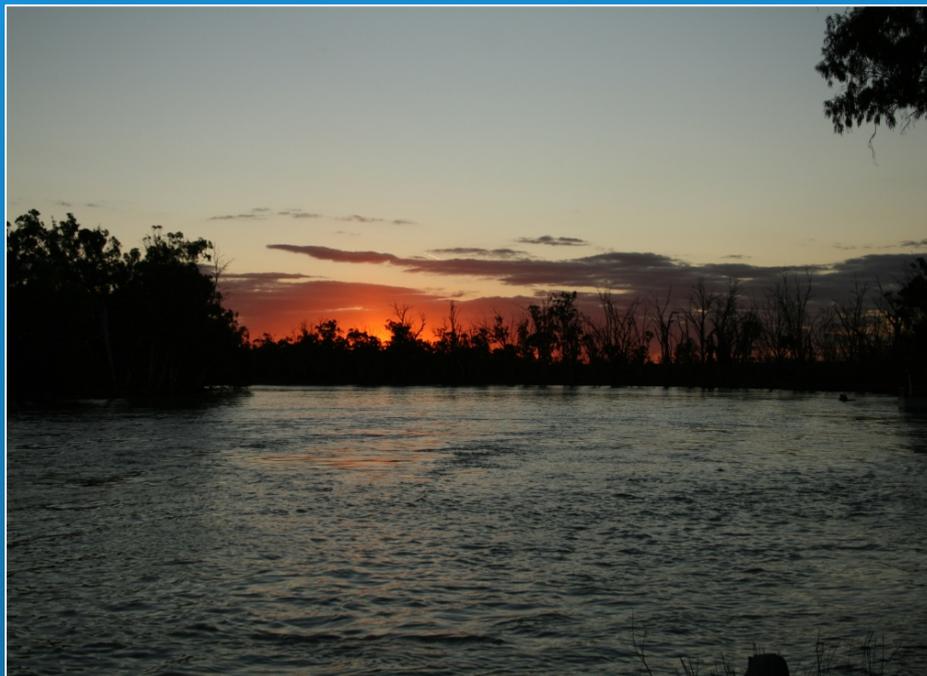


Changes in hydraulic complexity in the lower River Murray main channel in relation to flow variability



C. M. Bice, S. J. Leigh, J. M. Nicol and B. P. Zampatti

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Table of Contents

TABLE OF CONTENTS.....	I
LIST OF FIGURES.....	II
LIST OF TABLES.....	IV
ACKNOWLEDGEMENTS.....	V
EXECUTIVE SUMMARY.....	VI
1 INTRODUCTION.....	1
2 METHODS.....	4
2.1 Survey technique and study site.....	4
2.2 Data analysis.....	6
2.3 Ground-truthing existing hydraulic models.....	7
3 RESULTS.....	9
3.1 Hydrograph.....	9
3.2 Hydraulic complexity.....	10
3.3 Comparison of measured vs modelled average velocity.....	21
4 DISCUSSION.....	25
4.1 Variability in hydraulic complexity under variable flow.....	25
4.2 Ground-truthing existing hydraulic models.....	28
5 CONCLUSION.....	29
6 REFERENCES.....	30

List of Figures

Figure 1. Map of the River Murray main channel within South Australia, depicting the six locks and weirs across the gorge and floodplain geomorphic regions, and the location of the upper, mid and lower weir pool ADCP transects in the Lock 1–2 and Lock 5–6 weir pools.....5

Figure 2. Schematic representation of a river reach and the hydraulic metrics investigated (after Shields and Rigby 2005), including variation in cross transect velocities (U) between transects and the modified circulation metric (M_3), which represents the area averaged frequency and strength of eddies or flow rotation within a cross-section.7

Figure 3. Daily river flow (ML.d⁻¹) at a) Lock 6 (dotted line) and QSA (solid line) and at b) Lock 1 (as a proxy for the Lock 1–2 reach), from November 2011 – April 2012. Red lines represent dates and flows when ADCP transects were conducted.9

Figure 4. Horizontal current velocity and circulation (i.e. M_3 , curl.s⁻¹) profiles generated for the Lock 1–2 weirpool upper location in January (a & b) and March 2012 (c & d). Current velocity plots (a & c) present cross-transect velocities (U) in cells 0.5 m in width x 0.25 m in height. Circulation plots (b & c) present a combination of velocities in the vertical and horizontal planes (i.e. along-transect, W , and vertically, V), transverse to the banks, with vectors representing the direction of rotation.11

Figure 5. Horizontal current velocity and circulation (i.e. M_3 , curl.s⁻¹) profiles generated for the Lock 1–2 weirpool mid location in January (a & b) and March 2012 (c & d). Current velocity plots (a & c) present cross-transect velocities (U) in cells 0.5 m in length x 0.25 m in height. Circulation plots (b & c) present a combination of velocities in the vertical and horizontal planes (i.e. along-transect, W , and vertically, V), transverse to the banks, with vectors representing the direction of rotation.....12

Figure 6. Horizontal current velocity and circulation (i.e. M_3 , curl.s⁻¹) profiles generated for the Lock 1–2 weirpool lower location in January (a & b) and March 2012 (c & d). Current velocity plots (a & c) present cross-transect velocities (U) in cells 0.5 m in length x 0.25 m in height. Circulation plots (b & c) present a combination of velocities in the vertical and horizontal planes (i.e. along-transect, W , and vertically, V), transverse to the banks, with vectors representing the direction of rotation.13

Figure 7. Mean cross-transect velocity (U , m.s⁻¹) \pm standard deviation at the upper, mid and lower weir pool location transects of a) the Lock 1–2 reach and b) the Lock 5–6 reach in January and March 2012.....14

Figure 8. Velocity-frequency distributions of all cross-transect velocities (cells) measured at the a) upper, b) mid and c) lower weir pool locations in the Lock 1–2 reach (left-hand side) and Lock 5–6 reach (right-hand side).15

Figure 9. Horizontal current velocity and circulation (i.e. M_3 , curl.s⁻¹) profiles generated for the Lock 5–6 weirpool upper location in January (a & b) and March 2012 (c & d). Current velocity plots (a & c) present cross-transect velocities (U) in cells 0.5 m in length x 0.25 m in height.

Circulation plots (b & c) present a combination of velocities in the vertical plane (i.e. along-transect, W , and vertically, V), with vectors representing the direction of rotation.18

Figure 10. Horizontal current velocity and circulation (i.e. M_3 , curl.s^{-1}) profiles generated for the Lock 5–6 weirpool mid location in January (a & b) and March 2012 (c & d). Current velocity plots (a & c) present cross-transect velocities (U) in cells 0.5 m in length x 0.25 m in height. Circulation plots (b & c) present a combination of velocities in the vertical plane (i.e. along-transect, W , and vertically, V), with vectors representing the direction of rotation.19

Figure 11. Horizontal current velocity and circulation (i.e. M_3 , curl.s^{-1}) profiles generated for the Lock 5–6 weirpool lower location in January (a & b) and March 2012 (c & d). Current velocity plots (a & c) present cross-transect velocities (U) in cells 0.5 m in length x 0.25 m in height. Circulation plots (b & c) present a combination of velocities in the vertical plane (i.e. along-transect, W , and vertically, V), with vectors representing the direction of rotation.20

Figure 12. Comparison of mean measured velocities (black symbols) against WaterTech modelled (red symbols; Lock 5–6 upper weir pool only) and DEWNR modelled mean velocities (white symbols) in the upper weir pool (circles), mid weir pool (squares) and lower weir pool (triangles) locations of a) the Lock 5–6 reach and b) the Lock 1–2 reach under various levels of discharge (QSA; ML.day^{-1}). For the Lock 5–6 reach, QSA flow is used for simplicity despite the location of the upper weir pool location, above the Chowilla Creek junction, typically resulting in a lower discharge at this location compared to the mid and lower weir pool locations, which are downstream of the Chowilla Creek junction.....22

Figure 13. Modelled mean water velocities (m.s^{-1}) for the River Murray and Chowilla Anabranh system under flow conditions of QSA 15,000 ML.day^{-1} . The data point that corresponds to the measured transect in the current study is indicated by the red line.23

Figure 14. Example of modelled water velocity outputs from DEWNR modelling at QSA flow of a) 13,000 ML.day^{-1} and b) 24,000 ML.day^{-1} at the Lock 5–6 upper weir pool location.....24

List of Tables

Table 1. Location of upper, middle and lower weir pool ADCP transects in the Lock 1–2 and Lock 5–6 weirpools. Transect location is presented in ‘adopted middle thread distance’ (AMTD), which represents the distance of a middle point in the river at that transect from the Murray Mouth. Specific details of each transect are also presented.5

Table 2. Hydraulic habitat metrics calculated from ADCP generated data from the upper, mid and lower weirpool locations within the Lock 1–2 reach in January and March 2012. Metrics include point discharge ($m^3.s^{-1}$) at each location, the transect length (m), mean depth (m) across the cross-section, total area of the cross-section (m^2), mean cross-transect (upstream to downstream) velocity (U , $m.s^{-1}$), standard deviation in cross-transect velocities ($m.s^{-1}$), mean velocity along or parallel to each transect (V , $m.s^{-1}$), mean velocity in the vertical plane (W , $m.s^{-1}$) and the modified circulation metric (M_3 , s^{-1}).10

Table 3. Hydraulic habitat metrics calculated from ADCP generated data from the upper, mid and lower weirpool locations within the Lock 5–6 reach in January and March 2012. Metric include point discharge ($m^3.s^{-1}$) at each location, transect length (m), mean depth (m) across the cross-section, total area of the cross-section (m^2), mean cross-transect (upstream to downstream) velocity (U , $m.s^{-1}$), standard deviation in mean cross-transect velocity ($m.s^{-1}$), mean velocity along or parallel to each transect (V , $m.s^{-1}$), mean velocity in the vertical plane (W , $m.s^{-1}$) and the modified circulation metric (M_3).....17

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Executive Summary

The delivery of environmental flows in Australia and particularly the Murray-Darling Basin has typically focussed upon temporal variability in flow volume and floodplain inundation and often overlooked within channel processes such as spatio-temporal variability in stream hydraulics (i.e. the 'physical nature' of flow). Hydraulic complexity can be viewed as habitat heterogeneity and has a large influence on aquatic biodiversity. Stream hydraulics can be used to describe the hydrodynamic environments experienced by aquatic organisms. These environments influence the life cycles of fish and other aquatic biota through their effects on the availability of favourable physical habitat, provision of reproductive cues, facilitation of drift and prey capture. An understanding of how hydrodynamics vary with discharge will inform environmental flow delivery in regards to volumes likely to facilitate hydraulic complexity and biotic responses.

The lower River Murray was a lotic system prior to regulation and likely exhibited high levels of spatial hydraulic complexity, even at low flows. The river is now comprised of a series of contiguous weir pools that under predominant low flows are hydraulically uniform. The impact of such a change on native biota is difficult to determine but was likely profound. Hydraulic complexity, however, is reinstated, to a degree when discharge increases and the impact of the weirs is lessened. Nevertheless, there is little quantitative understanding of changes in the hydraulic character of the lower River Murray under different flows.

Initially, the current project aimed to investigate variability in hydraulic complexity between entitlement flow (3000–7000 ML.d⁻¹) and a flow of ~15,000 ML.d⁻¹ as influenced by environmental water delivery. Nonetheless, elevated flows occurred through the study period providing the opportunity to investigate variability in hydraulic complexity at higher flow bands. Subsequently, the project aimed to investigate variability in hydraulic complexity (i.e. mean velocities and variability in velocities and circulation) across three locations (upper weir pool: the vicinity downstream of a weir, mid weir pool: approximately halfway between weirs, and lower weir pool: vicinity upstream of a weir) in two reaches of the lower River Murray (Lock 1–2 weir pool and Lock 5–6 weir pool) at flows of 13,000–16,000 ML.d⁻¹ (which included supplementary flows from the Commonwealth Environmental Water Holder (CEWH)) and 23,000–33,000 ML.d⁻¹. Furthermore, the project aimed to ground-truth existing hydraulic models for the lower River Murray and ultimately, to develop an understanding of the relationship between flow and hydraulic complexity within the lower River Murray main channel to inform future environmental water delivery.

A boat-mounted Acoustic Doppler Current Profiler (ADCP) was used to collect cross-sectional velocity data during flows of 13,000–16,000 ML.d⁻¹ in January 2012 and 23,000–33,000 ML.d⁻¹ in March 2012. Mean cross-sectional velocities varied with weir pool location and discharge. In both reaches, mean velocities decreased in a downstream direction, being greatest in the upper weir pool and least in the lower weir pool. Mean velocities and velocity ranges increased at all locations in both reaches with increased discharge. Changes in within location variability in velocities (i.e. standard deviation and coefficient of variation) were not consistent across sites. Furthermore, the modified circulation metric adopted, which represents a measure of the frequency and strength of eddies (i.e. flow rotation in the vertical plane) within a cross-section per unit area, typically increased with flow.

