australian Bureau of Meteorology 2014). Significantly greater numbers of fish were recorded moving upstream through the fishways in 2011 (4183 individuals) compared to 2010 (1760 individuals); which is consistent with the hydroecological relationships of Beatty *et al.* (2014). Significant differences also existed between the three most abundant species in terms of the number moving upstream and downstream and a significantly greater number of fish passed upstream through the spillway compared to the bypass.

Hydrology (principally discharge and flow rates) and life-cycles of these species explain many of those fishway usage patterns that were observed. The Western Minnow was the dominant user (in terms of abundance) of the Rushy Creek fishway system and is a species that undergoes annual potamodromous migrations (Beatty *et al.* 2014). It managed to successfully pass through both fishways in all months; including when the average flow velocity was ~97 $cm.sec^{-1}$. The Western Minnow spawns between early winter and mid-spring and therefore the current sampling occurred towards the latter part of its breeding period (Pen & Potter 1991a; Beatty *et al.* 2014). The length-frequency distributions of the Western Minnow in the resting pools and also those moving upstream and downstream over the fishways indicated they were negotiable by multiple age classes; including both adults and juveniles.

The Western Minnow was recorded utilising both upstream tributaries of Rushy Creek that provide spawning habitats for the species. South-western Australian freshwater fishes generally retreat downstream to permanent aquatic habitats (usually refuge pools) during the annual dry period (Beatty *et al.* 2014). As Rushy Creek is ephemeral, it is likely that at least part of the population of the Western Minnow and other species utilise the newly created reservoir as a permanent refuge habitat rather than exiting downstream through the spillway to permanent habitats further downstream. Such utilisation of large water supply dams by native freshwater fishes in the region has previously been documented (e.g. Beatty *et al.* 2003; Morgan *et al.* 2008).

The Western Pygmy Perch was also found to utilise the fishway system, albeit in lower abundances than the Western Minnow. A much stronger upstream movement of the Western Pygmy Perch occurred over both the bypass and spillway, along with an increase in downstream movement over both structures and an overall increase in abundance of the species in the upstream tributaries of Rushy Creek in 2011 relative to 2010. The Western Pygmy Perch may spawn multiple times during late winter and spring (Pen & Potter 1991b) and attain approximately 40–45 mm TL at age one. The wide size range (including juveniles) recorded moving upstream over both the bypass and spillway fishways in October 2011, and in the spillway in October 2010, suggested that the fishways may provide passage for both spawning (as indicated by adult size classes) and general population dispersal (as indicated by juvenile size classes). However, there was a relatively high abundance of larger individuals in the stream below the dam and/or resting pools in August and September in both years. This suggested a congregation of mature fish probably on an upstream spawning migration and it therefore appeared that its upstream passage over the fishways was largely precluded in August and September. It also appeared that a stronger recruitment occurred in both the southern and northern tributaries in 2011 than in the northern tributary in 2010; as evidenced by the presence of adults and juveniles in those systems in 2011 and adults in the latter system in 2010. However, a strong downstream movement of the Western Pygmy Perch occurred particularly in October with a wide size range found moving on both structures in both years highlighting that the structures were used for downstream dispersal and that recruitment had occurred in both years in the upstream habitats sampled.

Average water velocities on the spillway during October 2011 (when the largest upstream movement of Western Pygmy Perch occurred) approximated the average velocities on the bypass in that month in 2010 (when effectively no upstream passage of that species occurred). Flow velocity alone therefore does not explain the lack of upstream passage of the Western Pygmy Perch in October 2010 on the bypass. Indeed, greater and earlier onset of flows in Rushy Creek in 2011 probably facilitated an overall increase in population abundances of most species which then resulted in an overall increase in fishway passage of the Western Minnow, Blue-spot Goby and Western Pygmy Perch. During the high-flow months of August and September in both years, no upstream passage of the Western Pygmy Perch occurred at a time when a relatively high density of mature individuals congregated below the dam. It appears that hydrology on the fishways during peak flow may prevent upstream passage of the species during the majority of its spawning period. Although the bypass starts flowing earlier in the year (i.e., prior to the spillway), the relative overall greater usage of the spillway fishway by all species suggests that the bypass may be, to a degree, superfluous for facilitating fish passage. Monitoring of fish passage earlier in the year when the bypass begins to operate and flow rates are lower than those recorded in the current study, would provide greater certainty of the role of the bypass in facilitating free passage of these species.

