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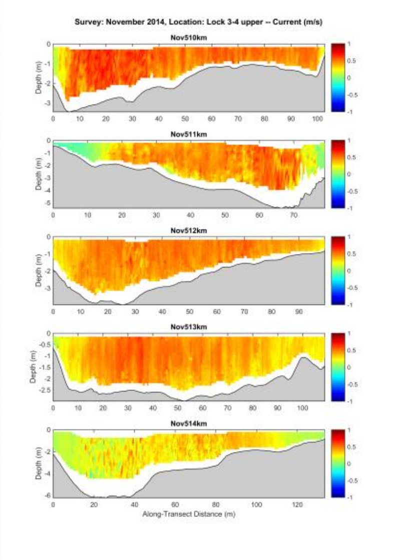
The influence of weir pool raising on main channel hydraulics in the lower River Murray



C. M. Bice and B. P. Zampatti

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June 2015

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EXECUTIVE SUMMARY

River regulation and consumptive water use have dramatically altered the flow regime of the lower River Murray. Reductions in flow volumes have led to decreases in the frequency, magnitude and duration of within-channel and overbank flows, whilst the construction of 10 low-level weirs, has transformed over 800 km of free-flowing river into a series of contiguous weir pools that are predominantly lentic in character. As such, hydrological variability in the lower River Murray has been diminished, water levels are highly stable and the within-channel hydraulic environment (i.e. water depth, velocity and turbulence) is homogenous when compared to the unregulated river. Substantial changes in ecological patterns and processes have been associated with these aspects of flow regime alteration.

Weir pool manipulations (i.e. raising or lowering river stage using existing lock and weir infrastructure) are currently being investigated by South Australian and federal agencies as a tool for reinstating greater water level variability in the lower River Murray. There has been considerable interest in the utility of raising weir pools with the objective of inundating littoral zones, and thus achieving environmental outcomes (e.g. responses from littoral and floodplain vegetation) in the absence of elevated flows. Nonetheless, the action of raising a weir pool, reduces the physical flow gradient and may thus, further impact hydraulic complexity. An understanding of the influence of weir pool raising on within channel hydraulic conditions and how this influence varies with discharge and location, both within and among weir pools, is required to inform future weir pool manipulations.

In spring/summer 2015, weir pool manipulation was undertaken in the Lock 1–2 and Lock 2–3 weir pools. Water levels in the weir pools were first raised to +0.3 m above ‘full supply level’ (FSL) and then further raised to a maximum of +0.5 m for a period of approximately two weeks, before being reduced to +0 m. The objective of the current study was to utilise cross-sectional velocity profiles to investigate the influence of raising the level of the Lock 1–2 and Lock 2–3 weir pools on within channel hydraulics. Specifically, the aims were to,

1) Characterise and compare spatio-temporal variability in the hydraulic environment in two raised (Lock 1–2 and Lock 2–3) and one unraised ‘reference’ weir pool (Lock 3–4) at +0 m (FSL), +0.3 m and +0.5 m, using a range of hydraulic metrics; and
2) To integrate these data, to determine the influence of weir pool raising on hydraulic complexity and inform future weir pool manipulations in the lower River Murray.

A vessel-mounted Acoustic Doppler Current Profiler (ADCP) was used to measure cross-sectional velocity profiles from five sites, within three reaches (i.e. lower, middle and upper weir pool), across the three weir pools. Velocity profiles were measured on three occasions, timed to coincide with different stages of the weir pool manipulation: 1–9 September 2014 (+0.3 m), 11–13 November 2014 (+0.5 m) and 9–11 February 2015 (+0 m). Water level in the Lock 3–4 weir pool was not actively raised and ranged 0.004–0.028 m during sampling. Discharge was generally low but variable over the study period ranging 3970–5011, 8231–9266 and 6500–7889 ML.day^{-1} in September 2014, November 2014 and February 2015, respectively, across all weir pools.

Patterns of spatio-temporal variability in mean downstream velocity and metrics, which indicate the level of turbulence (i.e. *Reynolds number*), 'rapidly' flowing water (i.e. *Froude number*), and strength and frequency of eddies (i.e. modified circulation metrics) in cross-sectional profiles, were consistent across weir pools, raised and unraised. There was little significant difference in these parameters, in all three weir pools, between periods of similar discharge in November 2014 (+0.5 m in Lock 1–2 and Lock 2–3, and +0 m in the Lock 3–4 weir pool) and February 2015 (+0 m in all weir pools). These results suggest that weir pool raising in the Lock 1–2 and Lock 2–3 weir pools had little impact on within channel hydraulics at the weir heights and discharges investigated.

Substantial spatial variability in hydraulics was observed both within and among the three weir pools. Typically, wetted width, depth and cross-sectional area increased and in association, mean velocities and turbulence decreased, in a downstream direction and proximity to the downstream weir, with upper reaches exhibiting the greatest levels of hydraulic complexity. This 'downstream weir effect' was present in each weir pool but differences in the length and sinuosity of the weir pools results in the level of impact of the 'downstream weir effect' differing between weir pools, which drove the observed differences in hydraulics. Relatively low velocities throughout the Lock 2–3 weir pool, including in the upper reach, suggests the 'downstream weir effect' extends upstream through the entire length of the weir pool. Alternatively, the presence of relatively high velocities in the upper reach of the Lock 3–4 weir pool, regardless of discharge, suggests that the 'downstream weir effect' is attenuated some distance below Lock 4 and this reach represents a comparatively 'free-flowing' reach in the otherwise lentic and hydraulically homogenous lower River Murray.

The results of the current study have important implications for future weir pool manipulations. Firstly, raising the Lock 1–2 and Lock 2–3 weir pools, at similar discharge to that experienced in the current study is unlikely to have a significant impact on hydraulic complexity. Alternatively, the upper reach of the Lock 3–4 weir pool appears to represent a unique lotic reach in the otherwise lentic lower River Murray, and thus, raising events in this weir pool should be carefully considered given potential risks to this now rare habitat. The spatial variability in hydraulics observed between weir pools suggests a greater understanding of weir pool specific hydraulics is required for other weir pools of the lower River Murray to assess potential impacts/benefits of water level manipulations. Ultimately, any future weir pool manipulation program is likely to elicit the greatest ecological benefit if it is integrated with broader riverine rehabilitation programs (e.g. hydrological rehabilitation through environmental flow delivery), planned over a long-term (> 10 years), incorporates both raisings and lowerings, and considers both potential risks (e.g. loss of hydraulic complexity) and benefits (e.g. vegetation response) in a spatial and hydrological context (i.e. where and at what flows manipulations occur).

1. INTRODUCTION

1.1. Background

River regulation and water abstraction typically result in the alteration of natural flow regimes to the detriment of ecosystem structure and function (Bunn and Arthington 2002). In general, regulation alters the hydrological and hydraulic nature of rivers, which impact different aspects of the ecosystem, but which may ultimately act in conjunction in many catchments. For instance, total discharge and subsequently floodplain inundation extent, frequency and duration are impacted by upstream storage and extraction, whilst instream hydraulics (i.e. depth, flow velocity and turbulence) or the 'physical nature of flow' are impacted by overall reductions in discharge but also the presence of smaller instream structures such as weirs (Poff *et al.* 1997). To achieve the greatest ecological benefit, the restoration of regulated rivers must be multifaceted and consider actions to mitigate hydrological and hydraulic impacts.

The hydraulic characteristics of fluvial ecosystems result from the interaction of discharge and physical features (e.g. channel morphology, woody debris, man-made structures, etc.), and have a profound influence on ecosystem structure and function (Biggs *et al.* 2005). Hydraulics vary spatially due to physical habitat heterogeneity and temporally with discharge; both sources of variability are important in lotic ecology. Spatial heterogeneity in hydraulics facilitates variability in microhabitats that may be utilised by different biota and subsequently, is often associated with high levels of biological diversity (de Nooij *et al.* 2006, Dyer and Thoms 2006). Temporal variability in hydraulic conditions performs other functions including scouring and sediment transport, altering biofilm composition (Sheldon and Walker 1997) and facilitating critical life history processes like fish spawning (Zampatti and Leigh 2013) and larval drift (Dudley and Platania 2007). Subsequently, changes to hydraulic conditions, as a result of river regulation, impact biota and processes reliant on complex hydraulic environments.

The lower River Murray was once a lotic system, which experienced highly variable discharge and heterogeneous hydraulics over a range of spatial scales, even during times of low flow (Mallen-Cooper *et al.* 2011). However, river regulation and increased consumptive water use has reduced overall flow volumes and subsequently reduced the frequency and duration of medium–high flows (Maheshwari *et al.* 1995). Furthermore, the construction of 10 low-level weirs in the 1920s and 1930s, transformed over 800 km of river into a series of contiguous, weir pools which are predominantly lentic in character (Walker and Thoms 1993). As such, variability in the flow regime has been diminished and water levels are now relatively stable (Maheshwari *et al.* 1995, Blanch *et al.* 2000). During low flows (<5,000 ML/d), variability in water velocities and thus hydraulic complexity, is far greater in unregulated reaches of the mid-Murray compared to the weir pool environments of the lower River Murray (Kilsby 2008). This suggests that under entitlement flows (3000–7000 ML.day^{-1}), which predominate, the lower River Murray is now hydraulically homogenous compared to the unregulated river, and significantly elevated flow may be required to reinstate hydraulic complexity (Bice *et al.* 2013).

Weir pool manipulations (i.e. raising or lowering river stage using existing lock and weir infrastructure) are currently being investigated by South Australian and federal agencies as a tool for reinstating greater variability in water level and riparian zone/floodplain inundation in the lower River Murray. In the lower River Murray in South Australia, there has been considerable interest in the utility of raising weir pools with the objective of inundating littoral zones and low-level floodplain, and thus achieving environmental outcomes (e.g. improved river red gum (*Eucalyptus camaldulensis*) condition and increased productivity) in the absence of elevated discharge. Nonetheless, the action of raising a weir pool effectively ‘backs’ water up from a downstream weir, which reduces the physical flow gradient of a weir pool and may potentially, further impact hydraulic complexity. An understanding of the influence of weir pool raising on the within-channel hydraulic environment and how this influence varies with discharge and location, both within and among weir pools, is required to inform future application of weir pool manipulation.

Weir pool raisings were undertaken in the Lock 1–2 and Lock 2–3 weir pools in spring/summer 2015. The weir pools were raised to +0.3 m above ‘full supply level’ (FSL, +0 m) and then further raised to a maximum of +0.5 m for a period of approximately two weeks, before being reduced back to pool level. This presented the opportunity to investigate the influence of weir pool raising on within channel hydraulics in two adjacent weir pools.

1.2. Objectives

The primary objective of this project was to utilise cross-sectional velocity profiles to investigate the influence of raising the level of the Lock 1–2 and Lock 2–3 weir pools on within channel hydraulics. Specifically, the aims were to,

3) Characterise and compare spatio-temporal variability in the hydraulic environment in two raised (Lock 1–2 and Lock 2–3) and one unraised ‘reference’ weir pool (Lock 3–4) at +0 m (FSL), +0.3 m and +0.5 m, using a range of hydraulic metrics; and
4) To integrate these data, to determine the influence of weir pool raising on hydraulic complexity in the Lock 1–2 and Lock 2–3 weir pools, and inform future weir pool manipulations in the lower River Murray.

