REACH-SCALE SPATIAL HYDRAULIC DIVERSITY IN LOWLAND RIVERS: CHARACTERISATION, MEASUREMENT AND SIGNIFICANCE FOR FISH

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ABSTRACT

Hydraulic conditions (velocity, depth, turbulence) strongly influence the distribution and abundance of organisms in rivers. A diverse hydraulic environment should foster biodiversity, because organisms have different hydraulic preferences. In fact, the relationship between spatial hydraulic diversity and biodiversity is largely presumed, and not well-supported by empirical studies, but it underpins efforts in river restoration and conservation. This is particularly so at the *reach* scale, indicating a stream- or river-section with large-scale homogeneous geomorphic and hydrological conditions and smaller-scale habitat patches, as perceived by organisms in the community under study.

This thesis considers the factors that create spatial hydraulic diversity, and the ways that fish respond. It presents a method to characterise hydraulic diversity, and uses this to describe temporal and spatial changes between reaches. It also demonstrates the use of hydraulic modelling for comparing reaches. Finally, it assesses the Acoustic Doppler Current Profiler (ADCP) as a method to describe hydraulic conditions in a large, open river channel.

Swimming ability tests were applied to three small freshwater fish, the pelagic Australian smelt (*Retropinna semoni*) and common galaxias (*Galaxias maculatus*) and the demersal flathead gudgeon (*Philypnodon grandiceps*). The latter species was the weaker swimmer, but the tests indicated that behaviour also should be considered.

A laboratory experiment was designed to investigate how two species with contrasting ecological habits (common galaxias, flathead gudgeon) behave in a diverse hydraulic environment. Habitat choices and activity were monitored in a constructed sinuous channel at three discharges over a 3-hour period. The galaxias favoured the pelagic habitat, and spent 20-60% of the time cruising, whereas the flathead gudgeon preferred the demersal habitat and spent <6% of the time cruising. The flathead gudgeons could access their preferred habitat at all discharges, but the common galaxias were limited by their swimming ability at the highest discharge.

Several methods to characterise reaches were compared for eight 3-D model reaches representing the effects of channel form, wood and aquatic plants. The *variogram* (a measure of the variance between samples as a function of distance) emerged as a superior method because it indicates hydraulic diversity, incorporates the spatial arrangement of hydraulic patches, and facilitates comparisons between reaches.

The ADCP proved a quick, reliable means to measure depth and 3-D velocity in rivers. It was effective only in depths >1.5 m, but modified instrumentation may overcome this limitation.

Six reaches, including weir-pool and free-flowing sections, were compared at two discharges in the River Murray, Australia. Variograms derived from the ADCP data clearly demonstrated spatial differences between the sections, but temporal differences were less well-defined, suggesting that reaches may retain characteristic hydraulic patterns despite changes in discharge.

Opportunities for further research include: the issue of optimal levels of hydraulic diversity for fish and other biota; use of variograms as a tool for field studies of aquatic biota; and measuring reach-scale hydraulic diversity and biodiversity before and after reach manipulation (e.g. the placement of wood), to elucidate the effects of changes in spatial hydraulic diversity on reach biodiversity.

DECLARATION

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. I give consent to this copy of my thesis, when deposited in the University Library, being made available in all forms of media, now or hereafter known.

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1 INTRODUCTION

1.1 Scope

The distribution and abundance of aquatic organisms in flowing waters are governed by combinations of abiotic (physical, chemical) and biotic factors (predation, competition) (Jackson *et al.* 2001; Pedersen *et al.* 2008). As one component of the abiotic environment, the hydraulic habitat for organisms represents 'the physical characteristics of flow' (Statzner and Higler 1986). Understanding the hydraulic environment is a central challenge for river ecology.

Some fifty years ago, Ambühl (1959) demonstrated the significance of the hydraulic boundary layer for benthic invertebrates, and many researchers since have confirmed the role of hydraulics in the ecology of lotic organisms, including other macroinvertebrates (Statzner and Higler 1986; Lancaster and Hildrew 1993; Gore *et al.* 2001), macrophytes (Biggs 1996; Green 2005a) and fish (Lamouroux *et al.* 1999; Grift *et al.* 2003; King 2004; Stewart *et al.* 2005; Lamouroux and Cattaneo 2006).

The hydraulic environment is manifest at virtually all scales of space and time relevant to living organisms, and may be viewed as a nested hierarchy (Statzner *et al.* 1988). Each level in the hierarchy is constrained by higher levels (Frissell *et al.* 1986), and influenced by lower levels (Dollar *et al.* 2007). For example, the micro-scale (mm-m) habitat preferences of fish can have consequences for the entire community (Lamouroux and Cattaneo 2006). In a research program, the appropriate scales depend on the observer's frame of reference (the nature of the problem) and, of course, the target organism (Thomson *et al.* 2001). However, many studies are conducted at the *reach* scale.

The term ‘reach’ lacks a clear, consistent spatial definition (e.g. Petts 2000; Petts *et al.* 2006). It has been used to describe river sections from tens to thousands of metres long (e.g. Blanch *et al.* 1999; cf. Kemp *et al.* 2000; Booker 2003; Emery *et al.* 2003). In (small) streams, but not (large) rivers, a reach may be referred to variously as “several” to “exactly ten” pool-riffle sequences (Newbury and Gaboury 1993; Deschênes and Rodríguez 2007). A reach may be better regarded as a stream- or river-section with large-scale homogeneous geomorphic and hydrologic conditions, i.e. it contains no easily observable discontinuities such as a waterfall, change in slope, or tributary junction. These kinds of discontinuities can change the character of the reach and, significantly, they may represent barriers for fish movement.

As mentioned above, the spatial extent of a reach should be influenced by the research program and target organism(s). While reaches are characterised by similar large-scale features, they contain a variety of smaller-scale physical hydro-geomorphic *patches* (Newson and Newson 2000; Thorp *et al.* 2006). In this context, a patch is an area of homogeneous hydraulic conditions, as perceived by fish or target organisms typical of the community under study. A variety of different patches may provide a variety of habitat options; fish are likely to visit a number of patches within a reach (Crook 2004).

Hydraulic conditions within a reach are created by the unique combination of discharge and physical features (James and Thoms 2007), including channel form and the presence of obstacles such as wood, macrophytes and man-made structures (Jackson *et al.* 2001; Yarnell *et al.* 2006). Whereas discharge plays a pivotal role in creating temporal hydraulic diversity, site-specific physical features govern reach-scale spatial hydraulic diversity.

1.2 Hydraulics and biodiversity

In ecology, it is axiomatic that a diverse physical habitat encourages a variety of organisms (e.g. Begon *et al.* 1996) and, by extension, physical diversity in rivers should promote biodiversity (Gore 1996; Biggs *et al.* 1997). Although this idea is widely supported (Harper and Everard 1998; Kemp *et al.* 2000; de Nooij *et al.* 2006), there have been few empirical studies in support of it (cf. Gorman and Karr 1978; Schlosser 1982; Downes *et al.* 1998; Katano *et al.* 1998; Eros 2007), and it arguably remains a concept rather than a confirmed relationship (Kemp *et al.* 1999).

As a component of physical habitat, hydraulic diversity alone should promote biodiversity (Mann and Bass 1997; Grift *et al.* 2003). The wide range of hydraulic preferences established for aquatic organisms (e.g. Gore *et al.* 2001; Lamouroux and Jowett 2005) supports this, but again, empirical evidence is wanting (cf. Statzner *et al.* 1988; Gore *et al.*

1992; Jungwirth *et al.* 1993; Jungwirth *et al.* 1995; Gore 1996). Nevertheless, promoting spatial hydraulic diversity in rivers as a method for enhancing biodiversity is considered promising (Dyer and Thoms 2006), particularly in situations where there is little scope to manipulate the discharge.

Most research on the hydraulic interactions of fish has been studies of swimming ability and habitat preferences. Swimming ability tests, generally conducted in laboratory flumes, aim to determine ‘how fast a fish can swim’ or ‘the maximum displacement velocity a fish can withstand’ (Brett 1964). Hydraulic preference studies aim to obtain the preferred hydraulic environment of species at a specific age, primarily for input into habitat models. They are usually based on field observations, made through direct observation (e.g. snorkelling (Bult *et al.* 1998; Crowder and Diplas 2000b) or electro-fishing (Lamouroux *et al.* 1999; Maddock *et al.* 2004)).

Both approaches serve their intended purpose, but do not specifically look at the hydraulics-biodiversity association, or whether the promotion of hydraulic diversity is ecological beneficial. There are few data to show how fish react if exposed to a wide variety of hydraulic patches (cf. Holm *et al.* 2001), and how they may use different patches over time. In this thesis, the first data chapter (Chapter 2) uses a standard swimming ability procedure to determine the swimming ability of three small fish species, and discusses the ecological relevance of the tests. The second data chapter (Chapter 3) considers how fish use different hydraulic patches over time, how this changes with the availability of patches, how behaviour and swimming ability affect habitat choice and whether a diverse hydraulic environment could therefore potentially promote a diverse ecological community.

1.3 Measuring spatial hydraulic diversity

Another obstacle to understanding the hydraulics-biodiversity relationship is lack of a standardised method to *measure* spatial hydraulic diversity. The terms “variability”, “diversity” and “heterogeneity” are commonly used in reference to hydraulic conditions in a reach, but are vaguely defined. Here, they are used interchangeably, and refer to a range of equitably-distributed hydraulic patches of velocity and depth: the greater the range of patches, or more evenly distributed the patches, the more diverse the reach.

One approach to the measurement of reach diversity is the calculation of diversity indices from the number of ‘surface flow-types’ present in a reach (Padmore 1998; Eisner *et al.* 2007). However, the identification of surface flow-types is subject to bias (Maddock and Hill 2005), and the hydraulic distinctiveness of the flow-type categories is questioned (Newson *et al.* 1998; Kemp *et al.* 2000; Clifford *et al.* 2006). Further, the differentiation of surface flow-types is only possible on some reaches: for example, there may be little surface flow-type differentiation present on large, lowland rivers.

More generalised, stochastic approaches to describing diversity have been proposed (Lamouroux 1998; Stewardson and McMahon 2002), but these sacrifice information about the spatial arrangement of hydraulic patches (Crowder and Diplas 2000b; Crowder and Diplas 2006). The spatial arrangement of patches can have biodiversity implications: fish may seek refuge in slow-velocity patches adjacent to prey-laden faster-velocity patches (Mitchell *et al.* 1998; Deschênes and Rodríguez 2007).

Consequently, a method is needed to measure spatial hydraulic diversity that incorporates spatial structure, and is applicable to a wide range of reaches. The variogram is a measure of the variance between samples as a function of distance (Brooker 1991). As the location of the sample is considered when calculating the variance, it is a promising alternative.

Hydraulic modelling can be used to quickly compare reaches (Lane 1998), and is therefore well suited for use in developing a new method to describe reach spatial hydraulic diversity. Accordingly, Chapter 4 uses hydraulic modelling to model a range of virtual reaches, and then uses the model output to explore the different methods available to describe reach diversity, including variograms.

Any method using spatial information benefits from many data points. While this can be satisfied by using hydraulic modelling, modelling does not replace field measurements. Many field studies have used point sampling instruments (such as velocimeters) to measure reach hydraulic conditions, but point sampling only covers a restricted area, particularly in large rivers. Further, as their name describes, point sampling measures only at a point, and hence misses the three-dimensionality of the flowing water, which is what aquatic organisms physically experience.

Acoustic Doppler Current Profilers (ADCP) are a relatively new technology that measure the 3-D velocity at numerous intervals in the water column, as well as calculating the depth (Muste *et al.* 2004). They can be deployed from moving boats, quickly obtaining hydraulic measurements over a wide area (Dinehart and Burau 2005b). As yet, there has been little use of ADCPs for ecohydraulic purposes (cf. Shields *et al.* 2003; Shields and Rigby 2005; Thoms *et al.* 2006), although they appear well suited.

Thus, the last two data chapters of this thesis are dedicated to investigating the use of ADCPs to measure ecohydraulic conditions in a large river environment. As there has been limited use of ADCPs in an ecohydraulic context, reliability and suitability are first assessed (Chapter 5). Then, Chapter 6 considers whether ADCP data and variograms (developed in Chapter 4) can be used to identify the spatial and temporal differences between reaches.

1.4 Thesis outline

An outline of the data chapters is given below. Each chapter is written as a stand-alone chapter, which requires some repetition. Chapter 7, the general discussion, reviews the aims and contents of each chapter, highlights areas of new research, and offers recommendations for future work.

Chapter 2: Swimming ability of three species of small-bodied freshwater fish

Swimming ability studies have been performed for a variety of non-ecological reasons, but it has been suggested that their results can inform reach-scale habitat studies (Nikora *et al.* 2003). While attractive because they are straight-forward to perform, there are many procedural assumptions that can influence the swimming ability results, and therefore their ecological interpretation.

The aim of this chapter was to use a standard swimming ability test procedure to assess the swimming ability of three small-bodied fish. A small, recirculating flume was used, and three species, with contrasting body forms and ecological habits, were tested. The size, body form and ecological habit of the fish were expected to influence the test results. The chapter finishes with a discussion of the assumptions, application and ecological relevance of the swimming ability tests.

Chapter 3: Contrasting behaviour of two small pelagic and demersal fish species in diverse hydraulic environments

Most fish-hydraulic research has focussed either on fish swimming ability or hydraulic preferences. Hydraulic preferences (patch preferences) are dependent on a number of factors, including age, history, environment, season and activity, and fish may use different patches for different purposes (e.g. feeding, resting) – visiting a number of different patches over time. However, the behaviour of fish over time, given a choice of hydraulic patches, has not been studied.

The aim of this chapter was to study how fish respond to, and use, diverse hydraulic environments over time, how this might change with a change in hydraulic patches, and how it might differ between species. An artificial channel providing a variety of hydraulic conditions was created, and the behaviour of two species, chosen for their contrasting ecological habits, was recorded at three discharges. It was anticipated that the two species would have contrasting behaviour, and responses to changes in the hydraulic conditions, which characterise their ecological habits. The significance of these results to habitat modelling and the promotion of hydraulic diversity is discussed.

Chapter 4: Using Computational Fluid Dynamics and variograms to characterise reach-scale spatial hydraulic diversity

There is no standardised method to measure reach-scale spatial hydraulic diversity, although it is essential to understanding reach-scale spatial hydraulic diversity and biodiversity interactions. A number of different methods could be used to describe the diversity of samples from a reach, but only a variogram incorporates spatial arrangement. Thus, the variogram looks like a promising method, but its application to a variety of reaches with different hydraulic characteristics needs to be tested. Hydraulic modelling is well suited to systematically model a number of comparable, yet contrasting, reaches, and 3-D modelling is recommended for studies focussing on spatial features.

The aim of this chapter was to demonstrate the application of 3-D hydraulic modelling by modelling the effects that common instream features (channel form, wood and vegetation) have on the hydraulic environment of eight synthetic reaches. The spatial hydraulic diversity of the theoretical channels is then characterised using a number of common methods, and variograms. The use of 3-D modelling, the factors that affect, and methods to characterise (in particular the use of variograms), spatial hydraulic diversity, are discussed.

Chapter 5: Reliability and suitability of an Acoustic Doppler Current Profiler for use in large, lowland rivers

Hydraulic modelling complements, but does not replace, field measurements. Sampling the hydraulic environment to capture spatial diversity can be logistically difficult, particularly in non-wadeable rivers. ADCPs can be deployed from moving vehicles, rapidly measuring the 3-D velocity over wide areas, and therefore could be used to capture the spatial hydraulic diversity of reaches.

The aim of this chapter was to assess the reliability and suitability of an ADCP to measure hydraulic conditions in a large, lowland river. This was done by deploying an ADCP at six reaches along the River Murray, Australia, assessing the measured morphology, velocity and discharge, and discussing the associated practicalities and results.

Chapter 6: Using variograms and ADCPs to identify spatial and temporal differences between reaches

Channel form, instream obstacles (such as vegetation, wood and man-made structures) and discharge, influence spatial hydraulic diversity. Thus, spatial hydraulic diversity differs between reaches (spatially) and over time (temporally). For any method to be successful at measuring and characterising spatial hydraulic diversity, it must be able to portray this spatial and temporal diversity.

The aim of this chapter was to investigate whether variograms (discussed in Chapter 4) can be used to identify spatial and temporal differences between reaches, from data measured with an ADCP (discussed in Chapter 5). An ADCP was used to measure the spatial hydraulic diversity of six reaches along the River Murray at two discharges. The measured data are characterised using variograms, and the ability of variograms and ADCPs to represent spatial and temporal differences is discussed.

2 SWIMMING ABILITY OF THREE SPECIES OF SMALL-BODIED FRESHWATER FISH

2.1 Introduction

Swimming ability tests are performed for a number of reasons, including: physiological studies (Brett 1964; Hammer 1995); capacity to traverse fish ladders (Mallen-Cooper 1994; Davies *et al.* 2003; Cheong *et al.* 2006) or other hydraulic obstacles (Haro *et al.* 2004; Bice and Zampatti 2005; Tudorache *et al.* 2008); and for use in habitat modelling (Jowett 2002; Booker 2003). While most swimming ability tests are designed for a specific purpose, the results may also inform ecological knowledge; for example, stronger swimmers are more likely to be found in the pelagic zone of rivers than weaker swimmers. Other ecological characteristics of fish are also based on their swimming ability, such as migration, feeding niches, and escape and competition strategies (Nikora *et al.* 2003; Wolter and Arlinghaus 2003).

Between-species differences in swimming ability are related to body size and form: the body shape, muscle composition and ecological habit determine the swimming ability of fish. For example, a streamlined fish is likely to be a faster swimmer than a deep-bodied fish. White muscle fibre is associated with anaerobic metabolic processes, such as sprinting, and red muscle fibre is associated with aerobic processes, used in sustained, endurance swimming (Peake *et al.* 1997; Bice 2004). Therefore the proportion of red to white muscle fibre will affect swimming ability; a demersal species is less likely to have a high proportion of red muscle fibre than a pelagic species which is constantly exposed to current.

Swimming ability tests are generally divided into three categories of time (Beamish 1978). *Burst swimming* tests identify the greatest speed a fish can swim over short periods (<15 seconds), testing the fish's anaerobic metabolism (Hammer 1995). The *sustained speed* is the speed a fish can maintain for indefinite periods (>200 minutes), and tests the fish's aerobic metabolism (Hammer 1995). Between these is the *prolonged swimming* test (2-200 minutes), where a fish will use both anaerobic and aerobic metabolism, and thus both red and white muscles. A fish's performance in the different tests will therefore be dependent, among other factors, on the proportion of red and white muscle fibres (Bice 2004).

Prolonged swimming tests are usually conducted using one of two methods, the results of which are not directly comparable (Nikora *et al.* 2003):

- In the *fixed velocity (or fatigue)* test, fish (often in a group) are subjected to a constant velocity until they become fatigued (Hammer 1995). The *mean maximum sustainable swimming speed* is defined as the point where 50% of the fish fatigue (Brett 1967).
- The *incremental velocity* test involves incrementing the velocity by x m s^{-1} every y minutes until the fish (often singular) reaches exhaustion, and is used to calculate the *critical swimming speed* (U_{crit}) (Brett 1964).

The aim of this chapter is to assess the swimming ability of three relatively common species of small-bodied native Australian freshwater fish, and discuss the assumptions, application and ecological relevance of swimming ability trials and the results.

These species have different ecological habits, and therefore may have different swimming abilities. The common galaxias (*Galaxias maculatus*) occurs in the pelagic zone of slow-flowing environments at low elevations. It is a slender, streamlined fish that generally grows to 100 mm, although it can reach 190 mm (McDowall 1980; Allen *et al.* 2002) (Figure 2.1 (a)). The Australian smelt (*Retropinna semoni*) is a schooling, pelagic species also found in slow-flowing waters. It is moderately deep-bodied, usually growing to 50-60 mm, but can reach 100 mm (McDowall 1980; Allen *et al.* 2002) (Figure 2.1 (b)). The flathead gudgeon (*Philypnodon grandiceps*) is demersal and uses burst movements to ambush prey. It is also found in slow-flowing environments, including lakes. It has a broad, flattened head with a large mouth, and a slender body growing to 115 mm, but more commonly 80 mm (McDowall 1980; Allen *et al.* 2002) (Figure 2.1 (c)).

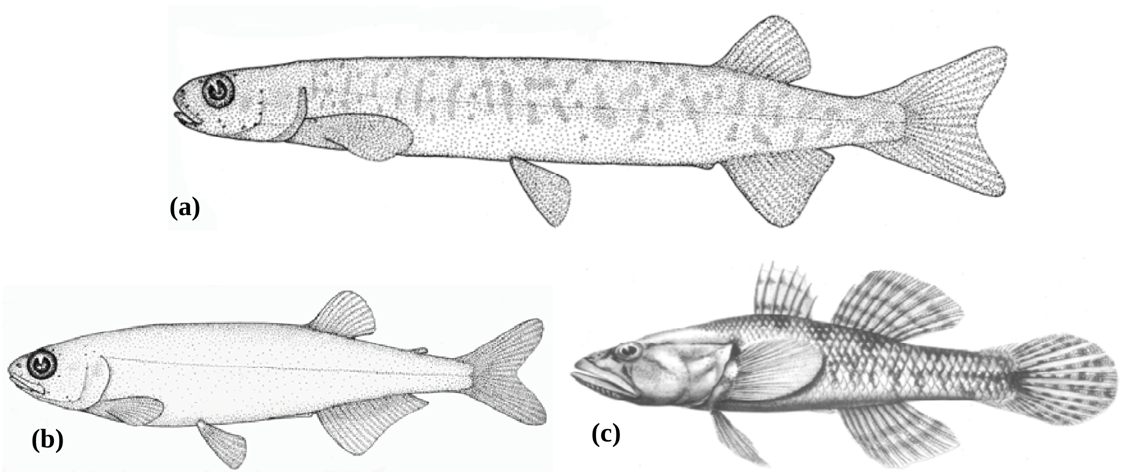


Figure 2.1: The three species studied: note their contrasting body shapes. (a) common galaxias (McDowall 1980), (b) Australian smelt (McDowall 1980), (c) flathead gudgeon (A.R. McCulloch in McDowall 1980).

2.2 Methods

2.2.1 Fish collection, housing and feeding

Australian smelt and common galaxias were netted from Lake Alexandrina, South Australia, in November 2006 and returned the laboratory in aerated containers. Flathead gudgeon were collected from the River Torrens, South Australia, using box traps. Fish were kept in filtered, aerated 40-L holding tanks and fed daily to satiation on live brine shrimp (*Artemia* sp.) and frozen bloodworms (Chironomidae). Five fish of each species were tested.

2.2.2 Flume and hydraulics

The recirculating flume used for the swimming tests is shown in Figure 2.2. Flow was generated by a four-blade propeller powered by an electrical motor (Baldock Industrial Motors, model 17417A); the velocity was controlled by the motor speed. Water depth was held at 150 mm, and the swimming zone was bounded at the upstream end by a flow collimator and the downstream end by a rigid flyscreen mesh. Velocity samples were measured using a Valeport Braystoke model 0012B current flow meter. Three 10 second samples were taken at 0.6 × depth (90 mm) at four locations within the swimming zone, for 20 motor speeds. From this a motor speed-average velocity curve was developed. After the trials, the velocity was again measured, but at 65 mm above the bottom, nearer where the fish were observed swimming. Three 10-second samples were taken for each velocity increment used in the trials. Water temperature was constant at 24°C, and the salinity at 300 ppm, as in the holding tanks.

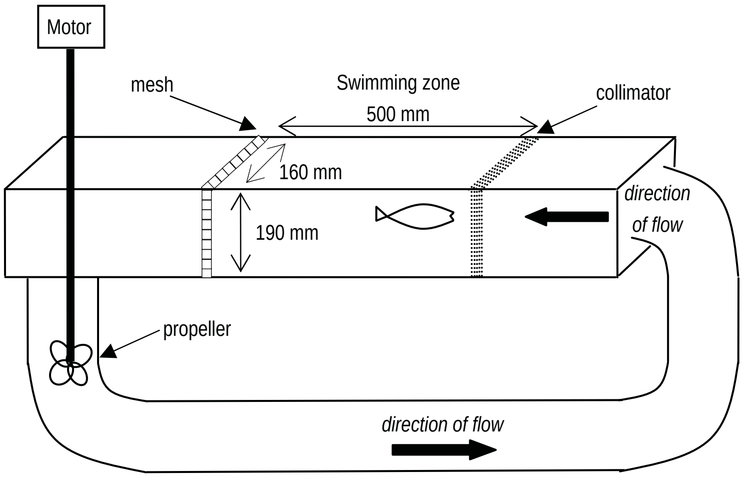


Figure 2.2: Schematic of the recirculating flume used for the fish trials. The swimming zone was made of clear Perspex.