Mean cross-sectional velocities measured in this study were compared with mean velocities generated with MIKEFLOOD modelling by Water Technology and the Department of Environment, Water and Natural Resources (DEWNR). In general measured and modelled mean velocities were comparable. The models appeared to have the greatest accuracy in the Lock 1–2 weir pool compared to the Lock 5–6 weir pool. Furthermore, the models were most accurate at the lower end of the flows measured (<16,000 ML.d⁻¹) but underestimated measured velocities at flows >23,000 ML.d⁻¹.

Based on the metrics utilised, flows of 23,000–33,000 ML.d⁻¹ produced greater hydraulic complexity in river cross-sections than flows of 13,000–16,000 ML.d⁻¹. As such, environmental flows of >23,000 ML.d⁻¹ may elicit a greater ecological response than flow of 13,000–16,000 ML.d⁻¹, and are thus preferred for future environmental flow delivery. Nonetheless, discharge of 13,000–16,000 ML.d⁻¹ appeared to create substantial hydraulic complexity, but further comparison with hydraulic complexity at lower flows is required.

It has been hypothesised that hydraulic complexity may be important to native fish of the Murray-Darling Basin. Coarse associations of some species (e.g. Murray cod) with particular meso-habitats (e.g. fast-flowing habitats with abundant woody debris) are known but empirical evidence of the association of native fish with particular hydraulic conditions is lacking. Investigating the influence of hydraulics on native fish distribution, life history processes and population dynamics should be a priority for future research. The hydraulic metrics adopted in the current project, together with other biologically relevant metrics, appear useful for such approaches and are suggested for future characterisation of hydraulics in the lower River Murray.

1 Introduction

In riverine ecosystems, hydrological variability is widely accepted as the primary driver of ecosystem structure and function (Sparks et al. 1990, Poff and Allan 1995). As such, contemporary management and flow restoration in regulated rivers typically subscribes to the ‘natural flow paradigm’ (Poff et al. 1997), with the objective of restoring aspects of the natural flow regime. The approach assumes that mimicking ecologically important aspects of the natural flow regime, in regards to variability in magnitude, frequency, duration, timing or predictability and rate of change of flow events, will facilitate the maintenance or enhancement of ecological integrity in regulated river systems.

Flow restoration and the delivery of environmental flows in regulated rivers in Australia and particularly the Murray-Darling Basin predominantly focus upon temporal variability in flow volumes and floodplain inundation. Hydrological variability, however, results in spatio-temporal variability in the physical characteristics of flow (i.e. depth, velocity and turbulence) within river channels, and the importance of such variability is an often overlooked objective of flow restoration. The hydraulic conditions experienced within a river are a function of discharge and physical features such as channel morphology, sediment type, woody debris and man-made structures (e.g. bridges), and hydraulic variability may directly influence river geomorphology and the diversity, distribution and abundance of aquatic biota (Statzner and Higler 1986, de Nooij et al. 2006).

Spatial complexity in flow hydraulics provides habitat heterogeneity across micro-, meso- and macro-scales. Several studies, both internationally and in Australia, have indicated the preference of different fish species, including salmonids, cyprinids, gobiids and galaxiids, for ‘patches’ (i.e. micro-habitats) and ‘reaches’ (i.e. meso-habitats) with particular hydraulic conditions (Freeman and Grossman 1993, Henderson and Johnston 2010, Kilsby and Walker 2012). Thus, it stands to reason that a high diversity of hydraulic patches may result in high levels of biological diversity (de Nooij et al. 2006, Dyer and Thoms 2006). Additionally, the presence of microhabitats with particular hydraulic characteristics have been shown to influence the foraging efficiency of fish, including juveniles of some species (e.g. Atlantic salmon), and is subsequently integral to fish retention in streams and potentially recruitment (Nislow et al. 1999). Furthermore, larval drift is an important process in the life history of many riverine fish species (e.g. golden perch) and the provision of particular hydraulic conditions is important in facilitating the downstream drift and dispersal of larval and juvenile fish (Brown and Armstrong 1985).

Prior to regulation, the lower River Murray was a lotic system and likely exhibited heterogeneous hydraulic conditions over a range of spatial scales, even at low flows (Mallen-Cooper et al. 2011). Following the construction of 10 low-level weirs in the 1920s and 1930s, over 800 km of river was transformed into a series of contiguous, predominantly lentic weir pools (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). Under low flow conditions (<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 regulated flows, which predominate, the lower River Murray is now hydraulically homogenous compared to the unregulated river.

Investigations of explicit associations of fishes of the Murray-Darling Basin with particular hydraulic conditions are rare (but see Kilsby and Walker 2012) compared to the northern hemisphere (e.g. Moir and Pasternack 2008, Ayllon et al. 2009, Kozarek et al. 2010). In the lower River Murray, several permanently lotic and hydraulically diverse habitats remain in off-channel anabranch habitats (e.g. the Chowilla Anabranch system) and such habitats harbour greater abundances of Murray cod (*Maccullochella peelii*), and other native fish species, than adjacent lentic habitats, implying an association with hydraulically diverse lotic habitats (Zampatti et al. 2011). Furthermore, such habitats appear favourable for the recruitment of Murray cod during times of low flow within the main river channel, where recruitment does not appear to be facilitated. Spawning and recruitment in both golden perch (*Macquaria ambigua ambigua*) and silver perch (*Bidyanus bidyanus*) are also potentially associated with hydraulic diversity. Whilst initially thought to spawn and recruit with overbank floods (Lake 1967) recent evidence suggests that small to medium within-channel flow events (e.g. >15,000 ML.d⁻¹) support significant recruitment of golden perch (Mallen-Cooper and Stuart 2003; Zampatti and Leigh 2013). Additionally, all three species undergo larval drift (Humphries et al. 1999) and hydraulic conditions undoubtedly influence downstream drift.

Large floods in the lower Murray are little affected by river regulation, however, smaller floods and within channel flow pulses are the component of the flow regime that has been most significantly altered by river regulation (Maheshwari et al. 1995). Paradoxically, flows of this magnitude (e.g. 15,000–25,000 ML.d⁻¹) could practically be restored with the delivery of environmental water, within the current constraints of system operation (Zampatti and Leigh 2013). Hydraulic modelling indicates that as flows approach 15,000–20,000 ML.d⁻¹, the river begins to regain its lotic nature (Mallen-Cooper et al. 2011), thus increasing hydraulic complexity and potentially promoting diversity in fish assemblages and facilitating life history processes such as spawning and recruitment. Nevertheless, changes in the hydraulic character of the river

channel within this range of flows have not previously been verified in the field, yet these data are imperative to supporting the delivery of environmental water. Ultimately the successful restoration of hydraulic complexity will be paramount in restoring the ecological integrity of the lower River Murray.

The hydraulic characteristics of rivers have traditionally been investigated using one-dimensional (1-D) metrics and hydraulic models. Such models assume flow in a downstream direction and whilst informative, do not take into account the complexity of flow in regards to transverse flows, gradients, vortices, eddies and other complex phenomena. Thus, 1-D models are limited when quantifying flow complexity, particularly in a biological context (Crowder and Diplas 2000a, 2006). Nonetheless, instruments that measure river depths and current velocities in multiple planes, such as Acoustic Doppler Current Profilers (ADCP) and two (2-D) and three-dimensional (3-D) hydraulic models, and metrics, allow investigation of biologically relevant complex flow patterns (Crowder and Diplas 2000a, 2000b, 2002, Shields and Rigby 2005).

The objective of this project was to investigate variability in hydraulic complexity in the lower River Murray between entitlement flows (3000–7000 ML.d⁻¹) and flows of ~15,000 ML.d⁻¹, resulting from environmental water delivery. Nonetheless, elevated natural flows were experienced over the study period meaning the original objective could not be met. Nevertheless, this provided the opportunity to investigate the same parameters at higher flows and inform future environmental water delivery at similar flow volumes. Specifically the aims were to 1) characterise hydraulic complexity under variable flow (i.e. 13,000–16,000 ML.d⁻¹ and 23,000–33,000 ML.d⁻¹) by collecting real-time data and utilising various hydraulic metrics, 2) to use these data to ‘ground truth’ existing hydraulic models, and 3) integrate these data to inform the future delivery of environmental water in the lower River Murray in regards to flows required to reinstate hydraulic diversity.

2 Methods

2.1 Survey technique and study site

Cross-sectional velocity profiles were collected by the Department for Environment, Water and Natural Resources (DEWNR) Resource Monitoring Unit using a boat mounted SonTek River Surveyor M9 Acoustic Doppler Current Profiler (ADCP). In brief, ADCPs 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 bow of the boat and transects are driven across a river reach to generate cross-sectional flow velocity profiles for the given river reach.

Velocity profiles were measured across transects in two reaches (weir pools) in the main channel of the lower River Murray, one in the valley or floodplain region, between Lock 5 and Lock 6 and the other in the gorge region, between Lock 1 and Lock 2 (Table 1; Figure 1). Within each weir pool, cross-sectional velocity profiles were generated for 3 locations, 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) (Table 1; Figure 1). Multiple transects were measured at each location and the 'best' (i.e. most complete) transect from each location was chosen for analysis. Velocities were measured on two occasions at two different flow bands, firstly during January 2012 at flows to South Australia (QSA) of 16,214–16,898 ML.d⁻¹ and in March 2012 during flow of 33,241–38,627 ML.d⁻¹. Velocities could not be measured during typical summer/autumn entitlement flows (4,000–7,000 ML.d⁻¹) due to persistent high flows over the study period.

Table 1. Location of upper, middle and lower weir pool ADCP transects in the Lock 1–2 and Lock 5–6 weir pools. Transect location is presented in ‘adopted middle thread distance’ (AMTD), which represents the distance of a middle point in the river at that transect from the Murray Mouth. Specific details of each transect are also presented.

Transect	Location (river km (AMTD))	Details
Lock 1–2		
Upper	200 downstream Nigra Creek junction (360 km)	Site representative of river velocities in this reach.
Mid	Morgan (A4261110) (317 km)	Close to existing acoustic flow station. Morphology typical of the river reach.
Lower	Immediately upstream Lock 1 (278 km)	Representative of the lower part of the Lock 1–2 reach. Relatively uniform depth. Heavily influenced by Lock 1.
Lock 5–6		
Upper	200 upstream of Chowilla Creek junction (612.1 km)	Representative of river upstream Chowilla Creek junction. Irregular channel morphology.
Mid	Downstream Headings cliff (594 km)	Representative of mid section of reach. Higher discharge than upper location as it is below Chowilla Creek junction. Cross-section wide with uniform depth.
Lower	200m downstream Paringa Bridge (563.6 km)	Representative of lower section of reach. Wide with uniform depth. Heavily influenced by Lock 5 and ski-boat traffic.

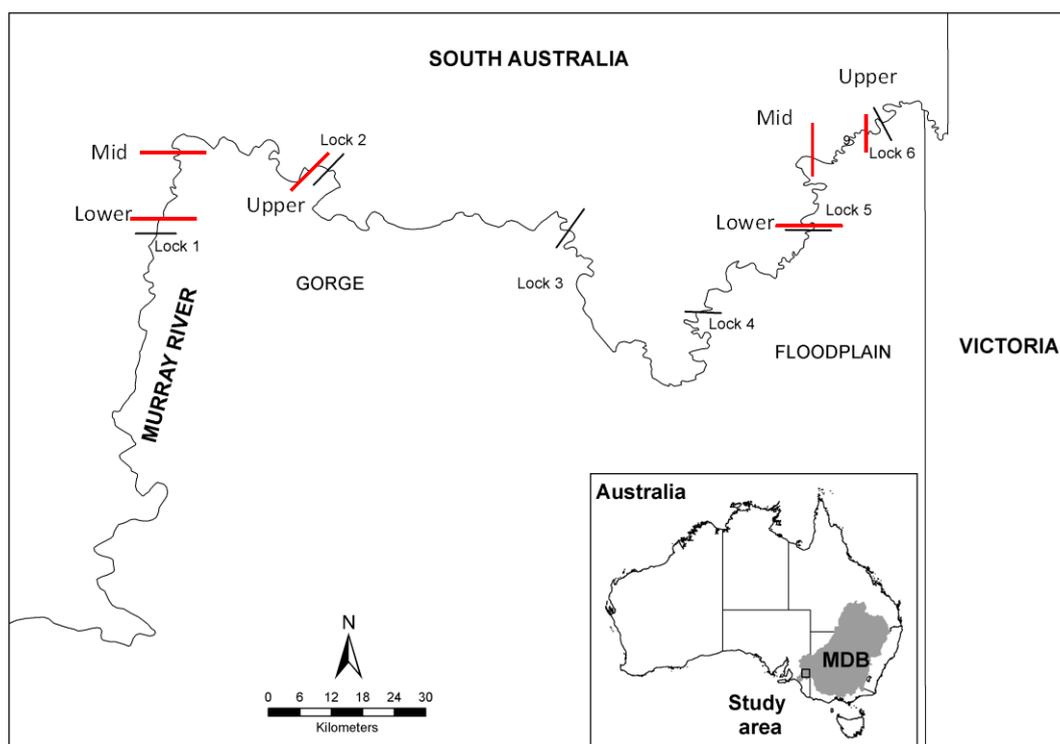


Figure 1. Map of the River Murray main channel within South Australia, depicting the six locks and weirs across the gorge and floodplain geomorphic regions, and the location of the upper, mid and lower weir pool ADCP transects in the Lock 1–2 and Lock 5–6 weir pools.