2. METHODS

2.1. Study site

Velocity profiles were measured across transects in three weir pools in the main channel of the lower River Murray; Lock 1–2 and Lock 2–3, within which water levels were raised, and Lock 3–4, within which water levels were not raised. Within each weir pool, cross-sectional velocity profiles were undertaken at 5 sites, separated by approximately 1 km, within each of 3 ‘reaches’, 1) the upper weir pool (in the vicinity of the upstream weir), 2) the mid weir pool (approximately mid-way between the two weirs) and 3) the lower weir pool (within the vicinity of the downstream weir) (Figure 1 and Table 1). Below bank-full discharge (~50,000 $ML.day^{-1}$) within weir pools of the lower River Murray there is a general downstream gradient of decreasing water velocity and water level variability. As such, hydraulics and geomorphic processes (i.e. erosion and deposition) differ between ‘reaches’ within individual weir pools, and may thus respond differently to weir pool manipulations. The terms ‘upper’, ‘middle’ and ‘lower’ weir pool are adopted from previous authors (Walker *et al.* 1994). Velocity profiles were measured on three occasions, which were timed to coincide with different stages of the weir pool manipulation: 1–9 September 2014 (+0.3 m above FSL), 11–13 November 2014 (+0.5 m above FSL) and 9–11 February 2015 (+0 m FSL).

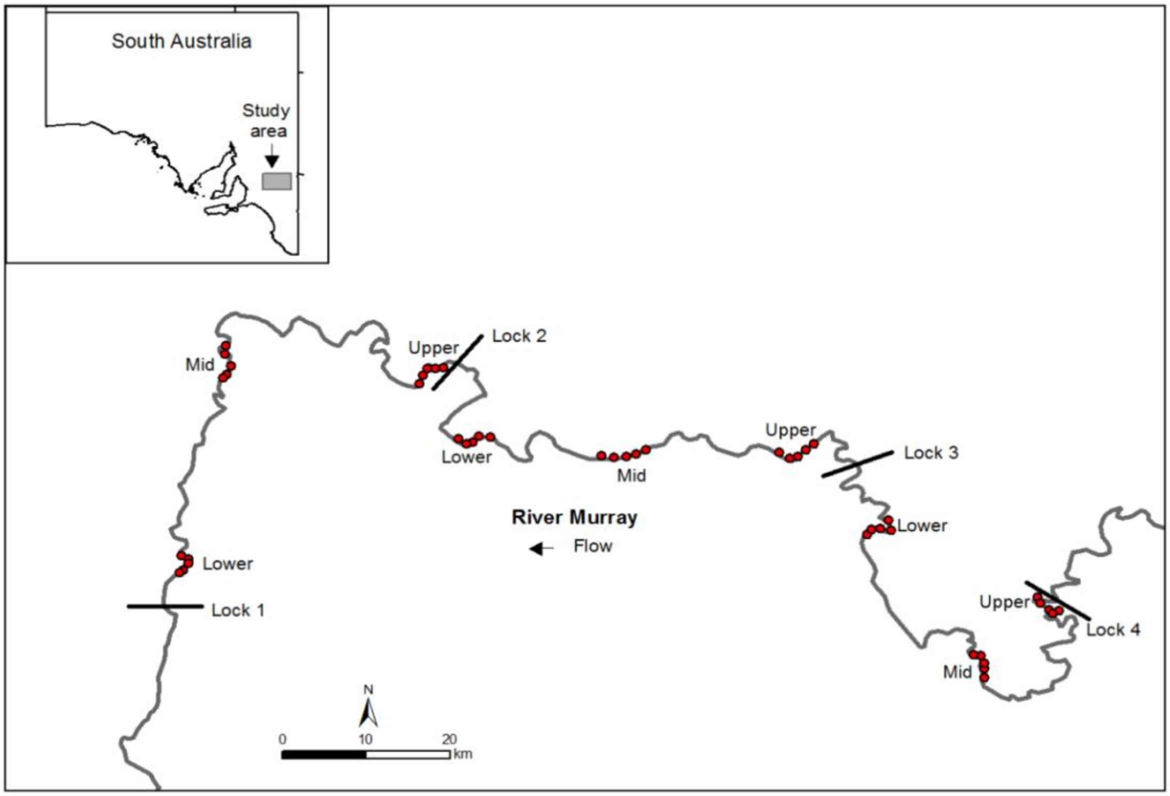

Figure 1. Map of the study area in the lower River Murray, South Australia, depicting the Locks 1, 2, 3 and 4, and sites (red dots) where cross-sectional velocity profiles were undertaken in the lower, mid and upper reaches of the Lock 1–2, Lock 2–3 and Lock 3–4 weir pools. These sites correspond with those presented in Table 1.

Table 1. Location of sites indicated as middle thread distance (MTD, km), latitude and longitude where cross-sectional velocity profiles were undertaken in the lower, middle and upper reaches of the Lock 1–2, Lock 2–3 and Lock 3–4 weir pools. MTD is the distance, measured along the middle of the river, from a specific point to the river's mouth.

Weir pool	Reach	Site	Middle thread distance (km)	Latitude	Longitude
Lock 1–2	lower	1	278	-34.31307	139.63138
		2	279	-34.31073	139.63528
		3	280	-34.30386	139.64095
		4	281	-34.29832	139.64137
		5	282	-34.29425	139.63351
	middle	1	310	-34.09372	139.67863
		2	311	-34.08958	139.68272
		3	312	-34.08081	139.68723
		4	314	-34.06710	139.68060
		5	316	-34.05790	139.68175
	upper	1	356	-34.10050	139.88994
		2	357	-34.09122	139.89282
		3	358	-34.08313	139.89793
		4	359	-34.08324	139.90637
		5	360	-34.08190	139.91483
Lock 2–3	lower	1	376	-34.16262	139.93123
		2	377	-34.16879	139.93976
		3	378	-34.16600	139.94679
		4	379	-34.16007	139.95306
		5	380	-34.16045	139.96623
	middle	1	397	-34.18191	140.08530
		2	398	-34.18369	140.09853
		3	399	-34.18229	140.11159
		4	400	-34.17952	140.12218
		5	401	-34.17498	140.13234
	upper	1	418	-34.17813	140.27609
		2	419	-34.18495	140.28760
		3	420	-34.18251	140.29639
		4	421	-34.17456	140.30458
		5	422	-34.16854	140.31305
Lock 3–4	lower	1	446	-34.25627	140.39619
		2	447	-34.26559	140.39651
		3	448	-34.26380	140.38525
		4	449	-34.26489	140.37570
		5	450	-34.27085	140.37054
	middle	1	476	-34.40580	140.48557
		2	477	-34.40699	140.49330
		3	478	-34.41606	140.49686
		4	479	-34.42175	140.49654
		5	480	-34.43158	140.49712
	upper	1	510	-34.35940	140.57028
		2	511	-34.35612	140.57640
		3	512	-34.35566	140.56619
		4	513	-34.34800	140.55652
		5	514	-34.34154	140.55424

2.2. Survey technique

Cross-sectional velocity profiles were collected using a vessel-mounted SonTek River Surveyor M9 Acoustic Doppler Current Profiler (ADCP) (Figure 2a). In brief, ADCP measure the Doppler shift in acoustic signals as they are reflected off of suspended particles in the water column. Transducers on the unit send acoustic pulses vertically into the water column and, after a brief blackout period, begin recording pulses reflected from suspended particles, assuming that the velocity of suspended particles equates to fluid flow velocities (Shields and Rigby 2005). The water column is divided into depth 'cells' and the instrument uses the speed of sound in water to group reflected signals from given depth cells. Data, including water depth, heading, echo intensity and velocity are recorded at intervals of ~1 second and are used to produce measures of mean velocity for each depth cell. The ADCP unit is mounted on the gunwale of the vessel and transects are driven across a river reach to generate cross-sectional flow velocity profiles for the given transect (Figure 2b).

a) b)

Figure 2. a) The SonTek River Surveyor M9 ADCP mounted on hydroboard and b) undertaking a transect with the ADCP.

2.3. Data analysis

Data that were generated from ADCP transects were first viewed in the SonTek ADCP software package RiverSurveyor Live. Data were then exported to the numerical computing program MATLAB and interpolated across grids with equal cell sizes (0.5 m long x 0.25 m high) using the Delaney triangulation scattered data function (The Mathworks Inc. 2010). Water velocities for each cell are generated in three planes; perpendicular or cross-transect (i.e. upstream to downstream), parallel to or along a transect (i.e. from bank to bank) and vertically (i.e. up or down). These velocity data may then be used to calculate various hydraulic metrics. In the current study, spatio-temporal variability in hydraulic complexity was investigated at two scales; 1) the reach-scale (i.e. lower, middle and upper reaches) and 2) site-scale (i.e. individual transects).

Variability in discharge between sampling events has implications for data analysis and interpretation in the current project. Discharge was most similar between November 2014 (+0.5 m) and February 2015 (+0 m) (see results Section 3.1), and on both occasions greater than that experienced in September 2014. The hydraulic metrics outlined below cannot be standardised for discharge as a linear relationship with flow cannot be assumed and consequently, direct comparisons between hydraulic metrics from November 2014 and February 2015 provide the greatest insight into the influence of weir pool raising on river channel hydraulics.

Reach-scale hydraulic complexity

Spatio-temporal variability in hydraulic complexity within each weir pool was investigated by computing the following hydraulic metrics from cross-sectional velocity profiles and comparing between sampling events, and reaches: 1) cross-sectional downstream velocity (U), 2) modified vertical circulation metric (M_3), 3) modified horizontal circulation metric (M_4), 4) Reynolds number (Re) and 5) Froude number (Fr).

The vertical and horizontal modified circulation metrics are spatial hydraulic metrics developed by Crowder and Diplas (2000a) to quantify flow complexity over a defined area, in this case, river cross-sections as measured by ADCP transects. In brief, the modified circulation metrics expand on the point calculation of vorticity, which is defined as twice the rate at which a fluid rotates about its vertical axis (Crowder and Diplas 2000, 2002). Vorticity is a point measure, but the modified circulation metrics (M_3 and M_4) (after Shields and Rigby 2005) build upon the calculation of vorticity and represent a weighted average of absolute vorticity (i.e. flow rotation) in the vertical and horizontal planes per unit area, transverse to the channel, and are a measure of the strength and frequency of eddies in a river cross-section (Figure 3). Calculation of M_3 is explained by Equation 1, where w represents velocity in the vertical plane z and v represents velocity in the lateral plane y. Calculation of M_4 is explained by Equation 2 where v represents velocity in the lateral plane y and u represents velocity in the lateral plane x. Absolute values of velocity are used so that the direction of calculation (i.e. clockwise or counter-clockwise) does not result in the cancellation of eddies of equal strength in opposing directions. Higher values of M_3 and M_4 indicate greater frequency and strength of eddies or greater levels of circulation (i.e. flow rotation) within a cross-section. Crowder and Diplas (2002) present an example of utilising M_3 to describe the hydraulic habitat surrounding a series of brown trout (*Salmo trutta*) redds (i.e. spawning sites) relative to reaches without redds. Furthermore, this metric has been adopted by Shields and Rigby (2005) to analyse river habitat quality and found to be a good discriminator of differences in hydraulic conditions between modified and natural stream reaches.