2.2.3 *U_{crit} swimming ability tests*

The procedure was based on the incremental velocity test (Brett 1964; Brett and Sutherland 1965; Brett 1967). Brett (1964) recommended a time increment of one hour, but Nelson *et al.* (2002) modified this test for small fish species, decreasing the time increments to 5 minutes, the velocity increments to 5 cm s^{-1}, and confirming that their procedure produced repeatable results. Here, one major procedural change was introduced (for ethical reasons): the test was terminated when the fish reached exhaustion *or* when a maximum velocity (U_{test}) was reached. The increments for both velocity and time followed Nelson *et al.* (2002).

Swimming tests were performed from 12-15 February 2007. Fish were fasted for 24 hours before the trial (Beamish 1978). One fish at a time was transferred from a holding tank to the flume, flowing at 4 cm s^{-1}, and allowed to acclimate for 30 min. Thirty minutes was used rather than the recommended one hour, as the fish were not anaesthetized prior to transfer (cf. Nelson *et al.* 2002). After 30 minutes acclimation, each fish was exposed to an increasing velocity of 4 cm s^{-1} every 5 minutes, until U_{test} or exhaustion was reached. At this point, the time was noted, flow stopped, fish removed from the flume, measured, and returned to the holding tanks. U_{test} was defined as 0.46 m s^{-1}, equivalent to 45 minutes of active swimming. Exhaustion occurred when the fish became entrapped on the downstream mesh and did not respond to prodding. If exhaustion occurred, U_{crit} was calculated from Brett (1964) and Nelson *et al.* (2002) (Equation 2.1):

$$ {}_{U_{ii}}^{T}U_{crit} = U_i + \left(\frac{T_i}{T_{ii}} \times U_{ii} \right) \tag{2.1} $$

where U_{crit} = critical swimming speed (cm s^{-1}) calculated using time increments of T min and velocity increments of U_{ii} cm s^{-1} (here 4 cm s^{-1}, 5 min)
U_i = the highest velocity (cm s^{-1}) obtained for the full time increment
T_i = time of fatigue at last velocity (min)
T_{ii} = time increment (5 min)
U_{ii} = velocity increment (4 cm s^{-1}).

2.3 Results

A summary of the trial procedure and conditions is given in Table 2.1. The velocities reported are based on the conservative post-trial sampling, when samples were measured at a lower depth. In general, the velocity in the flume, based on measurements at two different heights at three locations within the flumes, varied within 0.07 m s^{-1} of the reported average for a given motor speed.

Table 2.1: A summary of the timing and velocity of the swimming ability test.

Start time (minutes)	End time (minutes)	Mean upstream velocity (m s^{-1})
0	30	0.04
0	5	0.08
5	10	0.12
10	15	0.17
15	20	0.21
20	25	0.25
25	30	0.28
30	35	0.36
35	40	0.41
40	45	0.46

The results of the modified swimming test are shown in Table 2.2. The Australian smelt and common galaxias successfully reached the maximum swimming speed (U_{test} = 0.46 m s^{-1}). The flathead gudgeon did not swim as strongly (U_{crit} = 0.23 m s^{-1}). Although direct comparisons of the results from different tests can be problematic (Nelson *et al.* 2002; Nikora *et al.* 2003), Table 2.2 includes a comparison of prolonged swimming ability results for the species studied, giving an indication on how results from one procedure may vary from another. Values are reported in m s^{-1} (not Body Length s^{-1}), as it is the absolute velocity that is of interest.

Table 2.2: Comparison of results from various studies on the swimming ability of the species studied. TL = total length (mm±SD) , Velocity = U_{crit} (incremental) or as specified (m s^{-1}), n = number of fish in study. * U_{test} maximum velocity tested, # for *Retropinna retropinna* (from New Zealand) not Australian smelt (*Retropinna semoni*). Studies are from Australia unless otherwise indicated.

Study	Type of test			Australian smelt	Common galaxias	Flathead gudgeon
This trial	Modified incremental 4 cm s^{-1}/ 5 min	n=5	TL	65.4±1.8	101±8.9	67.2±11.7
		24°C	*Velocity*	*0.46**	*0.46**	*0.23±0.04*
Bice (2004) & Bice and Zampatti (2005)	Constant velocity for 10 minutes. Velocity = 90% of fish passed.	n=100	TL			68.9±10.9
		18°C	*Velocity*			*0.107*
		n=100	TL			33.1±5.2
		18°C	*Velocity*			*0.075*
Davies *et al.* (2003)	Incremental 5 cm s^{-1}/ 5 min	n=10	TL		73±13.2	
		-	*Velocity*		*0.33±0.04*	
Nikora *et al.* (2003), New Zealand	Fixed (fatigue). Velocities estimated from the time-to-fatigue curve at 5 minutes	n=85	TL		48.0±2.5	
		18-22°C	*Velocity*		*0.23*	
		n=105	TL		62.2±6.5	
		18-22°C	*Velocity*		*0.3*	
		n=72	TL		91.8±10.3	
		16°C	*Velocity*		*0.42*	
Mitchell (1989), New Zealand	Variation on incremental – incremental flume	n=13-15#	TL	56-67#	52-73	
		17-20°C	*Velocity*	*0.27#*	*0.36*	

2.4 Discussion

This study aimed to assess and compare the swimming ability of three small-bodied fish with contrasting body forms and habits, and to discuss the assumptions and applications of the trials. Both Australian smelt and common galaxias (65±1.8, 101±8.9 mm TL respectively) swam in the open water, and withstood the maximum test velocity, U_{test} = 0.46 m s^{-1}. Conversely, the flathead gudgeon swam exclusively at the bottom of the flume, to a critical velocity of U_{crit} = 0.23 m s^{-1}.

Comparison of the three species

The results indicate a distinct difference in the swimming ability between the pelagic species (the common galaxias and Australian smelt) and the demersal species (the flathead gudgeon), reflecting their contrasting habits and body form. Pelagic species are adapted to constant swimming, whereas demersal species are adapted to resting, moving in a burst motion to change location or capture prey.

Given the different swimming abilities, it is expected that there is a difference in the proportion of white and red muscles between the species. Bice (2004) showed that the flathead gudgeon has a high proportion of white muscle fibre, which is why it is a poor prolonged swimmer but has good burst swimming ability. Unfortunately, no data are available on the comparative proportions of muscle in the other two species at present, but Bice (2004) did show that another small-bodied Australian pelagic species

(*Craterocephalus stercusmuscarum fulvus*) had a higher proportion of red muscle fibre than the flathead gudgeon. A similar pattern could therefore be expected for the common galaxias and Australian smelt.

Limited data exist on the swimming ability of other small-bodied Australian freshwater fish (see Mallen-Cooper (1994; 1996) for large Australian fish). Bice and Zampatti (2005) found that 90 % of adult *C. stercusmuscarum fulvus* (*c.*47 mm), could swim against 0.30 m s^{-1} for 10 min, and the deeper-bodied *Hypseleotris* spp. (*c.*35 mm) to 0.15 m s^{-1}. Another study of small fish in Germany shows comparable values: the *c.*50 mm teleost fish *Gasterosteus aculeatus* and *Leucaspius delineatus* have a critical swimming speed of *c.*0.37 m s^{-1}, while the larger, *c.*100 mm fish *Gobio gobio* and *Noemachelius barbatulus* attained speeds of >0.55 m s^{-1} (Stahlberg and Peckman 1987).

Procedural factors affecting reported values

Variations of incremental and fixed velocity tests have been widely used (Hammer 1995; Wolter and Arlinghaus 2003). For this experiment, the incremental velocity test was an appropriate and efficient procedure for assessing and comparing the swimming ability of three small-bodied species, as it: tested the swimming ability of each fish at each velocity (as opposed to different groups of fish being tested at different velocities, as in the fixed velocity test); and fish were tested individually, not in groups. However, based on Table 2.2, the procedure over-estimates the swimming ability of the test species. Farlinger and Beamish (1977) demonstrated that for the incremental test, U_{crit} is dependent on the increments of time and velocity used. Prolonged swimming involves anaerobic and aerobic metabolic processes; therefore the shorter the increments, the less build up of waste products from anaerobiosis, and therefore the higher velocity the fish can reach. The short time increments used in this study could partly explain why the common galaxias in this study appeared to be stronger swimmers than reported in other studies (Table 2.2).

Environmental factors such as water temperature, presence of pollutants, oxygen concentration, salinity and the ambient gas concentration will affect test results (Beamish 1978; Hammer 1995). Webb (1998) showed fish swimming performance differed with temperature, but that the magnitude of the effect depended on the species. In these trials, the temperature was relatively high (24°C), but it was consistent, allowing comparison between the species.

A fish’s race, population, training and rearing will also affect the swimming performance (Hammer 1995): for example, McDonald *et al.* (1998) demonstrated a difference in swimming performance between hatchery and wild Atlantic salmon (*Salmo salar*) fingerlings, as did Pedersen *et al.* (2008) for both Atlantic salmon and brown trout (*S. trutta*). For this trial, the fish tested were from the same population (within species).

The presence of other fish in the swimming flume may affect observed metabolic rates (Brett and Sutherland 1965) and observed swimming ability: the fish can either be excited by the presence of other fish, and increase their metabolic rate, or school with other fish, and decrease their energy expenditure. Australian smelt are a schooling species, and common galaxias can be found in schools, while the flathead gudgeon are a solitary species. In this study, the fish were trialled individually for consistency, but each species may have responded differently to the lack of fish: flathead gudgeon may be accustomed to it, but the Australian smelt may have been disorientated without the presence of other fish.

Water flow, as experienced by fish, consists of both velocity and turbulence components. Swimming costs can be affected by turbulence, increasing up to 1.3 to 1.6 times for increasing turbulence at a constant velocity (Enders *et al.* 2003). It is possible that the increase in opercular beat (a function of heart and ventilation rates) causes this increase in swimming cost (Davies *et al.* 2003). However, other studies have shown that different levels of turbulence have no effect (Nikora *et al.* 2003). It therefore appears that test results are specific to the trial (Nikora *et al.* 2003), and comparisons are relative.

Procedural assumptions affecting reported values

Most prolonged fish swimming ability tests make the assumption that the maximum velocity a fish can resist displacement is ‘how fast the fish can swim’. Nikora *et al.* (2003) mapped fish trajectories to test the assumption that the mean fish velocity is equal to the mean flow velocity in the experimental device and found that, in most cases, this was a reasonable assumption. However, this assumption, and the type of swimming (for example, steady versus burst-and-coast) should be considered when interpreting and using any results.

All prolonged swimming tests (incremental and fatigue), assume that the “fish swimming velocity” is identical to the cross-sectional mean velocity in an experimental device (Nikora *et al.* 2003). Swimming ability devices are generally designed to have as uniform a flow as possible; however, there will still be a range of velocities present, and this is not often reported. Nikora *et al.* (2003) took 39 velocity samples, reporting only the mean cross-sectional velocity in the time-to-fatigue curve, and Nelson *et al.* (2002) took 27 velocity samples, reporting only the mean. In this study a conservative estimate of the mean cross-section velocity has been reported (from the lower measured height), although, as stated, the sampled velocity varied within 0.07 m s^{-1} of the average for any given motor speed, revealing that a range of velocities were present in the flume.

As there were a range of velocities present within an experimental device, the velocity a fish experiences will depend on where the fish positions itself; that is, the fish’s behaviour, as influenced by its ecological habit. For example, although chub (*Leuciscus cephalus*) are weaker swimmers than roach (*Rutilus rutilus*) and dace (*L. leuciscus*), they were able to resist displacement in a rectangular flume because of their ability to locate slower velocity patches (Garner 1999). A difference in positioning was observed between the three species trialled in this study, which reflected their different habits; the flathead gudgeon differ significantly in their swimming style from both the common galaxias and Australian smelt.

The flathead gudgeon are limited in their sustained swimming ability; instead, to maintain position in a flowing channel, they rely on a burst-and-coast method. In the rectangular flume they resisted attempts to encourage them into the pelagic zone, instead staying on the base of the flume, and trying to resist displacement by securing their fins against the flume wall. They were therefore able to resist a stronger velocity than they could steadily swim against. This swimming style reflects their demersal and ambushing (bursting skills) habit.

Both Australian smelt and the common galaxias were comfortable in the pelagic zone, and used their swimming ability only to resist displacement. Their swimming style was steady for the lower velocities, but both species (more noticeably the common galaxias) were observed to gradually change their style to a more erratic burst-and-coast as the velocity increased. Both species used the whole flume; from the upstream to downstream ends, bottom to top of water column and both sides. Some appeared to find a slightly reduced velocity patch, generated by the collimator frame, and would favour that position. This swimming style also supports the pelagic habit of these species.

Application and ecological relevance of swimming ability trials

Given that swimming ability test data are dependent on the specific trial procedure used and common assumptions, does this mean that applications are confined to the laboratory (Beamish 1978), or can they be used for ecological purposes (Jowett 2002; Nikora *et al.* 2003)? While knowledge of fish swimming abilities might contribute to understanding broad-scale ecological patterns and distributions (e.g. a strong swimmer might occur in the pelagic zone of fast-flowing rivers), other interpretations of what the swimming ability results mean could be misleading.

Although this study showed that flathead gudgeon cannot swim for as long as, or against as strong a current as the Australian smelt and common galaxias, this does not indicate they will not be found in the same river reaches (Peake *et al.* 1997). This chapter has demonstrated that flathead gudgeon have the ability to locate, and use, tiny patches of lower velocity. The schooling behaviour of some species will also influence their distribution based on their swimming ability: Australian smelt are a schooling species, and the energy expenditure in the middle of a school would be significantly less than for a lone fish, enabling them to perhaps live in a greater range of habitats. Therefore, it is likely that, although these species were found to have differing swimming abilities, they would be able to cohabit the same locations (Peake *et al.* 1997). Further work is needed however, to understand the behaviour of fish species when exposed to a range of hydraulic conditions.

Swimming ability tests have successfully been used to investigate critical events related to ecosystem health, such as high flows (Booker 2003), the larval life stage (Mann and Bass 1997), and hydraulic barriers (Mitchell 1989; Wolter and Arlinghaus 2003), but careful interpretation is needed. Further, these applications are rarely underpinned by field data. More field data are needed to successfully start applying swimming performance data to ecological issues such as river management and restoration.

3 CONTRASTING BEHAVIOUR OF TWO SMALL PELAGIC AND DEMERSAL FISH SPECIES IN DIVERSE HYDRAULIC ENVIRONMENTS

3.1 Introduction

Determining environmental flow requirements for fish is a common task for aquatic scientists and river managers. One approach is to couple physical and biological models to determine habitat, and therefore flow requirements, in a river reach. PHABSIM (Physical Habitat Simulation, Bovee 1982; Bovee 1986) and RHYHABSIM (River Hydraulic and Habitat Simulation, Jowett 1989) are examples of this approach, combining a hydraulic model of a river reach (the physical model) with Habitat Suitability Indices (HSI) for the target species (the biological model) to determine the areas of usable habitat for that species at different flows. However, this approach is sensitive to hydraulic modelling assumptions (Gan and McMahon 1990; Booker and Dunbar 2004; Gard 2005) and to changes in the choice of the HSI (Holm *et al.* 2001; Booker and Dunbar 2004; Moir *et al.* 2005). While variations of this approach have been developed (e.g. Lamouroux *et al.* 1998; Stewart *et al.* 2005; Mouton *et al.* 2007b), there are issues linking the physical and biological models (Smith and Brannon 2007).

The use of HSIs as the biological model is one factor causing the mismatch in linking physical and biological models. Although HSIs can incorporate habitat features such as substrate, their focus is usually on the depth-averaged velocity preferences of the target species. While these preferences are often produced from field based sampling (Jowett and Richardson 1995; Lamouroux *et al.* 1999), and may include some knowledge of swimming ability (Nikora *et al.* 2003) and whether the fish is juvenile or adult, they do not take account of preferences varying due to factors such as: age (that is, the continuum of life stages); activity (e.g. resting, feeding); season (breeding, growing); competition from other species; the presence of predators; and the availability of habitat. These factors could significantly affect the outcomes from habitat modelling, which often guide river restoration and environmental flow designs.

Some river reach restoration projects aim to promote diverse ecology communities rather than focus on a specific species. Because of the potential for conflicts between the species-specific HSIs, (Jowett and Richardson 1995; Gore *et al.* 2001; Doledec *et al.* 2007), and their data-intensive nature, they are not the appropriate tool to guide these projects. Instead, increasing the range of habitats available in a reach, by increasing the hydraulic diversity, could provide for a range of species, and activities, thereby fostering biodiversity (Mann and Bass 1997; Thoms 2006). However, little is known of the behaviour of organisms in spatially and temporally diverse hydraulic environments, and whether the promotion of hydraulic diversity in river reaches is therefore ecologically beneficial.

The aim of this experiment was to study the behaviour of two species of common small Australian freshwater fish offered a range of hydraulic conditions. An artificial channel providing a variety of hydraulic conditions was created, and the behaviour of the fish was recorded at three different discharges. The species used were chosen for their contrasting ecological habits (pelagic *versus* demersal). It was anticipated that both species would use a variety of hydraulic habitats within the experimental time, but would have contrasting preferences and different responses to changes in the hydraulic conditions which characterise their ecological habits.

The demersal (bottom-dwelling) flathead gudgeon *Philypnodon grandiceps* (Krefft) (Eleotridae) (Figure 3.1) is a deep-bodied species with a flat, broad head and large mouth, growing to 80-115 mm (Total Length: TL) (McDowall 1980). It prefers quiet waters, but may occur in fast-flowing streams, estuaries and inland lake basins (McDowall 1980). It is an ‘ambush’ predator, reflected in its body shape and swimming ability (Bice 2004; Bice and Zampatti 2005).

The common galaxias, *Galaxias maculatus* (Jenyns 1942) (Galaxiidae) (Figure 3.1) is a pelagic (open water) species that is widely distributed across the Southern Hemisphere. It is also known as the common jollytail, spotted minnow, inanga (New Zealand) or puyen (Chile and Argentina), and sustains commercial fisheries in New Zealand and Chile. It is a slender, streamlined fish that generally grows to 100-190 mm TL (McDowall 1980). It occurs in estuaries and gently-flowing lowland rivers and streams, or the margins of lentic habitats (McDowall 1980), drift-feeding on passing invertebrates (Jowett 2002). There have been several studies on the biology and swimming ability of the species (Mitchell 1989; Jowett 2002; Nikora *et al.* 2003; Chapman *et al.* 2006; MacDonald and Davies 2007).

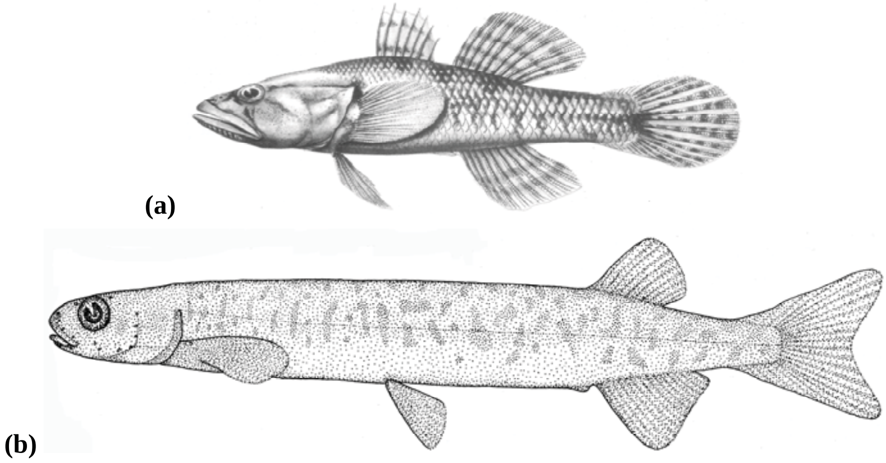


Figure 3.1: Sketch of (a) the flathead gudgeon (A.R. McCulloch in McDowall 1980), and (b) the common galaxias (McDowall 1980).

3.2 Methods

3.2.1 The channel

An artificial, sinuous channel was constructed in a flat rectangular flume in the Chapman Hydraulics Laboratory, The University of Adelaide, Australia (Figure 3.2). The base flume measured 25 m long by 1.2 m wide. One-year old reticulated water was recirculated through the flume from a holding tank situated above the flume, which was kept at a constant head. Flow through the flume was controlled from two points: a valve on the upstream end controlling the quantity of water, and a weir on the downstream end controlling the height of the water. The central 15.4 metres of the flume was partitioned with wood panelling and 5 mm mesh which allowed water, but not fish, to pass. The channel was shaped in sand and a cement render was applied to secure the sand. The majority of the channel had a standard curved cross-section of 100 mm base and 400 mm top, but the morphology included bends of different curvature and shallow benches. The topography of the flume was mapped using a regular grid of 0.2 m in the downstream, and 0.1 m across the flume (a total of 924 points). A contour diagram of the flume is shown in Figure 3.3, to highlight the sinuous channel, and the variety of cross-sections, with respect to the water level.

In addition to the variety of hydraulic conditions created by the morphology, two other common river features were mimicked: boulders and wood. Two piles of boulders were placed in the channel. The upstream boulders were placed in a straight section of channel, and consisted of one large, upright boulder at the upstream end, a short gap, and a randomly placed pile of 15 boulders of *c.*100×70×50 mm. The downstream boulders were placed on the downstream side of a bend, and consisted of one large boulder at the upstream end and a pile of eight boulders of similar dimensions. Two wood piles were mimicked using a combination of rectangular timber and cylindrical metal, positioned to ensure the timber did not float away. The upstream wood pile was placed just upstream of a bend and consisted of four pieces of timber and four pieces of metal of varying sizes, and the downstream wood pile was placed in a straight section of channel, upstream of the outflow, and consisted of four pieces of metal and six pieces of timber, also of varying sizes.

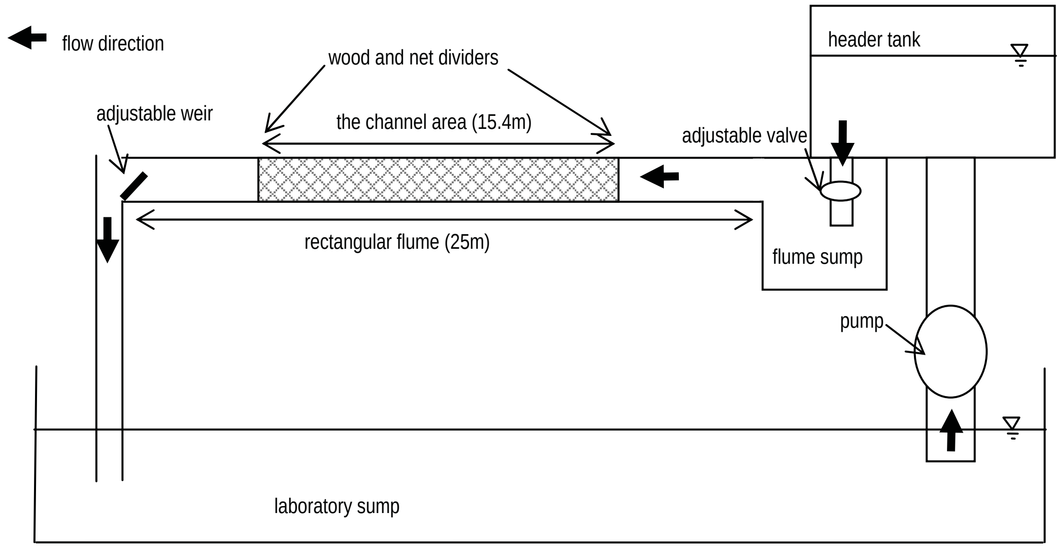


Figure 3.2: Sketch of the recirculating flume, showing the 15.4 metre section where the channel was built.

As well as a variety of hydraulic patches created, and visual cover caused by the boulders and wood, shading was the other habitat variable incorporated. During daylight hours a constant light intensity was provided by overhead fluorescent lights, offset to reduce reflection in the camera, and shading was created by the flume walls. The light intensity at the water surface stayed consistent at ~1 lux (shaded areas 0.2 lux).

Figure 3.4 shows a sketch of the above mentioned attributes and their placement in the channel, while Figure 3.5 shows some representative cross-sections. Photos of the actual channel can be seen in Figure 3.6.

Three discharges were used: low (12.7 L s^{-1}); medium (20.8 L s^{-1}); and high (40.2 L s^{-1}). The water depth stayed approximately constant between the different discharges, so that the discharge changed only the velocity and turbulence.