Swimming performance of the Western Pygmy Perch, Western Minnow and Eastern Gambusia increases with size, but does not vary substantially with water temperature (Keleher 2011). Based on Keleher (2011), average velocities <65 $cm.sec^{-1}$ over maximum distance of ~11 m should be suitable to allow the passage of Western Pygmy Perch. Based on 2010 flow data on the Rushy Creek bypass and spillway fishways, Keleher (2011) found that the greatest hypothetical distance that the Western Pygmy Perch could travel over those structures peaked in October at 1106 and 1384 cm on the bypass and spillway, respectively. Therefore, based on average velocities, the species would not have been predicted to negotiate either structure in 2010. In re-analysing this distance with the average velocities on both structures in October 2011 (see Table 2), the predicted ground distance the species could travel at its U_{sprint} would be further reduced to 896 and 1101 cm of passage on the bypass and spillway fishways (much less than their actual lengths), respectively, yet a substantial increase in passage of Western Pygmy Perch (average of ~9 $fish.hr^{-1}$) was recorded in October 2011. Therefore, although a very useful metric in predicting passage on structures with more uniform, laminar flow such as road culverts (Starrs *et al.* 2011), using average velocity and U_{sprint} values to predict fish passage on turbulent structures such as the cascade fishway in the current study has less utility. It is likely that the fish utilise burst swimming along with seeking low flow areas produced by the complex flow profile (see Figure 3) to successfully negotiate the fishways. It should also be noted that retrofitting of the larger steps was undertaken in May 2011 (Figure 2) both below the fishway system and particularly in the bypass that may at least partially account for the differences in the strength of passage over the fishways of the Western Pygmy Perch and other species between the years.

Although the Western Pygmy Perch can obviously travel greater distances on these fishways than would be predicted by using U_{sprint} value and average flow velocities (resulting in its successful passage in October 2010 and 2011), excessive flow rates in August and September at the time of sampling in both years (that approximated or exceeded its U_{sprint} value of 65 $cm.sec^{-1}$) apparently precluded its upstream passage during much of its spawning period. Furthermore, lower overall abundances of the species in 2010 and/or the presence of higher steps on the bypass and below the spillway, that were retrofitted between the sampling years, probably contributed to its lack of passage on the bypass in 2010.

The estuarine Blue-spot Goby consistently used the spillway fishway in all three sample periods in both years with almost no captures recorded in the bypass channel. That a wide size range of this species utilised the southern tributary upstream of the dam suggests that the Blue-spot Goby utilises the spillway fishway to move both upstream and downstream, and is a self-maintaining population within Rushy Creek. This species appears not to utilise the northern tributary above the dam nor the bypass channel. While swimming performance metrics need to be determined for this species, its ability to negotiate the spillway fishway may be aided by the anatomical structure of its pelvic fins; which are fused in most Gobiidae to form a suction-cup like structure that allows these species to cling onto rocks, logs or other hard substrates in high flow or turbulent conditions.

Very limited movement was observed of either the Nightfish or Western Mud Minnow on the fishway system. As the former species is known to migrate during winter and spring as part of its life-cycle (Beatty *et al.* 2014), it may be concluded that it was unable to successfully passage upstream on the fishways. However, the Nightfish was also not recorded moving upstream below the fishway during the sampling despite it coinciding with its breeding period and therefore it appeared not to be strongly migratory within Rushy Creek and it is therefore unclear as to whether it could indeed successfully passage the fishway system.

The threatened Western Mud Minnow is generally recorded in low numbers throughout its range (Morgan *et al.* 1998) and is not strongly migratory (Beatty *et al.* 2014). The downstream movement observed on the bypass channel in September 2010 indicated that it may be persisting in habitats upstream of the dam; however, no captures were recorded during population density surveys, so the size of the resident population there was probably low. The Western Hardyhead and South-western Goby were effectively not found to move upstream over either fishway and neither were they recorded moving upstream at the site below the dam (aside from the Western Hardyhead recorded once in September). All are known to occupy the main channel of the Blackwood River well inland of their typically estuarine habitats but are not commonly encountered in fresh tributaries (Beatty *et al.* 2008b, 2014). The absence of this species on the fishways is most probably due to the lack of significant migration within Rushy Creek rather than inability to negotiate them.

There are three other rock-ramp fishways that have previously been monitored in south-west Western Australia; all of these have been designed with an overall slope of 1:20 comprising 100 mm steps at 2 m intervals, inclusive of larger resting pools in-between each 1 m lift (Morgan & Beatty 2004a, b). The ratio of species observed utilising these fishway systems was generally similar to that of the current study with the Western Minnow being the dominant species. Therefore, the turbulent hydrological conditions on rock-ramp fishways are readily negotiable by the Western Minnow but much less so by sympatric freshwater fishes (Morgan & Beatty 2005; Beatty *et al.* 2007). Galaxiids, in general, are strong swimmers and can readily negotiate high velocity habitats such as riffle zones and smaller artificial barriers. Moreover, Close *et al.* (2014) demonstrated that *Galaxias truttaceus* could actually use jumping and climbing behaviour to negotiate a weir on the Goodga River, south-western Australia; despite there also being an operational vertical-slot fishway at the site (Morgan & Beatty 2006). The Western Minnow has also been observed by the primary author leaping vertically ~50 cm when attempting to pass over weirs in south-western Australia.