2.2 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 MATLAB (The Mathworks Inc. 2010) and interpolated across grids with equal cell sizes (0.5 m long x 0.25 m high) using the Delaney triangulation scattered data function. Water velocities for each cell were 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 vertical velocity (i.e. up or down).

In a flowing river, velocity across a transect, from upstream to downstream, is of obvious importance and is the vector that is likely to be of greatest magnitude. Hydraulic complexity in regard to cross-transect velocities (U) was investigated by comparing all velocity measurements (i.e. cells) within this plane across the different flow bands for each reach (Figure 2). Analysis of variance (ANOVA) was used to determine significant differences in mean cross-transect velocities between velocity profiles from the different locations (upper, mid and lower) and flow bands within each reach. Variability in U within cross-sections was investigated by determining standard deviation and the coefficient of variation, and generating velocity-frequency distributions. Mean velocities in the other planes, horizontally along transect (i.e. from bank to bank, W) and vertically (i.e. up or down, V) were also determined.

Whilst one dimensional approaches to explaining hydraulic characteristics (e.g. depth and velocities in a given plane) may be informative, they do not take into account velocity gradients, transverse flow, eddies and other complex flow patterns (Crowder and Diplas 2006). Thus we adopted a spatial hydraulic metric developed by Crowder and Diplas (2000a) known as the *modified circulation metric* to quantify flow complexity over a defined area, in this case, river cross-sections as measured during ADCP transects. In brief, the modified circulation metric expands 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 2000a, 2002). Vorticity is a point measure but the modified circulation metric (M_3) (after Shields and Rigby 2005) builds upon the calculation of vorticity and represents a weighted average of absolute vorticity (i.e. flow rotation) in the vertical plane per unit area, transverse to the channel, and is a measure of the strength and frequency of eddies in a river cross-section (Figure 2). 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 . 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 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 this metric 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.
$$M_3 = \frac{\sum \left| \left(\frac{\Delta w}{\Delta y} - \frac{\Delta v}{\Delta z} \right) \right| * \Delta y * \Delta z}{\sum \Delta y * \Delta z}$$

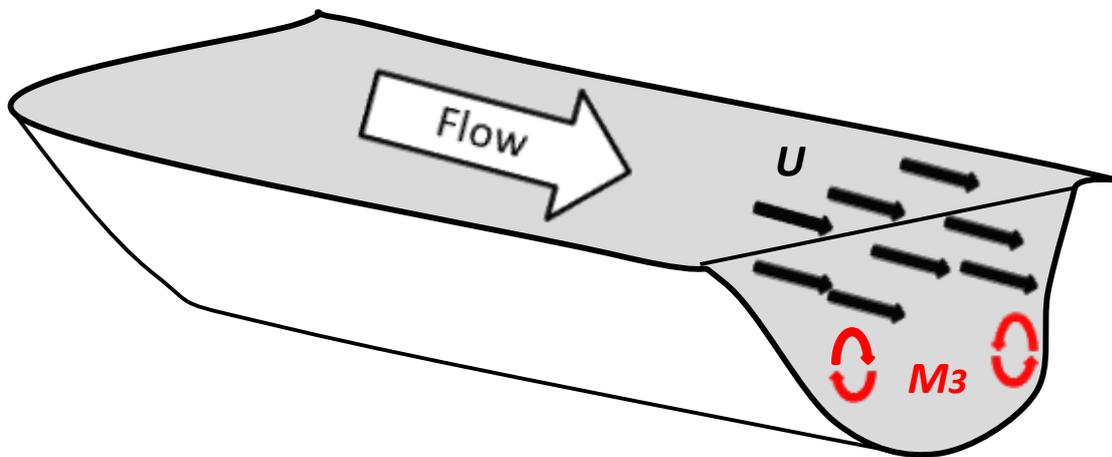


Figure 2. Schematic representation of a river reach and the hydraulic metrics investigated (after Shields and Rigby 2005), including variation in cross transect velocities (U) between transects and the modified circulation metric (M_3), which represents the area averaged frequency and strength of eddies or flow rotation within a cross-section.

2.3 Ground-truthing existing hydraulic models

The ‘measured’ mean velocities, generated by the ADCP, were compared with ‘modelled’ mean velocities for the same sites using two different modelling approaches. Firstly, hydrodynamic modelling has been undertaken in the Lock 6 region by Water Technology as part of a project investigating the risks posed to fish by the operation of the Chowilla regulator (Mallen-Cooper et al. 2011). This project utilised a one-dimensional Mike11 model, using MIKEFLOOD software, to generate mean velocities at a range of locations throughout the Chowilla Anabranh system and adjacent River Murray under several scenarios. The model was based upon 751 surveyed and interpolated cross-sections of stream channels between Locks 5 and 7. Mean velocities were modelled at flows (QSA) of 15,000 ML.day⁻¹ and 20,000 ML.day⁻¹, and are compared against velocities measured in the current study.

The second set of hydrodynamic modelling was undertaken by DEWNR and also utilised MIKE FLOOD software (DEWNR unpublished). This model generated two dimensional water velocity outputs for the reaches Lock 1–2 and Lock 5–6 at flows (QSA) of 13,000 ML.day⁻¹ and 24,000 ML.day⁻¹. In this approach the river is viewed from above across a grid of 15 x 15 m cells, with each cell representing mean velocity for that ‘vertical’ portion of river. Mean velocities of river cross-sections were calculated for the lower, middle and upper weir pool sites of the Lock 1–2 and Lock 5–6 reaches measured in the current study. The upper weir pool site in the Lock 5–6 reach is upstream of the Chowilla Creek junction and thus discharge at this site is less than QSA. The model assumed a QSA flow division of 74% over Lock 6 and 26% through the Chowilla system. This equated to flows at the upper weir pool site of 9620 and 17,760 ML.day⁻¹.

3 Results

3.1 Hydrograph

Flow within both river reaches varied over the period November 2011–April 2012 (Figure 3a and b). In the Lock 5–6 reach the upper weir pool transect is upstream of the Chowilla Creek junction, whilst the mid and lower weir pool transects are below the junction. As such, flow at Lock 6 is most relevant to the upper weir pool site whilst flow to South Australia (QSA) is most relevant to the mid and lower weir pool transects. During data collection in January 2012 flow at Lock 6 was 13,343 ML.d⁻¹ and QSA was 16,214 ML.d⁻¹, increasing in March to 25,815 and 33,241 ML.d⁻¹, respectively (Figure 3a). Flow at Lock 1 (as a proxy for the Lock 1–2 reach) was 13,725 ML.d⁻¹ during data collection in January and 23,712 ML.d⁻¹ in March (Figure 3b).

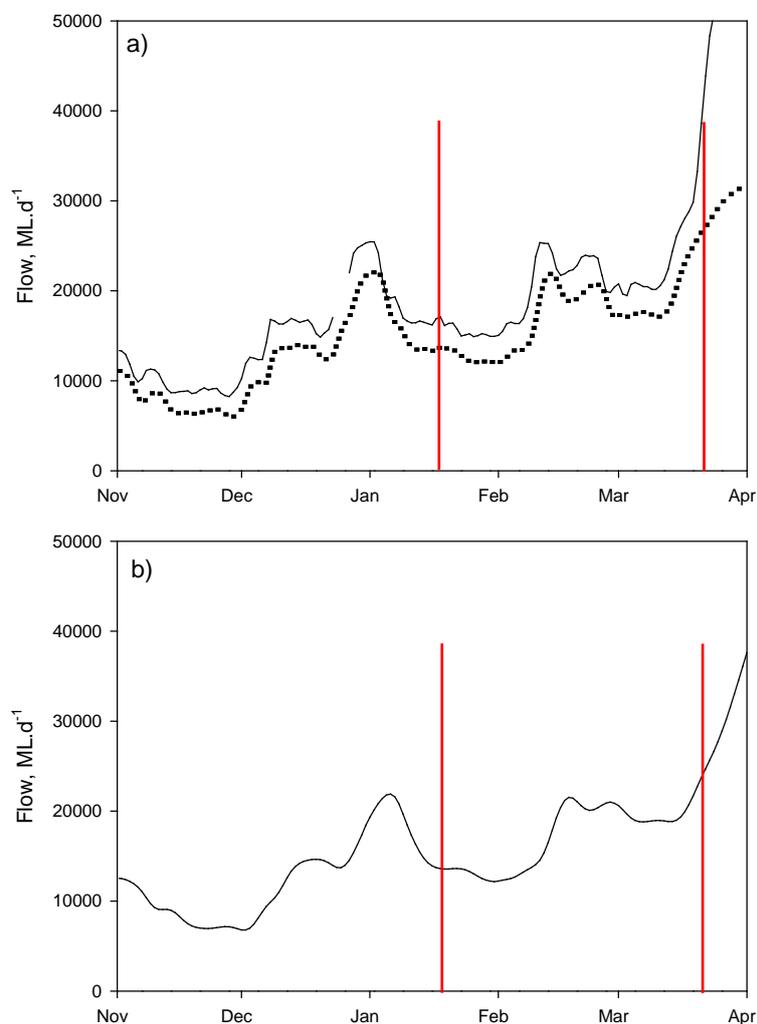


Figure 3. Daily river flow (ML.d⁻¹) at a) Lock 6 (dotted line) and QSA (solid line) and at b) Lock 1 (as a proxy for the Lock 1–2 reach), from November 2011–April 2012. Red lines represent dates and flows when ADCP transects were conducted.

3.2 Hydraulic complexity

Lock 1–2

Point discharge and transect length generally increased at all locations between January and March, whilst mean depth and cross-sectional area only increased marginally (Table 2). In all cross-sections, the lowest velocities were recorded near the edges of transects (at the bank), with more uniform and higher velocities in the middle of the river and often higher in the water column (Figure 4–6). The lower transect in March, however, exhibited significant variability in cross-transect velocities within the middle of the river (Figure 6), potentially due to irregular topography.

Table 2. Hydraulic habitat metrics calculated from ADCP generated data from the upper, mid and lower weirpool locations within the Lock 1–2 reach in January and March 2012. Metrics include point discharge ($\text{m}^3\cdot\text{s}^{-1}$) at each location, the transect length (m), mean depth (m) across the cross-section, total area of the cross-section (m^2), mean cross-transect (upstream to downstream) velocity (U , $\text{m}\cdot\text{s}^{-1}$), standard deviation in cross-transect velocities ($\text{m}\cdot\text{s}^{-1}$), mean velocity along or parallel to each transect (V , $\text{m}\cdot\text{s}^{-1}$), mean velocity in the vertical plane (W , $\text{m}\cdot\text{s}^{-1}$) and the modified circulation metric (M_3 , s^{-1}).