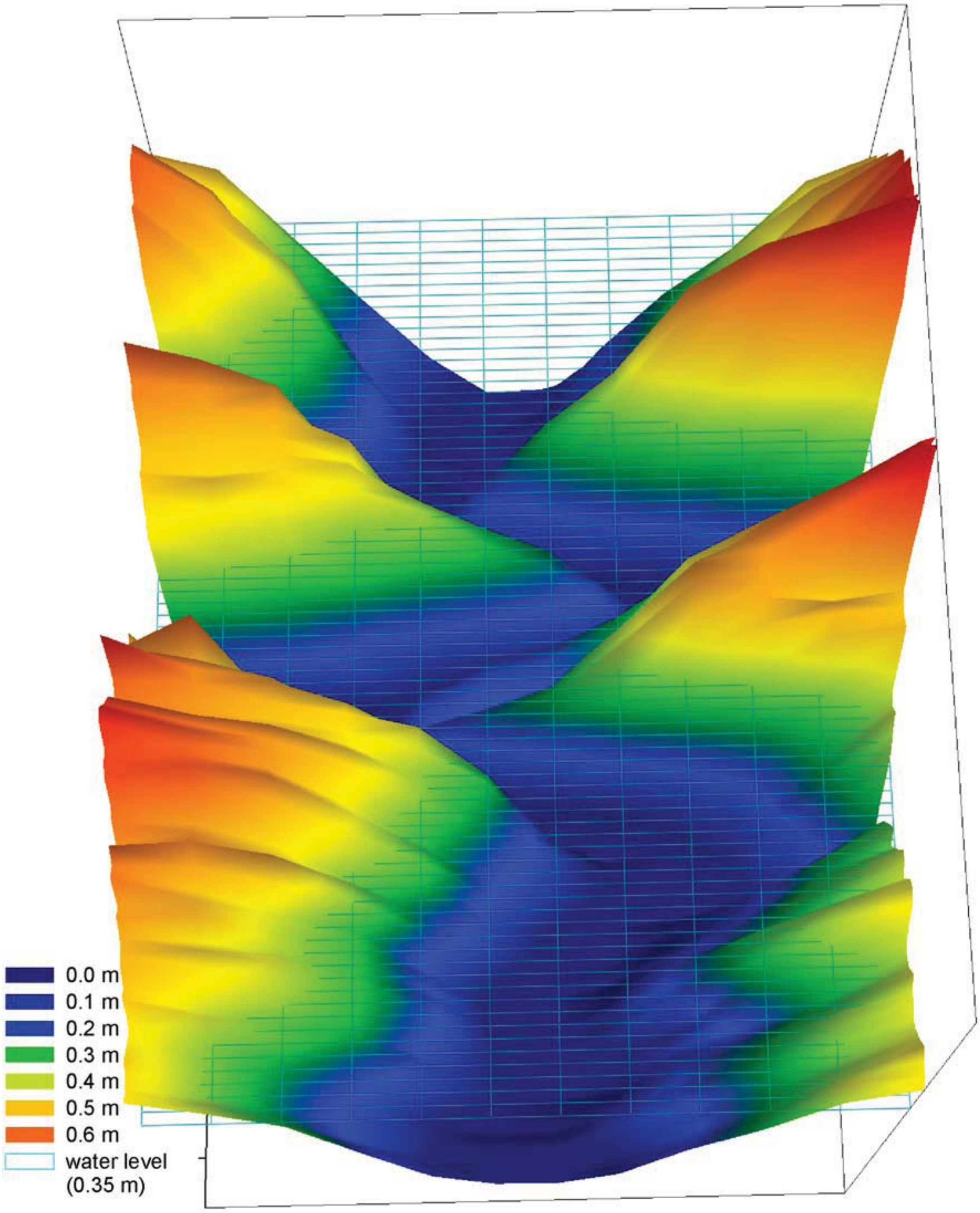


**Figure 3.3: Contour diagram of the channel, looking downstream.
The water level is shown by the blue grid.**

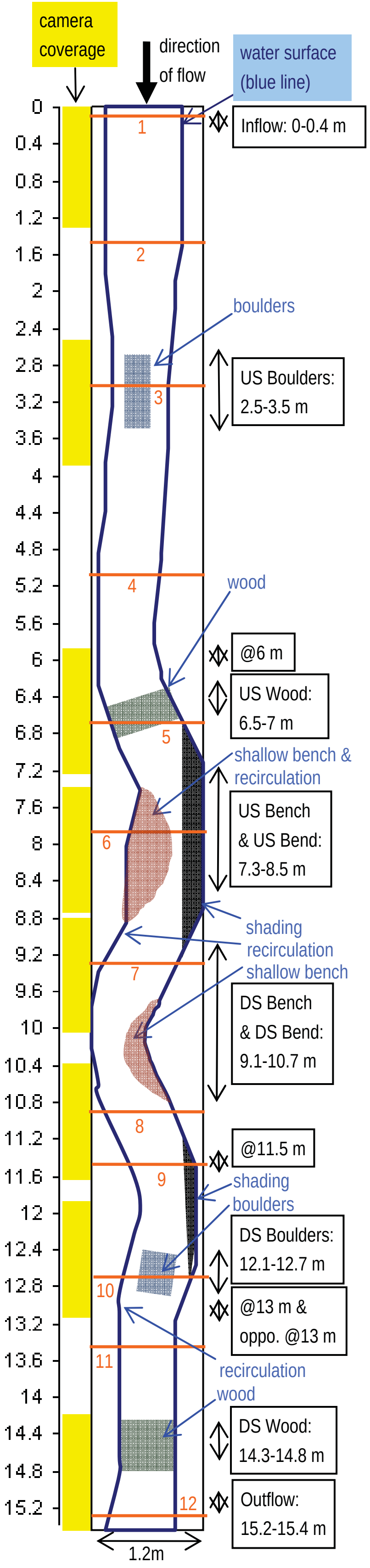


Figure 3.4: Sketch of the channel, showing the channel form and additional features. All distances are measured from the inflow, and descriptions of areas referred to in the text, including the area they cover, are shown in the boxes. The camera coverage is shown by the yellow blocks, and the red lines show the positions of cross-sections shown in Figure 3.5.

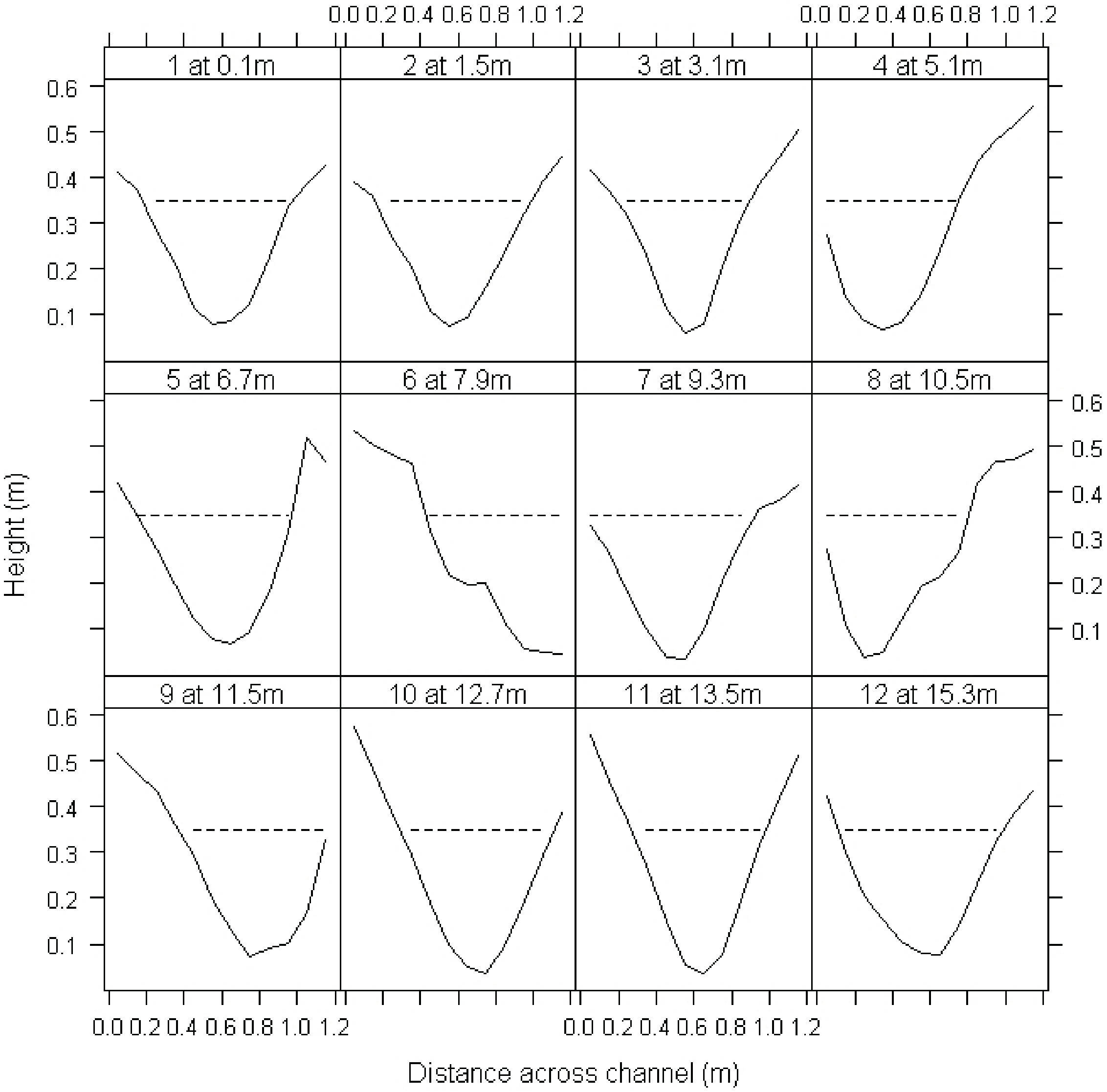


Figure 3.5: A sample of cross-sections of the channel, as shown in Figure 3.4. The water level is shown by the dashed line.

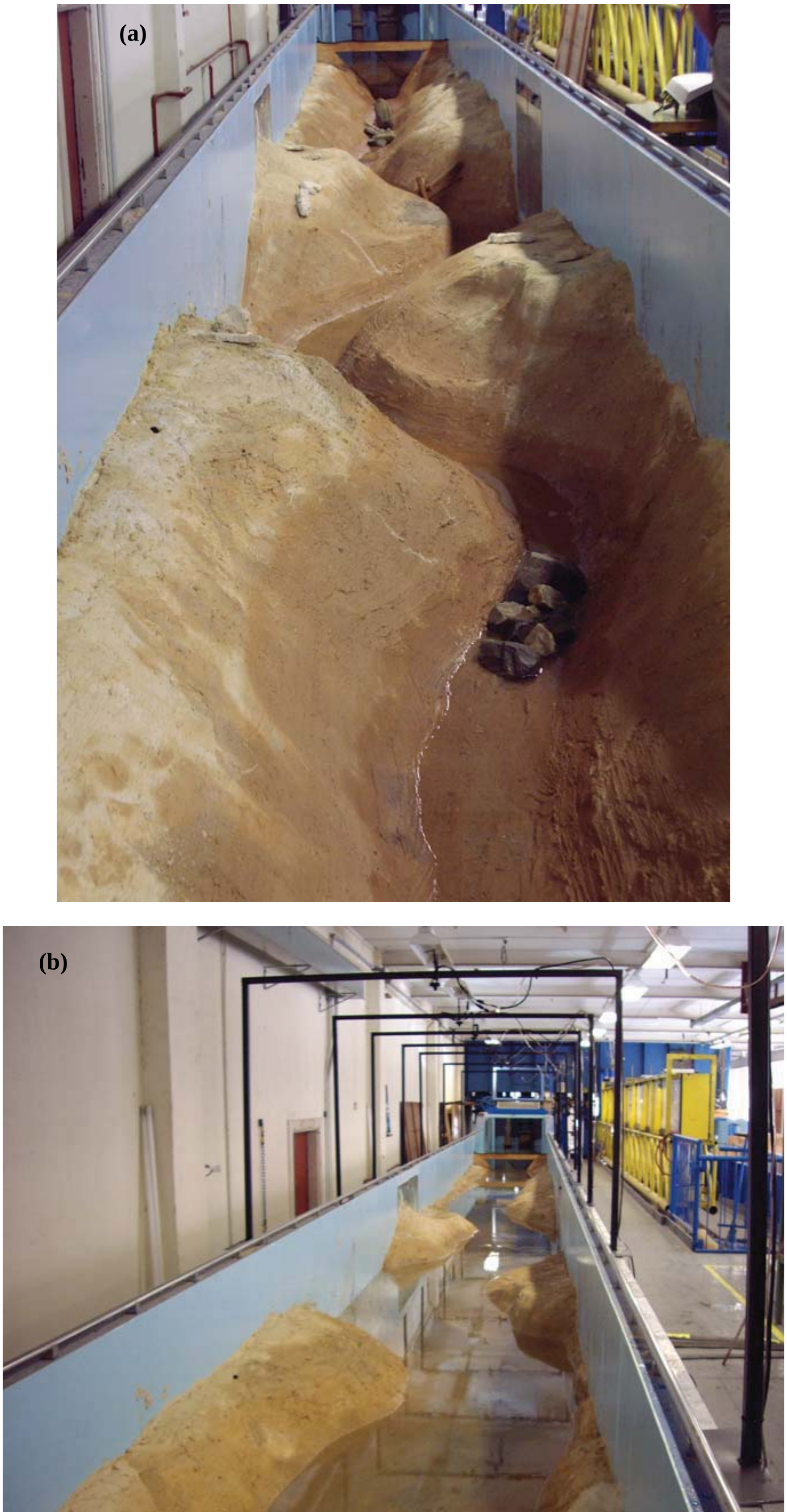


Figure 3.6: Photos of the flume, looking upstream (a) without water, showing the boulder piles and upstream wood pile, and (b) with water (low discharge), showing the cameras and camera frames.

3.2.2 The fish and trial procedure

Common galaxias were taken from Lake Alexandrina, South Australia, and flathead gudgeons were from the River Torrens, South Australia. The fish were kept in filtered, aerated, 40 L containers next to the flume, and water was exchanged weekly between the flume and containers. The fish were fed daily to satiation on a diet of live brine shrimp (*Artemia* sp.) and frozen bloodworms (Chironomidae).

Nine fish were used for each trial, and were chosen randomly from pools of 13 galaxias (100 ± 9 mm TL ± SD) or 15 gudgeons (65 ± 9 mm TL ± SD). The water temperature varied from 20-24°C during the period of the trials (November 2006 to February 2007), but the salinity was a constant 300 ppm. Both species were trialled at the three discharges, and each fish/discharge combination was repeated three times.

The procedure for the trials involved placing nine fish in a 10 L bucket; submerging the bucket in the middle of the channel (at 7.7 m – Figure 3.4), allowing the fish to escape; acclimating the fish to the channel for 22 hours at low discharge; and, at 22 hours either checking the flow (low discharge), or increasing the discharge to medium or high discharge, for a further 2 h acclimation before the 3 h recording period. The fish remained undisturbed by human presence from when they were first placed in the channel. At the end of the recording period the fish were returned to their housing containers.

3.2.3 Image capture

Eight colour CCTV cameras (512x492 pixels) were positioned ~1.5 m above the water level using adjustable steel frames (Figure 3.6(b)). Each camera covered approximately 1.3 m of the flume, so that ~70% of the channel was visible through the cameras (as shown in Figure 3.4). The cameras were linked to a computer and data recorded and viewed using KGuard Security digital surveillance software. The computer was connected to the university computer network and UltraVNC software used to remotely view and control the computer from an external building. In this way the fish could be monitored, and the software operated, without human interference.

3.2.4 Image analysis

The software allowed detailed viewing of the fish videos with the ability to pause, fast forward and rewind the footage and watch one, four or eight cameras at a time. Thus, the fish activity and position over the three hour period could be recorded to the second, and was usually completed within 10 hours' viewing time. One person did all the analysis, to limit possible bias.

Fish were recorded as 'holding position' or 'cruising'. The former applied to lone fish that remained in one continuous hydraulic patch for >30 seconds (s), or two or more fish that remained for >25 s. If these were joined by another fish, even briefly, every second of occupancy was counted. Fish were “cruising” (actively exploring) if they were in an area for less than this time. In this way, every second of fish activity within the 3 h period was accounted for. The behaviour results are reported in “fishsecs”, which for the purpose of this study has been defined as the “the number of fish multiplied by the time in seconds”. There was a total of 97,200 fishsecs (9 fish x 3 hours) in each trial.

As the two species have different swimming techniques and habitat choices, these two activity types took on slightly different forms. For the demersal flathead gudgeons, “holding position” generally referred to finding hydraulic refuge and cover, either under boulders or wood or directly on the rough cement render, while “cruising” referred to repeated bursts of swimming followed by a rest on the render. For the pelagic common galaxias, “holding position” referred to swimming against the current (often near the water surface) in one spot, and “cruising” involved actively swimming and exploring the flume.

3.2.5 Hydraulic measurements

Velocity measurements were taken using a SonTek 25 Hz laboratory downward-facing Acoustic Doppler Velocimeter (ADV). ADVs: sample a small volume of water at a distance from the probe, such that the probe itself does not interfere with the flow of water (here a volume of 0.25 cm^3, 5 cm from the probe); record a time series of the velocity, which can be used to calculate turbulence characteristics; and measure the three-dimensional velocity (stream-wise, cross-stream and vertical) (Nikora *et al.* 2003). The principles of operation are described by Nikora and Goring (1998; 1999).

As the reticulated laboratory water was clear and sand-filtered, seeding was needed to improve the Signal-to-Noise Ratio (SNR) of the ADV. Potters clay was suspended in water (to create turbid water) and inserted into the water stream through a 5 mm metal pipette approximately 150 mm upstream of the probe. The suspended clay proved to be effective at increasing the SNR to acceptable levels. Generally, the ADV correlation (a quality parameter for the velocity data; (SonTek 1995a)) was satisfactory (>70), often increasing with the SNR: however, the correlation was unacceptably low when significant turbulence could be seen in the water. This only occurred at the high discharge, and additional seeding did not improve the quality of the sample in these cases (see Mori *et al.* 2007). As well as improving the SNR, the seeding aided flow visualisation (Roy *et al.* 1999), highlighting areas of recirculation and parallel stream lines. During all measurements, the ADV was pointed in the same direction (parallel to the flume walls), regardless of the channel form, for consistency.

The purpose of the velocity sampling was to get an understanding of the variety of conditions present within the cross-sections at different discharges, rather than to provide a depth-averaged cross-sectional velocity, and therefore the velocity was sampled at a range of depths on a strict 3D grid. The horizontal grid was the same grid used to measure the form of the channel: adjacent cross-sections were spaced at 20 cm intervals, while points across the channel were spaced at 10 cm intervals. The shallowest sample was measured approximately 7 cm below the water surface, which was the shallowest depth feasible in allowing the probe to be fully submerged and taking into account the sample depth of 5 cm below the probe. Depending on the depth of water, and allowing for the sample to be at least 2 cm from the boundary (see Precht *et al.* 2006), another sample was taken either 5 *or* 10 cm deeper, and then again at either 5 *or* 10 cm deeper than that. The strict vertical grid meant an objective format between cross-sections. Thirty-five of the 77 cross-sections were sampled at the three discharges, for a total of 1425 sample points.

Each sample was filtered using WinADV (Wahl 2000) with the criteria: average correlation >70; average SNR>5; and phase threshold spiking (Goring and Nikora 2002), as recommended by SonTek (1995b) and Wahl (2000) (see discussion by Wahl). The aim of filtering was to ensure that each measurement had at least 500 'good' (filtered) samples. This number was chosen as a balance between data quantity and quality. If a measurement, once filtered, had fewer than 500 good samples, it was remeasured in the laboratory. If, on the second attempt, there were still fewer than 500 samples, then the measurement was used for the velocity (number of good samples >100), but not for turbulence calculations.

It is common to specify a time rather than a minimum number of good samples (e.g., Daniels and Rhoads 2003; Enders *et al.* 2003; Nikora *et al.* 2003; Wilson *et al.* 2003; Biron *et al.* 2005; Jonsson *et al.* 2006; Daniels and Rhoads 2007; Smith and Brannon 2007; Wilcox and Wohl 2007), but a time specification alone details only the quantity, not the quality of the data. Further, although some studies do describe filtering procedures (Daniels and Rhoads 2003; Daniels and Rhoads 2007; Smith and Brannon 2007; Wilcox and Wohl 2007), there is little reporting on the final quality of the data. This study is using a new approach to report the data. In general, to obtain >500 "good" samples per sampling location, measurements were for 30-45 seconds, depending on real time visual inspection of the quality of the time series. Individual files were created at each sampling location. After processing with WinADV, further filtering was carried out by manual inspection.

The velocity used here is the *Average Velocity Magnitude*, the average of the individual velocity magnitude values for the time series, as opposed to the *Magnitude Velocity Average,* calculated from the resultant three average velocity components (V_x, V_y, V_z) (Wahl 2000). The *Average Velocity Magnitude* therefore does not indicate the direction of the flow.

To describe turbulence, the average Turbulent Kinetic Energy (TKE) was calculated following Wilcox and Wohl (2007), representing the overall three-dimensional turbulence intensity in N/m^2 (Equation 3.1) (see also Clifford and French (1993), Smith and Brannon (2007) and Jonsson *et al.* (2006) for variations):

$$TKE = \frac{1}{2}\rho\left(RMS_u^2 + RMS_v^2 + RMS_w^2\right) \qquad \textbf{(3.1)}$$

Where ρ = fluid density (here assumed to be 1000 kg m^{-3})
RMS = root-mean-square of the velocity component (u, v, w)

All graphics were done using R: a language and environment for statistical computing (R Development Core Team 2007)

3.3 Results

3.3.1 Hydraulics

Box plots of the velocity and TKE samples from individual cross-sections of the three discharges are presented in Figure 3.7 and Figure 3.8 respectively. A further summary, including the number of sample points per cross-section, is shown in Table 3.1. The number of measurements per cross-section varied from 4-19 with an average of ~12-13. The number of good samples per cross-section generally decreased for the high discharge, and for the TKE calculations.

The Box plots show that a range of conditions was present at all three discharges. Generally, the narrow, featureless cross-sections (such as cross-section "11", Figure 3.5, at 13.5 m) had a narrower range of velocities, and a lower turbulence, than more diverse cross-sections (see cross-section "7"), where slow- and fast-flowing patches were present. The areas with boulders and wood also had a greater range of velocities, and increased turbulence, although their effects were localised. The inflow region (0.1-0.3 m) had a wider range of velocities, and was more turbulent than the outflow region (15.1-15.3 m). The hydraulic patterns appeared to be preserved between the different discharges, shown by the similarity of Box plot shapes (for example, see the cross-sections measured over the upstream boulder region, from 2.5-3.7 m).

Figure 3.9 shows plots of TKE against velocity for the individual samples for the three discharges. Velocity did not have a controlling effect on the turbulence, as shown by the low Kendall's correlation (for non-Normally distributed data) for each discharge (0.11, -0.01 and -0.12 for low, medium, high respectively). For example, for the wide range of velocities present at the upstream bend (7.7-8.1 m) there was a narrow range of TKE values, while the downstream boulder region (12.1-12.7 m) had a relatively small range of velocity, but there was a relatively wide range of turbulence. However, there was a general increase in turbulence at the higher discharge (Figure 3.8), demonstrated by the higher pooled correlation (0.28) and Figure 3.9.

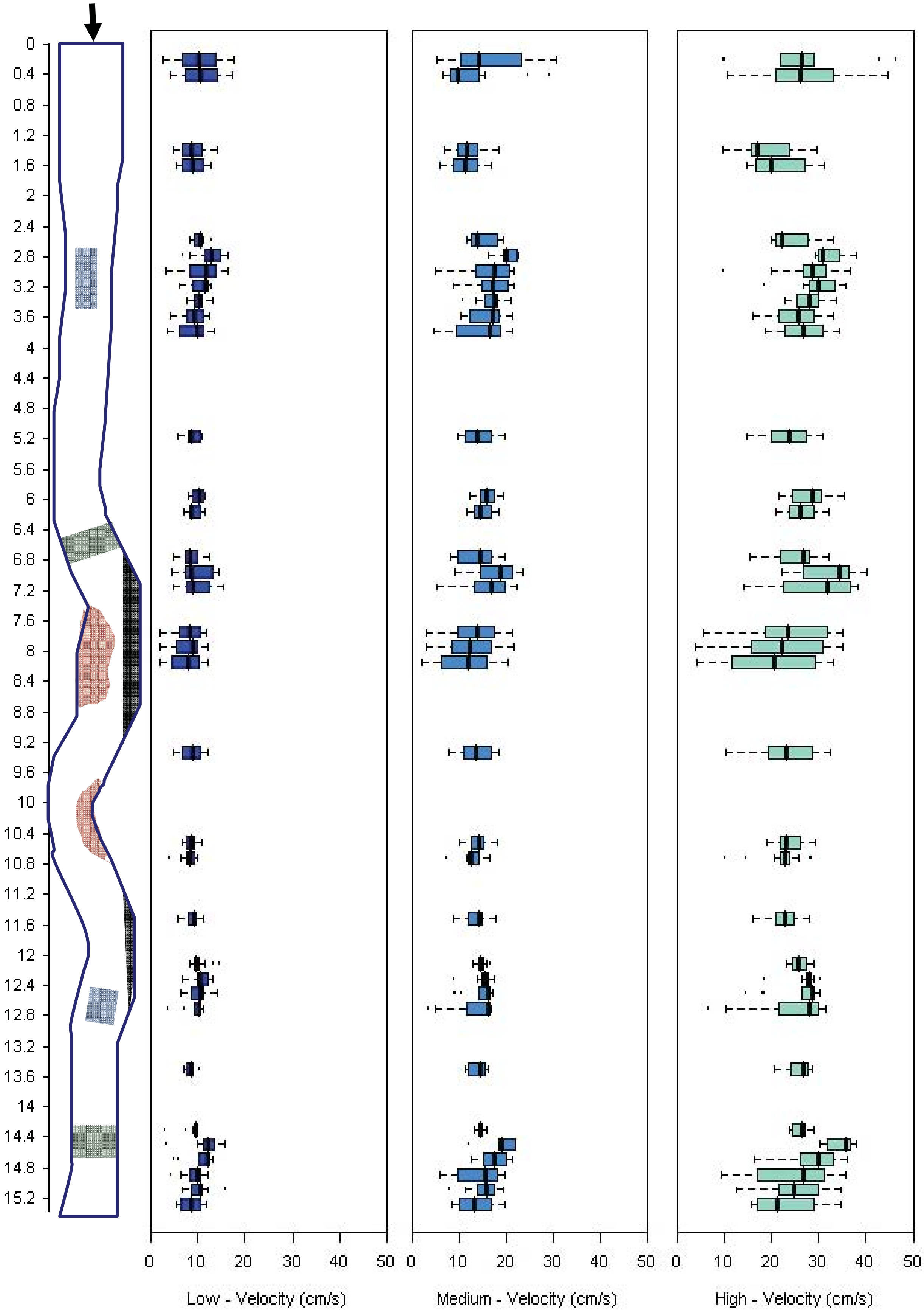


Figure 3.7: Box plots of average velocity magnitude measurements from different cross-sections for the three discharges (low, medium and high).