Equation 1. $$M_3 = \frac{\sum \left| \left(\frac{\Delta w}{\Delta y} - \frac{\Delta v}{\Delta z} \right) \right| * \Delta y * \Delta z}{\sum \Delta y * \Delta z}$$

Equation 2. $$M_4 = \frac{\sum \left| \left(\frac{\Delta v}{\Delta x} - \frac{\Delta u}{\Delta y} \right) \right| * \Delta x * \Delta y}{\sum \Delta x * \Delta y}$$

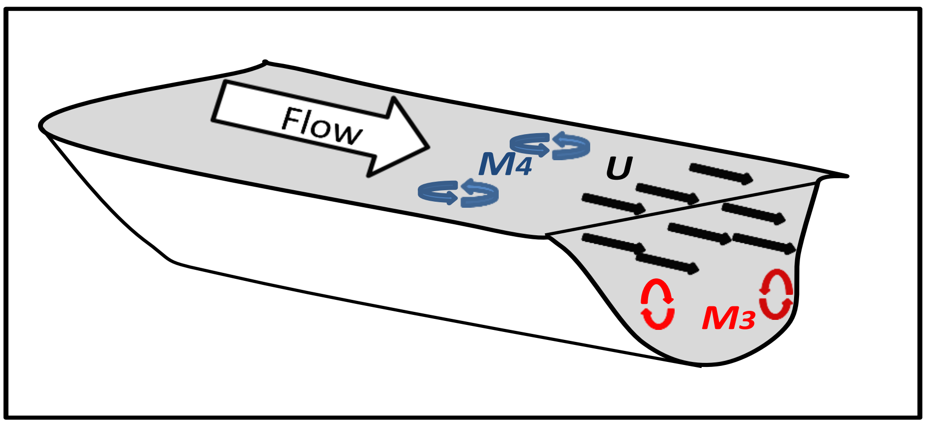

Figure 3. Schematic representation of a river reach and a subset of the hydraulic metrics measured (after Shields and Rigby 2005), downstream cross-sectional velocity (*U*) and vertical (M_3) and horizontal (M_4) modified circulation metrics, which represent the area weighted frequency and strength of eddies within a cross-section.

Reynolds number (*Re*) is a dimensionless metric that indicates whether flow in a channel is laminar or turbulent. In any open stream, flow is almost never laminar and thus the transition from laminar to turbulent flow is not of great importance (Gordon *et al.* 2004). Nonetheless, greater values of Reynolds number indicate greater levels of turbulence. Reynolds number is calculated using Equation 3, where *U* represents downstream cross-sectional velocity, *L* represents the hydraulic radius of a cross section (i.e. the cross-sectional area of the channel divided by the wetted perimeter (the river bed)) and *v* represents kinematic viscosity of water.

Equation 3. $$Re = \frac{U * L}{v}$$

Froude number (*Fr*) is a dimensionless metric that indicates the ratio of inertial to gravitational forces, where gravity encourages water to flow down an elevation gradient and inertial forces indicate the waters compulsion to follow this path (Gordon *et al.* 2004). The Froude number is calculated using Equation 4 where *U* represents downstream cross-sectional velocity, *D* represents average channel depth and *g* acceleration due to gravity (i.e. 9.81 $m.s^{-1}$). Values of *Fr* > 1 indicate supercritical or 'rapid' flow, whilst values < 1 indicate subcritical or 'tranquil' flow (Gordon *et al.* 2004). Much flow in large rivers like the lower River Murray, particularly under low flow, is likely to be subcritical, but higher relative values indicate a greater prevalence of faster flowing habitats and in streams can indicate a greater prevalence of 'riffles' over 'pool' habitat (Lamouroux and Souchon 2002).

Equation 4. $$Fr = \frac{U}{\sqrt{g * D}}$$

Values of the above metrics cannot be explicitly compared between weir pools due to the differing physical nature of each weir pool, but rather the relative change in metrics across time can be investigated to determine the influence of weir pool raising on hydraulics. All hydraulic metrics (i.e. U, M_3, M_4, *Re* and *Fr*) were compared between reaches (i.e. lower, middle and upper) and sampling events (i.e. September 2014 (+0.3 m), November 2014 (+0.5 m) and February 2015 (+0 m)) within weir pools, using univariate two-factor PERMANOVA (permutational ANOVA and MANOVA), in the software package PRIMER v. 6.1.12 and PERMANOVA+ (Anderson *et al.* 2008). All analyses were performed on Euclidean Distance similarity matrices and α = 0.05 for all comparisons. Should weir pool raising have a significant influence on within channel hydraulic conditions, patterns of temporal variability in the above metrics should be different between raised (Lock 1–2 and Lock 2–3) and unraised weir pools (Lock 3–4). Additionally, for downstream cross-sectional velocity an overall mean value for each reach within each weir pool (all sampling events combined) was determined. Values of variability (in standard deviations) from this mean for each reach, across all sampling events, was determined and qualitatively compared between weir pools.

Site-scale hydraulic complexity

The above analyses provide insight on spatio-temporal variability in reach- and weir pool-scale hydraulics, but they do not provide insight on variability in velocities at the site-scale (metres), particularly the prevalence of ‘patches’ of given velocities. Assessment of site-scale variability in hydraulics involved comparing downstream velocity distributions within individual cross-sections across sampling events (i.e. September 2014 (+0.3 m), November 2014 (+0.5 m) and February 2015 (+0 m)). Velocity distributions were explicitly compared between November 2014 (+0.5 m) and February 2015 (+0 m) using the Two-tailed Kolmogorov-Smirnov ‘goodness of fit’ test. Potential differences in velocity distributions were interpreted using box and whisker plots which present median and 10th, 25th, 75th and 90th percentile velocities for each individual transect.

3. RESULTS

3.1. Water level and hydrology

Velocity profiles were measured on three occasions, which were timed to coincide with different stages of the weir pool manipulation: 1–9 September 2014 (+0.3 m above FSL), 11–13 November 2014 (+0.5 m above FSL) and 9–11 February 2015 (+0 m FSL) (Figure 4a). Raising of water levels in the Lock 1–2 and Lock 2–3 weir pools began in early August 2014 and reached +0.3 m by mid-August. This level was maintained for ~8 weeks, before being gradually raised over a period of ~3 weeks, reaching the maximum level of +0.5 m in early November. This level was maintained for ~2 weeks before recession began. The water level in the Lock 1–2 weir pool was then rapidly drawn down over a period of ~1 week in response to water leakage through the structure. This leaking also resulted in the level of this weir pool dropping below +0 m (-0.096 m) during sampling in February 2015. Water level within the Lock 2–3 weir pool was more gradually drawn down over a period of ~4 weeks. Whilst not specifically raised, water level in the Lock 3–4 weir pool was +0.005–0.017 m and +0.004–0.010 m during the September and November 2014 sampling events, respectively. During sampling in February 2015 water level was +0.028 and +0.032 m in the Lock 3–4 and Lock 2–3 weir pools, respectively (Figure 4a).

Discharge was generally low, but variable over the study period (Figure 4b), with greatest discharge from all three weirs in November 2014 and lowest in September 2014. During sampling, discharge from Lock 4 was 3970 $ML.day^{-1}$, 8931–9266 $ML.day^{-1}$ and 7851–7889 $ML.day^{-1}$ in September 2014, November 2014 and February 2015, respectively. Discharge from Lock 3 was 3999 $ML.day^{-1}$, 8231 $ML.day^{-1}$ and 7183 $ML.day^{-1}$ in September 2014, November 2014 and February 2015, respectively. Discharge from Lock 2 was 3999–5011 $ML.day^{-1}$ in September 2014, 8304 $ML.day^{-1}$ in November 2014 and 6500 $ML.day^{-1}$ in February 2015.

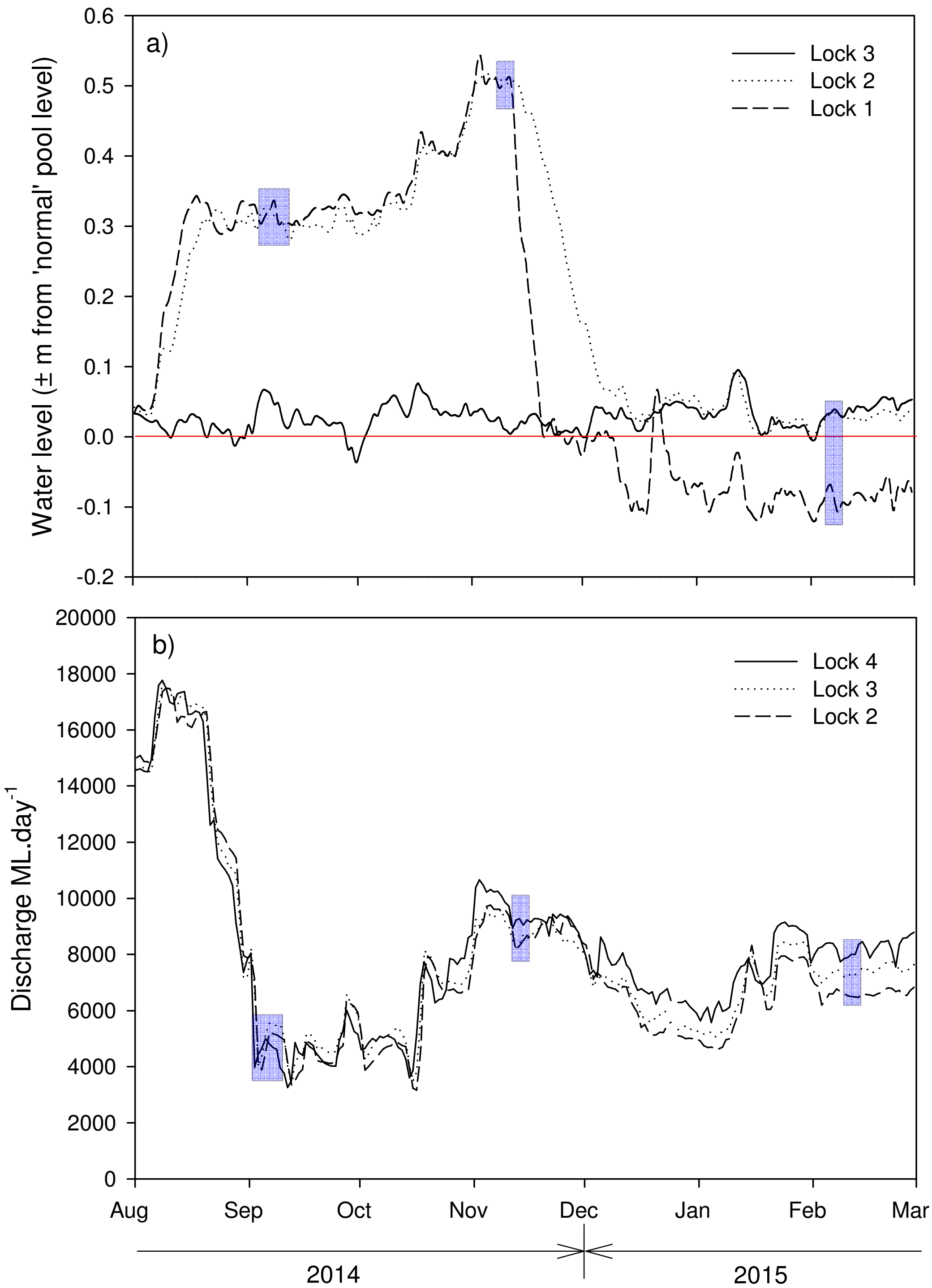

Figure 4. a) Daily pool level (normal 'pool level' ± m) upstream of Lock 3, Lock 2 and Lock 1 and b) daily discharge (ML.day^{-1}) over Lock 4, Lock 3 and Lock 2 from August 2014 to March 2015. The timing of sampling events are indicated by shaded boxes. Water level and discharge data were sourced from the Department of Environment, Water and Natural Resources (DEWNR 2015).