The number of species of introduced freshwater fishes now exceeds the number of native species in south-western Australia and there has been a sharp increase in introductions over the past decade (Beatty & Morgan 2013; Duffy *et al.* 2013). The potential passage of introduced species over barriers should be a key consideration in planning and designing fishways so as not facilitate their upstream colonisation past barriers (Beatty *et al.* 2013). The highly invasive Eastern Gambusia was recorded in both upstream and downstream fyke nets on the spillway in October 2010 and 2011. Low numbers were also captured in studies on other rock-ramp fishways in south-west Western Australia (Morgan & Beatty 2005; Beatty *et al.* 2007). This species prefers shallow, slow flowing waters and has an inferior swimming ability compared to native fishes of the region (Keleher 2011). We suspect the species was unlikely to be have undertaken upstream movement through the ~1:9 slope of the Rushy Creek fishway system. Their capture moving upstream on the fishways is most plausibly explained by the fact that the species was already present in the shallow waters on the spillway between the fyke nets and the crest, noting that this area was not cleared of fish prior to setting the nets in 2010. It is also likely that those individuals in 2011 still found their way around the blocked net as 100% blockage was not guaranteed given the small size of this species and its observed high abundances in the reservoir.

The Goldfish was also recorded in Rushy Creek for the first time having previously been recorded in very low abundance in the Blackwood River main channel (Beatty *et al.* 2008b). It was not recorded utilising the fishway system and was not recorded upstream of the reservoir. It is unlikely that the fishway system will facilitate the spread of Goldfish into upstream reaches of Rushy Creek. Therefore, whilst restricting some native species at least during higher flow periods, higher gradient fishways such as the Rushy Creek system could potentially be used where preventing introduced species passage is a priority.

The study also recorded the presence of a cestode worm in the Western Minnow population, which was probably the introduced *Ligula intestinalis* (see Morgan 2003) and caused an obvious swelling of the abdomen in infected individuals. Although present in both years, its prevalence was only quantified in 2011 when it was present in 3.3% of Western Minnows upstream of the dam and 4.3% of those downstream of the dam (including the fishways), and was most prevalent in August (9.4%) and September (2.0%). The impact of this and another introduced parasite *Lernaea cyprinacea* (Marina *et al.* 2008) on the region's freshwater fish requires ongoing research.

The study highlights the benefit of quantifying interannual variation in fishway usage. Replicating the sampling program in 2011 revealed that a wide size range of the Western Pygmy Perch could negotiate upstream over the bypass and spillway fishways in October 2011 (and spillway in October 2010) including both juveniles and adults. Sampling upstream movements and densities in Rushy Creek at the site below the dam also provided valuable information as it demonstrated that both adult and juvenile Western Pygmy Perch undertook strong upstream movements below the fishway system in October which corresponded to the species also moving over both the spillway and the bypass fishway at that time; however, it was probably unable to negotiate either fishway in August and September when congregations of adults were detected below the dam. Furthermore, the Freshwater Cobbler (the largest native south-western Australian freshwater fish) appeared unable to utilise either the bypass or spillway fishway as it is known to migrate in large numbers through riffle zones (Beatty *et* *al.* 2010). It is suggested that a substantial reduction in riffle slopes and cascades and an increase in water depth would improve fishway passage success for this species.

CONCLUSIONS

The study demonstrated that the Rushy Creek bypass and spillway structures were successful in allowing upstream passage of three of the four known migratory species in the system. The fishway system was also utilised for downstream dispersal of those species. While the bypass channel allowed upstream passage under low flow rates for a less mobile species and may allow earlier passage of resident species (i.e. early winter), greater overall utilisation of the spillway fishway was recorded for key species. The Western Minnow was shown to successfully passage upstream through the fishway system during the peak flow period of the sampling (i.e. ~97 $cm.sec^{-1}$).

The hydrological characteristics of the fishways along with the current limited understanding of swimming performance of the fishes help explain some but not all of the fish passage success. Other swimming performance metrics, particularly burst swimming, need to be quantified for south-western Australian species. Furthermore, the fine-scale movement patterns of fishes on fishways and indeed in unregulated rivers should be further investigated using mark-recapture. For the larger species (i.e. >~80 mm, such as most galaxiids of the region), this could involve telemetry utilising passive integrated transponders (PIT tags) and electronic monitoring stations (e.g. above and below fishways). For smaller species individually coded visible implant elastomer (VIE) tags and manual monitoring could be utilised.

Fishways have the potential to help offset the combined impacts of ongoing flow reductions and instream barriers on the migration of freshwater fishes in south-western Australia. Our results suggest rock-ramp fishways with 20 m long cascades (with maximum slopes of ~1:9) can provide varying degrees of native fish passage over relatively large on-stream dams in the region. However, as with previous studies in this region, our findings suggest more gradual riffle slopes and cascades are required to enable passage of a greater number of the migratory species (and potentially for a longer annual period). Designs should also include defined resting pools and, to enhance fishway longevity, the anchoring of ridges could be undertaken. It is also recommended that earth-movers experienced in fishway construction be employed and that designs should ensure that there are neither extended smooth sections nor any significant steps present.

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