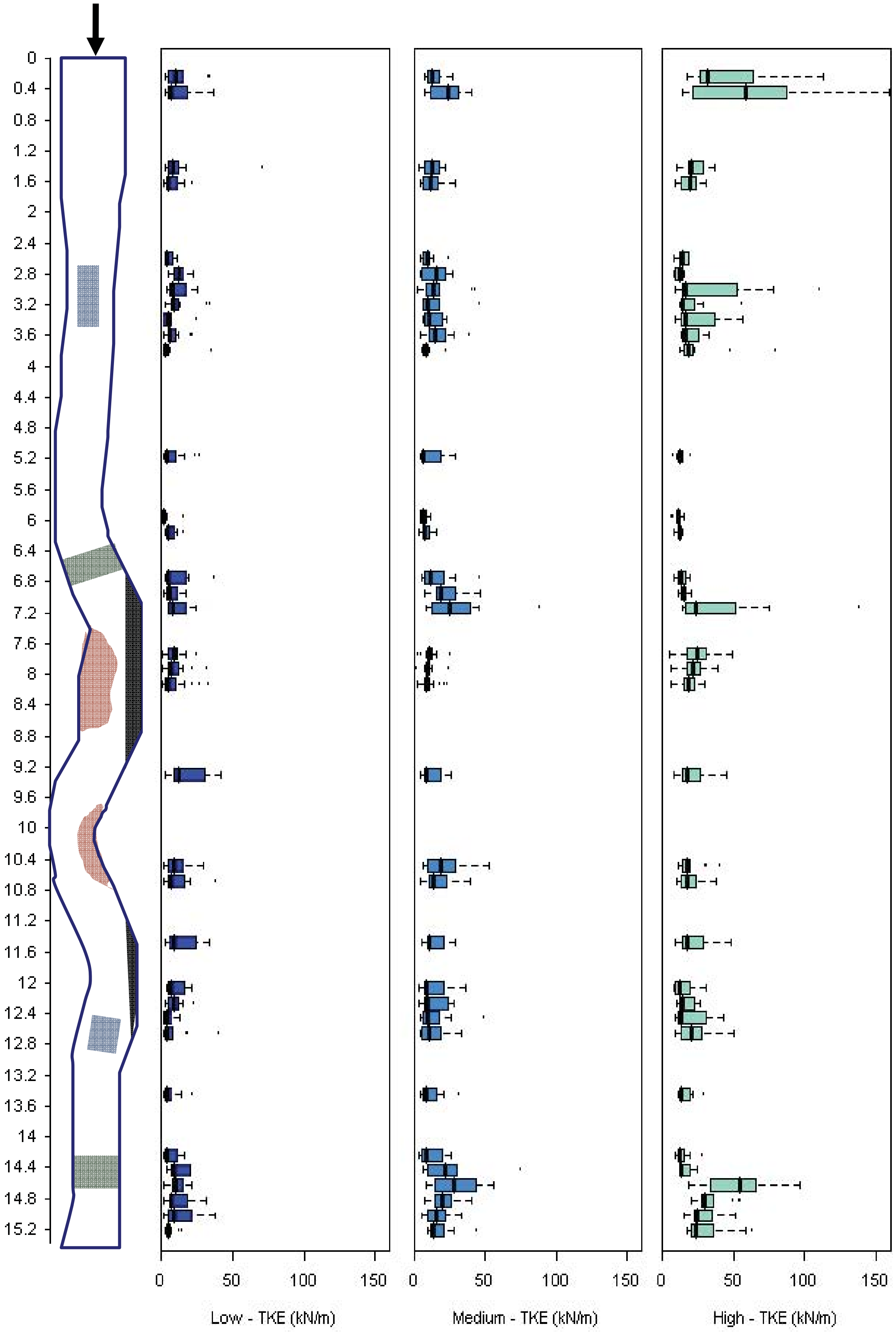


Figure 3.8: Box plots of turbulence parameter TKE for individual samples in different cross-sections sections for the three discharges (low, medium and high).

Table 3.1: Summary of the hydraulic measurements for the different cross-sections. *n* refers to the number of samples in that cross-section, while b refers to the benched area only, of 7.7-8.1m.

Cross-section (m)	LOW DISCHARGE				MEDIUM DISCHARGE				HIGH DISCHARGE			
	Velocity (cm s^{-1})				Velocity (cm s^{-1})				Velocity (cm s^{-1})			
	n	*min*	*max*	*diff*	*n*	*min*	*max*	*diff*	*n*	*min*	*max*	*diff*
0.1	11	2.37	17.68	15.31	11	5.18	30.77	25.59	10	9.99	46.74	36.75
0.3	14	4.08	17.4	13.32	15	6.56	29.34	22.79	14	10.71	44.8	34.1
1.3	16	4.79	13.91	9.11	15	6.81	18.31	11.5	14	9.8	29.62	19.82
1.5	14	5.53	12.74	7.21	14	6.08	16.75	10.67	14	14.72	31.11	16.39
2.5	11	8.39	13.14	4.75	10	11.79	19.4	7.61	9	19.96	33.28	13.33
2.7	9	7	16.38	9.37	7	16.06	22.58	6.53	4	29.11	37.89	8.78
2.9	11	3.23	16.46	13.23	10	4.98	21.65	16.67	10	9.87	36.68	26.81
3.1	11	5.98	12.89	6.91	11	8.94	21.62	12.68	9	18.63	35.69	17.06
3.3	12	7.53	13.04	5.51	11	11.05	21.05	10	10	22.78	33.77	10.99
3.5	12	4.17	12.42	8.25	13	10.43	21.4	10.96	12	16.23	33.06	16.82
3.7	12	3.33	13.42	10.09	12	4.72	21.37	16.65	12	18.73	34.29	15.56
5.1	14	5.77	11.01	5.25	14	9.86	19.72	9.87	14	14.72	30.77	16.05
5.9	10	7.91	11.61	3.69	10	12.47	19.47	7	10	21.58	35.3	13.72
6.1	11	6.94	11.5	4.55	11	11.84	18.58	6.74	11	20.88	32.24	11.36
6.7	13	4.7	12.31	7.61	14	8.3	19.88	11.58	14	15.37	32.18	16.81
6.9	9	4.52	14.23	9.71	12	9.03	23.67	14.63	10	22.17	40.05	17.88
7.1	12	4.88	15.46	10.58	11	5.4	22.35	16.95	11	14.12	38.24	24.12
7.7	13	5.47	11.72	6.25	13	9.48	21.29	11.82	13	18.43	34.99	16.56
7.9	13	5.33	12.01	6.68	13	8.45	21.71	13.26	13	15.76	34.97	19.21
8.1	14	4.59	12.09	7.5	14	7.96	20.41	12.45	13	14.47	33.03	18.56
7.7b	3	1.84	4.02	2.18	3	3.02	4.91	1.89	3	5.42	12.87	7.45
7.9b	4	1.85	5.08	3.22	4	3.13	4.67	1.54	4	3.99	9.83	5.84
8.1b	5	1.93	4.09	2.16	5	2.03	4.74	2.71	5	4.1	11.51	7.41
9.3	14	4.87	12.02	7.16	15	7.96	18.59	10.64	14	10.34	32.49	22.15
10.5	13	6.83	10.85	4.03	13	10.06	18.11	8.05	13	18.95	29.24	10.28
10.7	17	4.2	9.76	5.56	17	7.42	16.66	9.24	17	10.38	28.7	18.32
11.5	15	5.85	11.16	5.31	15	8.74	17.66	8.92	15	16.15	28.06	11.9
12.1	13	8.15	14.83	6.68	13	12.88	16.96	4.08	13	23.07	28.97	5.9
12.3	11	6.83	13.04	6.22	11	9.2	17.59	8.39	11	18.79	30.68	11.88
12.5	13	6.28	14.19	7.91	14	9.25	17.3	8.05	14	14.81	30.17	15.36
12.7	16	3.75	11.24	7.49	16	3.77	17	13.24	16	6.93	31.46	24.53
13.5	12	6.93	10.56	3.63	13	11.42	16.31	4.89	12	20.46	28.59	8.13
14.3	11	3.2	10.37	7.17	13	13.38	16.1	2.72	13	23.78	28.97	5.2
14.5	7	3.51	15.58	12.07	6	12.48	22.01	9.53	6	30.17	38.07	7.9
14.7	10	5	12.96	7.97	11	12.76	21.19	8.43	11	16.28	36.12	19.84
14.9	12	4.48	12.19	7.71	14	5.81	19.78	13.97	13	9.35	35.75	26.4
15.1	11	6.6	15.95	9.34	11	8.17	19.28	11.12	13	12.62	34.76	22.14
15.3	15	5.41	11.92	6.51	16	8.62	19.85	11.23	16	15.87	34.77	18.91

Table 3.1 cont: Summary of the hydraulic measurements for the different cross-sections. n refers to the number of samples in that cross-section, and b refers to the benched area only of 7.7-8.1m.

Cross-section (m)	LOW DISCHARGE				MEDIUM DISCHARGE				HIGH DISCHARGE			
	Turbulence - TKE - kN/m^2				Turbulence - TKE - kN/m^2				Turbulence - TKE - kN/m^2			
	n	*min*	*max*	*diff*	*n*	*min*	*max*	*diff*	*n*	*min*	*max*	*diff*
0.1	11	2.84	35.22	32.38	10	8.09	26.91	18.82	9	17.23	113.46	96.23
0.3	14	2.56	36.65	34.09	15	7.57	40.93	33.36	12	14.94	159.6	144.66
1.3	16	2.75	71.69	68.94	15	3.55	22.52	18.97	14	10.91	37.13	26.22
1.5	13	1.95	22.43	20.48	14	4.61	28.9	24.29	14	9.86	31.44	21.59
2.5	11	2.43	11.35	8.92	10	4.42	24.64	20.21	8	8.22	18.8	10.58
2.7	9	4.47	21.94	17.47	7	4.25	27.42	23.16	4	8.83	15.86	7.03
2.9	11	3.69	25.67	21.98	10	3.03	43.85	40.82	10	7.3	111.36	104.06
3.1	11	2.38	34.81	32.42	8	6.52	46.25	39.74	7	12	56.41	44.41
3.3	12	1.75	25.76	24.01	11	6.58	23.36	16.78	6	9.67	56.99	47.32
3.5	12	1.61	22.35	20.73	13	4.69	39.41	34.71	8	13.57	32.73	19.16
3.7	12	1.44	35.99	34.54	11	5.91	23.17	17.26	9	12.77	80.49	67.72
5.1	13	1.58	27.91	26.33	14	4.68	29.73	25.04	14	8.41	21.08	12.66
5.9	9	1.59	16.51	14.91	10	4.46	11.69	7.23	10	7.6	15.46	7.87
6.1	11	2.98	16.58	13.61	10	3.65	16.09	12.44	11	8.41	14.72	6.31
6.7	13	3.08	37.43	34.34	12	5.31	46.5	41.19	14	8.56	19.22	10.66
6.9	9	2.28	17.43	15.15	12	7.91	46.64	38.73	9	11.51	20.43	8.92
7.1	12	0.66	24.32	23.67	11	8.98	88.59	79.6	10	14.84	138.58	123.74
7.7	12	3.79	25.77	21.98	13	9.06	26.46	17.4	13	14.3	49.38	35.08
7.9	12	4.28	33.09	28.81	13	7.63	25.12	17.49	13	13.14	38.76	25.62
8.1	14	2.08	33.63	31.54	14	7.18	24.44	17.26	13	13.61	29.47	15.86
7.7b	3	0.79	9.88	9.09	3	3.49	12.71	9.22	3	5.64	44.69	39.06
7.9b	4	1	15.12	14.12	4	2.29	12.31	10.03	4	6.7	31.46	24.76
8.1b	5	0.92	9.02	8.1	5	2.05	13.9	11.85	5	6.44	27.83	21.39
9.3	13	3.28	41.49	38.2	15	4.19	26.4	22.2	14	8.02	44.94	36.92
10.5	12	2.1	30.08	27.98	11	6.37	52.39	46.02	12	13.2	40.96	27.76
10.7	15	1.38	39.21	37.83	15	5.02	39.79	34.76	15	10.05	38.65	28.6
11.5	14	3.06	33.81	30.75	15	6.08	29.03	22.95	15	9.18	48.18	39.01
12.1	13	3.71	21.1	17.39	13	3.67	36.44	32.77	13	8.32	31.02	22.7
12.3	11	2.56	23.8	21.24	10	3.8	28.28	24.48	11	10.34	26.87	16.53
12.5	13	1.75	13.54	11.79	14	4.91	49.85	44.94	14	8.94	43.21	34.27
12.7	13	2.2	40.46	38.25	16	4.92	33.5	28.58	15	9.83	50.02	40.19
13.5	12	1.58	21.92	20.34	13	4.34	32.64	28.3	12	11.5	30.43	18.93
14.3	11	2.34	16.31	13.97	13	3.38	25.68	22.3	13	9.37	28.94	19.57
14.5	6	4.04	20.12	16.08	6	6.75	75.51	68.76	6	12.47	180.98	168.51
14.7	10	2.26	21.74	19.47	11	8.64	56.16	47.51	9	18.96	96.98	78.03
14.9	12	1.81	31.93	30.12	14	7.73	40.3	32.57	13	21.13	55.7	34.58
15.1	11	2.21	38.32	36.11	11	5.64	33.82	28.18	13	15.91	51.16	35.25
15.3	14	3.23	15.03	11.8	16	10.21	44.74	34.52	13	17.23	64.27	47.04

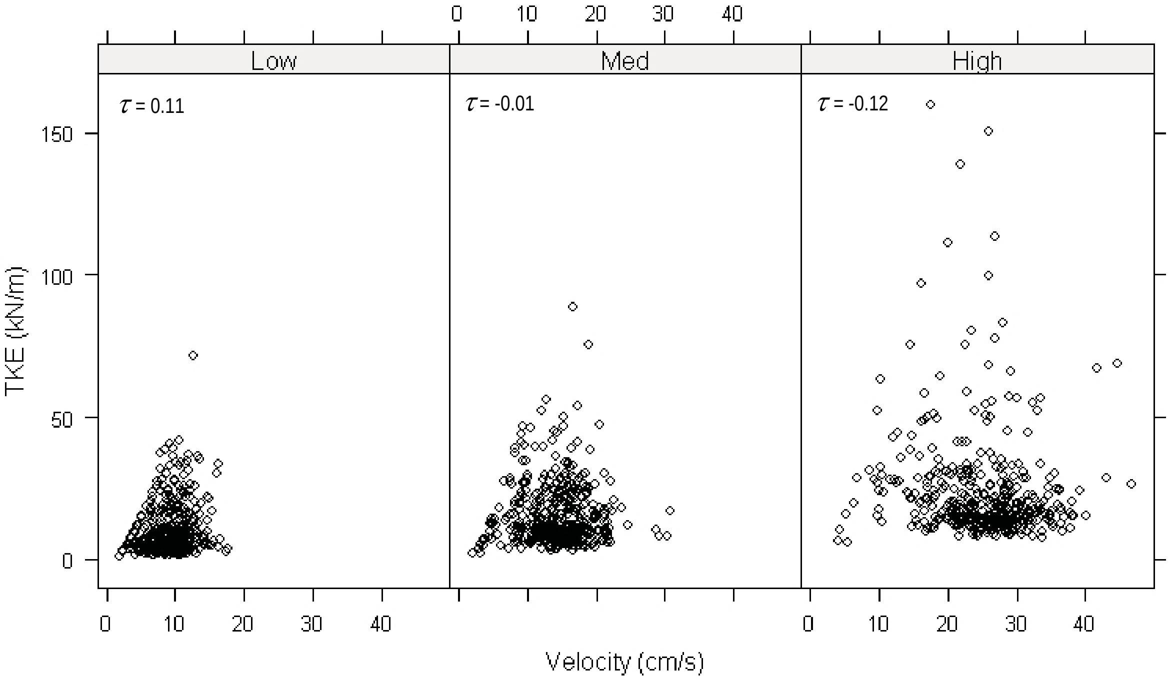


Figure 3.9: The turbulence parameter TKE versus the average velocity magnitude for individual samples at the three discharges. Kendall's correlation (τ) is shown for each discharge; $\tau = 0.28$ for the combined data (pooling all discharges).

Although the hydraulic conditions caused by the boulder and wood regions are reflected in the hydraulic measurements, the ADV could not reach all the points in that region (e.g. close to and under the boulders and wood) and therefore the full range of conditions present is not presented. From observations, and visualisation from the seeding material, the areas directly under the boulders had no flow, while the zone just above the boulders had slow, but turbulent flow. Similarly, within the wood there were patches of slow and fast flow, tiny recirculation patches behind pieces of wood, and general turbulence.

The seeding visualisation also highlighted other patches of very slow velocity or recirculation that have not been identified with the ADV measurements, either because the ADV could not measure those points, or they have not been identified in the Box plots, which show only the velocity magnitude. One large recirculation area was on the shallow bench of the upstream bend, but there were also smaller patches, such as behind the bend, near the surface, at 13 m and also just behind the bend at *c.* 9.1 m at the upstream end of the downstream bend (see Figure 3.4). Other slow flow areas were found in the shallow areas where there was a gentle slope, above the channel render (created by the relatively large bed roughness), and also the downstream bend benched area. A couple of ADV boundary measurements were taken (<1.5 cm from the render) and they indicated that the velocity in that region was *c.* 2 cm s^{-1} for the low discharge, increasing to 5-7 cm s^{-1} for the medium and high discharges.

3.3.2 Fish preferences and behaviour

Figure 3.10 shows the percentage of time spent either holding position or cruising, for the flathead gudgeon and the common galaxias (see section 3.2.4 for definitions of these activities as they refer to the different species). Figure 3.11 (flathead gudgeon) and Figure 3.12 (common galaxias) identify where the fish spent their time when they were holding position, compared to the time they spent cruising (as represented by the ‘general’ category), in fishsecs. These figures all show the nine different trials for both fish, as there was variability within the same discharge.

Flathead gudgeons

The flathead gudgeons spent almost all their time holding position, and this did not vary consistently between discharges. They heavily favoured the boulder regions, and to a lesser extent the wood, the outside of the edge of the upstream bend and the outflow area next to the net. When they were in these regions they were lying on the render, or underneath the boulders. They were rarely sighted in the pelagic zone, even when cruising. As mentioned, ‘cruising’ in reference to the flathead gudgeons refers to a combination of bursts and rests, but during their ‘bursts’ they were able to navigate strong current, and during their rests they were able to find a resting spot on the render.

Although the boulder regions were favoured, there were two behavioural traits that influenced the results. Firstly, as the fish did not move much, the spot they first chose was often where they stayed for the duration of the trial, and therefore had a large effect on the fishsecs total for an area. The ‘first spot chosen’ (heading upstream or downstream from the point they were placed in the channel) appeared relatively random, and strongly contributes to variation in fishsecs between the upstream and downstream boulder areas. Secondly, the territorial behaviour of the fish probably had an effect on the results. Observation showed a number of situations when a fish approached the boulder area, and another fish came out from underneath the boulders and scared the new arrival away. Sometimes the fish would enter the boulders despite the presence of other fish, but often they had to either then turn around or continue in the same direction. Further, occasionally two or more fish would burst out from underneath the boulders, have a stand-off, then return to the boulders, or one would have to leave. It is not clear what invoked the territorial behaviour, as high density did not always result in territorial behaviour, and at other times fish were observed to be comfortable next to other fish: for example, most of the time underneath the boulders (it can also be seen in Figure 3.13(a)).

Common galaxias

The common galaxias spent approximately a third of their time cruising, and, although the absolute percentage varied between the discharges, cruising generally decreased with increasing discharge. They had a preference for the inflow region (low and medium discharges)—although this is not reflected in the high discharge results, this was not for lack of trying, rather that the fish could spend only a few seconds in the inflow zone before being swept downstream. In general, there are more similarities between their habitat choices at low and medium discharges than the high discharge. This is highlighted by the importance of the upstream end of the downstream bend (at *c.*9.1 m) at high discharge, which had a small recirculation area suitable for resting from the high velocity (see Figure 3.13(b)). The outflow area was used more at the high discharge, although this was probably less a resting place than one where the fish could not swim away from easily.

Although the common galaxias were not observed to be obligatory schooling (they were often observed as individuals or small groups, and only occasionally were they all in the same place at the same time), their behaviour was influenced by the arrival or departure of other fish. For example, if a lone fish found a spot to hold position, and another fish arrived, the lone fish would often join the new fish when it left (which could be immediately), or, if cruising in a group of two or three fish, and one of the fish chose a spot, the others would normally follow.

During the recording and acclimation periods the common galaxias were near-surface swimmers at all times, except in the outflow during high discharge, when they were trapped by the turbulence and were resting near the bottom of the channel. However, during capture at the end of a trial, when disturbed they did seek refuge underneath the boulder and wood, similar to those spots used by the flathead gudgeons.

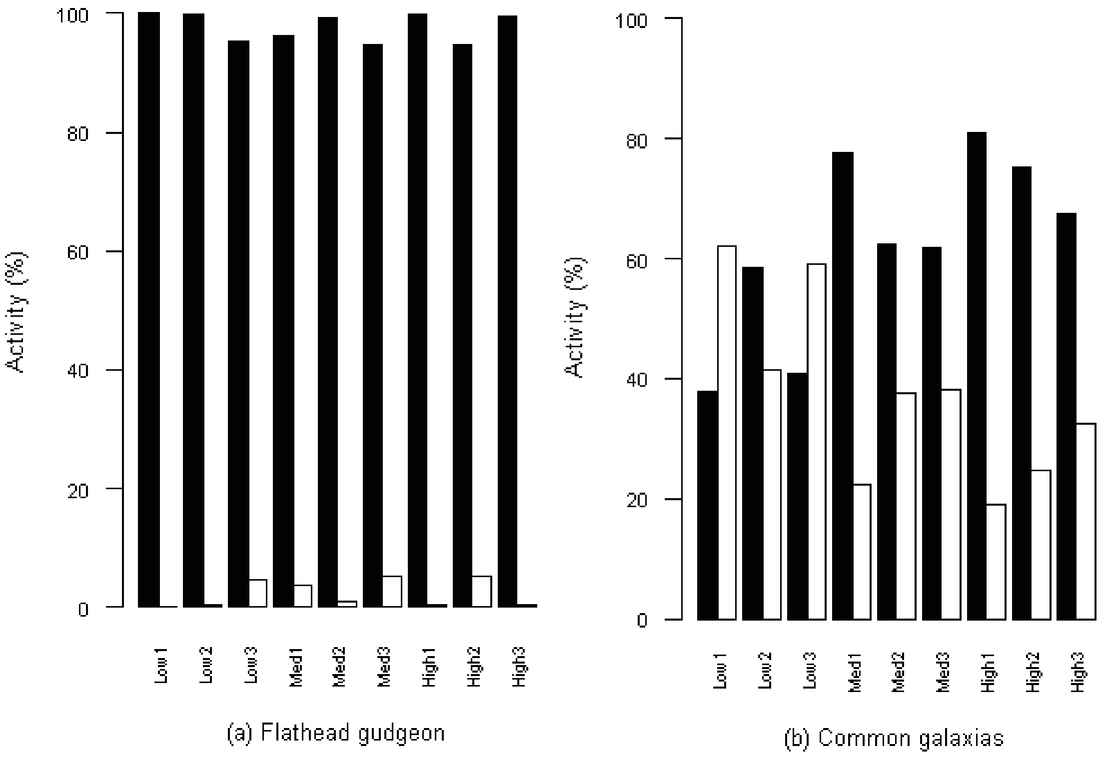


Figure 3.10: The percentage time (based on fishsecs-see text) the (a) flathead gudgeon and (b) common galaxias spent holding position (black bars) or cruising (white bars) for all trials.