3.2. General hydraulic parameters

Changes in general hydraulic parameters were evident within all weir pools between sampling events (Tables 2–4). In the Lock 3–4 weir pool, discharge ($m^3.s^{-1}$) as measured from ADCP transects, varied in association with calculated discharge over Lock 4 (Table 2 and Figure 4b). Transect length, as an indication of wetted width, did not vary substantially, but max depth and cross-sectional area exhibited minor variations in association with variation in discharge, particularly in the upper reach.

In the Lock 2–3 and Lock 1–2 weir pools, measured discharge also reflected calculated discharge over the locks (Tables 3–4 and Figure 4b). Transect length did not vary substantially between sampling events, but maximum depth and cross-sectional area increased in the following order February 2015 < September 2014 < November 2014 reflecting the different weir pool levels, +0 m, +0.3 m and +0.5 m, during these sampling events.

All weir pools exhibited variability in general hydraulic metrics in a downstream direction, including increases in max depth and cross-sectional area, whilst mean velocity decreased reflecting the influence of the downstream lock and weir structure in each weir pool (Tables 2–4). This difference, however, was not as pronounced in the Lock 2–3 weir pool.

The different physical nature of the weir pools is evident from the general hydraulic metrics. The upper reach of the Lock 3–4 weir pool in particular, is noticeably different to all other reaches; with much lower transect length and cross-sectional area (Tables 2–4). Accordingly, the greatest velocities recorded in the study occurred in this reach, with mean downstream velocity ranging 0.262–0.392 $m.s^{-1}$ (Table 2). The upper reach of the Lock 1–2 weir pool also exhibited mean downstream velocities >0.2 $m.s^{-1}$ in both November 2014 and February 2015, but all other reaches exhibited mean downstream velocities of <0.2 $m.s^{-1}$ and often <0.15 $m.s^{-1}$.

Table 2. Mean values (± SE) and ranges (in brackets) of hydraulic habitat metrics calculated from ADCP generated cross-sectional velocity profiles from the upper, middle and lower reaches of the Lock 3–4 weir pool in February 2015 (+0 m), September (+0.3 m) and November (+0.5 m). Metrics include measured discharge ($m^3.s^{-1}$), transect length (m), max depth (m), cross-sectional area (m^2), downstream cross-sectional velocity (U, $m.s^{-1}$), the modified vertical circulation metric (M_3, s^{-1}), the modified horizontal circulation metric (M_4, s^{-1}), Reynolds number and Froude number. Note: no water level manipulation occurred in this weir pool.

	February 2015 (+0 m)			**September 2014 (+0.3 m)**			**November 2014 (+0.5 m)**		
Means	**Lower**	**Mid**	**Upper**	**Lower**	**Mid**	**Upper**	**Lower**	**Mid**	**Upper**
Discharge ($m^3.s^{-1}$)	88.14 ± 0.69 (85.72–89.50)	95.31 ± 1.71 (90.86–101.43)	85.75 ± 1.89 (81.75–92.54)	54.08 ± 1.73 (49.43–57.25)	62.66 ± 1.48 (59.11–66.73)	53.82 ± 1.19 (51.82–58.39)	99.64 ± 0.76 (97.87–102.23)	108.82 ± 2.86 (103.20–116.23)	94.29 ± 2.00 (91.40–102.18)
Transect length (m)	174.14 ± 15.31 (130.31–205.19)	167.92 ± 14.19 (137.47–214.34)	103.00 ± 8.95 (76.42–132.47)	174.27 ± 15.95 (134.55–207.11)	165.87 ± 14.10 (136.57–212.65)	102.98 ± 8.15 (76.85–127.24)	175.81 ± 15.85 (133.45–206.49)	166.89 ± 14.59 (136.41–215.82)	104.69 ± 8.77 (79.01–133.46)
Max depth (m)	6.11 ± 0.45 (5.06–7.20)	6.17 ± 0.54 (4.70–7.65)	4.24 ± 0.49 (3.10–5.84)	6.38 ± 0.50 (4.89–7.38)	6.13 ± 0.54 (4.60–7.26)	4.09 ± 0.64 (2.58–5.88)	5.98 ± 0.40 (5.06–6.99)	6.21 ± 0.57 (4.64–7.60)	4.41 ± 0.61 (2.99–6.22)
Area (m^2)	756.82 ± 24.10 (691.36–814.68)	704.01 ± 27.64 (617.99–772.08)	266.48 ± 45.14 (205.09–444.36)	759.26 ± 26.12 (696.27–830.60)	697.84 ± 22.47 (629.16–757.17)	246.63 ± 43.65 (163.74–415.51)	762.69 ± 23.73 (698.97–835.27)	705.73 ± 26.27 (620.77–773.19)	285.33 ± 47.99 (203.18–473.42)
U ($m.s^{-1}$)	0.125 ± 0.004 (0.116–0.139)	0.146 ± 0.006 (0.133–0.165)	0.389 ± 0.043 (0.224–0.463)	0.077 ± 0.003 (0.072–0.087)	0.098 ± 0.006 (0.085–0.115)	0.262 ± 0.034 (0.152–0.363)	0.141 ± 0.005 (0.130–0.158)	0.158 ± 0.006 (0.145–0.177)	0.392 ± 0.043 (0.242–0.501)
M_3 (s^{-1})	0.171 ± 0.017 (0.130–0.228)	0.158 ± 0.014 (0.113–0.189)	0.142 ± 0.016 (0.108–0.201)	0.173 ± 0.007 (0.152–0.191)	0.163 ± 0.011 (0.130–0.190)	0.120 ± 0.020 (0.075–0.184)	0.151 ± 0.028 (0.086–0.224)	0.135 ± 0.025 (0.043–0.185)	0.146 ± 0.018 (0.101–0.184)
M_4 (s^{-1})	0.083 ± 0.008 (0.066–0.106)	0.084 ± 0.012 (0.055–0.112)	0.062 ± 0.008 (0.046–0.088)	0.063 ± 0.008 (0.044–0.091)	0.075 ± 0.007 (0.058–0.101)	0.039 ± 0.007 (0.025–0.063)	0.075 ± 0.018 (0.034–0.119)	0.065 ± 0.013 (0.022–0.095)	0.062 ± 0.008 (0.043–0.082)
Reynolds number	55910 ± 5322 (45462–73571)	62624 ± 5938 (47202–79163)	94826 ± 7653 (75076–122209)	34599 ± 3717 (26633–46822)	41986 ± 3942 (30810–52901)	58801 ± 4857 (49568–76723)	63031 ± 5852 (51885–77875)	68493 ± 5658 (52522–81607)	101216 ± 6050 (85738–121852)
Froude number	0.019 ± 0.001 (0.018–0.021)	0.023 ± 0.001 (0.020–0.027)	0.080 ± 0.011 (0.039–0.105)	0.012 ± 0.000 (0.011–0.013)	0.015 ± 0.001 (0.012–0.019)	0.057 ± 0.010 (0.027–0.090)	0.021 ± 0.001 (0.019–0.024)	0.025 ± 0.002 (0.020–0.029)	0.079 ± 0.014 (0.041–0.114)

Table 3. Mean values (± SE) and ranges (in brackets) of hydraulic habitat metrics calculated from ADCP generated cross-sectional velocity profiles from the upper, middle and lower reaches of the Lock 2–3 weir pool in February 2015 (+0 m), September (+0.3 m) and November (+0.5 m). Metrics include measured discharge ($m^3.s^{-1}$), transect length (m), max depth (m), cross-sectional area (m^2), downstream cross-sectional velocity (U, $m.s^{-1}$), the modified vertical circulation metric (M_3, s^{-1}), the modified horizontal circulation metric (M_4, s^{-1}), Reynolds number and Froude number.

	February 2015 (+0 m)			September 2014 (+0.3 m)			November 2014 (+0.5 m)		
Means	**Lower**	**Mid**	**Upper**	**Lower**	**Mid**	**Upper**	**Lower**	**Mid**	**Upper**
Discharge ($m^3.s^{-1}$)	86.27 ± 1.46 (82.46–89.76)	83.47 ± 0.44 (82.03–84.59)	84.38 ± 0.83 (81.77–86.07)	44.92 ± 0.53 (42.90–45.81)	51.71 ± 0.87 (48.68–53.90)	49.00 ± 0.88 (46.10–51.08)	99.87 ± 0.85 (97.80–102.06)	98.96 ± 0.66 (97.01–101.14)	101.35 ± 2.55 (96.57–108.71)
Transect length (m)	149.01 ± 13.05 (113.85–193.13)	182.05 ± 13.69 (146.14–227.87)	147.71 ± 9.94 (112.21–172.72)	149.95 ± 13.06 (110.94–191.01)	182.64 ± 13.81 (146.07–226.30)	146.94 ± 9.53 (113.25–170.71)	152.09 ± 13.48 (112.17–195.56)	181.63 ± 12.68 (149.84–224.05)	151.18 ± 9.14 (119.25–175.21)
Max depth (m)	6.48 ± 0.65 (5.10–8.07)	3.96 ± 0.39 (2.80–5.15)	5.06 ± 0.59 (3.32–6.78)	6.82 ± 0.66 (5.44–8.47)	4.30 ± 0.47 (3.01–5.94)	5.21 ± 0.55 (3.67–7.06)	7.06 ± 0.67 (5.70–8.83)	4.68 ± 0.48 (3.31–6.29)	5.44 ± 0.59 (3.79–7.34)
Area (m^2)	662.82 ± 15.35 (605.30–695.23)	535.86 ± 18.61 (488.49–572.41)	550.68 ± 25.80 (459.34–599.17)	704.30 ± 10.44 (675.75–729.99)	571.57 ± 16.39 (531.08–630.19)	588.40 ± 27.22 (511.17–651.07)	737.44 ± 17.82 (672.67–771.96)	614.11 ± 22.81 (550.28–684.66)	619.60 ± 22.60 (546.51–680.73)
U ($m.s^{-1}$)	0.139 ± 0.005 (0.128–0.155)	0.166 ± 0.006 (0.156–0.187)	0.167 ± 0.009 (0.148–0.201)	0.069 ± 0.000 (0.067–0.070)	0.096 ± 0.003 (0.087–0.106)	0.092 ± 0.004 (0.083–0.102)	0.146 ± 0.003 (0.139–0.155)	0.171 ± 0.005 (0.158–0.188)	0.171 ± 0.006 (0.155–0.191)
M_3 (s^{-1})	0.153 ± 0.017 (0.097–0.200)	0.080 ± 0.017 (0.037–0.121)	0.146 ± 0.028 (0.056–0.202)	0.148 ± 0.016 (0.095–0.195)	0.062 ± 0.025 (0.031–0.160)	0.148 ± 0.020 (0.086–0.183)	0.177 ± 0.010 (0.152–0.198)	0.113 ± 0.021 (0.051–0.161)	0.141 ± 0.020 (0.086–0.205)
M_4 (s^{-1})	0.072 ± 0.009 (0.050–0.096)	0.031 ± 0.005 (0.018–0.042)	0.051 ± 0.011 (0.021–0.087)	0.083 ± 0.015 (0.044–0.135)	0.033 ± 0.014 (0.015–0.087)	0.057 ± 0.011 (0.042–0.099)	0.080 ± 0.008 (0.057–0.098)	0.043 ± 0.008 (0.021–0.070)	0.058 ± 0.012 (0.037–0.106)
Reynolds number	63381 ± 5476 (45116–78142)	50231 ± 3927 (38733–62362)	62905 ± 4361 (53378–78766)	33362 ± 3484 (24644–45128)	30911 ± 2776 (22524–38504)	36983 ± 2175 (30460–43946)	73022 ± 7069 (54844–97439)	58767 ± 4084 (45306–69165)	70917 ± 5536 (59583–92087)
Froude number	0.021 ± 0.001 (0.017–0.024)	0.031 ± 0.002 (0.027–0.039)	0.028 ± 0.003 (0.022–0.039)	0.010 ± 0.001 (0.009–0.012)	0.017 ± 0.001 (0.015–0.019)	0.015 ± 0.001 (0.011–0.019)	0.021 ± 0.001 (0.019–0.024)	0.030 ± 0.001 (0.026–0.034)	0.027 ± 0.002 (0.024–0.035)

Table 4. Mean values (± SE) and ranges (in brackets) of hydraulic habitat metrics calculated from ADCP generated cross-sectional velocity profiles from the upper, middle and lower reaches of the Lock 1–2 weir pool in February 2015 (+0 m), September (+0.3 m) and November (+0.5 m). Metrics include measured discharge ($m^3.s^{-1}$), transect length (m), max depth (m), cross-sectional area (m^2), downstream cross-sectional velocity (U, $m.s^{-1}$), the modified vertical circulation metric (M_3, s^{-1}), the modified horizontal circulation metric (M_4, s^{-1}), Reynolds number and Froude number.