	January			March		
	Upper	Mid	Lower	Upper	Mid	Lower
Discharge ($\text{m}^3\cdot\text{s}^{-1}$)	195.98	185.56	182.36	360.68	353.26	324.92
Transect length (m)	112	109	157	122.35	113.18	167.02
Mean depth (m)	1.91	2.64	2.65	2.08	2.70	2.71
Area (m^2)	528.63	650.26	954.66	584.18	698.71	980.22
Mean U ($\text{m}\cdot\text{s}^{-1}$)	0.37	0.29	0.19	0.62	0.51	0.33
Standard deviation U	0.14	0.12	0.10	0.15	0.15	0.15
Coefficient of variation	0.38	0.41	0.50	0.25	0.31	0.45
Mean V	-0.034	-0.041	-0.021	-0.110	-0.023	0.085
Mean W	-0.012	-0.005	0.002	0.008	-0.012	-0.016
M_3 (s^{-1})	0.053	0.095	0.079	0.078	0.102	0.115

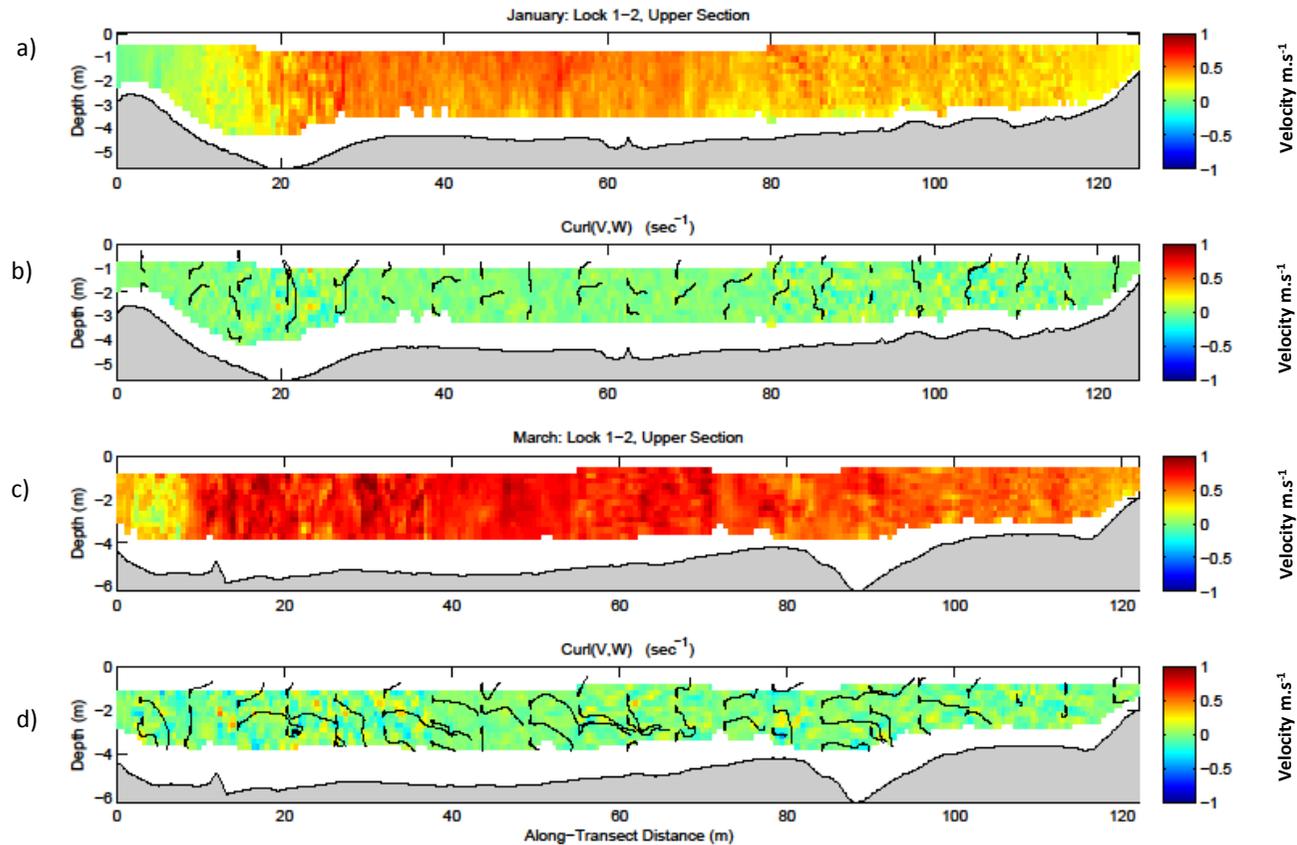


Figure 4. Horizontal current velocity and circulation (i.e. M_3 , $\text{curl}\cdot\text{s}^{-1}$) profiles generated for the Lock 1-2 weirpool upper location in January (a & b) and March 2012 (c & d). Current velocity plots (a & c) present cross-transsect velocities (U) in cells 0.5 m in width x 0.25 m in height. Circulation plots (b & c) present a combination of velocities in the vertical and horizontal planes (i.e. along-transsect, W , and vertically, V), transverse to the banks, with vectors representing the direction of rotation.

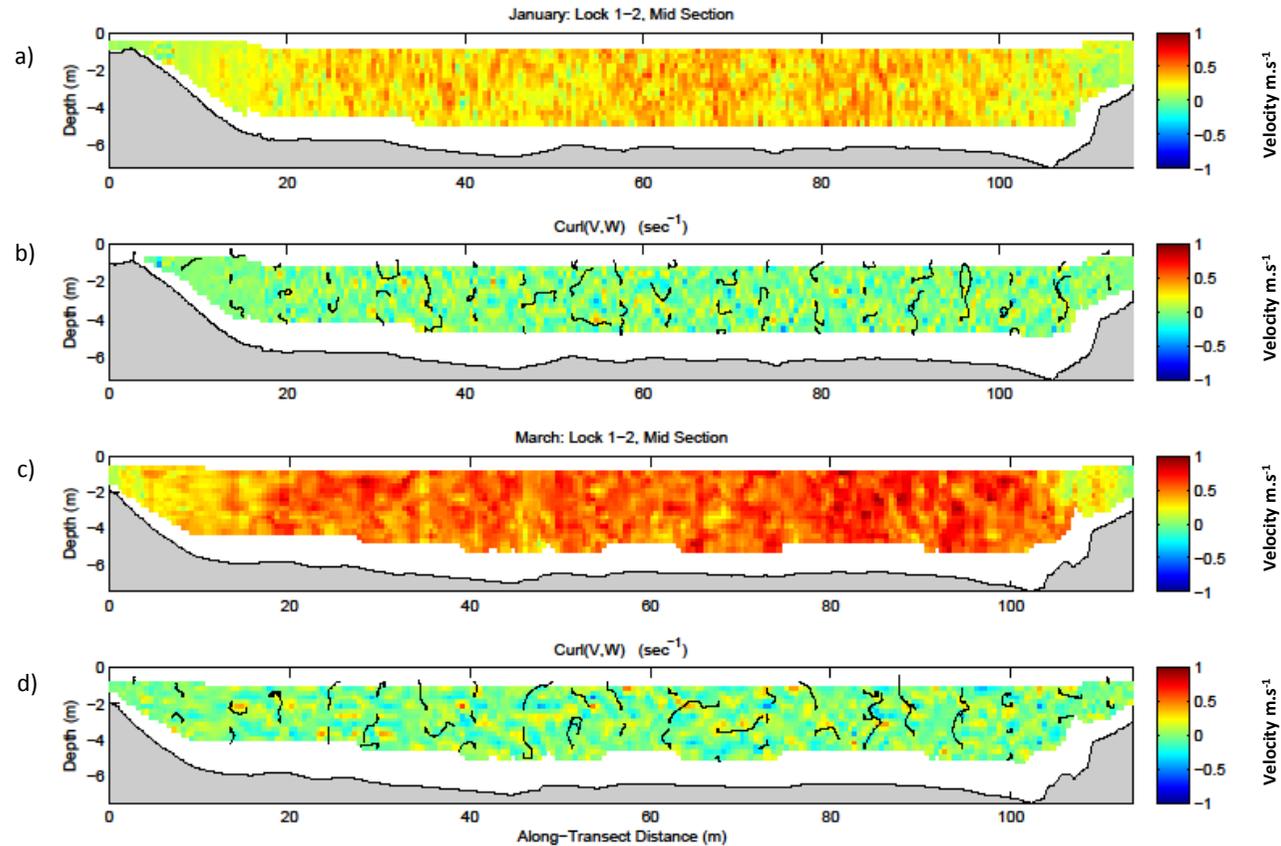


Figure 5. Horizontal current velocity and circulation (i.e. M_3 , curl.s^{-1}) profiles generated for the Lock 1–2 weirpool mid location in January (a & b) and March 2012 (c & d). Current velocity plots (a & c) present cross-transsect velocities (U) in cells 0.5 m in length x 0.25 m in height. Circulation plots (b & c) present a combination of velocities in the vertical and horizontal planes (i.e. along-transsect, W , and vertically, V), transverse to the banks, with vectors representing the direction of rotation.

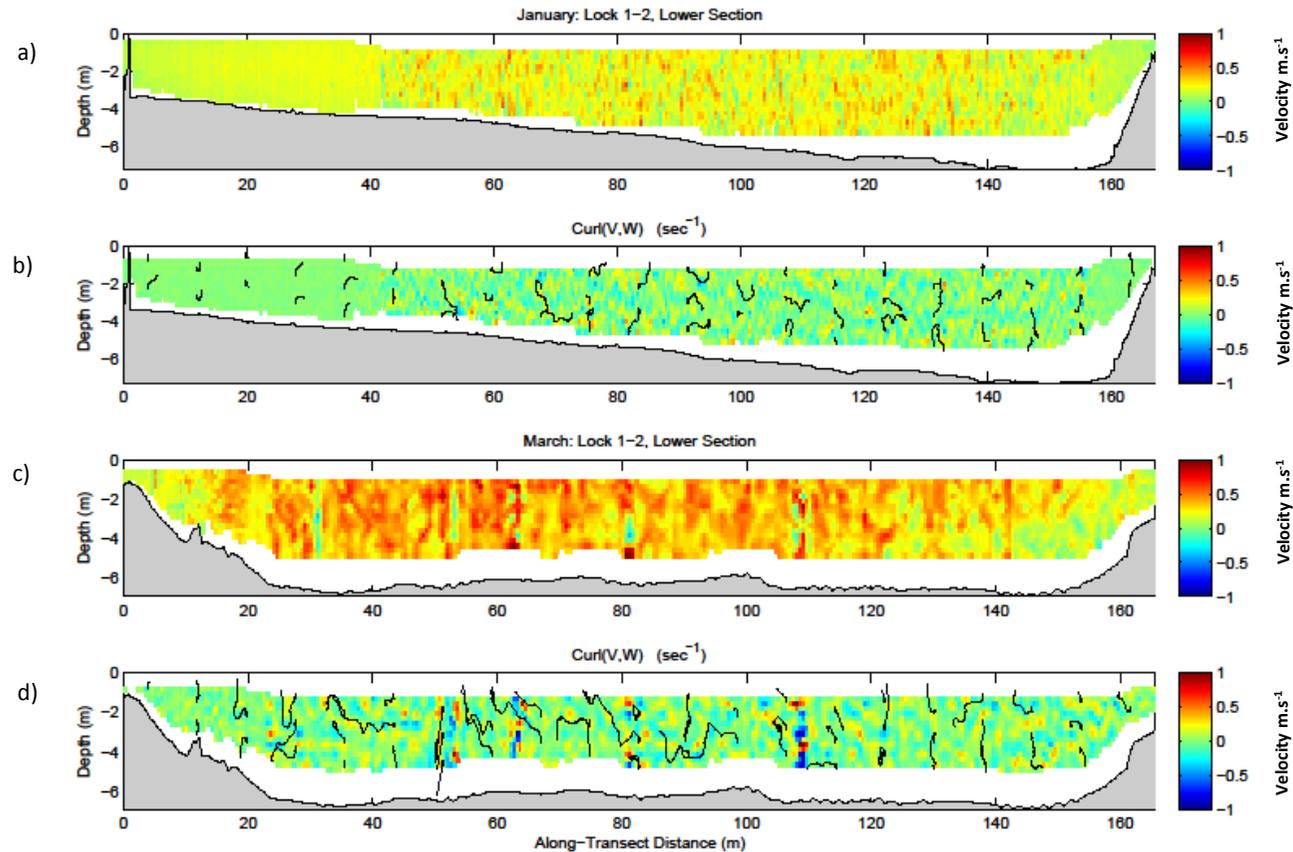


Figure 6. Horizontal current velocity and circulation (i.e. M_3 , curl.s^{-1}) profiles generated for the Lock 1–2 weirpool lower location in January (a & b) and March 2012 (c & d). Current velocity plots (a & c) present cross-transsect velocities (U) in cells 0.5 m in length x 0.25 m in height. Circulation plots (b & c) present a combination of velocities in the vertical and horizontal planes (i.e. along-transsect, W , and vertically, V), transverse to the banks, with vectors representing the direction of rotation.

Mean cross-transect velocities (U) differed significantly between both weir pool location (i.e. upper, middle, lower) (ANOVA; $F_{2, 24864} = 5468.39, p < 0.001$) and months (i.e. different flow bands, $F_{1, 24864} = 12,171.40, p < 0.001$) and there was a significant interaction ($F_{2, 24864} = 5.93, p < 0.001$). This indicates that the change in mean velocity between months across weir pool locations were of significantly different magnitudes. Mean velocity was greatest in the upper weir pool and decreased to be least in the lower weir pool location during both flow bands (Figure 7a). Mean cross-transect velocity increased significantly at each weir pool location with increasing flow between January and March (Figure 7a). Standard deviation, as a measure of variation in the cross-sectional velocities increased marginally at all locations, however, the coefficient of variation decreased slightly at all sites (Table 2).