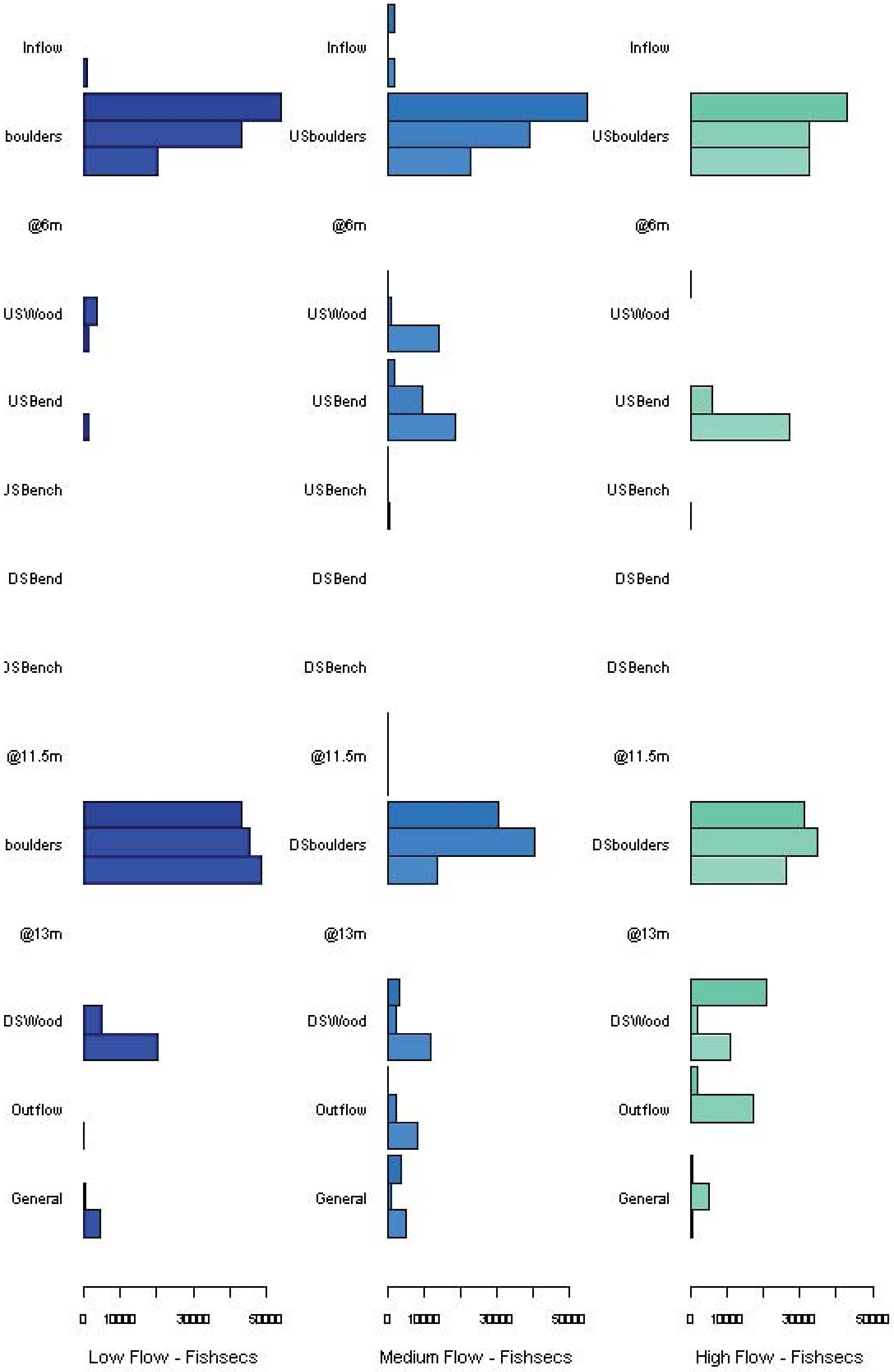


Figure 3.11: Patches where the flathead gudgeon spent their time while holding position during the three trials at the three discharges (see Figure 3.4 for patch location). The relative time spent cruising is shown by the category, 'general'. All times are in fishsecs (see text for explanation).

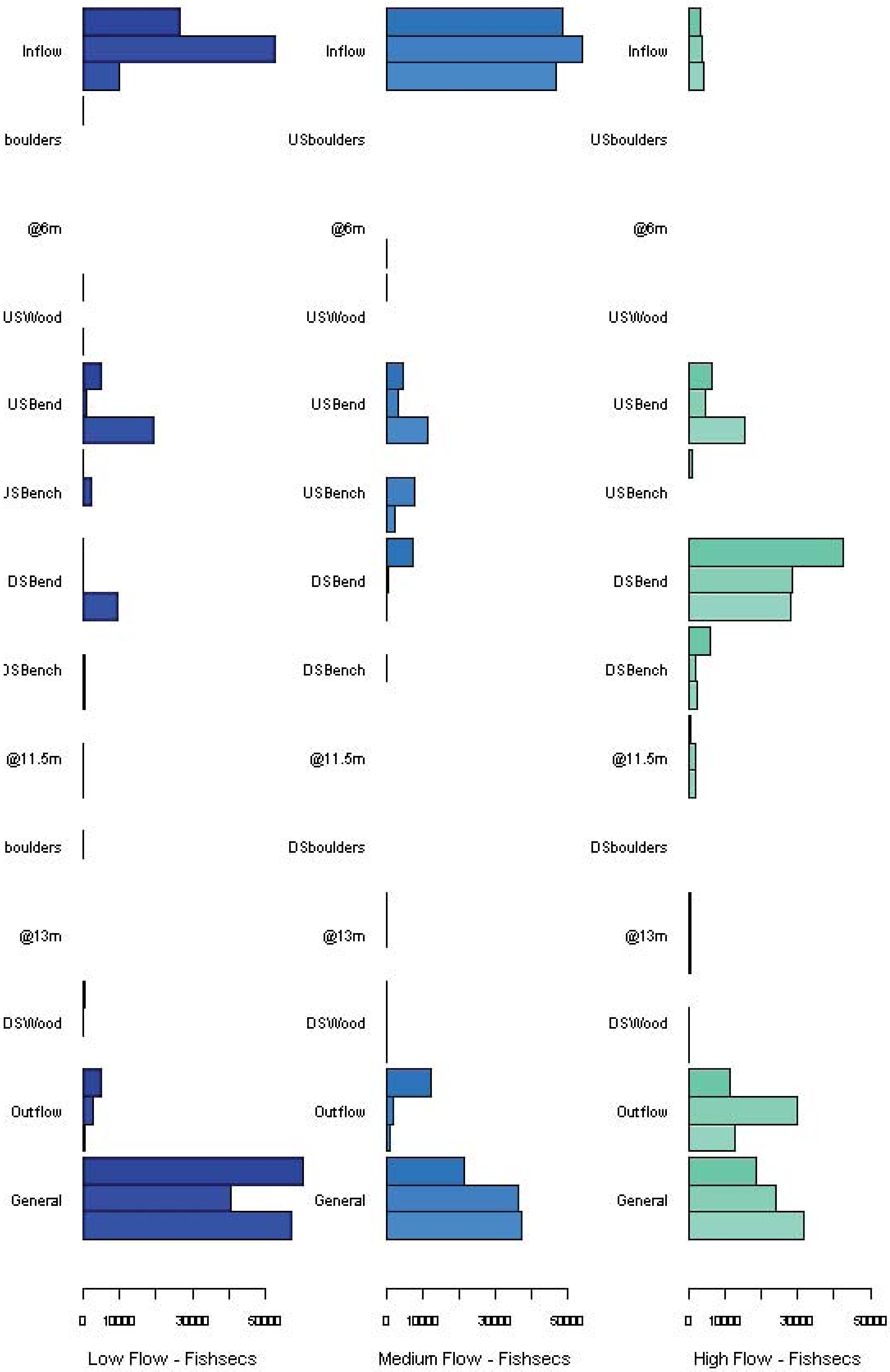
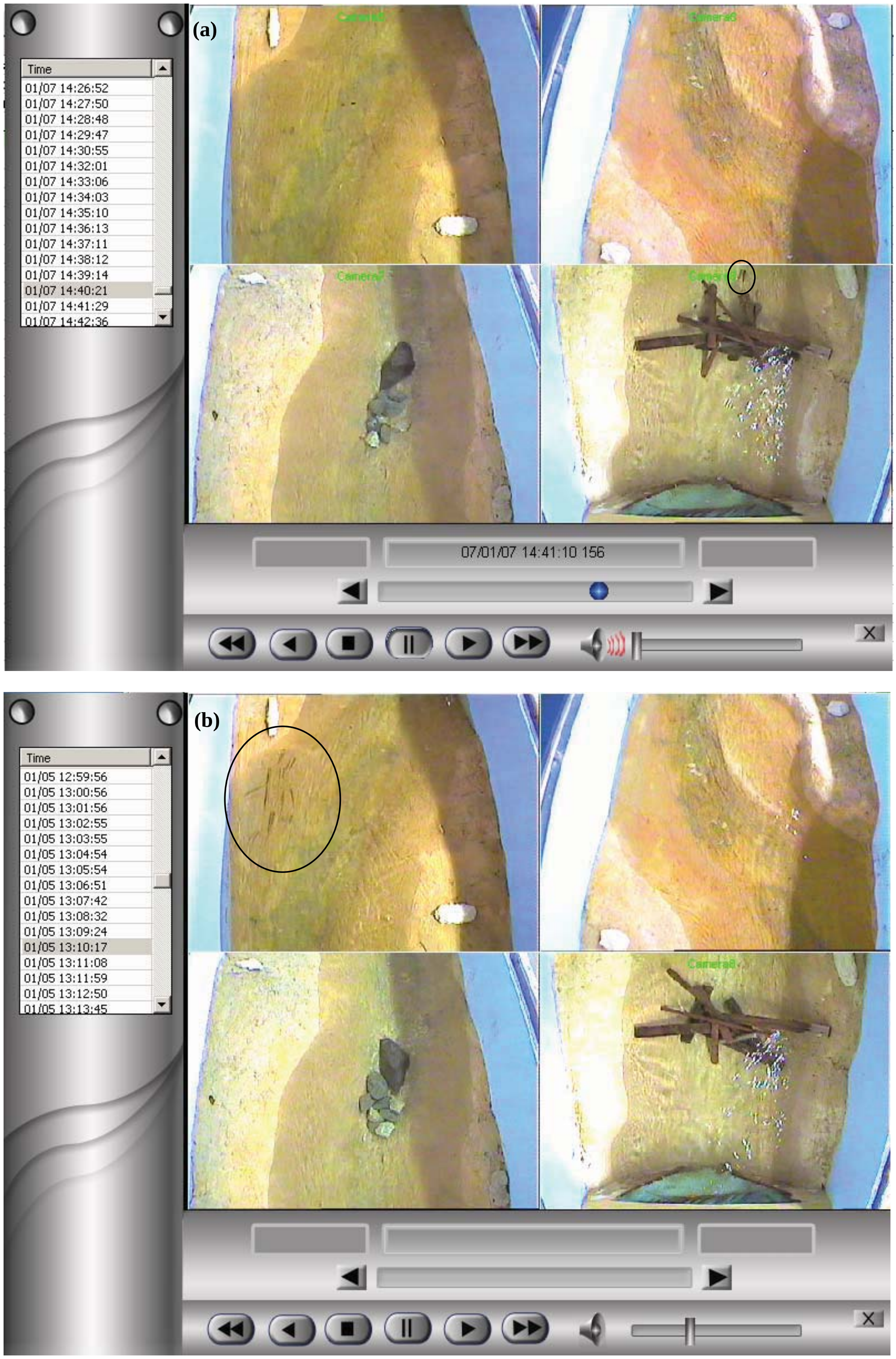


Figure 3.12: Patches where the common galaxias spent their time while holding position during the three trials at the three discharges (see Figure 3.4 for patch location). The relative time spent cruising is shown by the category, 'general'. All times are in fishsecs (see text for explanation). Note that High 3 (the lightest green, bottom bar) @13m also includes 75 fishsecs at a patch on the opposite side of the channel.



Time
01/07 14:26:52
01/07 14:27:50
01/07 14:28:48
01/07 14:29:47
01/07 14:30:55
01/07 14:32:01
01/07 14:33:06
01/07 14:34:03
01/07 14:35:10
01/07 14:36:13
01/07 14:37:11
01/07 14:38:12
01/07 14:39:14
01/07 14:40:21
01/07 14:41:29
01/07 14:42:36

07/01/07 14:41:10 156

Time
01/05 12:59:56
01/05 13:00:56
01/05 13:01:56
01/05 13:02:55
01/05 13:03:55
01/05 13:04:54
01/05 13:05:54
01/05 13:06:51
01/05 13:07:42
01/05 13:08:32
01/05 13:09:24
01/05 13:10:17
01/05 13:11:08
01/05 13:11:59
01/05 13:12:50
01/05 13:13:45

Figure 3.13: A sample of the video image, showing four cameras at once, (a) two flathead gudgeon holding position at the bottom of the channel (circled) (high discharge), and (b) eight common galaxias holding position at position ~9.1 m (circled) (high discharge).

3.4 Discussion

Experimental procedure

The aim of this experiment was to compare the behaviour of demersal and pelagic fish species with access to a variety of hydraulic conditions. The sinuous channel built in the rectangular flume was an effective method of creating a variety of hydraulic conditions. The ADV was a suitable instrument to use to measure the velocity and turbulence, the main issues being the ability to sample some shallow areas, the reliance on seeding making it difficult to sample corners where there was not room for the upstream seeding pipette, and correlation issues in the turbulent flow. Although quantifying the minimum number of good samples per measurement is different to the usual approach (of specifying time), it is a transparent assessment of the measured data.

The diversity of hydraulic conditions created in the channel was described by Box plots and tables. This was adequate in this study for describing the range of conditions, but it does highlight the need for a method to characterise reach spatial hydraulic diversity; at present there is no common, accepted method.

Video recording has been used in fish behaviour studies before (e.g. Flore and Keckeis 1998; Webb 1998; Haro *et al.* 2004; Swanson *et al.* 2005; Kemp *et al.* 2006), but none have used security surveillance software to coordinate multiple cameras. Using this software was useful for coordinating the cameras in one file, ensuring that the time stamp on each camera was the same, and the ability to remotely access the software reduced human interference. Increased resolution of the CCTV cameras would allow a greater range of fish species to be watched.

The flume acclimation period was set conservatively to encourage use of the channel, and corresponding patches, in as natural a behaviour as possible. Other flume experiments have used comparable or lesser time (Flore and Keckeis 1998, 30 min; Enders *et al.* 2003, 24 hours; Nikora *et al.* 2003, 10 min; Cheong *et al.* 2006, 30 min) or the fish were placed directly in the experimental apparatus, and were not kept in separate holding containers (Mallen-Cooper 1994; Haro *et al.* 2004; Kemp *et al.* 2005). In this study the fish may have changed their behaviour during the 3-month trial period, due to repeated exposure to the channel, and people. However, Figure 3.11 and Figure 3.12 do not show a consistent pattern: although there appears to be an increase in cruising time for the flathead gudgeons from 0 and 0.25% (Low 1 and Low 2, respectively) to 4.7% (Low 3), this pattern is contradicted by medium discharge (3.8, 1, and 5.25% for Medium 1, 2 and 3, respectively).

Fish behaviour

The flathead gudgeons chose no- or slow-velocity patches, preferably with cover, and this did not change with increasing discharge. The boulder areas provided good habitat, but because of their demersal habit, the flathead gudgeons were also able to exploit other patches throughout the channel as velocity refuge, such as by the channel render, underneath the wood, and the small patch between the flat bottom of the channel and straight sides of the flume on the outside of the upstream bend (cross-section 6, Figure 3.5). The wood also provided overhead cover, and the upstream bend was shaded, which may have contributed to their attractiveness as habitats. Social interaction between individual fish also contributed to habitat choice, which has been demonstrated elsewhere in the laboratory (Kemp *et al.* 2005) and field (David and Stoffels 2003; David *et al.* 2007). However, in general, the behaviour of the flathead gudgeon was independent of the discharge: they chose the habitat first and, and, although they could be seen as weak swimmers (as demonstrated in Chapter 2), because they can withstand strong currents (with their strong burst capacity (Bice 2004) and ability to locate rest spots), their behaviour was not moderated by the range of discharges tested.

The habitat preference of the common galaxias (the inflow zone) was also independent of discharge. Unlike the flathead gudgeons, however, their behaviour was moderated by the velocity (despite being stronger pelagic swimmers than the flathead gudgeon – see Chapter 2). This is demonstrated by the common galaxias repeatedly attempting to reach the inflow zone during the high discharge, and being washed downstream. Swimming ability tests show that common galaxias should be able to swim against the velocities present in the inflow zone (they swam against 0.46 cm s^{-1} (Chapter 2), and the maximum recorded in the inflow zone was 0.46 cm s^{-1}).

The common galaxias also demonstrated their ability to find areas of low velocity if necessary (such as at *c.* 9.1 m during high discharge), but did not seek these until a threshold level (somewhere between medium and high discharges, or 15 and 25 cm s^{-1}), resulting in the behaviour at low and medium discharge being similar to each other, but different from their behaviour at high discharge.

Despite being challenged by the current at high discharge, the fish never sought velocity refuge underneath the boulders or wood, even though they were capable of locating these places. Garner (1999) also noticed a difference in the ability to locate and exploit patches of low velocity between different species of fish. In Garner's laboratory experiment, chub were better at locating the slow flowing patches than either roach or dace, and could therefore withstand stronger discharges, although dace were the stronger swimmers).

The preferred inflow zone was characterised by a wide range of velocities and a relatively high level of turbulence, which may indicate that the common galaxias were not choosing the hydraulic environment *per se*, but were instead responding to cues caused by the turbulent water indicating a passage upstream. Common galaxias are a migratory species, laying their eggs in streamside vegetation, with the larvae heading to sea if a passage is possible (there are cases of common galaxias breeding wholly within a freshwater system (Chapman *et al.* 2006)), returning to fresh water 5-6 months later (McDowall 1980). Therefore it is possible that the fish saw the inflow turbulence as a cue to head upstream, and hence spent a large portion of their time there, even after 24 hours of experiencing the lack of passage upstream.

Schooling of fish at inflow regions can be seen in the field, and this behaviour is exploited by the use of a 'trickle flow' to attract fish to the entrance of fish ladders. Mitchell (1989) also noted the common galaxias consistently swimming upstream when exposed to a current in a flume experiment, as did MacDonald and Davies (2007) when testing the ability of the common galaxias to swim through a pipe culvert. They also noted the use of the 'wetted lateral margins' as a resting place from the centre of current (as was observed here, by the use of the shallow areas with a gentle slope), and the ability of the species to find low-velocity zones in heterogeneous hydraulic conditions. Jowett (2002) made observations of habitat use of drift-feeding common galaxias in three New Zealand streams. He observed the fish holding position in patches where the current concentrated the drifting prey items, but was not too strong to hold position against, optimally at 3-7 cm s^{-1}. Observations that the common galaxias had to modify their behaviour in the high discharge supports his observation that they prefer slower velocities.

Significance of the results

Fish use a range of habitats, and choose specific habitats for activities such as feeding (Jowett 2002) and migrating (Svendsen *et al.* 2007). This study has shown that, presented with a choice of hydraulic habitats, the two test species use the environment in varying manners, and their behaviour is moderated to different extents by the hydraulic conditions. Other studies have shown that preferred habitats can change with discharge (Holm *et al.* 2001) and the presence of predators (Sunardi *et al.* 2005). This indicates that fish are making continuous habitat choices based on energetic balances (such as the trade-off between drift-feed rate and water velocity) (Flore and Keckeis 1998; Holm *et al.* 2001) and other factors (such as the trade-off between foraging rate and predation), and that they show behavioural flexibility based on the present environmental conditions.

HSIs are usually developed from one set of hydraulic conditions, for one activity and age class, and do not consider the range of factors that might influence habitat choice. The complexity of incorporating behaviour (including changing hydraulic preferences and social dynamics) in fish habitat modelling has impeded its inclusion, but this study clearly demonstrates that behaviour, and not just swimming ability (as described in Chapter 2), has significant effects on the distribution and abundance of fish populations, and therefore the accuracy of habitat models.

Despite their different ecological habits, both species had preferred hydraulic habitats, but also used and explored a number of different habitats, indicating a positive response to a diverse hydraulic environment. This, combined with their different habitat preferences, supports increasing the hydraulic diversity of rivers as a tool to sustain diverse ecological communities.

4 USING COMPUTATIONAL FLUID DYNAMICS AND VARIOGRAMS TO CHARACTERISE REACH-SCALE SPATIAL HYDRAULIC DIVERSITY

4.1 Introduction

The distribution and abundance of river biota are influenced by the hydraulic environment (Statzner and Higler 1986). The hydraulic environment varies spatially and temporally: temporal variation is largely influenced by changes in discharge, and spatial variation by the physical features of the river, such as channel form and the presence of wood and aquatic vegetation. As in general ecological theory, high spatial physical diversity within rivers is believed to promote biodiversity. As a component of physical diversity, high spatial hydraulic diversity should therefore promote high biodiversity (Mann and Bass 1997; Grift *et al.* 2003; Dyer and Thoms 2006, Chapter 3). However, there are few field data to support this assumption. One reason for this may be a lack of a standardised method to compare spatial hydraulic diversity between river reaches (Kilsby *et al.* 2007).

A river *reach* may be described as a section of river with large-scale homogeneous geomorphic and hydrological conditions, containing a variety of smaller-scale habitat *patches* of similar potential habitat (in this case, hydraulic conditions). The spatial extent of reaches and patches varies with the river's character and the investigator's aims, but in general a reach containing a greater range of patches will have more spatial hydraulic diversity than a reach of similar extent containing fewer patches.

The range and distribution of hydraulic patches in a reach are important, but so too is the spatial arrangement of the patches (Maddock 1999; Crowder and Diplas 2000a; Crowder and Diplas 2006). A fast velocity patch next to a slow patch may be ecologically significant, as fish may seek areas where flow refuge (slow velocity) and good drift-feeding (fast velocity) patches are in close proximity (Mitchell *et al.* 1998; Deschênes and Rodríguez 2007). Other patches may be unattractive to fish (the velocity or turbulence may be too great), but their placement nonetheless may be influential in limiting fish movement and distribution.

Diversity can be expressed by a number of measures. Common methods include reporting the range or coefficient of variation (CV) of samples. The same data can also be shown graphically: histograms show the range and frequency of a parameter (e.g. Booker 2003), and scatter-plots show how two parameters co-vary. Ecological diversity indices, traditionally used to describe biodiversity, can also be used by replacing the 'species' with another parameter (e.g. Kemp *et al.* 1999; Stewart *et al.* 2005).

The above diversity measures may show the range of conditions, and give an indication of their equitability (evenness), but none incorporates spatial arrangement. The variogram is a measure of variance as a function of distance (Brooker 1991), and incorporates the location of samples. Initially developed for earth science applications (Jaksa 1995), it has been used in other fields (e.g. Legleiter *et al.* 2007; Schaefer and Mayor 2007) and appears to be a promising method to characterise spatial hydraulic diversity.

By using hydraulic modelling, spatial differences between, or changes within, reaches can be systematically compared. One-dimensional models consider the channel cross-sectional shape, and average cross-sectional velocity, and have been used in many ecohydraulic studies (Bovee 1982; Jowett 1989; Stewardson 2004). Two-dimensional models give a better indication of the range of hydraulic conditions by modelling the depth-averaged velocity at a number of points across the cross-section, and offer greater spatial resolution (Crowder and Diplas 2000b; Stewart *et al.* 2005).

With increasing computer power, 3-D modelling has become more accessible (Lane *et al.* 1999; Carney *et al.* 2006), and has been used to model a number of natural river channels (Olsen and Stokseth 1994; Booker *et al.* 2001; Clifford *et al.* 2004b). Although more complex, 3-D modelling has the benefit of modelling the change in velocity with depth as well as across the channel. This provides greater detail of the hydraulic conditions around habitat features such as boulders, and thereby a better representation of the conditions that aquatic organisms experience (Booker *et al.* 2004; Mouton *et al.* 2007a).

This chapter demonstrates the application of 3-D hydraulic modelling by modelling the effects that common instream features (channel form, wood and vegetation) have on the hydraulic environment. Methods to characterise spatial hydraulic diversity are then applied, and the use of variograms in particular is discussed.

4.1.1 3-D Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics (CFD) models can be used to simulate three-dimensional hydraulic patterns in rivers (Lane 1998). The CFD code used for this study was SSIIM (Simulation of Sediment at Intakes with Multiblock option) (Olsen 2007), outlined below (for more detail, see: Olsen and Stokseth (1995); Lane (1998); Booker (2003); Ruether *et al.* (2005); and Olsen (2007)).