	February 2015 (+0 m)			**September 2014 (+0.3 m)**			**November 2014 (+0.5 m)**		
Means	**Lower**	**Mid**	**Upper**	**Lower**	**Mid**	**Upper**	**Lower**	**Mid**	**Upper**
Discharge ($m^3.s^{-1}$)	75.28 ± 2.79 (66.01–81.76)	79.08 ± 0.81 (76.23–80.61)	76.26 ± 0.85 (73.09–78.02)	57.14 ± 1.68 (50.56–59.94)	49.73 ± 1.57 (44.09–53.34)	46.44 ± 0.59 (44.73–47.50)	123.01 ± 6.46 (112.92–223.38)	97.65 ± 1.51 (92.42–100.79)	95.98 ± 4.88 (85.49–114.04)
Transect length (m)	161.69 ± 17.29 (120.81–221.48)	139.57 ± 9.96 (107.96–167.66)	157.50 ± 18.30 (109.80–203.73)	163.87 ± 16.28 (121.9–219.03)	141.32 ± 9.87 (110.98–170.64)	154.56 ± 15.61 (109.27–194.9)	163.86 ± 17.78 (119.22–223.38)	139.89 ± 10.69 (105.20–169.55)	153.39 ± 15.51 (108.84–194.77)
Max depth (m)	6.89 ± 0.51 (5.63–8.16)	6.60 ± 0.83 (4.43–8.95)	3.81 ± 0.50 (2.37–4.88)	7.57 ± 0.56 (6.01–8.70)	7.05 ± 0.92 (4.68–9.68)	4.26 ± 0.53 (2.40–5.43)	7.24 ± 0.49 (6.06–8.47)	7.07 ± 0.84 (4.92–9.30)	4.37 ± 0.52 (2.64–5.56)
Area (m^2)	826.41 ± 21.48 (752.71–874.42)	643.11 ± 15.84 (583.90–670.41)	399.57 ± 28.65 (301.95–477.13)	867.74 ± 33.30 (738.62–912.79)	682.56 ± 13.94 (633.22–705.81)	426.04 ± 24.70 (362.08–497.04)	906.74 ± 32.57 (780.07–950.67)	702.30 ± 22.03 (615.62–731.11)	454.54 ± 25.61 (395.03–519.90)
U ($m.s^{-1}$)	0.101 ± 0.004 (0.087–0.110)	0.132 ± 0.005 (0.124–0.153)	0.217 ± 0.018 (0.170–0.277)	0.069 ± 0.003 (0.060–0.082)	0.080 ± 0.003 (0.069–0.087)	0.117 ± 0.007 (0.103–0.140)	0.139 ± 0.008 (0.120–0.165)	0.151 ± 0.007 (0.136–0.176)	0.221 ± 0.009 (0.191–0.245)
M_3 (s^{-1})	0.179 ± 0.015 (0.127–0.217)	0.166 ± 0.015 (0.132–0.207)	0.104 ± 0.017 (0.061–0.147)	0.175 ± 0.007 (0.153–0.191)	0.131 ± 0.021 (0.055–0.161)	0.081 ± 0.017 (0.047–0.143)	0.191 ± 0.003 (0.182–0.200)	0.164 ± 0.009 (0.146–0.195)	0.118 ± 0.022 (0.057–0.179)
M_4 (s^{-1})	0.082 ± 0.010 (0.043–0.096)	0.073 ± 0.008 (0.049–0.088)	0.037 ± 0.006 (0.021–0.052)	0.100 ± 0.009 (0.068–0.117)	0.086 ± 0.017 (0.034–0.124)	0.034 ± 0.008 (0.017–0.059)	0.087 ± 0.005 (0.069–0.096)	0.076 ± 0.010 (0.043–0.105)	0.044 ± 0.007 (0.025–0.058)
Reynolds number	53344 ± 4970 (38789–66028)	62269 ± 5569 (49347–82807)	56316 ± 6030 (43019–76140)	38056 ± 4028 (27008–49575)	39193 ± 2926 (32345–49275)	33209 ± 3150 (25994–43177)	80047 ± 9681 (54004–108137)	78048 ± 7331 (58667–102941)	68014 ± 7590 (49600–87610)
Froude number	0.014 ± 0.001 (0.011–0.017)	0.020 ± 0.001 (0.018–0.021)	0.045 ± 0.008 (0.031–0.071)	0.010 ± 0.000 (0.008–0.011)	0.012 ± 0.001 (0.010–0.014)	0.023 ± 0.003 (0.018–0.033)	0.019 ± 0.001 (0.017–0.021)	0.021 ± 0.000 (0.021–0.023)	0.041 ± 0.004 (0.033–0.055)

3.3. Reach-scale hydraulic complexity

In the Lock 3–4 weir pool, mean velocity, *Re* and *Fr* were significantly different between sampling events and reaches, with no interaction (Figure 5 and Table 5). Pairwise comparisons revealed mean velocity, *Re* and *Fr* were significantly less during low discharge in September 2014 than during higher discharge in both November 2014 and February 2015, when these metrics were comparable. Mean velocity and *Fr* in each reach were also significantly different, with substantial declines from the upper reach to the middle reach, and a moderate decline between the middle and lower reach. *Re* was significantly greater in the upper reach than in both the middle and lower reaches. The circulation metrics exhibited a different pattern with no significant difference in M_3 between sampling events or reaches, but M_4 was significantly different between reaches, with greater circulation in the middle and lower reach, compared with the upper reach.

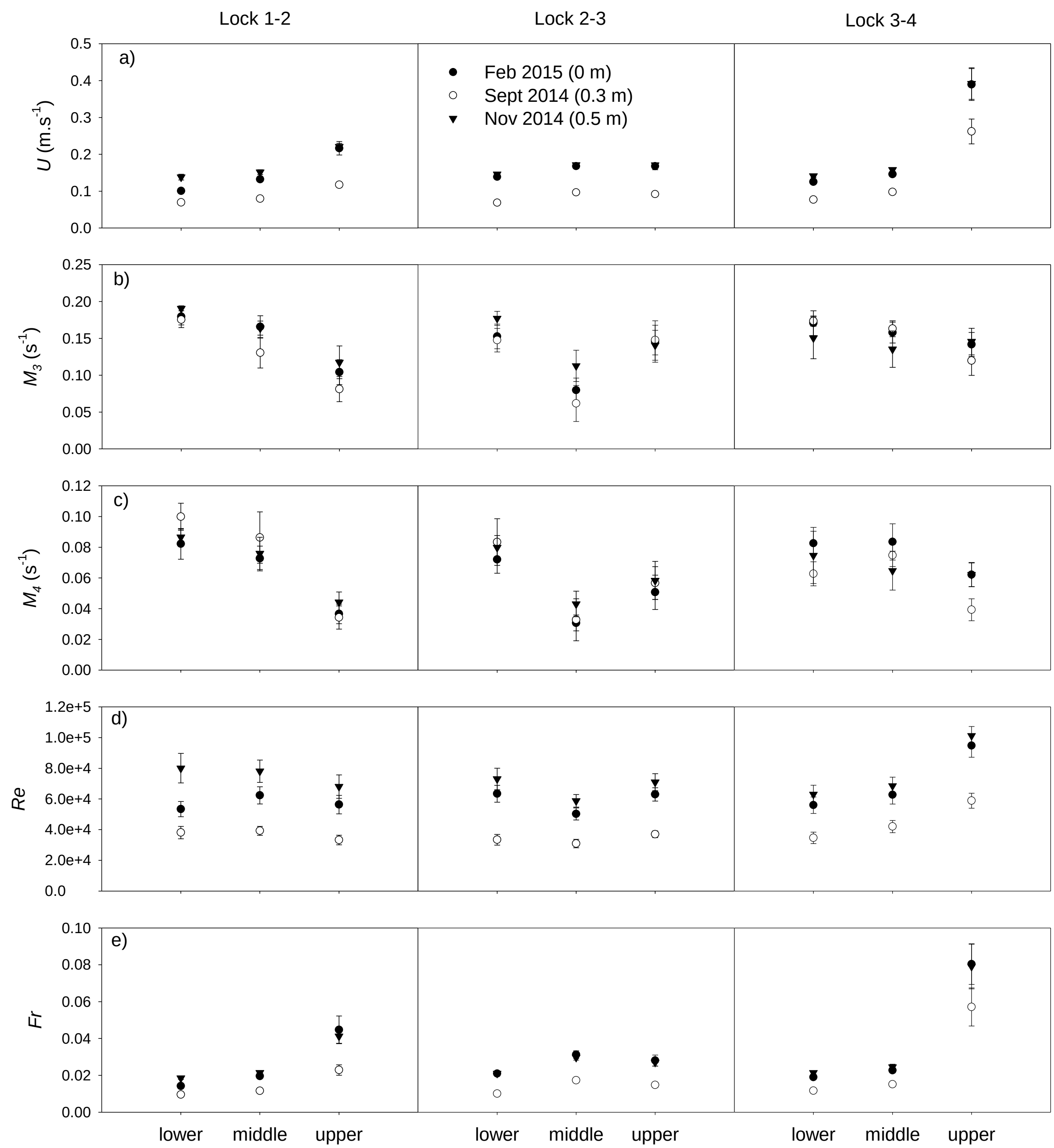

Figure 5. Mean ± SE values of a) downstream cross-sectional velocity (*U,* m.s^{-1}), b) the modified vertical circulation metric (M_3, s^{-1}), c) the modified horizontal circulation metric (M_4, s^{-1}), d) Reynolds number (*Re*) and e) Froude number (*Fr*) in the lower, middle and upper reaches of the Lock 1–2 (left column), Lock 2–3 (middle column) and Lock 3–4 (right column) weir pools.