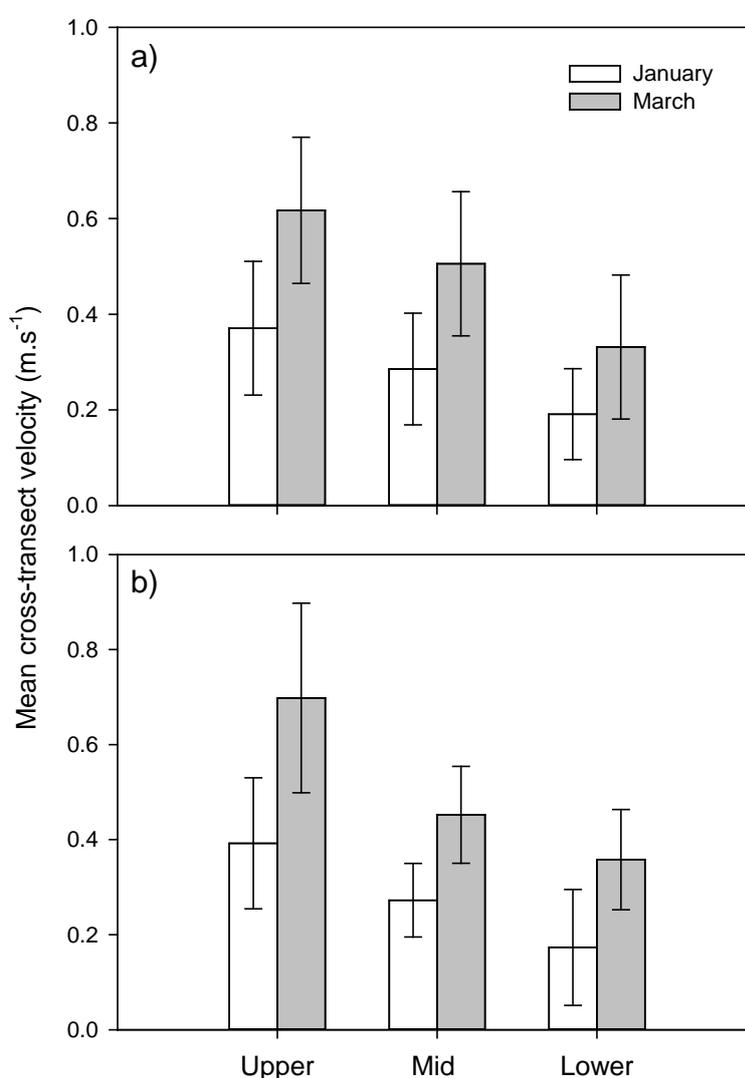


Figure 7. Mean cross-transect velocity (U , $m.s^{-1}$) \pm standard deviation at the upper, mid and lower weir pool location transects of a) the Lock 1-2 reach and b) the Lock 5-6 reach in January and March 2012.

Velocity-frequency distributions, generated from data from the cross-section profiles, changed with increasing flow (Figure 8). In the upper weir pool in January cross-transect velocities ranged from -0.080 – 0.737 m.s^{-1} (note; negative velocities represent water movement in an upstream direction), with $>80\%$ of ‘cells’ exhibiting a velocity of 0.2 – 0.6 m.s^{-1} and $<2\%$ of cells with velocities >0.6 m.s^{-1} . In March, the velocity range expanded to -0.031 – 1.066 m.s^{-1} , with velocities in $\sim 50\%$ of all cells >0.6 m.s^{-1} (Figure 8a). Similar patterns were evident in the mid and lower weir pool location, albeit at slightly lower velocity ranges. In the mid weir pool location in January (velocity range -0.162 – 0.660 m.s^{-1}), $>50\%$ of cells had velocities between 0.2 and 0.4 m.s^{-1} and $<1\%$ were >0.6 m.s^{-1} . In March, velocities ranged 0.091 – 0.983 m.s^{-1} , with $>75\%$ of cells exhibiting velocities >0.4 m.s^{-1} , including $\sim 25\%$ >0.6 m.s^{-1} (Figure 8b). The range of velocities in the lower weir pool increased from -0.169 – 0.617 m.s^{-1} in January to -0.38 – 1.378 m.s^{-1} in March. Velocity-frequency distributions also changed with a decrease in the proportion of cells in the 0.0 – 0.2 m.s^{-1} range and an increase in proportion of cells in the 0.4 – 0.6 m.s^{-1} range (Figure 8c).

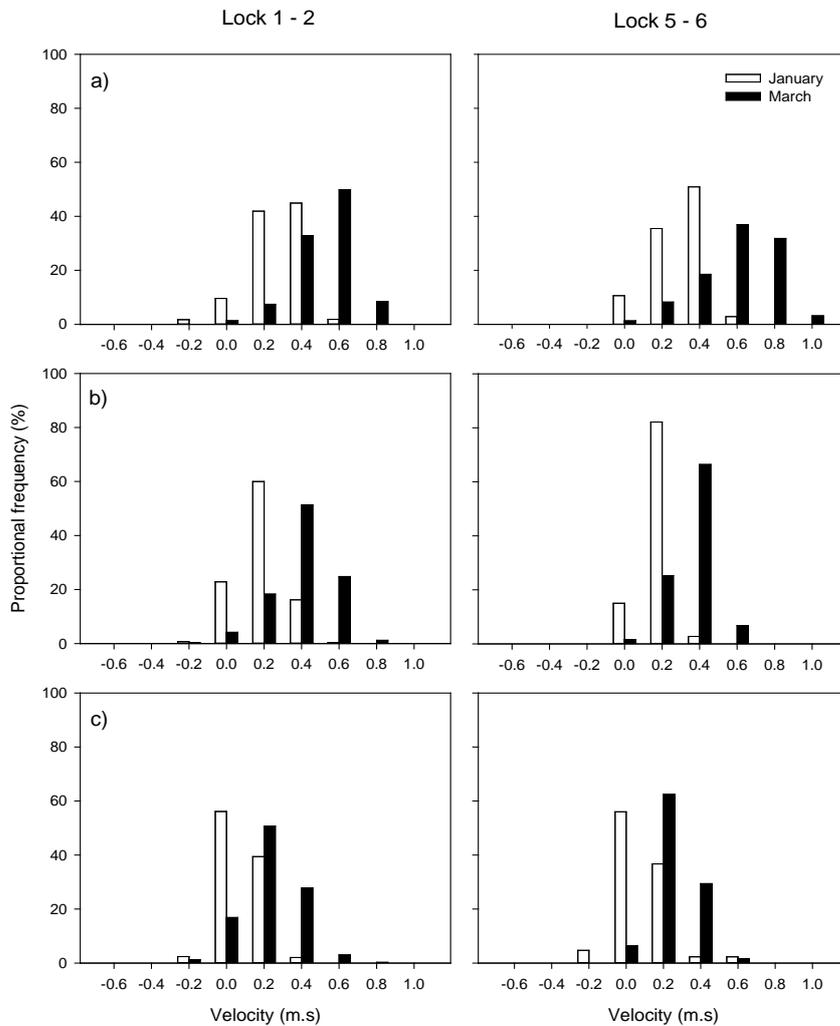


Figure 8. Velocity-frequency distributions of all cross-transect velocities (cells) measured at the a) upper, b) mid and c) lower weir pool locations in the Lock 1–2 reach (left-hand side) and Lock 5–6 reach (right-hand side).

The modified circulation metric (M_3) increased at each location between January and March (Table 2) indicating that the strength and frequency of eddies in river cross-sections were greater under higher flow conditions. Contrastingly, mean cross-transect velocities (M_3) displayed no discernible pattern of change with weir pool location, potentially as this metric is influenced by the channel morphology of a given river cross-section rather than weir pool position. The circulation plots depicted in Figures 4–6 present velocities in the vertical plane and are thus typically lower than those presented in the cross-transect velocity plots. The overlaid arrows represent the direction of significant flow rotation. During March, all locations exhibited higher M_3 values, indicating greater frequency and strength of eddies or circulation, as depicted by a greater frequency of circulation vectors (Figures 4–6).

Lock 5–6

Point discharge increased at all locations in the Lock 5–6 reach between January and March, whilst mean depth was little affected (Table 3). Cross-sectional areas increased marginally between January and March at sites in the upper and mid weir pool but were slightly less at the lower weir pool site, whilst transect length increased marginally at all sites (Table 3). Similar to the Lock 1–2 reach, cross-transect velocities in the Lock 5–6 reach were typically lowest at transect edges (the ‘banks’) and uniformly higher in the middle of the river (Figures 9–11). The mid weir pool transect was similar between months (Figure 10). There appeared to be some erroneous readings during January at the lower weir pool location (river width of ~185 m) (Figure 10) and these values were subsequently removed from mean velocity analyses.

Cross-transect velocities differed significantly between both weir pool location (i.e. upper, middle, lower) (ANOVA; $F_{2, 25096} = 8517.79, p < 0.001$) and month (i.e. different flow bands, $F_{1, 25096} = 17,580.17, p < 0.001$) and there was a significant interaction ($F_{2, 25096} = 6.62, p < 0.001$), indicating that the change in mean velocity between months across weir pool locations were of different magnitudes. Similar to the Lock 1–2 reach, mean velocity was greatest in the upper weir pool and decreased gradually to be lowest in the lower weir pool during both flow bands (Figure 7b). Mean cross-transect velocity increased significantly at each weir pool location with increasing flow (Figure 7b). Standard deviation, as a measure of variation in the cross-sectional velocities increased at all locations but only marginally in the mid and lower weir pool, whilst the coefficient of variation decreased at all sites (Table 3).

Table 3. Hydraulic habitat metrics calculated from ADCP generated data from the upper, mid and lower weir pool locations within the Lock 5–6 reach in January and March 2012. Metric include point discharge ($\text{m}^3.\text{s}^{-1}$) at each location, transect length (m), mean depth (m) across the cross-section, total area of the cross-section (m^2), mean cross-transect (upstream to downstream) velocity (U , $\text{m}.\text{s}^{-1}$), standard deviation in mean cross-transect velocity ($\text{m}.\text{s}^{-1}$), mean velocity along or parallel to each transect (V , $\text{m}.\text{s}^{-1}$), mean velocity in the vertical plane (W , $\text{m}.\text{s}^{-1}$) and the modified circulation metric (M_3).

	January			March		
	Upper	Mid	Lower	Upper	Mid	Lower
Discharge ($\text{m}^3.\text{s}^{-1}$)	156.10	206.42	205.74	312.84	367.38	395.22
Transect length (m)	95	213	187	101	225	188
Mean depth (m)	1.97	1.61	2.65	1.96	1.64	2.58
Area (m^2)	397.87	757.44	1187.86	448.16	812.33	1104.12
Mean U ($\text{m}.\text{s}^{-1}$)	0.39	0.27	0.17	0.70	0.45	0.36
Standard deviation U	0.14	0.08	0.10	0.20	0.10	0.11
Coefficient of variation	0.35	0.28	0.63	0.29	0.23	0.29
Mean V	-0.056	-0.006	-0.053	0.049	0.033	0.029
Mean W	-0.012	-0.005	0.001	-0.011	-0.010	-0.008
M_3	0.068	0.042	0.095	0.067	0.062	0.083

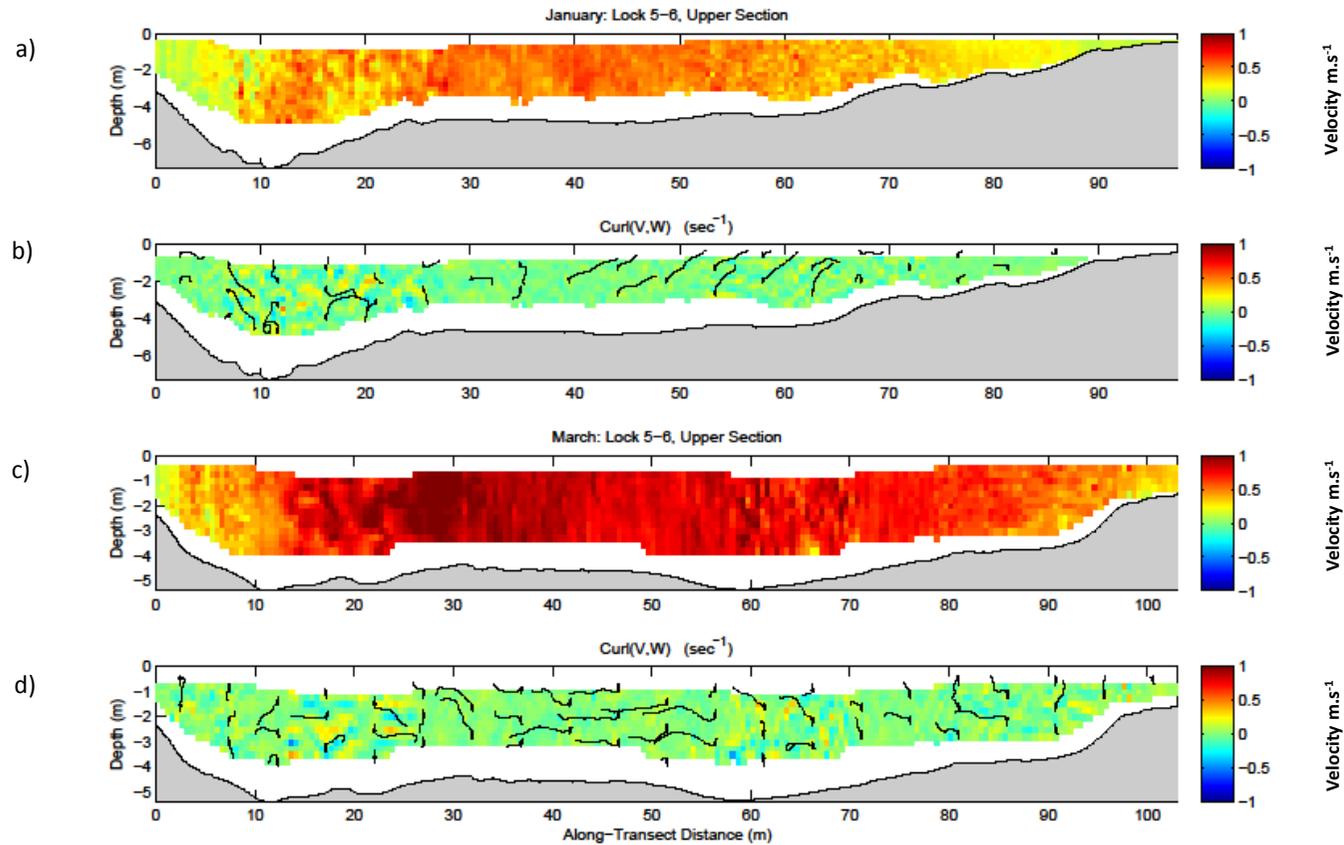


Figure 9. Horizontal current velocity and circulation (i.e. M_3 , curl.s^{-1}) profiles generated for the Lock 5–6 weir pool upper location in January (a & b) and March 2012 (c & d). Current velocity plots (a & c) present cross-transsect velocities (U) in cells 0.5 m in length x 0.25 m in height. Circulation plots (b & c) present a combination of velocities in the vertical plane (i.e. along-transsect, W , and vertically, V), with vectors representing the direction of rotation.