SSIIM solves the Reynolds-averaged Navier-Stokes equations for non-compressible and constant density turbulent flow (Equation 4.1) on a three-dimensional, structured, non-orthogonal grid (Olsen and Stokseth 1995) (see Table 4.1 for notation):

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = \frac{1}{\rho} \frac{\partial}{\partial x_j} \left(-P\delta_{ij} - \rho \overline{u_i u_j} \right) \tag{4.1}$$

The Boussinesq approximation is used to model the Reynolds Stress term (the second term of the right hand side of Equation 4.1) (Equation 4.2):

$$-\overline{u_i u_j} = \nu_T \left(\frac{\partial U_j}{\partial x_i} + \frac{\partial U_i}{\partial U_j} \right) + \frac{2}{3} k \delta_{ij} \tag{4.2}$$

The *k*-ε turbulence models calculates the eddy-viscosity as (Equation 4.3):

$$\nu_T = c_\mu \frac{k}{\varepsilon^2} \tag{4.3}$$

The turbulent kinetic energy, *k*, is defined as (Equation 4.4):

$$k \equiv \frac{1}{2} \overline{u_i u_j} \tag{4.4}$$

and modelled as (Equation 4.5):

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\frac{\nu_T}{\sigma_k} \frac{\partial k}{\partial x_j} \right) + P_k - \varepsilon \tag{4.5}$$

with P_k defined as (Equation 4.6):

$$P_k = \nu_T \frac{\partial U_j}{\partial x_i} \left(\frac{\partial U_j}{\partial x_i} + \frac{\partial U_i}{\partial x_j} \right) \tag{4.6}$$

and the dissipation of *k* (denoted ε), modelled as (Equation 4.7):

$$\frac{\partial \varepsilon}{\partial t} + U\frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\nu_T}{\sigma_k}\frac{\partial \varepsilon}{\partial x_j}\right) + C_{\varepsilon^1}\frac{\varepsilon}{k}P_k + C_{\varepsilon^2}\frac{\varepsilon^2}{k} \qquad \textbf{(4.7)}$$

A control-volume approach with the Power-Law scheme is used for the discretization of the equations, and SIMPLE (Semi-Implicit Method for Pressure-Linked Equations: Patanker (1980)) was used for the pressure correction. Parameters are calculated for the centre of each cell.

Table 4.1: Notation used for Equations 4.1-4.8.

$C_\mu C_{\varepsilon 1} C_{\varepsilon 2}$ = constants (*k-ε* model)	*U* = average velocity
K = constant (wall function)	u_* = shear velocity
k = turbulent kinetic energy	V_T = turbulent eddy viscosity
k_s = roughness height	δ_{ij} = Kronecker delta
P = pressure	ρ = density
P_k = term for production of turbulence	σ_k = constant *(*k-ε *model)*
u = fluctuating velocity, subscripts refer to the computational planes of *i* and *j*: *x, y* and *z* refer to coordinates in the horizontal (*x,y*) and vertical (*z*) planes	

SSIIM is well-suited for modelling rivers because it is one of few CFD codes that calculates a free water surface, using standard backwater calculations (Manning's formula for head loss) from a reference downstream point. The influence of rough boundaries is included with the addition of a wall law (Equation 4.8):

$$\frac{U}{u_*} = \frac{1}{\kappa}\ln\left(\frac{30y}{k_s}\right) \qquad \textbf{(4.8)}$$

4.1.2 Variograms

The *variogram* (aka 'semivariogram') is "a measure of the degree of spatial dependence between samples along a specific orientation and represents the degree of continuity of the property in question" (Jaksa 1995). It is calculated as half the mean of the squared difference between pairs of points separated by displacement, *h*, (Brooker 1991), as described by Equation 4.9:

$$\gamma^*(\vec{h}) = \frac{1}{2N(\vec{h})}\sum_{i=1}^{N(\vec{h})}\{f(\vec{x}_i + \vec{h}) - f(\vec{x}_i)\}^2 \qquad \textbf{(4.9)}$$

where $f(\vec{x})$ = value of sample at location *x*

$N(\vec{h})$ = number of data pairs in the sampling region

h = the lag distance; distance between data pairs

By increasing the size of *h*, a plot is developed showing the distance between sample pairs and the semivariance (the variogram value) (Figure 4.1). Thus, the variogram provides additional information about the spatial variability of a reach, as opposed to a single value of variance. A curve fitted to the data has three key parameters (Figure 4.1): C_o is the *nugget effect* (cf. a nugget of gold in soil) which reflects the inherent variability between samples; $C_o + C$ is the *sill*, which measures the average semivariance between data pairs; and a is the *range* of the distance beyond which the data behave independently (there is correlation between data points up to this point) (Brooker 1991). The higher the semivariance, the weaker the spatial auto-correlation (Legleiter *et al.* 2007), i.e. the more variable the samples, the more diverse the conditions. The distance between two sample pairs can be defined in a specific direction, such that a variogram not only takes into account the distance between the sample pairs (h), but also the direction between the pairs (Brooker 1991).

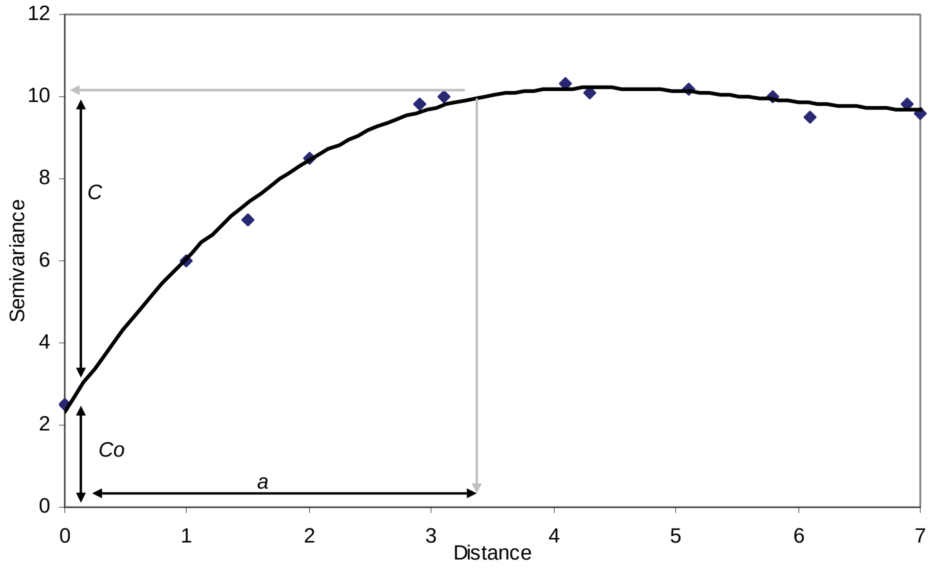


Figure 4.1: Example of a variogram (after Brooker 1991).

4.2 Methods

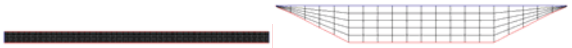
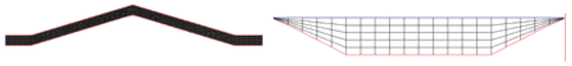
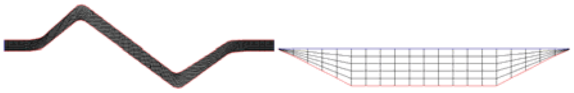
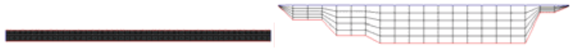
4.2.1 Reach design

The eight reaches were designed to mimic different levels of single common instream features that change the hydraulic environment. Channel form (including sinuosity and cross-sectional shape) is a primary driver of hydraulic conditions in rivers (Resh *et al.* 1988; Petts *et al.* 1995), and wood and vegetation provide habitat and change hydraulic conditions (Crook and Robertson 1999; Shi and Hughes 2002; Brooks *et al.* 2004; Green 2005b).

The base reach was a 250 m long, 1.25 m deep, straight, trapezoidal channel (base 5 m; top 10 m), with slope 1/2000 and discharge 5 $m^3 s^{-1}$. The grid was 250 cells long by 20 cells wide, with five cells in the vertical. A Strickler's value of 28.57 (equivalent to a Manning's n of 0.035) was used for the initial calculation of the water surface, and the first-order upwind scheme was used for the control volume discretization.

One hydraulic attribute was added to the base form in turn, selected from bends (in planform), benching (in cross-section), wood or vegetation; all other features and calculations remained invariant across model runs (Table 4.2). To model instream wood, the *outblocking* option in SSIIM was used. This blocks specified cells from flow calculations, creating a solid obstacle. The size and placement of the wood are shown in Table 4.2. To model instream vegetation, the *vegdata* file option was used. This option models vegetation as vertical cylinders: for each vegetated cell a vegetation parameter is specified, incorporating a drag coefficient and the diameter and density of stems (Brooks *et al.* 2004; Olsen 2007). The drag caused by the stems is then calculated as a sink term in the Navier-Stokes equations (Fischer-Antze *et al.* 2001). For this study the vegetation was modelled through the full height of the water column, with the vegetation parameter varying from 0.55 at the base to 0.25 near the water surface. The vegetation covered a width of 1.5 m on the sloped sides, starting 1 m from the edge of both sides and ending at the bottom of the slope.

Table 4.2: The features of the eight reaches modelled.

Reach name	Hydraulic attribute	Comments
1 Straight	Straight, trapezoidal channel.	
2 Single Bend	One bend added.	
3 Double Bend	Two bends added.	
4 Benched	Benched cross-section.	 Cross-sectional area same as trapezoidal channels.
5 Parallel Wood	Five wood pieces added, oriented with the flow.	Channel & planform as for 1 Straight. No wall laws specified for the outblocked cells. Wood 1: 7 m long x 0.5 m wide x 1.25 m deep, at 75-82 m. Wood 2: 8 m long x 0.5 m wide x 1.25 m deep, at 100-108 m. Wood 3: 5 m long x 1 m wide x 1.25 m deep, at 155-160 m. Wood 4: 5 m long x 1 m wide x 1.25 m deep, at 185-190 m. Wood 5: 8 m long x 1 m wide x 0.75 m deep, at 122-130 m.
6 Perpendicular Wood	Three wood pieces added across the flow.	Channel & planform as for 1 Straight. No wall laws specified for the outblocked cells. Wood 1: 2.5 m long x 0.5 m wide x 1.25 m deep, at 75 m. Wood 2: 1 m long x 0.5 m wide x 1.25 m deep, at 160 m. Wood 3: 1.5 m long x 0.5 m wide x 0.75 m deep, at 130 m.
7 Continuous Vegetation	Littoral vegetation added to both sides of entire reach.	Channel & planform as for 1 Straight.
8 Patchy Vegetation	Littoral vegetation added in 50 m sections on alternating sides.	Channel & planform as for 1 Straight.

4.2.2 Velocity sampling

The output from SSIIM (*u, v, w* for each cell) was converted to depth-averaged velocity (DAV) samples in Microsoft Excel for most of the analyses, for consistency in characterisation comparisons. The first 25 m of each reach was influenced by the modelled inflow, and was removed from further analysis. Thus, there were 4500 regularly-spaced samples of DAV and depth for all model runs, except Parallel Wood and Perpendicular Wood where, due to outblocking, the numbers of samples were 4459 and 4491, respectively.

4.2.3 Characterising diversity

A number of common techniques used to describe diversity were employed to characterise the reaches. These included: common statistics; ecological diversity indices; graphical representation; and variograms. Calculations were primarily of DAV, as depths did not vary between reaches (except for 'Benched') (see Table 4.2).

Common statistics

Statistics often used to characterise a reach, and reach hydraulic diversity, are the mean and CV of velocity, and Pearson's product-moment correlation (*r*) between velocity and depth. A high CV, or a low correlation, is taken to mean a more diverse hydraulic environment. However, these statistics should be used only if the data are normally distributed; otherwise, the median and Kendall's correlation (τ) are more reliable. Again, a low correlation indicates a higher range of hydraulic conditions: a particular DAV may be associated with a range of depth conditions. Normality was confirmed in R (R Development Core Team 2007), using the Shapiro-Wilk Test ($\alpha = 0.05$) to determine the likelihood that the sample could have come from a Normally-distributed population with the same mean and standard deviation. The range of DAV also was calculated (a wide range indicates high hydraulic diversity).

Ecological diversity indices

Simpson's Index of Diversity and Shannon's Indices of Diversity and Evenness were used as diversity indices (Magurran 1988). There are several versions of these indices in the literature (e.g. Hill 1973; Patil and Taillie 1982; Begon *et al.* 1996), but this study follows McCune and Grace (2002) (Equations 4.10-4.12):

Simpson's Index of Diversity $$D = 1 - \sum_{i=1}^{S} p_i^2 \qquad \textbf{(4.10)}$$

where S = number of species in the community (richness)
p_i = proportion of S made up of the ith species

Shannon's Index $$H = -\sum_{i=1}^{s} p_i \log p_i \quad \textbf{(4.11)}$$

Evenness $$E_H = \frac{H}{H_{MAX}} = \frac{H}{\log S} \quad \textbf{(4.12)}$$

where S = total number of species in the community (richness)
p_i = proportion of S made up of the ith species
E_H = equitability (evenness)
H_{MAX} = the value of H for the given number of species if the samples were perfectly equal

DAV categories were the 'species' (S) (same categories as used for the graphical representation – see below) and the samples were the number of 'organisms' (p_i).

Simpson's Index represents the likelihood that two randomly chosen individuals will be of different species (McCune and Grace 2002). Simpson's Index for a given richness D increases with equitability, and for a given equitability, D increases with species richness (Begon *et al.* 1996): the higher the index value, the more diverse the hydraulic conditions.

A similar pattern applies for Shannon's Index. Shannon's Evenness is the ratio of the calculated index to the maximum value that index could be if all species were evenly distributed. The higher the value, the more even the distribution of species (or velocity samples), i.e. the population does not contain a large proportion of particular species compared to the other species present.

Graphical representation

DAV frequency histograms, and depth and DAV scatter-plots and bubble-plots were used for graphical representation. The latter are a combination of the first two: samples are assigned to a depth and DAV category, and the corresponding frequency of samples is shown by the size of the circle in the bubble-plot (after Kemp *et al.* 1999). Depth and DAV categories were consistent across reaches (and between histograms, bubble-plots and ecological indices), and were chosen to produce evenly-spaced divisions in the straight reach.

Variograms

DAV values were taken as the *sample* in a two-dimensional plane. Calculations followed Dowd (2006), assuming stationarity. Directional variograms followed streamlines (down-channel) and cross-sections (across-channel). Two directional variograms were suitable: an omni-directional (isotropic) variogram was inappropriate given the different scales (10 m across versus 225 m down). Spatial coordinates were taken directly from SSIIM, except for non-straight reaches (Single Bend and Double Bend) where the coordinates were transformed (straightened) to match those of the straight reaches.

Variograms were also calculated across-channel for different cell depths and compared to the DAV values. The cell depths are given in percentage depth (from the reach bed), as they correspond to SSIIM grid layers (see Table 4.2 for examples of grid cross-sectional structure); calculation points for SSIIM are the centre of each cell. R statistical software was used for these calculations (R Development Core Team 2007).

4.3 Results

4.3.1 Reach hydraulics

The average velocity, calculated as the ratio of discharge to cross-sectional area, is similar for all reaches, at 0.53 m s^{-1} (similar discharge and cross-sectional area). Figure 4.2 shows the centre DAVs for four reaches, and Figure 4.3 shows in plan view how the DAV varies between the channels. Straight, Benched and Continuous Vegetation reaches have relatively parallel streamlines (ranging from slower at the edge to faster velocities in the centre). There are significant departures from parallel streamlines when bends, wood or patchily-distributed vegetation are added. There is an increase in velocity through the centre of the vegetated reaches, countering the slower edge velocity caused by the vegetation.

Figure 4.4 shows the DAV across-channel for four different cross-sections of each reach. The Straight reach shows a predictable smooth curve (slow to faster velocities in the middle of the channel). The addition of the hydraulic attributes changes the distribution: slow velocities are noted on the edge of the vegetated channels; streamlines are skewed by bends; and wood can cause unpredictable shapes (note particularly the first cross-section for Perpendicular Wood).

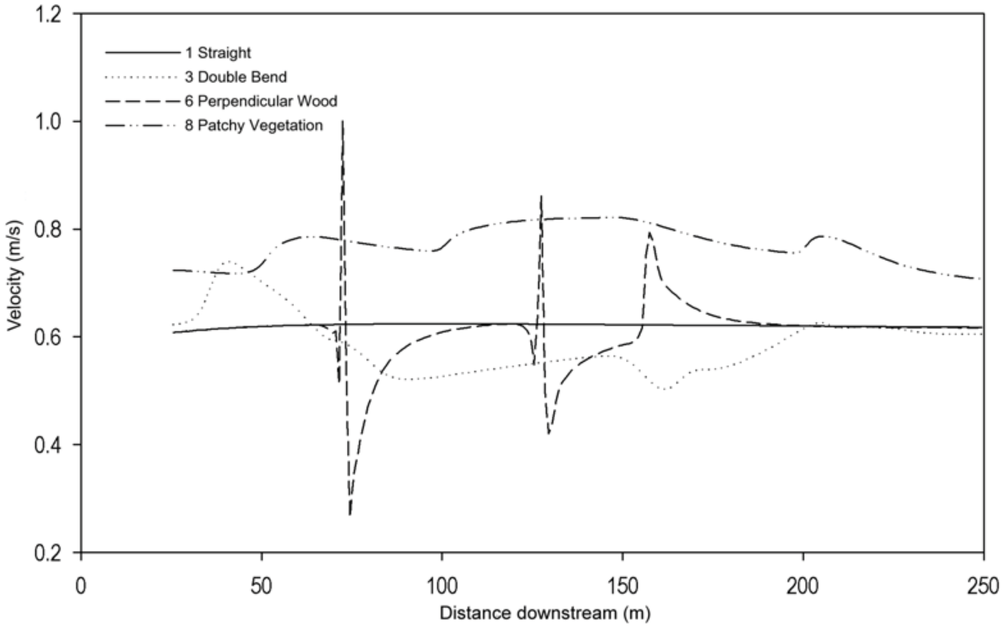


Figure 4.2: Down-channel centre depth-averaged velocity for four reaches.

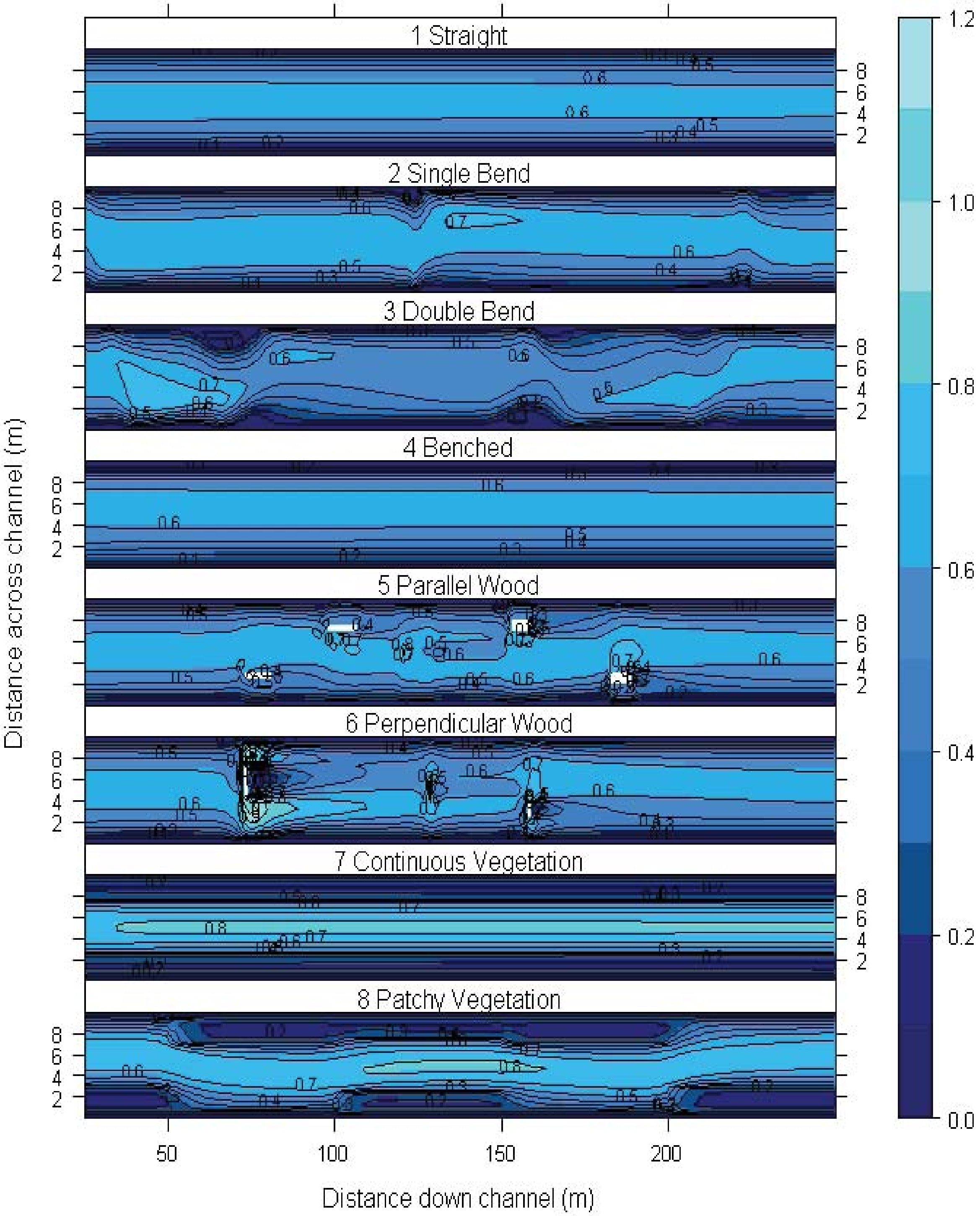


Figure 4.3: Depth-averaged velocity distribution in plan view for the eight reaches. Velocity scaling is shown in the colour key to the right, in m s^{-1}. Blank regions show the position of the wood pieces.

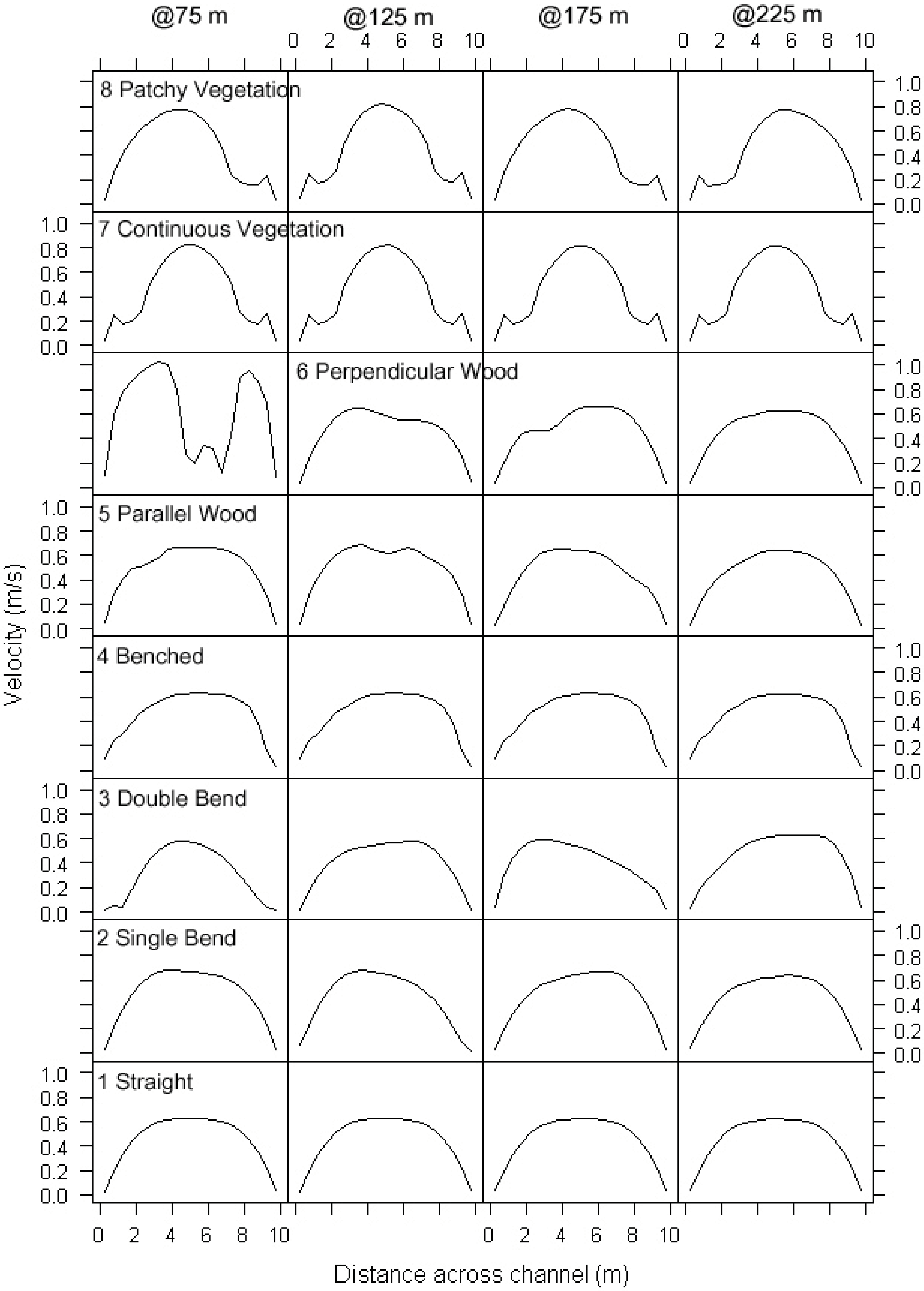


Figure 4.4: Depth-averaged velocity across-channel for four cross-sections of the eight reaches. Reach shown in row heading. Cross-section positions are 75, 125, 175 and 225 m from the inflow respectively.