Table 5. Summary of two-way univariate PERMANOVA comparing downstream cross-sectional velocity (*U,* $m.s^{-1}$), the modified vertical circulation metric (M_3, s^{-1}), the modified horizontal circulation metric (M_4, s^{-1}), Reynolds number (*Re*) and Froude number (*Fr*) between sampling events (February 2015 (+0 m), September 2014 (+0.3 m) and November 2014 (+0.5 m)) and reaches (upper, middle, lower) in the Lock 3–4 weir pool. When significant differences occurred, pairwise comparisons were used to determine the groups that drove this difference. α = 0.05 for all analyses. Significant *p*-values indicated in bold.

Factor	df	Pseudo-F	*P*	Pairwise comparison
U				
Event	2, 44	11.61	**0.002**	(Feb 15 = Nov 14) > Sept 14
Reach	2, 44	90.63	**<0.001**	Upper > middle > lower
Event x reach	4, 44	1.10	0.368	-
M_3				
Event	2, 44	0.37	0.694	-
Reach	2, 44	1.90	0.171	-
Event x reach	4, 44	0.65	0.605	-
M_4				
Event	2, 44	2.03	0.155	-
Reach	2, 44	3.42	**0.049**	(Middle = lower) > upper
Event x reach	4, 44	0.65	0.624	-
Re				
Event	2, 44	28.66	**<0.001**	(Feb 15 = Nov 14) > Sept 14
Reach	2, 44	31.17	**<0.001**	Upper > (middle = lower)
Event x reach	4, 44	0.82	0.53	-
Fr				
Event	2, 44	4.13	**0.026**	(Feb 15 = Nov 14) > Sept 14
Reach	2, 44	66.57	**<0.001**	Upper > middle > lower
Event x reach	4, 44	0.55	0.678	-

Mean velocity, *Re* and *Fr* were also significantly different between sampling events and reaches in the Lock 2–3 weir pool, with no interaction (Figure 5 and Table 6). Pairwise comparisons revealed mean velocities, *Re* and *Fr* were significantly less during the +0.3 m raising in September 2014, when discharge was lowest, than during higher discharge in both November 2014 and February 2015. There was no significant difference in mean velocity, *Re* and *Fr* between sampling during the +0.5 m raising in November 2014 and +0 m in February 2015. M_3 and M_4 did not differ between sampling events, but were significantly different between reaches, with typically greater levels of circulation in the upper and lower reaches, relative to the middle reach.

Table 6. Summary of two-way univariate PERMANOVA comparing downstream cross-sectional velocity (*U,* m.s^{-1}), the modified vertical circulation metric (M_3, s^{-1}), the modified horizontal circulation metric (M_4, s^{-1}), Reynolds number and Froude number between sampling events (February 2015 (+0 m), September 2014 (+0.3 m) and November 2014 (+0.5 m)) and reaches (upper, middle, lower) in the Lock 2–3 weir pool. When significant differences occurred, pairwise comparisons were used to determine the groups that drove this difference. α = 0.05 for all analyses. Significant *p*-values indicated in bold.

Factor	df	Pseudo-F	*P*	Pairwise comparison
U				
Event	2, 44	206.18	**<0.001**	(Feb 15 = Nov 14) > Sept 14
Reach	2, 44	25.91	**<0.001**	(Upper = middle) > lower
Event x reach	4, 44	0.12	0.977	-
M_3				
Event	2, 44	1.21	0.346	-
Reach	2, 44	11.80	**<0.001**	(Upper = lower) > middle
Event x reach	4, 44	0.57	0.678	-
M_4				
Event	2, 44	0.59	0.584	-
Reach	2, 44	11.90	**<0.001**	Lower > upper > middle
Event x reach	4, 44	0.11	0.98	-
Re				
Event	2, 44	44.66	**<0.001**	(Feb 15 = Nov 14) > Sept 14
Reach	2, 44	4.96	**0.012**	(Upper = lower) > middle
Event x reach	4, 44	0.52	0.724	-
Fr				
Event	2, 44	55.65	**<0.001**	(Feb 15 = Nov 14) > Sept 14
Reach	2, 44	21.77	**<0.001**	(Upper = middle) > lower
Event x reach	4, 44	0.24	0.941	-

In the Lock 1–2 weir pool, mean velocity differed significantly between sampling events and reaches, and there was a significant interaction, indicating changes in velocity between sampling events was not consistent across reaches (Figure 5 and Table 7). Pairwise comparisons revealed that mean velocities in both the upper and middle reaches were similar between November 2014 (+0.5 m) and February 2015 (+0 m), but significantly lower in September 2014 (+0.3 m). Alternatively, velocities in the lower reach were significantly different between all sampling events and decreased in magnitude in the following order November 2014

> February 2015 > September 2014. *Re* differed between events, but not between reaches, and was greatest in November 2014, followed by February 2015 and then September 2014. *Fr* varied between sampling events and reaches in a similar pattern to Lock 3–4, with similar *Fr* in November 2014 and February 2015, and lower *Fr* in September 2014. *Fr* also decreased in a downstream direction from upper to middle to lower reaches. As with both other weir pools, M_3 and M_4 did not differ between sampling events, but differed between reaches, with typically greater circulation in the lower and middle reaches than the upper reach.

Table 7. Summary of two-way univariate PERMANOVA comparing downstream cross-sectional velocity (*U,* m.s^{-1}), the modified vertical circulation metric (M_3, s^{-1}), the modified horizontal circulation metric (M_4, s^{-1}), Reynolds number and Froude number between sampling events (February 2015 (+0 m), September 2014 (+0.3 m) and November 2014 (+0.5 m)) and reaches (upper, middle, lower) in the Lock 1–2 weir pool. When significant differences occurred, pairwise comparisons were used to determine the groups that drove this difference. α = 0.05 for all analyses. Significant *p*-values indicated in bold.

Factor	df	Pseudo-F	*P*	Pairwise comparison
U				
Event	2, 44	77.10	**<0.001**	-
Reach	2, 44	79.67	**<0.001**	-
Event x reach	4, 44	4.41	**0.006**	Upper: (Feb 15 = Nov 14) > Sept 14
				Middle: (Feb 15 = Nov 14) > Sept 14
				Lower: Nov 14 > Feb 15 > Sept 14
M_3				
Event	2, 44	2.78	0.078	-
Reach	2, 44	21.71	**<0.001**	Lower > middle > upper
Event x reach	4, 44	0.32	0.869	-
M_4				
Event	2, 44	0.78	0.473	-
Reach	2, 44	24.42	**<0.001**	(Lower = middle) > upper
Event x reach	4, 44	0.52	0.731	-
Re				
Event	2, 44	30.27	**<0.001**	Nov 14 > Feb 15 > Sept 14
Reach	2, 44	1.12	0.330	-
Event x reach	4, 44	0.42	0.801	-
Fr				
Event	2, 44	15.63	**<0.001**	(Feb 15 = Nov 14) > Sept 14
Reach	2, 44	46.73	**<0.001**	Upper > middle > lower
Event x reach	4, 44	2.29	0.079	-

Patterns of variability in hydraulic metrics between sampling events appeared consistent between weir pools, despite raising occurring in the Lock 1–2 and Lock 2–3 weir pools. In particular, mean velocity, *Re* and *Fr* did not differ between November 2014 and February 2014 in the Lock 3–4 weir pool, and the same result was typical of the Lock 1–2 and Lock 2–3 weir pools, despite raising of +0.5 m during November 2014. Whilst we cannot quantitatively compare velocities between the different weir pools, due to their underlying geomorphological differences, Figure 6 demonstrates the change in mean velocity in each weir pool reach, between sampling events, as *x* deviations from their collective mean (e.g. the mean of all cross-sectional velocities from a weir pool reach across all sampling events). With the exception of the lower reaches in February 2015 (Figure 6c), there was no difference in the relative change in mean velocity between sampling events at the upper, middle and lower reaches between weir pools (Figure 6a–c).

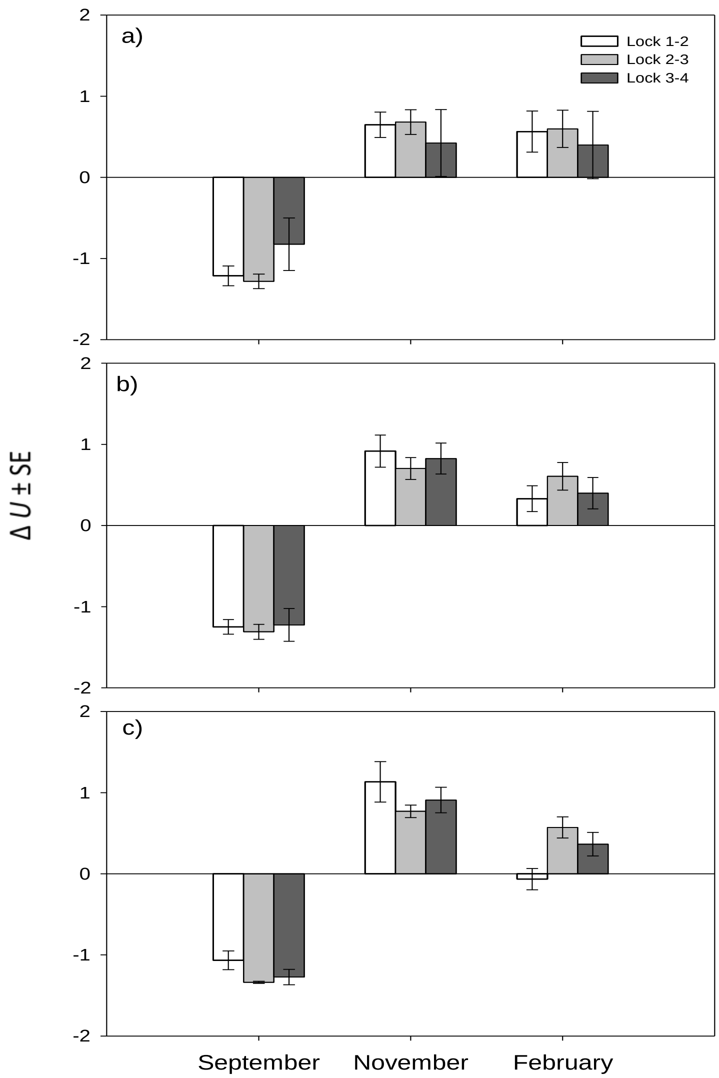

Figure 6. Change in mean downstream velocity (*U,* m.s^{-1}) in the a) upper, b) middle and c) lower reaches of the Lock 1–2, Lock 2–3 and Lock 3–4 weir pools in September 2014, November 2014 and February 2015, plotted as the number of standard deviations away from their common average (±SE).

3.4. Within site hydraulic complexity

The above analyses are suitable for determining reach-scale and weir pool-scale variability in hydraulic conditions, but they are not suitable for determining site-scale variability in velocities between sampling events. Figure 7 presents examples of cross-sectional velocity profiles for sites in the upper reach of the Lock 3–4 weir pool in September 2014 (3970 ML.day^{-1}) and February 2015 (~7850 ML.day^{-1}), and the presence of 'patches' of varying velocity within individual cross-sections across sampling events. In this section we investigate how the frequency of occurrence of patches of different velocities changed within sites between sampling events.