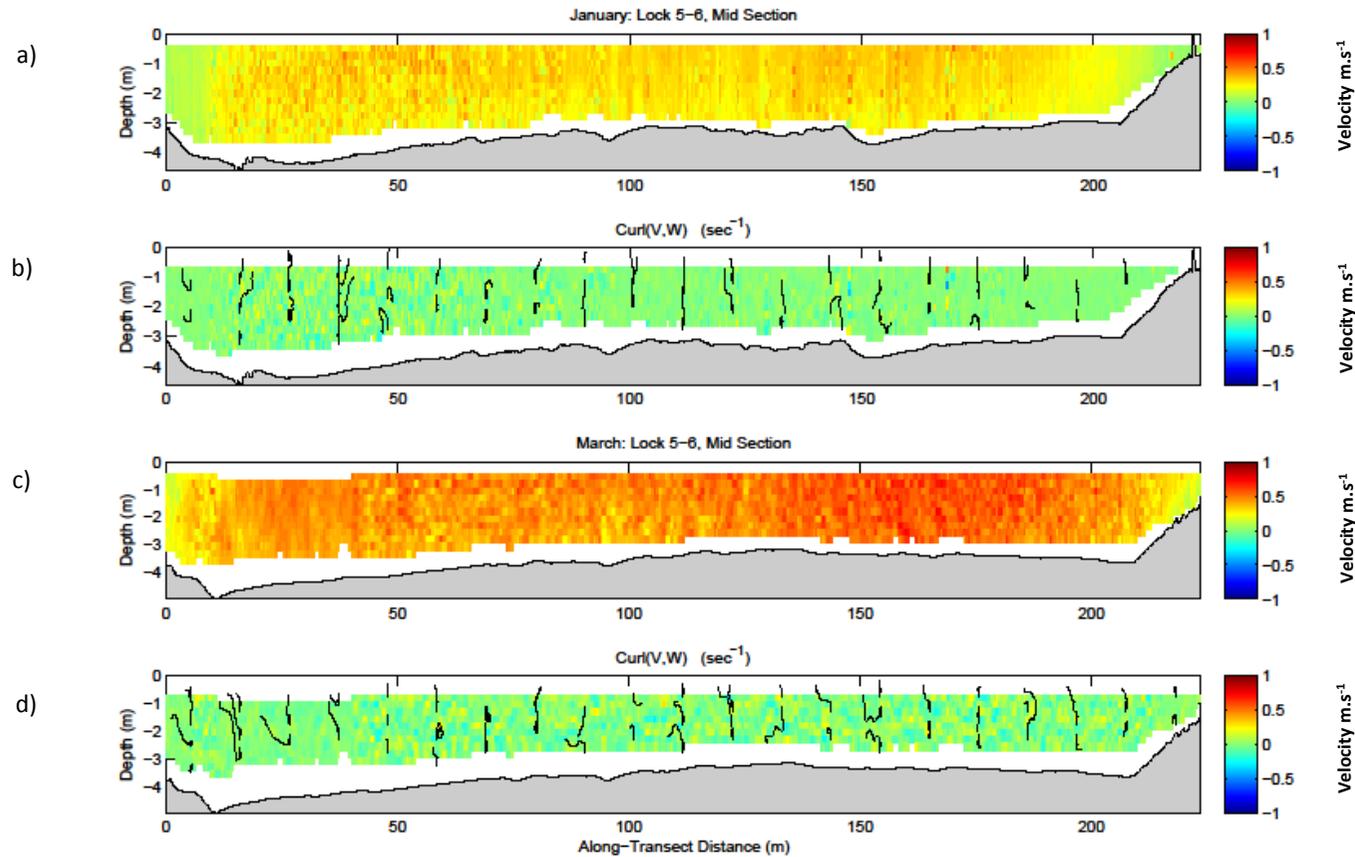


Figure 10. Horizontal current velocity and circulation (i.e. M_3 , curl.s^{-1}) profiles generated for the Lock 5-6 weir pool mid location in January (a & b) and March 2012 (c & d). Current velocity plots (a & c) present cross-transsect velocities (U) in cells 0.5 m in length x 0.25 m in height. Circulation plots (b & c) present a combination of velocities in the vertical plane (i.e. along-transsect, W , and vertically, V), with vectors representing the direction of rotation.

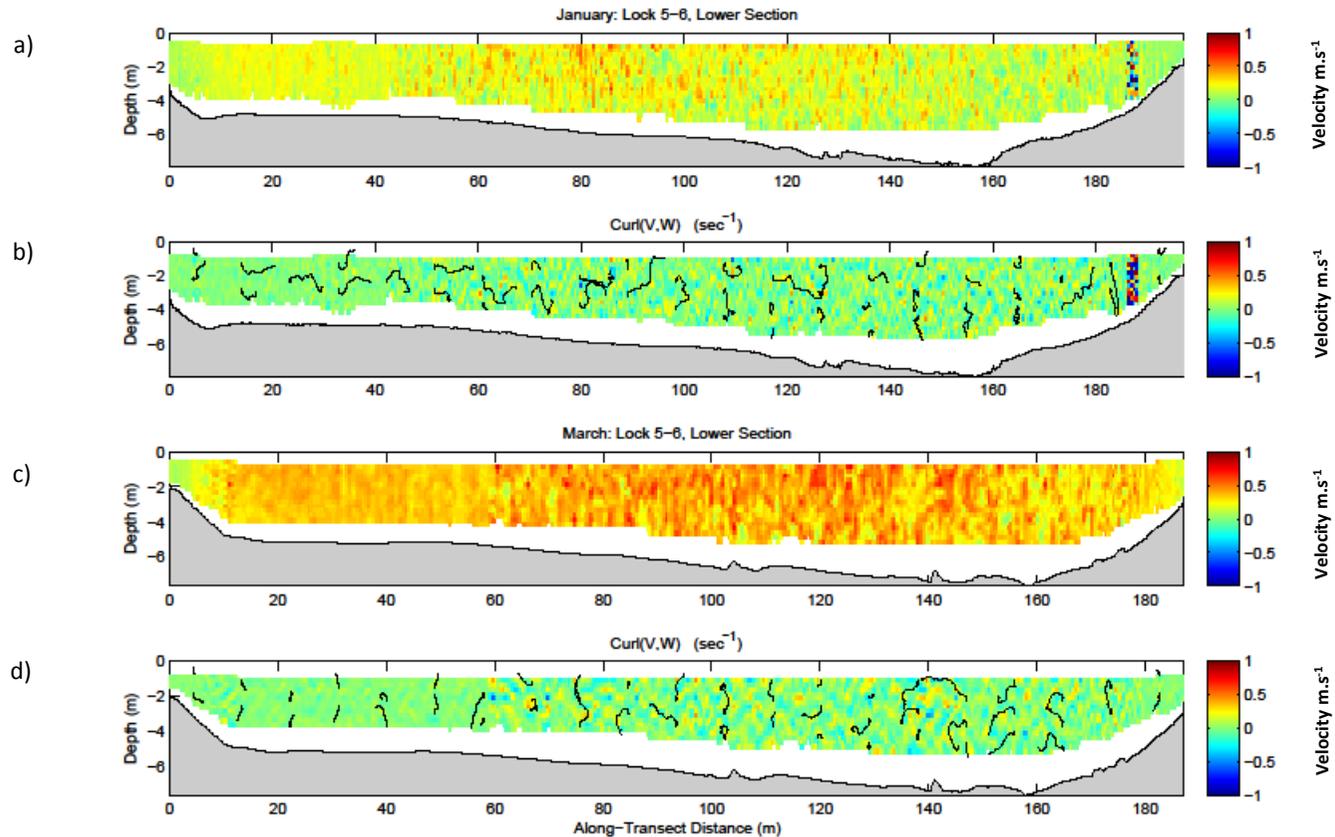


Figure 11. Horizontal current velocity and circulation (i.e. M_3 , $\text{curl}\cdot\text{s}^{-1}$) profiles generated for the Lock 5–6 weir pool lower location in January (a & b) and March 2012 (c & d). Current velocity plots (a & c) present cross-transect velocities (U) in cells 0.5 m in length x 0.25 m in height. Circulation plots (b & c) present a combination of velocities in the vertical plane (i.e. along-transect, W , and vertically, V), with vectors representing the direction of rotation.

Velocity-frequency distributions, generated from the cross-section profiles in the Lock 5–6 reach, changed with increasing flow, with general increases in the proportion of cells with higher velocities in March at all weir pool locations (Figure 8). In the upper weir pool in January, velocity ranged -0.013 – 0.806 m.s^{-1} with $>95\%$ of ‘cells’ having a mean velocity of 0.0 – 0.6 m.s^{-1} and $<3\%$ of cells with velocities >0.6 m.s^{-1} . In March, the velocity range increased to 0.084 – 1.156 m.s^{-1} with $>60\%$ of all cells having velocities >0.6 m.s^{-1} (Figure 8a). Similar patterns were evident in the mid and lower weir pool, albeit at slightly lower velocity ranges. In the mid weir pool location in January, velocities ranged -0.045 – 0.543 m.s^{-1} with $>80\%$ of cells having velocities 0.2 – 0.4 m.s^{-1} and in March velocities ranged 0.072 – 0.779 m.s^{-1} with $\sim 25\%$ of cells ranging 0.2 – 0.4 m.s^{-1} and $\sim 66\%$ ranging 0.4 – 0.6 m.s^{-1} (Figure 8b). After removing the apparent erroneous readings from the January transect in the lower weir pool, velocities ranged -0.265 – 0.648 m.s^{-1} and -0.099 – 0.811 m.s^{-1} in March. In January, the majority of cells had velocities of 0.0 – 0.4 m.s^{-1} increasing to 0.2 – 0.6 m.s^{-1} in March.

The modified circulation metric (M_3) did not increase between January and March in the upper weir pool but increased substantially in the mid weir pool (Table 3). M_3 also appeared to decrease in the lower weir pool location between January and March but this was due to the aforementioned erroneous readings in the January transect at this site which likely elevated the value of M_3 . M_3 displayed no discernible pattern of change with location in the weir pool, potentially as this metric is more influenced by the geomorphology of a given river cross-section rather than position in the weir pool.

3.3 Comparison of measured vs modelled average velocity

It is difficult to directly compare measured and modelled velocities in the Lock 5–6 reach due to variability in discharge between that measured in the field and that utilised for modelling (we used pre-existing model runs so discharge could not be specified). There is also the complexity of proportioning flow to South Australia (QSA) between the River Murray and the Chowilla Anabranch system. In particular, discharge at the upper weir pool location does not reflect QSA flow but rather is typically considerably less, as it is located upstream of the Chowilla Creek junction. Depending on river operations and discharge the proportion of flow divided between Lock 6 and Chowilla Creek can vary. Thus, whilst it is recognised that both actual and modelled velocities may be derived from discharges of variable proportioning between Lock 6 and Chowilla Creek; we have adopted QSA for simplicity. Nonetheless, mean velocities derived from DEWNR modelling at QSA of $13,000$ and $24,000$ ML.day^{-1} , and the Water Technology modelling at QSA of $15,000$ and $20,000$ ML.day^{-1} , appear quite accurate when compared to measured mean velocities at QSA of $16,214$ and $33,241$ ML.day^{-1} (Figure 12a). Water Technology modelling for the upper weir pool at $40,000$ ML.day^{-1} , however, appears to underestimate mean

velocity, being considerably lower than measured mean velocity at QSA of 33,241 ML.day⁻¹ (Figure 12a).