4.3.2 Reach diversity characterisation

Common statistics

The Shapiro-Wilk Test indicated that DAV samples from all reaches were not Normally distributed. Therefore, the median velocity and Kendall's correlation between DAV and depth were calculated (Table 4.3) for comparison with the mean, CV and Pearson's correlation (cf. Howes and Stewardson 2005) (Table 4.3).

The sample mean and median differ from each other, indicating a skewed, non-Normal distribution. They also differ from the "reach-average" velocity (the ratio of discharge to cross-sectional area, at 0.53 m s^{-1}), because the DAV samples used are area averaged (evenly distributed across the planform area), while the reach-average considers the volume.

Straight reach had the lowest DAV range, and Perpendicular Wood the highest, indicating that more diverse conditions were present in the Perpendicular Wood reach. Pearson's and Kendall's correlation coefficients ordered the reaches slightly differently. Both indicated that Patchy Vegetation had the lowest correlation (therefore a particular velocity could be associated with a number of different depths, creating a diverse hydraulic environment), but Kendall's correlation indicated the Parallel Wood had the highest (cf. Straight for Pearson's).

Table 4.3: Common statistics for the depth-averaged velocity for the different reaches. Lowest values of variability are shown in grey, and highest in bold.

Reach	Range Min–Max		Mean	CV	Pearson's correlation	Median	Kendall's correlation
1 Straight	0.028	0.624	0.46	0.422	0.991	0.55	0.671
2 Single Bend	0.001	0.715	0.48	0.430	0.970	0.57	0.598
3 Double Bend	0.001	0.783	0.42	0.481	0.891	0.50	0.567
4 Benched	0.029	0.630	0.46	0.415	0.986	0.55	0.666
5 Parallel Wood	0.001	0.823	0.47	0.429	0.957	0.54	0.673
6 Perpendicular Wood	0.005	1.184	0.47	0.442	0.880	0.53	0.582
7 Continuous Vegetation	0.043	0.824	0.44	0.613	0.819	0.39	0.582
8 Patchy Vegetation	0.017	0.822	0.45	0.572	0.790	0.48	0.541

Ecological diversity indices

Diversity indices are shown in Table 4.4. Diversity indices were minimal for Single Bend, and Evenness was minimal for Parallel Wood. The highest diversity indices and Evenness were for Patchy Vegetation.

Table 4.4: Depth-averaged velocity diversity indices. Lowest values of variability are shown in grey, and highest in bold.

Reach	Simpson's	Shannon's	Evenness
1 Straight	0.748	0.643	0.919
2 Single bend	0.720	0.622	0.890
3 Double bend	0.760	0.674	0.866
4 Benched	0.747	0.642	0.919
5 Parallel Wood	0.746	0.645	0.829
6 Perpendicular Wood	0.765	0.685	0.880
7 Continuous Vegetation	0.740	0.639	0.914
8 Patchy Vegetation	0.789	0.721	0.927

Graphical representation

Figure 4.5 shows the histograms, depth-DAV scatter-plots and bubble-plots plotted adjacent each other to facilitate direct comparison. Straight reach had a predictable DAV distribution, given its trapezoidal cross-section: DAV was greatest in the middle of the cross-section, which accounted for most of the cross-sectional area, and therefore had greatest frequency. The addition of obstacles (wood and vegetation) created slow-flowing areas, which were compensated for by higher DAVs (the addition of the 0.75+ m s^{-1} category). Double Bend also created higher velocities, caused by a decrease in reach hydraulic conveyance.

The scatter-plots show the depth classes that the different velocities are associated with. For Straight reach (and to a lesser extent Benched, and Continuous Vegetation), each depth was associated with one DAV, but the pattern changed with the addition of the features: one depth was associated with many different DAVs. The same patterns are shown in the bubble-plot, with dominant depth and DAV categories clearly visible.

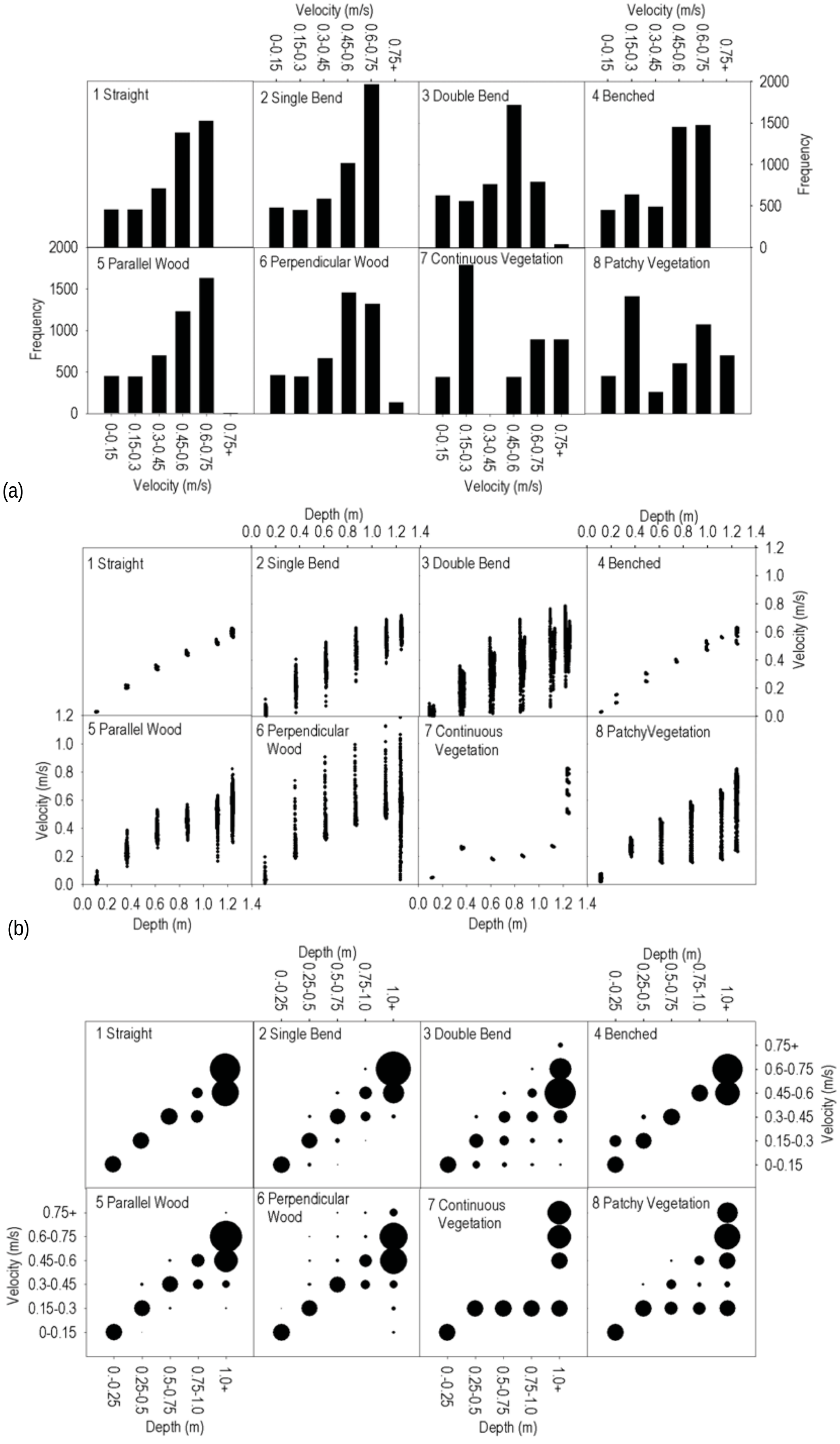


Figure 4.5: (a) Histograms, (b) depth-DAV scatter-plots, and (c) bubble-plots for the eight reaches.

Variograms

Directional experimental variograms are shown in Figure 4.6. Only half the maximum distance between sample pairs is shown, as past this point the relative numbers of sample pairs are unreliable (Jaksa 1995). Lines of best fit (model curves) have not been added to the plots as there is little scatter and the variogram shape is clear.

The highest across-channel semivariance was in the vegetated reaches. The high semivariances reflect the large difference in velocity between the vegetated and non-vegetated areas across the reach (see Figure 4.4), and indicate that the vegetated reaches had the most diverse velocity samples as measured across the channel. The other reaches had similar variogram curves. The absolute across-channel semivariance was higher for all reaches than the down-channel semivariance, as the DAV range is greater across-channel than down-channel.

Patchy Vegetation, Double Bend and Perpendicular Wood had the most down-channel semivariance. Parallel wood and Single Bend exhibited less semivariance, and there was negligible semivariance in the Straight, Benched and Continuous Vegetation reaches. The down-channel variograms highlight the difference between the 50 m vegetation patches in Patchy Vegetation (peak at 50 m lag distance) and Continuous Vegetation. They also distinguish Single and Double Bends: a streamline in Double Bend goes from the inside to the outside of a bend (thus, medium to fast to medium to slow DAVs), a streamline in Single Bend goes only from medium to fast or slow (but not the other) DAVs (see Figure 4.2). The difference between Perpendicular and Parallel Wood is also clear, reflecting the greater velocity range in the former.

Across-channel variograms calculated for velocity at different depths and compared to the DAV are shown in Figure 4.7(a)-(h). In all the reaches the specific-depth variograms have the same shaped variogram as the DAV, with the deepest depth (10% of depth) comprising the lowest semivariance, graduating to the shallowest depth (90% of depth) comprising the highest semivariance. The DAV variogram is located in the middle of these extremes.

General

Most indicators used here show that Patchy Vegetation, followed by Continuous Vegetation, showed most hydraulic diversity. This demonstrates relative consistency, with some expected deviations and biases, between the different diversity measures.

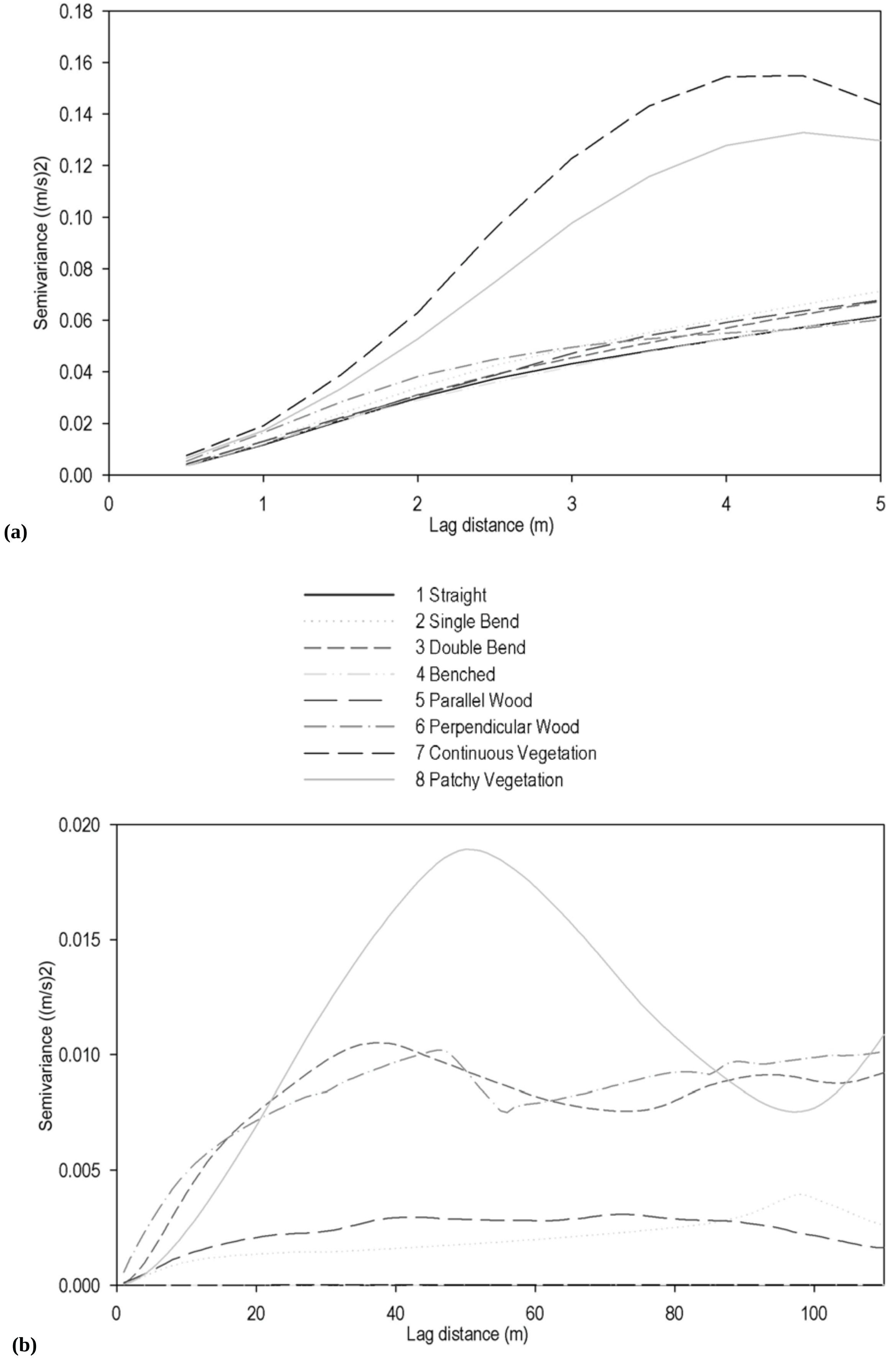
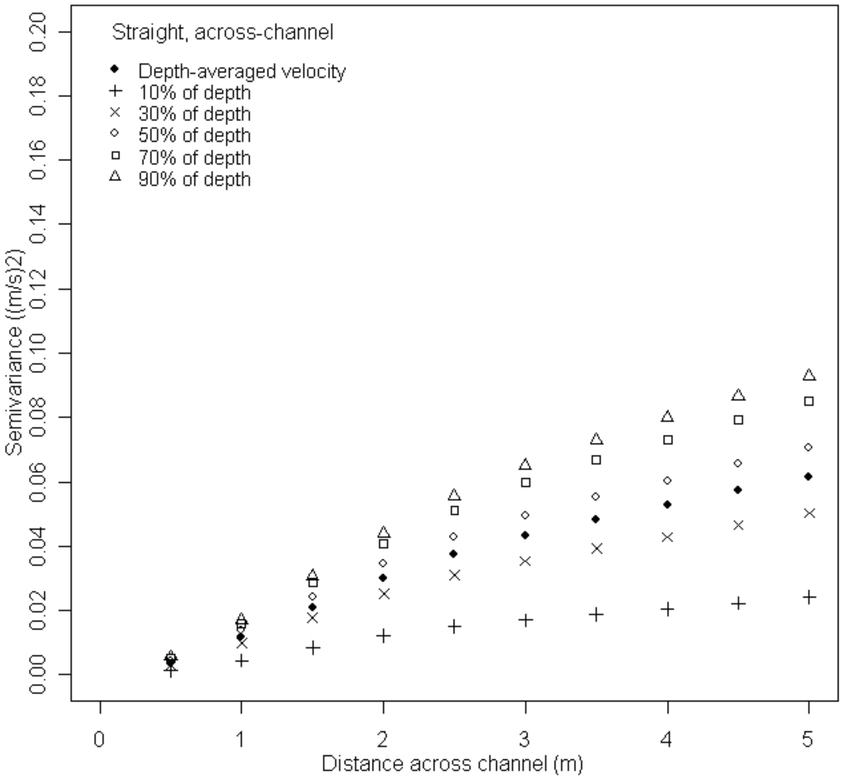
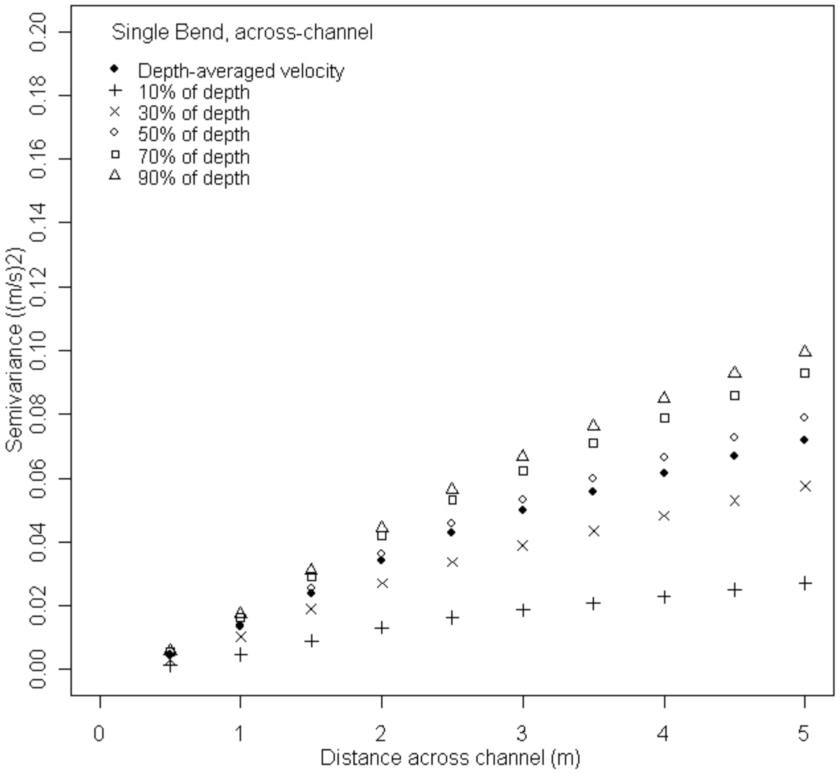


Figure 4.6. Directional experimental variograms of depth-averaged velocity for the eight reaches. (a) across-channel, and (b) down-channel.

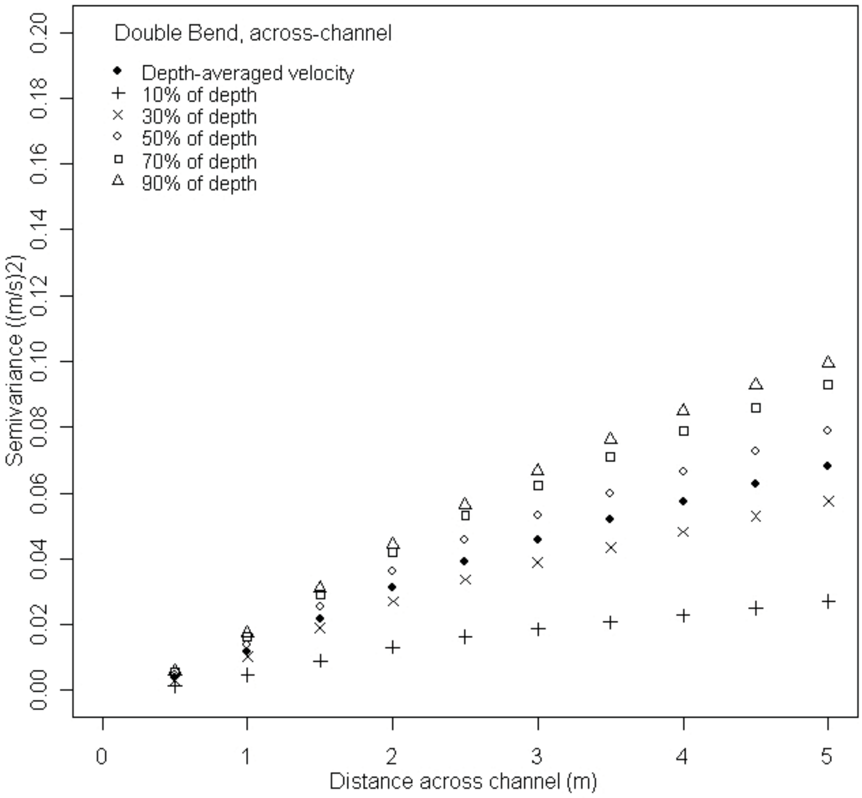


(a)

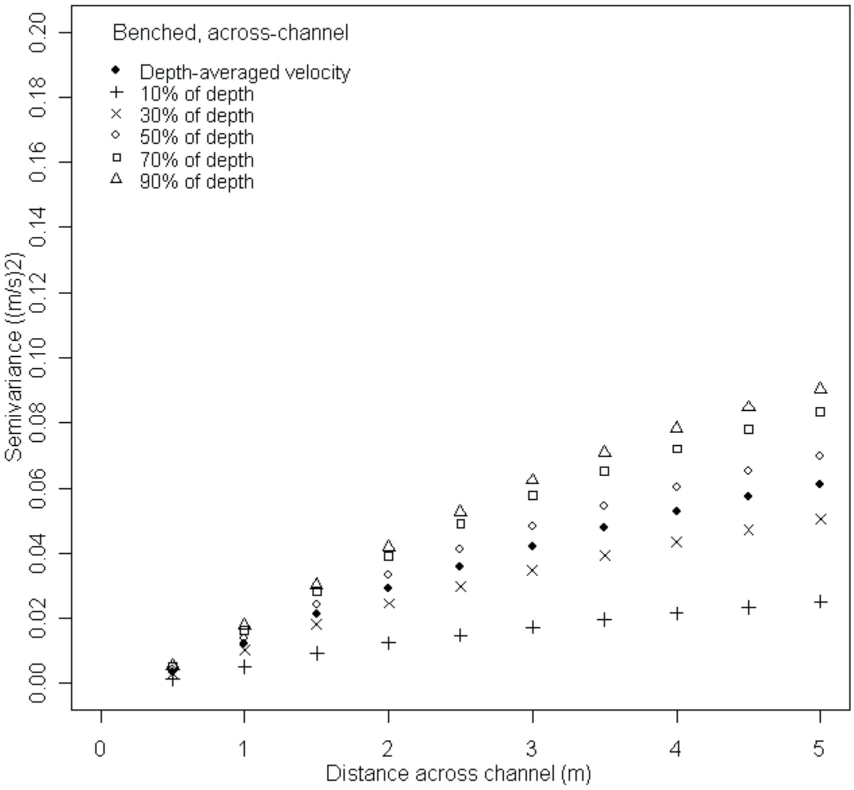


(b)

Figure 4.7: Experimental across-channel variograms for the depth-averaged velocity and velocity at different depths (see legend). (a) 1 Straight (b) 2 Single Bend

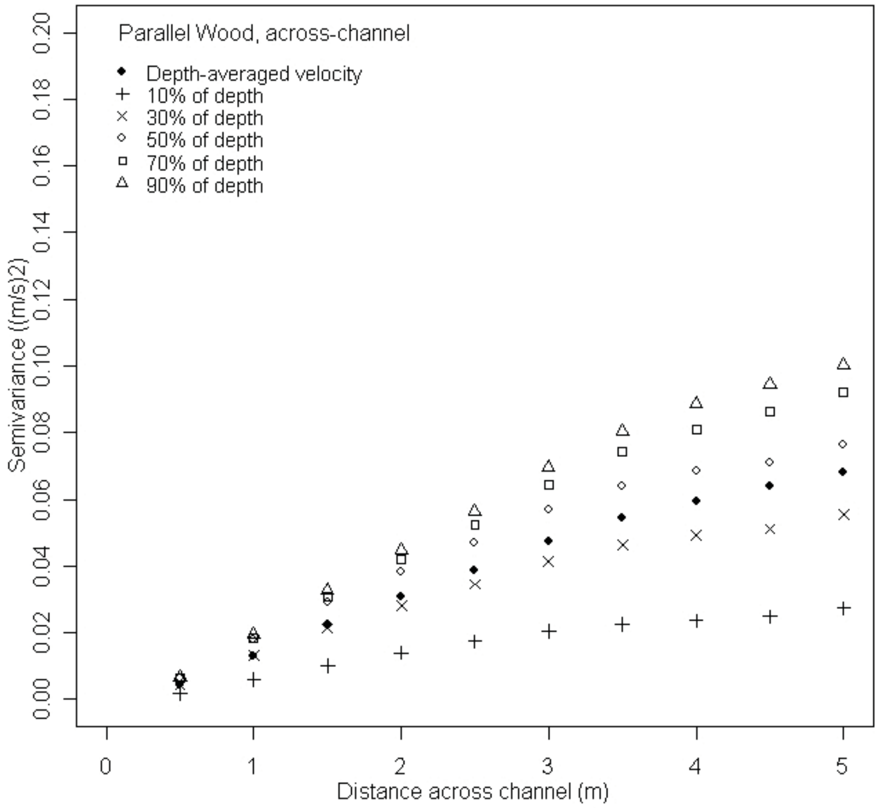


(c)