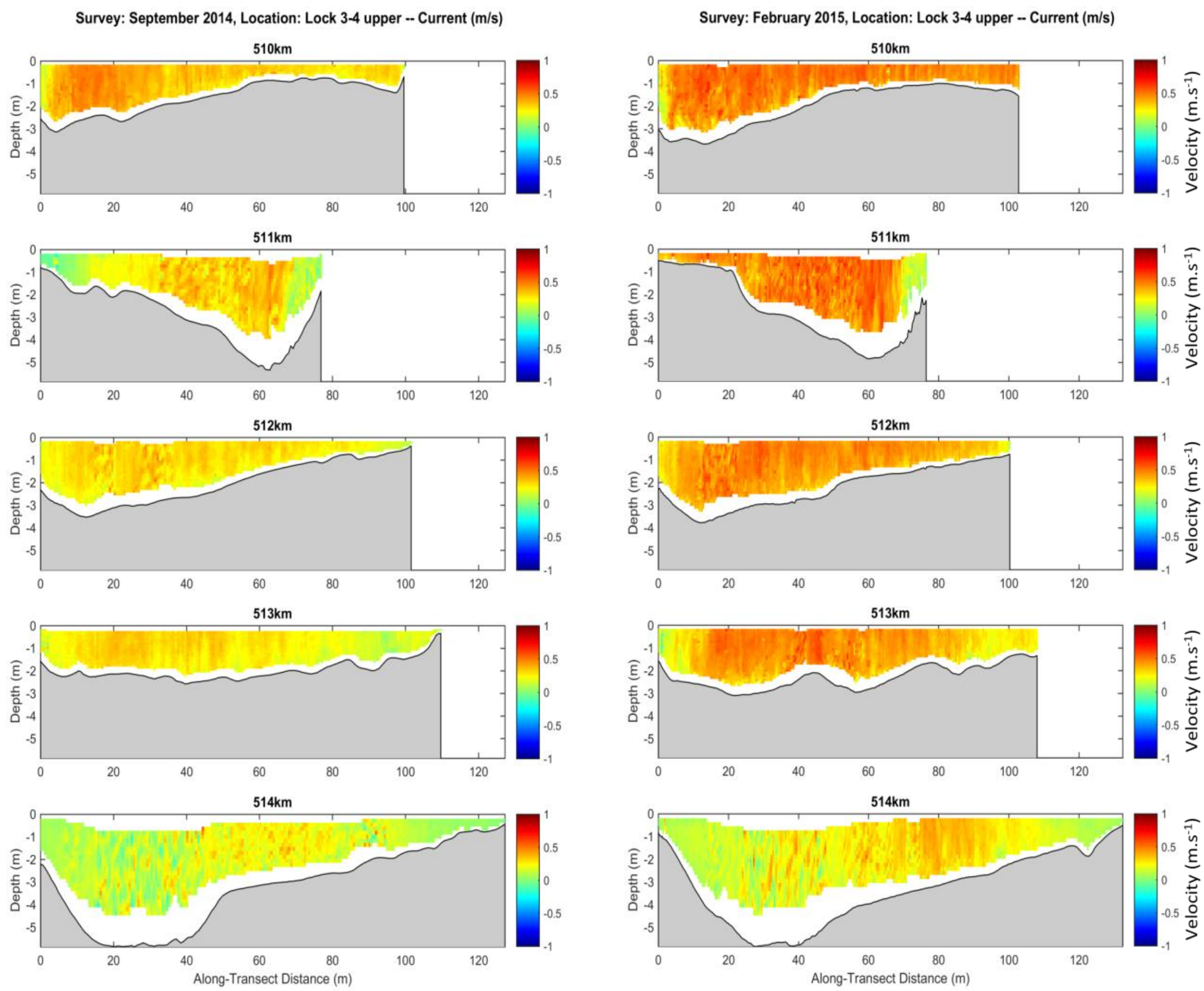

Figure 7. Cross-sectional velocity profiles generated from ADCP transects undertaken at five sites in the upper reach of the Lock 3–4 weir pool in September 2014 (left column; discharge 3970 ML.day^{-1}) and February 2015 (right column; discharge ~7850 ML.day^{-1}).

Velocities of different 'cells' within individual cross-sections varied between sampling events as detailed in Figure 8, which presents the median and 10th, 25th, 75th and 90th percentile velocities for all sites, reaches, weir pools and sampling events. The frequency distribution of velocities from each site were compared between February 2015 (approximately +0 m in all weir pools) and November 2014 (+0.5 m in Lock 1–2 and Lock 2–3, and +0 m in Lock 3–4) using the Kolmogorov-Smirnov 'goodness of fit test'. This test compares the 'shape' of a data distribution rather than testing for differences in the mean. All transects, with the exception of those at 377 (Lock 2–3 lower) and 420 km MTD (Lock 2–3 upper), were significantly different ($\alpha = 0.05$) (Table 8).

In the Lock 3–4 weir pool, 7 of the 15 sites exhibited greater 25th to 75th percentile velocity ranges during slightly elevated discharge in November 2014 (8231–9266 ML.day^{-1}), relative to February 2015 (6500–7889 ML.day^{-1}) (Table 8). In the Lock 2–3 and Lock 1–2 weir pools, 9 of 15 sites and 12 of 15 sites, respectively, exhibited greater 25th to 75th percentile velocity ranges in November 2014 during +0.5 m raising, relative to February 2015 at approximately +0 m. As such, despite raising, there was greater evidence of increased velocity ranges with slightly elevated discharge in November 2014, relative to February 2015, in the Lock 1–2 and Lock 2–3 weir pools than in the 'unraised' Lock 3–4 weir pool.

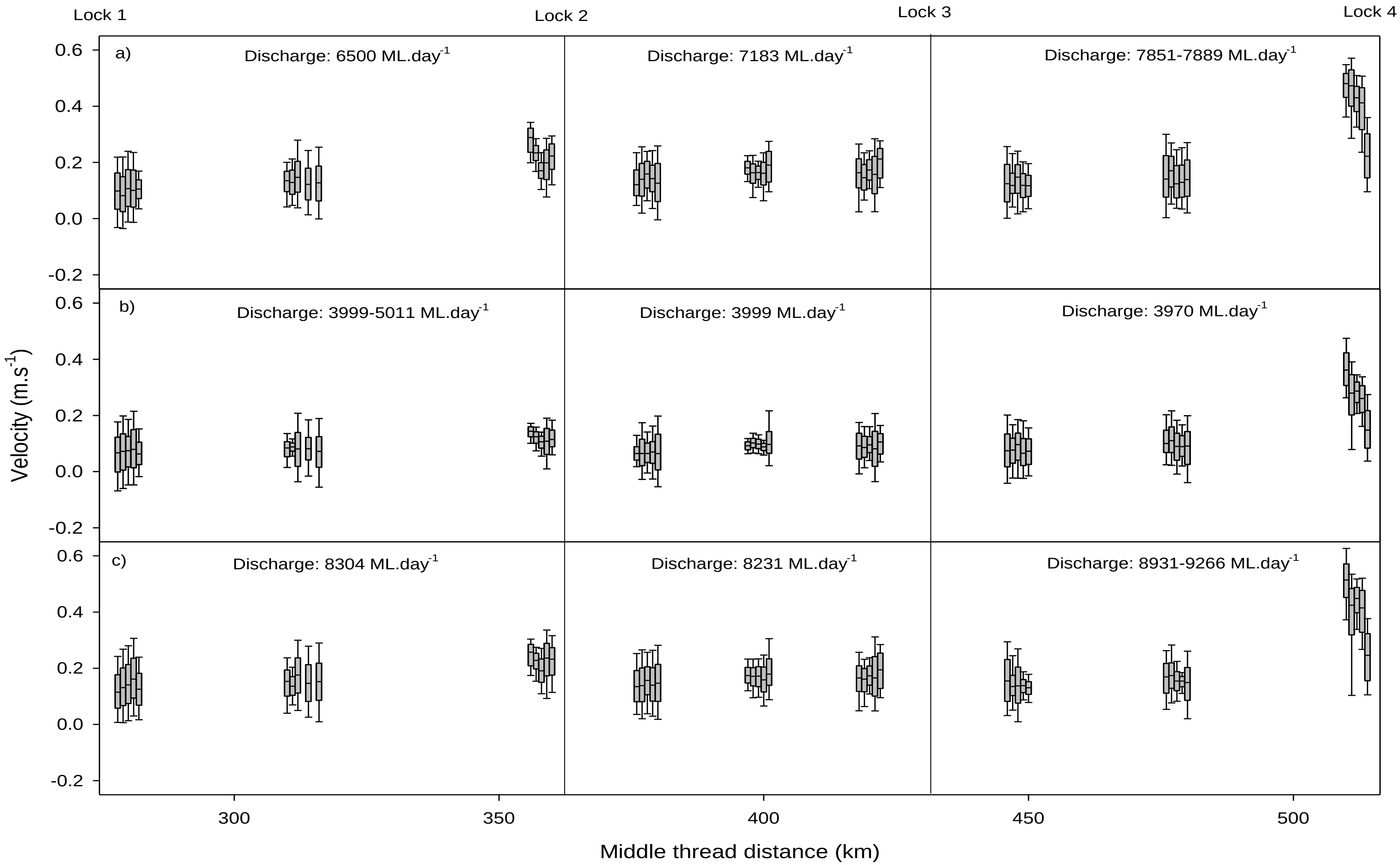

Figure 8. Box plots presenting median velocity, 25th and 75th percentiles (enclosed box), and 10th and 90th percentiles ('whiskers') for each cross-sectional velocity profile undertaken in the Lock 3–4, Lock 2–3 and lock 1–2 weir pools in a) February 2015 (+0 m), b) September 2014 (+0.3 m) and c) November 2014 (+0.5 m). Velocity profile location is expressed as middle thread distance (km). Discharge from the upstream weir is indicated for each weir pool during each sampling event.

Table 8. 25th and 75th percentile downstream velocity ranges ($m.s^{-1}$) for all cross-sectional velocity profiles measured in February 2015 (+0 m), September 2014 (+0.3 m) and November 2014 (+0.5 m), and results of Kolmogorov-Smirnov 'goodness of fit' comparison (*D* statistic and *p*-value, α = 0.05. Significant *p*-values indicated in bold) between February 2015 and November 2014 data.