Measured discharge and that used for DEWNR modelling were similar for the Lock 1–2 reach. At QSA of ~13,000 ML.day⁻¹, measured and modelled mean velocities were comparable throughout the Lock 1–2 reach (Figure 12b). At the higher discharge of ~24,000 ML.day⁻¹, there was greater variation between measured and modelled mean velocities with DEWNR modelling underestimating velocity, particularly in the upper weir pool (Figure 12b).

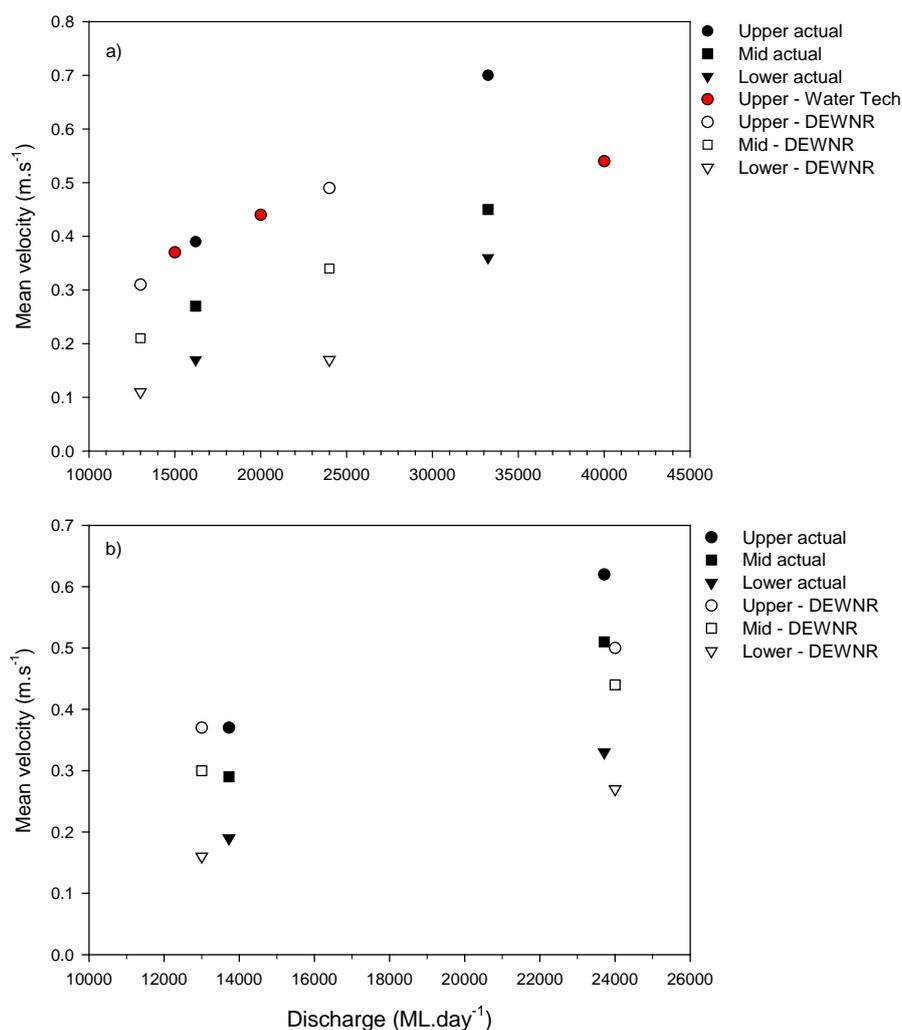


Figure 12. Comparison of mean measured velocities (black symbols) against WaterTech modelled (red symbols; Lock 5–6 upper weir pool only) and DEWNR modelled mean velocities (white symbols) in the upper weir pool (circles), mid weir pool (squares) and lower weir pool (triangles) of a) the Lock 5–6 reach and b) the Lock 1–2 reach under varying discharge (QSA; ML.day⁻¹). For the Lock 5–6 reach, QSA is used for simplicity despite the upper weir pool transect being above the Chowilla Creek junction, typically resulting in a lower discharge at this location compared to the mid and lower weir pool, which are downstream of the Chowilla Creek junction.

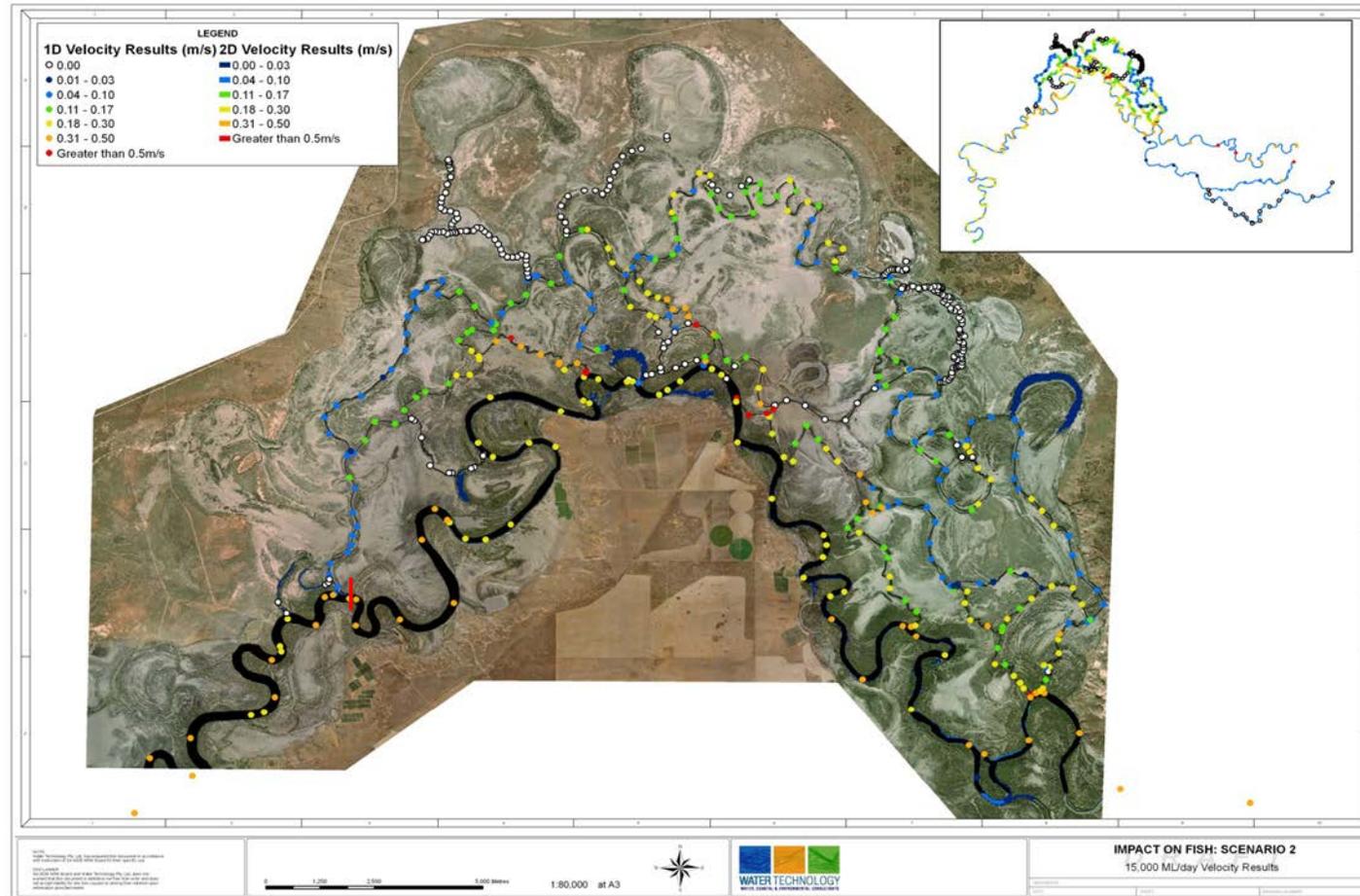
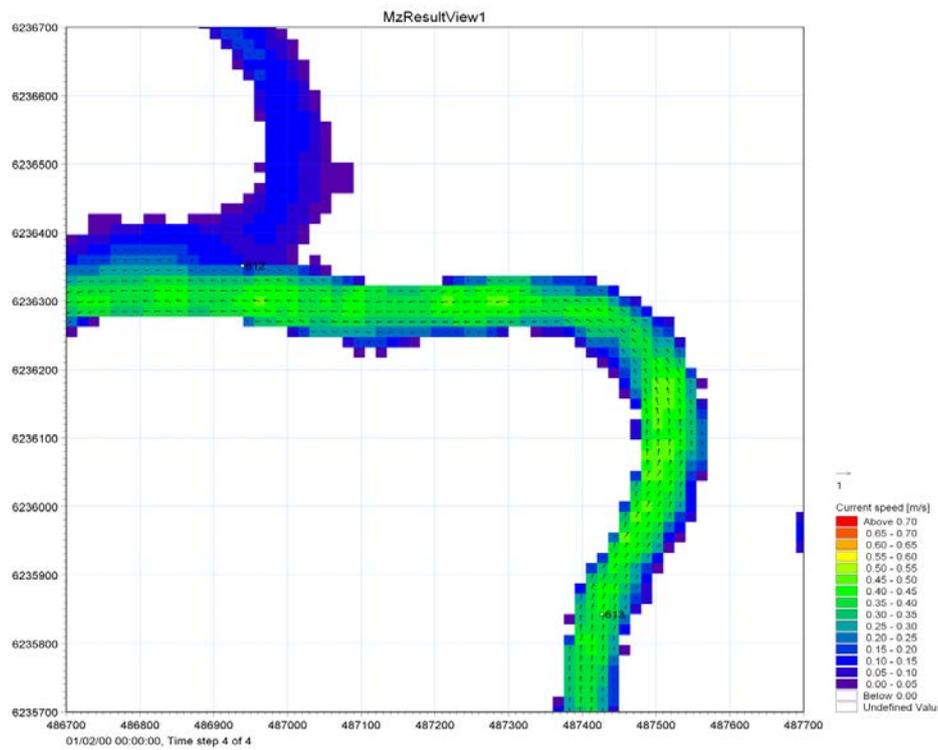


Figure 13. Modelled mean water velocities ($m \cdot s^{-1}$) for the River Murray and Chowilla Anabranch system at QSA 15,000 $ML \cdot day^{-1}$. The data point that corresponds to the measured transect in the current study is indicated by the red line.

a)



b)

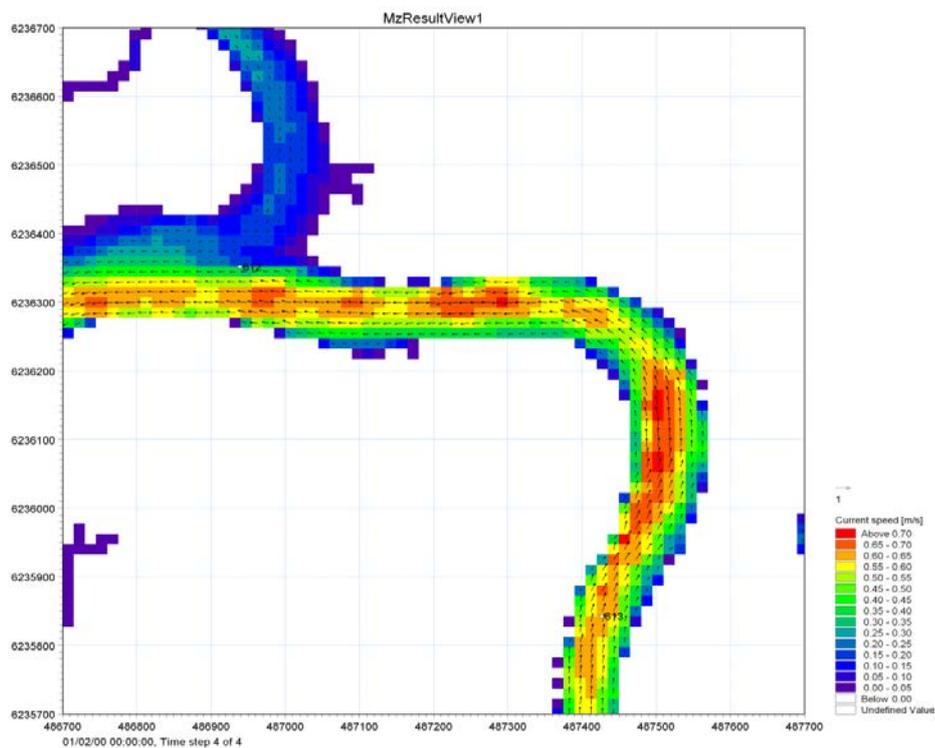


Figure 14. An example of modelled water velocity outputs from DEWNR modelling at QSA of a) 13,000 ML.day⁻¹ and b) 24,000 ML.day⁻¹ is the Lock 5–6 upper weir pool.