	February 2015 (+0 m)	**September 2014 (+0.3 m)**	**November 2014 (+0.5 m)**	**Feb v Nov K-S**	
MTD (km)				***D***	***p***
278	0.033–0.162	-0.001–0.123	0.058–0.177	0.09	**<0.001**
279	0.025–0.149	0.005–0.135	0.067–0.201	0.20	**<0.001**
280	0.043–0.174	0.017–0.125	0.074–0.213	0.13	**<0.001**
281	0.041–0.173	0.013–0.149	0.094–0.236	0.23	**<0.001**
282	0.071–0.138	0.025–0.105	0.069–0.182	0.21	**<0.001**
310	0.096–0.169	0.053–0.107	0.101–0.194	0.15	**<0.001**
311	0.087–0.173	0.073–0.102	0.104–0.170	0.10	**<0.001**
312	0.094–0.204	0.019–0.140	0.112–0.237	0.15	**<0.001**
314	0.067–0.179	0.041–0.122	0.082–0.213	0.14	**<0.001**
316	0.063–0.187	0.015–0.125	0.086–0.218	0.12	**<0.001**
356	0.236–0.322	0.124–0.160	0.209–0.285	0.30	**<0.001**
357	0.207–0.260	0.102–0.142	0.198–0.253	0.07	**<0.001**
358	0.143–0.199	0.084–0.126	0.150–0.233	0.20	**<0.001**
359	0.139–0.245	0.061–0.154	0.173–0.289	0.22	**<0.001**
360	0.175–0.266	0.089–0.148	0.175–0.273	0.06	**<0.001**
376	0.082–0.173	0.041–0.089	0.081–0.192	0.09	**<0.001**
377	0.080–0.197	0.021–0.116	0.081–0.201	0.02	0.316 ns
378	0.109–0.204	0.033–0.102	0.106–0.205	0.05	**<0.001**
379	0.096–0.190	0.029–0.107	0.083–0.202	0.05	**<0.001**
380	0.061–0.197	0.006–0.134	0.082–0.214	0.09	**<0.001**
397	0.158–0.204	0.076–0.102	0.148–0.203	0.09	**<0.001**
398	0.126–0.195	0.085–0.119	0.137–0.202	0.08	**<0.001**
399	0.140–0.187	0.082–0.116	0.134–0.206	0.16	**<0.001**
400	0.120–0.201	0.075–0.101	0.115–0.204	0.04	**<0.001**
401	0.131–0.240	0.065–0.143	0.139–0.234	0.08	**<0.001**
418	0.110–0.213	0.045–0.137	0.118–0.209	0.03	**0.020**
419	0.101–0.193	0.051–0.126	0.116–0.199	0.10	**<0.001**
420	0.137–0.210	0.068–0.125	0.140–0.208	0.02	0.472 ns
421	0.089–0.221	0.019–0.143	0.101–0.242	0.06	**<0.001**
422	0.145–0.250	0.063–0.135	0.128–0.254	0.10	**<0.001**
446	0.060–0.193	0.017–0.134	0.082–0.231	0.12	**<0.001**
447	0.090–0.162	0.030–0.119	0.103–0.175	0.16	**<0.001**
448	0.091–0.192	0.041–0.137	0.076–0.204	0.07	**<0.001**
449	0.075–0.160	0.021–0.118	0.113–0.160	0.22	**<0.001**
450	0.079–0.154	0.026–0.117	0.107–0.152	0.18	**<0.001**
476	0.077–0.224	0.069–0.148	0.111–0.217	0.14	**<0.001**
477	0.113–0.222	0.068–0.159	0.129–0.219	0.06	**<0.001**
478	0.074–0.189	0.040–0.137	0.120–0.188	0.23	**<0.001**
479	0.076–0.191	0.054–0.128	0.134–0.171	0.32	**<0.001**
480	0.079–0.208	0.025–0.143	0.086–0.203	0.05	**<0.001**
510	0.432–0.516	0.307–0.423	0.452–0.571	0.25	**<0.001**
511	0.400–0.530	0.202–0.346	0.319–0.484	0.21	**<0.001**
512	0.381–0.471	0.246–0.319	0.398–0.488	0.13	**<0.001**
513	0.317–0.466	0.211–0.306	0.328–0.477	0.06	**<0.001**
514	0.145–0.302	0.084–0.217	0.155–0.323	0.07	**<0.001**

4. DISCUSSION

Hydraulic conditions (i.e. depth, flow velocity and turbulence) have a great influence on ecological patterns and processes in riverine ecosystems. The use of weir pool manipulations (i.e. water level raising) to achieve environmental outcomes in the lower River Murray is becoming increasingly common; nonetheless, there remains a need to quantify the impact/benefit of weir pool manipulations on the within-channel hydraulic environment. The current study aimed to determine the influence of a +0.5 m water level raising in the Lock 1–2 and Lock 2–3 weir pools in spring 2014, by generating cross-sectional velocity profiles and calculating a range of hydraulic metrics, and comparing spatio-temporal variability in these parameters with the Lock 3–4 weir pool, in which no water level manipulation occurred. Patterns of temporal variability in hydraulic metrics were consistent across weir pools, raised and unraised, with little significant difference between periods of similar discharge in November 2014 (8231–9266 ML.day^{-1}) and February 2015 (6500–7889 ML.day^{-1}). These results suggest that weir pool raising in the Lock 1–2 and Lock 2–3 weir pools had negligible impact on within channel hydraulics at the discharges investigated. Additionally, the current study has documented important spatial differences in the physical nature and hydraulic environment between, and within weir pools. The results of the study are discussed in the context of their implications for future weir pool manipulations.

Mean downstream velocity, as well as metrics that indicate the level of turbulence (*Reynolds number*) and ‘rapidly’ flowing water (*Froude number*) in cross-sectional velocity profiles were similar in November 2014 and February 2015, but significantly lower in September 2014, in all weir pools. Furthermore, the magnitude of temporal change in mean downstream velocity was similar between the raised and unraised weir pools. At a site-scale, velocity distributions were significantly different between November 2014 and February 2015, but consistently exhibited greater ranges during slightly greater discharge across all weir pools in November 2014. In contrast, the circulation metrics indicated no significant change in the frequency and strength of eddies in the vertical and horizontal planes between sampling events, suggesting the metrics may be insensitive to variability in discharge of the magnitude experienced in the current study.

Substantial spatial variability in hydraulics was observed both within and between the three weir pools, and these differences were consistent across sampling events. Typically, wetted width, depth and cross-sectional area increased in a downstream direction, with proximity to the downstream weir. In association, mean velocities and turbulence decreased in a downstream direction, with upper reaches exhibiting the greatest levels of hydraulic complexity. This ‘downstream weir effect’ has been measured previously in the Lock 1–2 and Lock 5–6 weir pools at flows of up to 33,000 $ML.day^{-1}$, suggesting the influence of downstream weirs on hydraulic complexity is likely only mitigated once weirs are inundated and stop logs, and navigation passes, are removed (i.e. at discharge >50,000 $ML.day^{-1}$) (Bice *et al.* 2013).

Differences in the length and sinuosity of the weir pools investigated in the current study results in the level of impact of the ‘downstream weir effect’ differing between weir pools, which drives the observed differences in hydraulic conditions. The Lock 3–4 and Lock 1–2 weir pools are both ≥85 km in length, whilst the Lock 2–3 weir pool is ~69 km in length. Additionally, the upper reach of the Lock 3–4 weir pool is narrower and more sinuous than the other two weir pools. Relatively low velocities throughout the Lock 2–3 weir pool, including in the upper reach, suggests the ‘downstream weir effect’ extends upstream through the entire length of the weir pool. Alternatively, the presence of relatively high velocities in the upper reach of the Lock 3–4 weir pool, across the range of discharge experienced in this study, suggests that the ‘downstream weir effect’ ceases some distance below Lock 4 and this reach represents a comparatively ‘free-flowing’ reach of river. The Lock 1–2 weir pool, whilst of similar length to Lock 3–4, exhibited velocities in the upper reach lower than those seen in the corresponding reach of Lock 3–4, likely due to its greater width and lower sinuosity. However, the upper reach of Lock 1–2 exhibits greater hydraulic complexity than the upper reach of Lock 2–3.

Substantial hydraulic variation between weir pools has important implications for future weir pool raising events. Firstly, the upper reach of the Lock 3–4 weir pool appears to represent a unique lotic reach in the otherwise lentic and hydraulically homogenous lower River Murray. Consequently, raising events in this weir pool should be carefully considered given potential risks to this now rare habitat. Secondly, the hydraulic nature of other weir pools that may be the subject of weir pool raising needs to be characterised to determine the potential impacts/benefits associated with weir pool manipulations.

That weir pool raisings had little impact on within-channel hydraulics in 2014 has implications for the discharges at which future weir pool manipulations are undertaken. The weirs on the main channel of the lower River Murray, significantly compromise a historically lotic ecosystem and substantial increases in discharge are required to restore hydraulic complexity when the weir pools are at FSL (Bice *et al.* 2013). The current study was undertaken at discharges (4000–

9000 $ML.day^{-1}$) similar to the range of 'entitlement flows' (4000–7000 $ML.day^{-1}$) in the lower River Murray and it appears, that under such discharge, the existing impact of the weirs on hydraulic complexity overshadows any influence of a further +0.5 m raising of water levels. Nevertheless, raising events may reduce hydraulic complexity, relative to +0 m FSL, if undertaken at higher discharges, when the existing impact of the weirs is reduced.

Discharges at which ecologically relevant hydraulic complexity is restored are uncertain, partly due to limited understanding of explicit links between hydraulics and ecological processes and patterns. Nonetheless, hypotheses can be developed from biological data collected in association with variable discharge, including fish spawning and larval drift. Golden perch (*Macquaria ambigua ambigua*) and silver perch (*Bidyanus bidyanus*) are the only fish species in the lower Murray known to be stimulated to spawn by elevated discharge, and the eggs and larvae of both species undergo an obligate drifting stage (Mallen-Cooper and Stuart 2003, Tonkin *et al.* 2007, Zampatti and Leigh 2013). Fish are likely to perceive and thus respond to changes in discharge through changes in hydraulics, whilst specific hydraulics (e.g. velocity and turbulence) are likely required to facilitate the suspension of larvae and downstream drift (Dudley and Platania 2007). Evidence of spawning of golden perch and silver perch, and indeed recruitment to young-of-year, is typically only observed in the lower River Murray following discharges >15,000 $ML.day^{-1}$ that coincide with temperature thresholds (Zampatti and Leigh 2013).

Evidence of spawning and recruitment of golden perch and silver perch in association with within-channel flow events of >15,000 $ML.day^{-1}$ suggests ecologically relevant hydraulic complexity, in regards to flow-cued spawning fish species, may be restored to the lower River Murray at these flows. As such, any potential for impacts to hydraulic complexity and resulting ecological processes, should be considered and evaluated when planning weir pool manipulations at such discharges. Nonetheless, it is likely that the discharge at which ecologically relevant hydraulic complexity is restored will differ between weir pools given the geomorphological differences between weir pools and the inter-weir pool hydraulic variation detected in this study. This is a priority for future research together with investigations of the explicit link between ecological processes (e.g. fish spawning) and hydraulics.

5. CONCLUSION

Raising the water level within the Lock 1–2 and Lock 2–3 weir pools in spring 2014 had little impact on the within-channel hydraulic environment, with consistent patterns of temporal variability in hydraulic metrics between these weir pools and the 'unraised' Lock 3–4 weir pool. Accordingly, future raisings of the Lock 1–2 and Lock 2–3 weir pools at discharges ≤9000 ML.day^{-1} are unlikely to have a significant impact on within-channel hydraulics. Alternatively, raising weir pools at discharges of 10,000–20,000 ML.day^{-1} may present risks to ecologically important hydrodynamics, necessitating rigorous monitoring of any such events to assess impact. Ultimately, the influence of weir pool manipulations on hydraulic complexity and concomitant benefits/impacts to riverine biota, over a range of discharges from entitlement to bank-full, requires further quantification.

The current study demonstrated that there are substantial physical and hydraulic differences between weir pools, and thus, the potential for differences in the impact/benefit of weir pool manipulations. The upper reach of the Lock 3–4 weir pool exhibits considerable hydraulic complexity, representing a rare reach of free-flowing river in the regulated lower River Murray. Raising events in this weir pool may have considerable impact.

Future weir pool manipulations (i.e. raisings and lowerings) will be greatly informed by hypothesis-driven research and monitoring investigating ecological response (e.g. productivity, reproduction, recruitment) to weir pool raisings. Furthermore, the application of weir pool lowerings should be investigated, given the potential to restore lotic habitats and promote hydraulic complexity. Ultimately, a future weir pool manipulation program that is integrated with broader riverine rehabilitation programs (e.g. environmental flow delivery), is planned over a long-term (> 10 years), incorporates both raising and lowering, and considers both potential risks (e.g. loss of hydraulic complexity) and benefits (e.g. recruitment of flood-dependent vegetation) in a spatial and hydrological context (i.e. where and at what discharges manipulations are undertaken) is likely to elicit the greatest ecological benefit.

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