4 Discussion

The use of environmental flows to maintain or enhance ecological values in regulated rivers is now commonplace worldwide (Arthington et al. 2006), and frequently places a large emphasis on flow volumes, timing and floodplain inundation. Whilst these parameters and outcomes of environmental water delivery are critical for eliciting positive biotic responses they often overlook within-channel patterns and processes, such as spatio-temporal variability in stream hydraulics. Indeed a growing body of literature supports the notion that within-channel hydraulic complexity, in the form of patches of varying velocity, eddies, transverse flows, etc, supports high levels of biodiversity (Statzner and Higler 1986, Harper and Everard 1998, de Nooij et al. 2006, Dyer and Thoms 2006). Furthermore, particular hydraulic conditions, for example convective acceleration, may influence important life history processes in fish (e.g. spawning) (Moir and Pasternack 2008). The current study aimed to characterise the hydraulic complexity of the lower River Murray in two reaches (Lock 1–2 and Lock 5–6), under entitlement flow and a flow of ~15,000 ML.d⁻¹ as a result of environmental flow delivery by the Commonwealth Environmental Water Holder (CEWH). Nonetheless, higher volume flows were experienced throughout the study period, due to a combination of natural inflows and environmental flow delivery. Thus, we investigated variability in hydraulic complexity at flows of ~13,000–16,000 ML.d⁻¹ and 23,000–33,000 ML.d⁻¹. Additionally, these data were used to ‘ground truth’ existing predictive hydraulic models developed by Water Technology and DEWNR. Ultimately, these data will inform future environmental flow delivery in the lower River Murray in regards to likely changes in hydraulic diversity under different flow scenarios.

4.1 Variability in hydraulic complexity under variable flow

Hydraulic complexity was characterised in the current study using a series of metrics, including mean cross-transect velocities, standard deviation, coefficient of variation, frequency distribution of cross-sectional velocities (characterisation of ‘within location’ variability) and the modified circulation metric (M_3) (Crowder and Diplas 2000a, 2002), which represents the area-weighted level of flow rotation within the vertical plane within a river cross-section. In general, as discharge increased, mean cross-transect velocities increased, velocity range increased, and often, but not in all cases, variability in cross-transect velocities and circulation also increased, indicating greater hydraulic complexity at flows of 23,000–33,000 ML.day⁻¹ relative to flows of ~13,000–16,000 ML.day⁻¹.

In both the Lock 1–2 and Lock 5–6 reaches, mean velocity decreased gradually in a downstream direction, being greatest at the upper weir pool and least in the lower weir pool, during both flow bands, indicating that even discharges of up to 33,000 ML.day⁻¹, the influence of the downstream weir is still apparent. The flow at which this influence becomes negligible and the river returns to

a completely hydrologically connected and lotic environment is unknown but probably requires removal of weir stop logs and navigation passes leading to the effective ‘drowning out’ of locks and weirs at flows $>50,000$ ML.day⁻¹.

Despite variability in mean velocities, variability in cross-transect velocities within locations (i.e. standard deviation, coefficient of variation and velocity-frequency distributions) and circulation (M_3) did not differ consistently in relation to weir pool location. There are two possible explanations for this result, firstly, that ‘within cross-section’ variability in cross-transect velocities and circulation is more greatly influenced by local channel morphology at the site of the transect, irrespective of weir pool location, and secondly, the flow bands at which velocities were measured were beyond a threshold, whereby weir pool location (i.e. upper, mid and lower) becomes irrelevant in regards to flow complexity. For example, weir pool location may influence hydraulic complexity at lower “entitlement” flows (3,000–7,000 ML.day⁻¹), when deceleration of flow within the lower part of a weir pool may result in velocities below a critical threshold to create hydraulic diversity. Entitlement flows, however, did not occur during the current study and such data were not collected.

Water velocities were measured by ADCP in the Lock 4–5 reach in 2006 and 2007 by Kilsby (2008) during very low flows of 3150–3670 ML.day⁻¹ and 724–1345 ML.day⁻¹ respectively. Whilst transect locations were different from those in the current study, they still provide some comparison of hydraulic conditions at low flows (e.g. <5000 ML.day⁻¹) compared to higher flows within the regulated lower River Murray. Compared to the current study, low flows resulted in hydraulically homogenous cross-sections, narrow velocity ranges and low mean depth-averaged velocities (Kilsby 2008). At a flow of 3150 ML.day⁻¹, depth averaged velocity ranged 0.05–0.33 m.s⁻¹, with a mean of 0.014 m.s⁻¹ downstream of Lock 5, compared to a range of -0.01–0.80 m.s⁻¹ and a mean of 0.39 m.s⁻¹ downstream of Lock 6 at a flow of 13,343 ML.day⁻¹ in the current study. Kilsby (2008) also found little difference in these parameters between flows of 3150–3670 ML.day⁻¹ and 724–1345 ML.day⁻¹ in the Lock 4–5 reach indicating that flows below 4000 ML.day⁻¹ produce little variation in hydraulic conditions.

Hydraulic complexity is greatly influenced by the physical nature of the river channel (Gordon et al. 2004). Indeed, channel morphology, sediment type, position in a river reach (e.g. a bend or straight section of river) and the positioning of physical objects (e.g. boulders and instream woody debris), all influence hydraulic complexity (Klaar et al. 2011). Thus, hydraulic complexity as calculated from transects in the current study will vary between locations due to differences in their physical attributes. This dictates that variability in hydraulic complexity over time for each location is probably more informative than variability through space. Transects measured in the

current study were typically characterised by relatively uniform depths and low abundances of instream woody debris (Paul Searle DEWNR, Pers. Comm.). River cross-sections with such characteristics are generally elected by hydrographers to provide favourable data for determining discharge and mean velocities for flow gauging. As such the hydraulic complexity of river cross-sections presented in this study is likely lower than that in locations with more complex morphology and physical habitat. Nonetheless, the current locations provided an adequate measure of general changes in hydraulic metrics with varying discharge.

Characterising and quantifying the biological relevance of hydraulic environments within large, deep, lowland rivers has many inherent difficulties. Most approaches to characterising hydraulic environments were developed from studies of small streams and few, with the exception of Kilsby (2008), have investigated hydraulics in large lowland systems like the River Murray. Some of the metrics used in the current study, particularly standard deviation and the coefficient of variation, appear unsuitable for characterising hydraulic complexity in a large river. Under high flows, the greater proportion of the river, towards the middle of the channel, is characterised by relatively uniform high velocities. Contrastingly, the greatest diversity in velocity patches occurs on the edge of the channel, which represents the smallest proportional area of the river and thus one-dimensional metrics that are derived over a whole river cross-section may mask important variability on the edge or littoral zone. The middle of large river channels are often biologically hostile environments, whilst littoral zones (here defined as the area within 20 m of the bank) typically harbour a diversity of biota and represent important habitat for fish for foraging, spawning and recruitment. Thus approaches which focus on biologically important habitat areas (e.g. littoral zones), take into account the spatial configuration of velocity patches (e.g. variograms, see Kilsby 2008) and/or calculate specific metrics related to hydraulic habitat (Crowder and Diplas 2000b, 2006) would be preferable for future studies. The use of the circulation metric (Crowder and Diplas 2000a, 2006) appeared suitable in the current study and adoption of further such metrics may enhance the characterisation of hydraulic environments in regards to biotic patterns. All approaches would benefit from increased understanding of the relationships between aquatic biota and hydraulic environments in the River Murray.

Whilst the current study quantified changes in the main channel hydraulic environment of the lower River Murray under variable flows, the explicit association of native fish species with specific hydraulic conditions is not well understood. Kilsby and Walker (2012) investigated the preference of flat-headed gudgeon (*Philypnodon grandiceps*) and common galaxias (*Galaxias maculatus*) for 'patches' with specific hydraulic characteristics in a laboratory setting but there is little such information from field studies. Nonetheless, associations of native species with

particular hydraulic conditions are likely related to cues for spawning, larval dispersal (drift), changes to food availability and provision of favourable feeding areas for different life stages.

Golden perch and silver perch are cued to spawn by increases in within-channel flows and floods (Lake 1967, Mallen-Cooper and Stuart 2003). Given that variability in hydraulics is how fish perceive changes in flow volumes, in concert with other cues such as temperature (Lake 1967), specific hydraulic conditions may provide the cue for reproductive activity in these species. Additionally, these species together with Murray cod, undergo downstream larval drift (Humphries 2005, Tonkin et al. 2007), likely for the purpose of dispersal (reducing competition and predation) and potentially compensation for upstream adult spawning migrations. Thus, hydraulic conditions that facilitate downstream drift and transportation to favourable nursery habitats are likely integral to the recruitment success of these species.

Several studies have demonstrated that specific hydraulic environments provide favourable feeding zones for different fish species. High velocity gradients are important for the positioning of feeding stations in brown trout (*Salmo trutta*) and brook trout (*Salvelinus fontinalis*), with individuals utilising low velocity resting areas bordered by high velocities, within which forays are made for foraging (Hayes and Jowett 1994). Similarly, foraging rosyside dace (*Clinostomus funduloides*) aggregate within depositional areas or eddies adjacent to areas of high velocity (Freeman and Grossman 1993). In the case of species native to the MDB, similar associations with specific hydraulic conditions in relation to feeding may also exist and may be life stage specific and thus have the capacity to influence recruitment success. Nonetheless, such associations require further research, particularly concurrent investigation of fish distribution, abundance, movement, spawning and recruitment patterns, and hydraulic conditions, at relevant biological scales. Such knowledge will further inform the delivery of environmental flows by defining specific hydraulic targets which may represent mechanisms through which fish distribution, abundance, spawning and recruitment in the lower River Murray are influenced.

4.2 Ground-truthing existing hydraulic models

Mean water velocities calculated from modelled outputs by both Water Technology and DEWNR were generally similar to measured mean velocities, except during higher flows. Mean velocities modelled for the Lock 5–6 reach at flows (QSA) of 13,000, 15,000, 20,000 and 24,000 ML.day⁻¹ by Water Technology and DEWNR appear accurate when compared to actual mean velocities measured at 16,214 ML.day⁻¹ (QSA). The Water Technology modelled mean velocity for the upper weir pool location at 40,000 ML.day⁻¹ (QSA), however, was considerably less than the actual mean velocity at QSA 33,241 ML.day⁻¹. This could in part be due to the complex nature of flow provisioning between the River Murray and the Chowilla Anabranch

system or potentially greater inundation at 40,000 ML.day⁻¹ and its subsequent impact on within channel velocities.

Discharges at which modelling was undertaken for the Lock 1–2 reach by DEWNR were nearly identical to discharge when transects were measured in the field, allowing for direct comparison of actual and modelled mean velocities. At discharge of ~13,000 ML.day⁻¹, modelled and actual mean velocities were similar but at discharge of ~24,000 ML.day⁻¹ the modelling underestimated mean velocities across the reach and particularly in the upper weir pool location. These results highlight potential errors in the current hydraulic models at discharges of >20,000 ML.day⁻¹.

5 Conclusion and recommendations

We were unable to meet the original objectives of the project, investigating variability in hydraulic complexity between entitlement flows (3000–7000 ML.d⁻¹) and flows of ~15,000 ML.d⁻¹, but the current study was able to characterise hydraulic complexity at flows between 13,000 and 34,000 ML.d⁻¹ and will thus inform future environmental flow delivery of similar volumes. Typically, there was an increase in hydraulic complexity in regards to mean flow velocity, velocity ranges, within location variability in flow velocity and circulation, with increased discharge (23,000–33,000 ML.d⁻¹ QSA). This suggests that a greater diversity of hydraulic microhabitats may be provided at flows of this magnitude, potentially resulting in a greater ecological response. Nevertheless, given that some level of hydraulic complexity was present at 13,000–16,000 ML.d⁻¹ but virtually absent in the Lock 4–5 reach at flows <4,000 ML.d⁻¹, as presented by Kilsby (2008), a priority for future monitoring should be the collection of velocity data at flows of 4,000–13,000 ML.d⁻¹ to determine potential threshold flow rates beyond which hydraulic complexity begins to increase.

Of considerable importance for future research is developing an understanding of the association of native fish species with hydraulic habitats (at biologically relevant scales) and the explicit link between hydraulics and ecological processes (e.g. spawning and recruitment). Understanding the causal link between hydraulics and vital life history events, and determining the best hydraulic metrics to do so, will provide a powerful tool to inform future environmental water delivery. Ultimately, environmental water requirements could be specified as the provision of particular hydraulic conditions and the flow, and delivery strategies, required to create such conditions rather than a sole reliance on hydrological metrics.

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