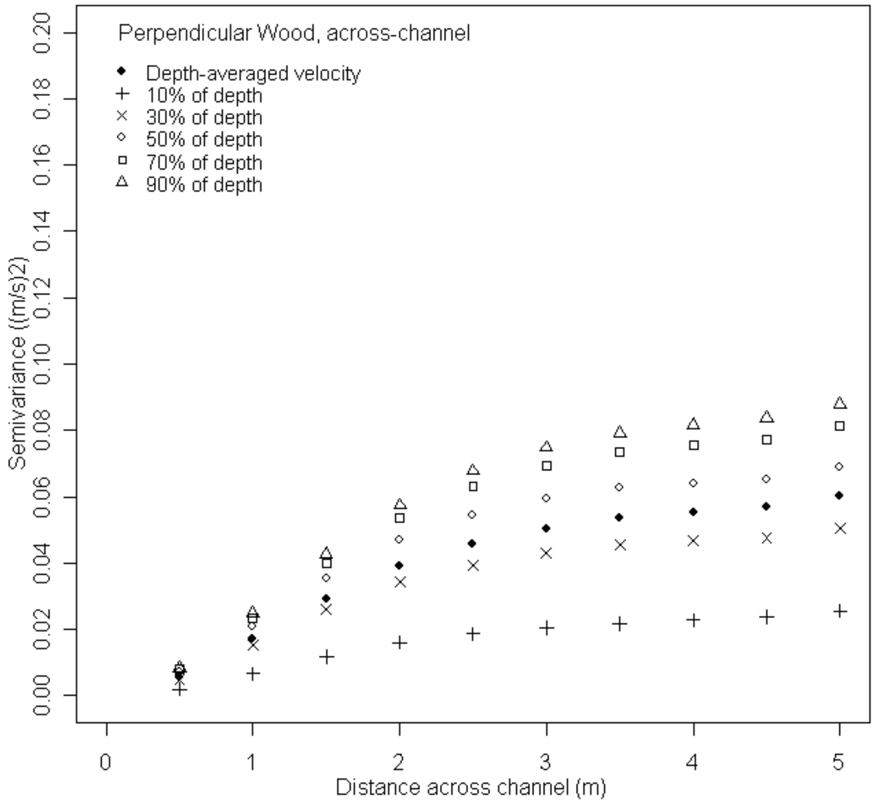


(d)

Figure 4.7 cont: Experimental across-channel variograms for the depth-averaged velocity and velocity at different depths (see legend). (c) 3 Double Bend (d) 4 Benched

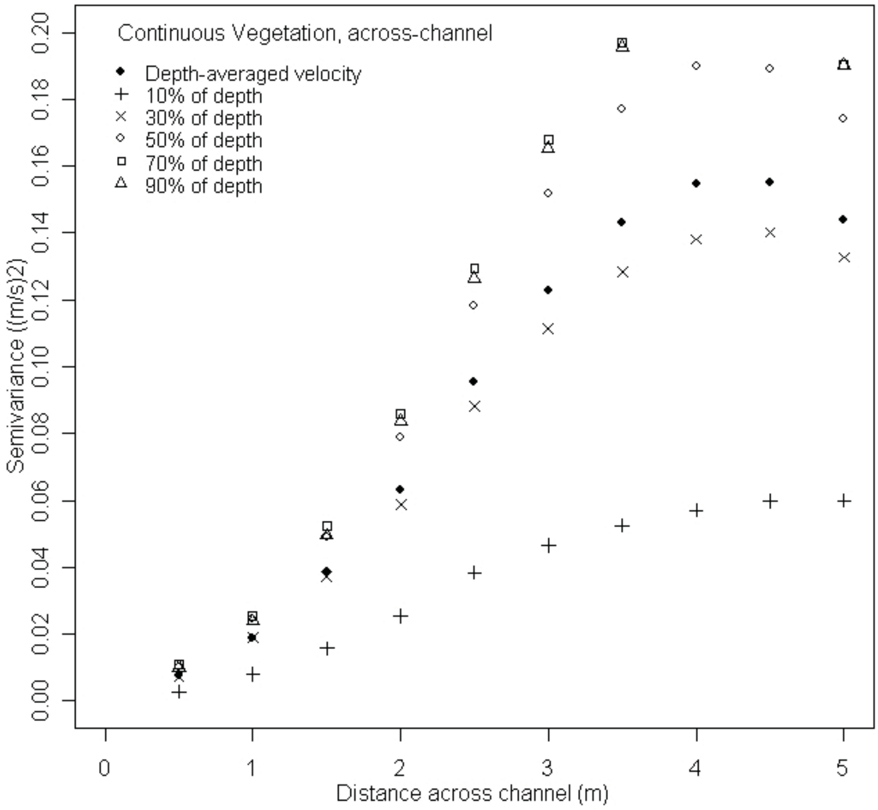


(e)

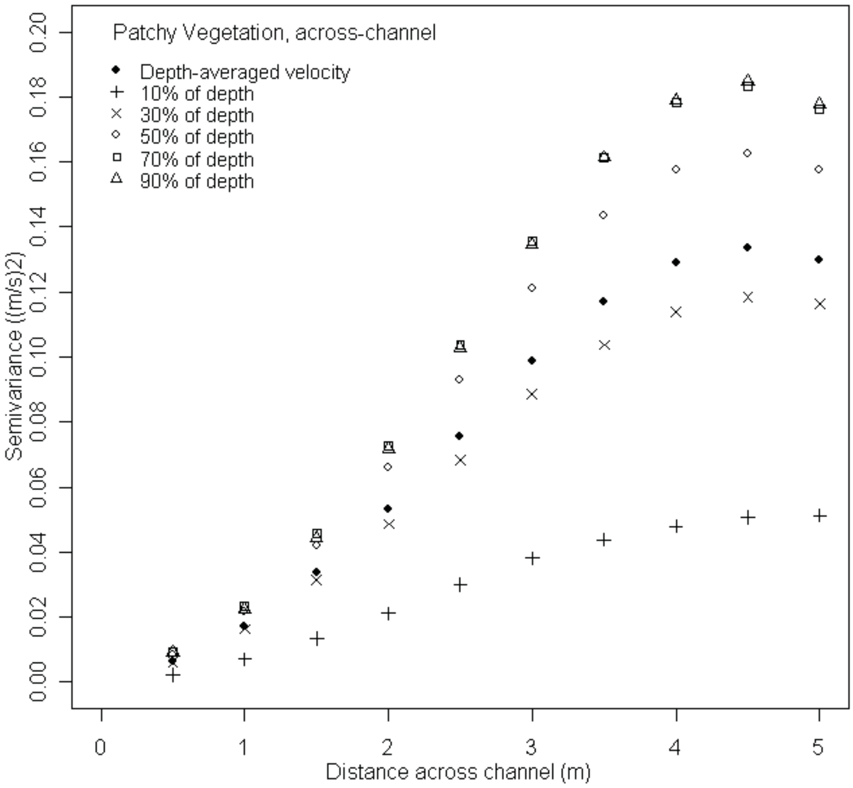


(f)

Figure 4.7 cont: Experimental across-channel variograms for the depth-averaged velocity and velocity at different depths (see legend). (e) 5 Parallel Wood (f) 6 Perpendicular Wood



(g)



(h)

Figure 4.7 cont: Experimental across-channel variograms for the depth-averaged velocity and velocity at different depths (see legend). (g) 7 Continuous Vegetation (h) 8 Patchy Vegetation

4.4 Discussion

This study aimed to demonstrate the application of 3-D CFD modelling, assess the effect that common instream features have on hydraulic conditions and compare different methods to describe reach hydraulic diversity. It also proposes a new approach, using variograms.

3-D hydraulic modelling

Three-dimensional hydraulic modelling is an appropriate tool to use to compare the effects of specific changes to a reach, such as a change in channel form, or additions of wood or vegetation. SSIIM was well-suited to the task as it models the water surface (Olsen 2007), and vegetation, wood and boulders can be included (Olsen and Stokseth 1995; Wilson *et al.* 2006).

Hydraulic models can also provide detailed spatial sampling, permitting a comprehensive comparison of conditions, and assisting in development of variograms. Three-dimensional modelling provides the most detail for examining reach spatial hydraulic diversity (Clifford *et al.* 2005), but comparing and analysing 3-D data are not straightforward. In this study, 3-D data were converted to 2-D data (DAV) for ease of comparison between the different characterisation methods. The variograms calculated at different depths show a similar shape as the DAV variogram, therefore DAV data have been adopted for the purposes of this study. Studies with a different focus (e.g. examining the flow around vegetation: Fischer-Antze *et al.* (2001)) are likely to specifically use vertical data.

Factors changing the hydraulic environment

Adding common river features to a straight channel, namely changes in morphology, and additions of vegetation or wood, changed the hydraulic conditions of the reach, and correspondingly, the potential hydraulic habitat. An exhaustive discussion of the changes is unwarranted, as the modelled characteristics were hypothetical. Nevertheless, all features modelled had a significant effect: the more sinuous the channel, or the more the wood is orientated against the flow, or the more patchily distributed the vegetation, the greater the spatial diversity.

Describing diversity

The average velocity of a reach is commonly used to indicate whether the reach is fast- or slow- flowing, but it does not represent patchiness. Conventional statistics can provide more information on the hydraulic conditions. The range highlights the extreme conditions, but does not indicate the predominant ones. The CV indicates the spread of data (thus, the dominance of one hydraulic condition), but does not differentiate between shapes (compare, for example, the CVs and histograms for Double Bend and Parallel Wood).

Shannon’s and Simpson’s diversity indices incorporate the number of categories (‘species’) and the equitability of those categories, and here gave a similar ranking to the reaches. By themselves, they do not indicate the origin of the diversity (that is, they do not differentiate the number and equitability of categories). For example, although Parallel Wood and Benched have similar Shannon’s and Simpson’s values, Parallel Wood has more velocity categories (six cf. five), but is less evenly distributed than Benched. It is better to also compare the Evenness index to identify the source of diversity (see Evenness for Parallel Wood and Benched). As a measure of the spatial diversity, these indices are sensitive to the designation of the categories.

The histogram shows the mode and spread of data. A benefit of the scatter-plot and bubble-plot is added depth information. Both show whether velocities are associated with particular depths, or if a given depth has a range of associated velocities. The bubble-plots are contrived through use of artificial depth and velocity categories, but allow quick comparisons in a way that scatter-plots do not (points plotted on a graph on top of each are not visible to the viewer).

Variograms

Variograms are the only method here that incorporate spatial arrangement. In this analysis they do not include depth, but comparisons of directional variograms do reveal how velocity varies across- and down-channel. If diversity is primarily across the reach (e.g. both vegetated reaches), then different velocities are likely to be associated with particular depths. If the diversity is mainly down-channel, it is likely that any given velocity is associated with a range of depths.

A few factors should be considered when interpreting variograms. Different values of the lag distance (h) will produce different variograms: greater lag distance may smooth the curve (e.g. Clifford *et al.* 2002a), but might miss smaller scale features. The number of samples, and the spatial arrangement of the samples, can also change the sensitivity and shape of the variogram (Rivas-Casado *et al.* 2005; Rivas-Casado *et al.* 2007). Defining the direction, including the cone distance and angle, particularly in reference to irregularly sampled data, will change the sampling pairs, and therefore possibly the variogram. Variograms are scale-specific, and therefore comparisons need to consider the scale of the samples and the aims of the study. For example, if the scale of the velocity samples differs, it is possible to convert the absolute velocity values to relative velocity values (e.g. Legleiter *et al.* 2007), but this may change the interpretation of the variogram (Clifford *et al.* 2005), and discards biologically-significant information (the physical velocity).

The shape of the variogram provides information about the spatial structure of the flow. The presence of a *nugget* (C_o; Figure 4.1) depends on the size of microscale spatial structures (Clifford *et al.* 2002a) and the sampling strategy. If distances between samples are greater than the size of the structure, this may not be present, but if it is smaller, it may be present (Clifford *et al.* 2005). A short *range* (*a*; Figure 4.1) indicates little correlation between neighbouring sampling points: if a sample has the value *x*, then another sample, further than the range distance away, will not be correlated to *x* (just to the background semivariance, the *sill*). The value of the *sill* (*C*; Figure 4.1) indicates the range of conditions, a general value of the diversity. A smaller semivariance indicates stronger spatial auto-correlation (less over-all diversity) (Legleiter *et al.* 2007). The shape of the sill tail also provides information: while many experimental variograms have a straight sill, others may more closely resemble Patchy Vegetation (Figure 4.6), which shows a periodic effect due to the patchy distribution.

The use of variograms can be flexible. This study only used velocity values, for comparison with the other methods, but other hydraulic properties, such as depth, turbulence and local Froude number could also be used. As shown here, variograms can be calculated at different depths, if data are available. Comparing variograms at a range of depths provides information about the 3-D hydraulic conditions. For example, the Straight reach shows a steady increase in velocity semivariance from the bed to the surface, as may be predicted by a velocity profile of increasing velocity, whereas the vegetated reaches have a less predictable pattern, indicating that assuming a velocity profile of increasing velocity would not correctly describe the hydraulic conditions. Variograms can also be calculated vertically (cf. across- and down-channel), but were not calculated as five vertical points are not considered enough to compute a reliable variogram.

Variograms have been used in river hydraulics: to assess the effects of the boundary roughness on stage-dependent flow structures (Clifford *et al.* 2002a; Legleiter *et al.* 2007); as an alternative method to compare modelling and field data (emphasising the importance of flow structures rather than absolute point velocities) (Clifford *et al.* 2002b; Clifford *et al.* 2005); and to guide field sampling (Rivas-Casado *et al.* 2005; Rivas-Casado *et al.* 2007) and modelling (Clifford *et al.* 2002b) approaches (balancing capturing spatial structure with time). The variograms calculated here are for the purpose of reach spatial hydraulic characterisation, and therefore do not replace methods such as hydraulic mapping, or the calculation of specific metrics (Crowder and Diplas 2000a; Crowder and Diplas 2006), to identify patches of particular hydraulic conditions (such as the location and extent of fast velocity patches next to slow ones).

5 RELIABILITY AND SUITABILITY OF AN ACOUSTIC DOPPLER CURRENT PROFILER FOR USE IN LARGE, LOWLAND RIVERS

5.1 Introduction

Field measurements of reach hydraulic conditions are essential for understanding reach hydraulic-biological relationships. Traditionally, these have been described by the average reach velocity, but organisms do not live by averages (Kondolf *et al.* 2000) and an average value does little to represent the variety of conditions that may be present (Beebe 1996; Crowder and Diplas 2000b).

One method to try and capture the diversity is take to numerous measurements using point-sampling instruments (such as velocimeters or depth sticks) (e.g. Emery *et al.* 2003; Mouton *et al.* 2007a). However, this is a time consuming process in streams, and it is impractical for larger rivers.

Flow-type mapping, through the visual identification of surface flow patterns, has been proposed as a method to rapidly categorise conditions within a reach (Padmore 1998). This approach assumes that surface flow-types are associated with distinct hydraulic conditions (Howes and Stewardson 2005). Although widely used (e.g. UK Environment Agency's *River Habitat Survey*: Clifford *et al.* (2006)), there is argument over the hydraulic uniqueness of the described flow-types (Kemp *et al.* 2000), and the consistency of visual identifications (Maddock and Hill 2005). Furthermore, flow-type identification was developed for streams and is unsuitable for large rivers – particularly slow-flowing lowland rivers where there may be little differentiation in surface flow patterns (Thoms *et al.* 2006).

ADCPs were developed to calculate discharge by measuring the velocity at numerous intervals in the water column, and the corresponding depth, throughout a cross-section (SonTek 2005). This is often achieved by mounting an ADCP to a boat (Muste *et al.* 2004) and measuring the velocity and depth from the moving boat while traversing a cross-section. The capacity of ADCPs to quickly capture 3-D hydraulic measurements over a wide area (Dinehart and Burau 2005b; Dinehart and Burau 2005a) has since been used for purposes other than discharge calculations, including physical studies (e.g. Kostaschuk *et al.* 2004; Chen *et al.* 2007; Sime *et al.* 2007) and a limited number of ecohydraulic studies (Shields *et al.* 2003; Shields and Rigby 2005; Thoms *et al.* 2006).

The moving ADCP, in effect, measures a spatial and temporal average of the instantaneous velocities present in the water column; repeated traverses of the same cross-section will never give exactly the same results as the spatial and temporal reach of each measurement will slightly differ. For discharge calculations the individual velocity measurements are not required to be as accurate as the resultant calculated discharge value. In ecohydraulic and habitat studies it is not only the magnitude, but the diversity of velocity that is of interest. For ADCPs to be a suitable instrument for use in ecohydraulic studies, they should reliably capture the diversity of velocity within a cross-section with one traverse, to minimise data processing (Shields and Rigby 2005) whilst maximising the potential study area.

The reliability and suitability of ADCPs for ecohydraulic purposes in a large, lowland river, such as the River Murray, Australia, where conditions vary from shallow to deep, slow to fast, has not been tested. The aim of this study was to assess an ADCP under these conditions. Six reaches along the River Murray provided a range of hydraulic conditions. Reliability and suitability was assessed by comparing the morphology, and velocity profiles and density plots, from repeated traverses of the same cross-section. Practical considerations and data processing requirements are also discussed.

5.2 Methods

5.2.1 Velocity and depth sampling using an ADCP

ADCPs use the Doppler Shift principle to measure the velocity—the frequency of the sound at a receiver is shifted, relative to the transmit frequency, if the sound source is moving relative to the receiver (Yorke and Oberg 2002) (Equation 5.1):

$$F_D = 2F_S\left(\frac{V}{c}\right) \tag{5.1}$$

where F_D = change in received frequency at the receiver (the Doppler shift) (Hz)
F_S = frequency of the transmitted sound (Hz)
V = relative velocity between source and receiver (m s^{-1})
c = speed of sound (m s^{-1})

ADCPs release a sound wave (a "ping") at regular intervals, and measure the frequency shift reflected from particles in the water at discrete depth intervals (*cells*) in the water column (Figure 5.1). A column of cells from one ping is referred to as one *profile.* The *blanking distance* defines the minimum distance to the first cell (Cell 1 in Figure 5.1), and depends on the frequency of the ADCP. ADCPs usually use three or four beams and can be employed in an upright (stationary placement on the river bed) or downward facing position. Further information on the principles of operation is given by Muste *et al.* (2004) and Kostaschuk *et al.* (2005).

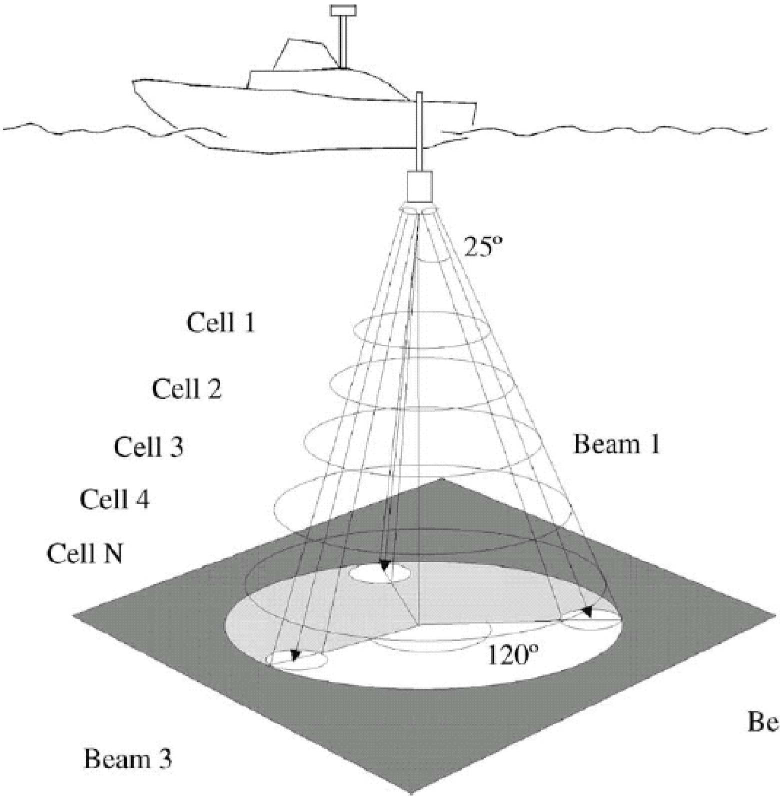


Figure 5.1: Sketch of an ADCP, showing the beam geometry and sampling cells (from Kostaschuk *et al.* 2005).

This study used a Sontek 1000 kHz, three-beam ADCP in the downward facing position. The ADCP was mounted to a 3.7 m semi-v hulled boat with an adjustable pole, made of aluminium to reduce magnetic interference with the internal compass (Figure 5.2). RiverSurveyor software (SonTek 2005) was used to collect the data and make real-time assessment of the progress and conditions (Figure 5.3) via an onboard laptop (Figure 5.2). The ping rate was set to 0 s (the fastest setting) and the profile interval to 5 s. As the boat was moving during this time, the average distance covered was about 5 m per profile; the number of profiles per traverse therefore depends on the cross-sectional width. The cell size (depth) was set to either 0.25 m (reaches Hat, BDS and BUS – see below) or 0.5 m (reaches L4, L5 and L11 – see below). The blanking distance was 0.5 m. Bottom tracking was used to take into account the speed of the boat movement relative to the observed speed of water movement, and is considered adequate for this study (Dinehart and Burau 2005b). A separate file was made for each cross-section, but not for each traverse.

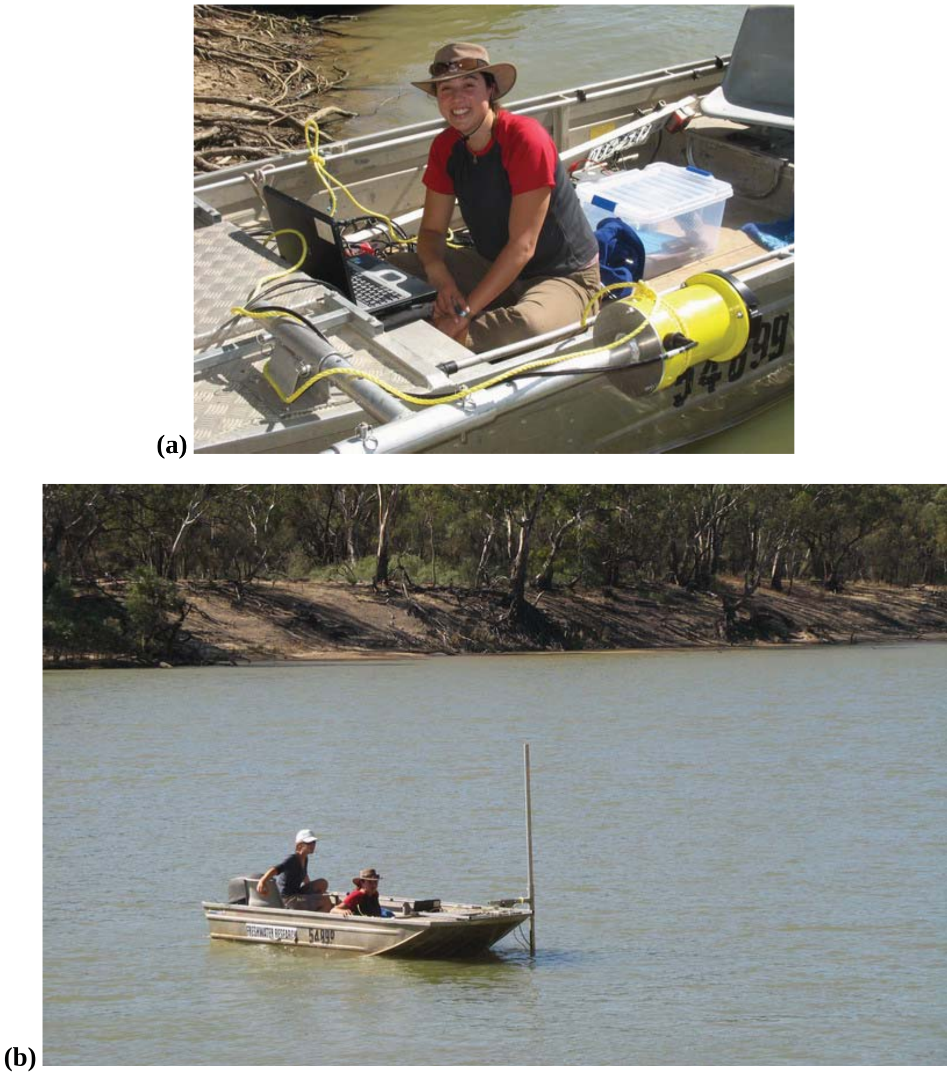


Figure 5.2: The boat-mounted, downward facing ADCP (a) set up and (b) in deployment.

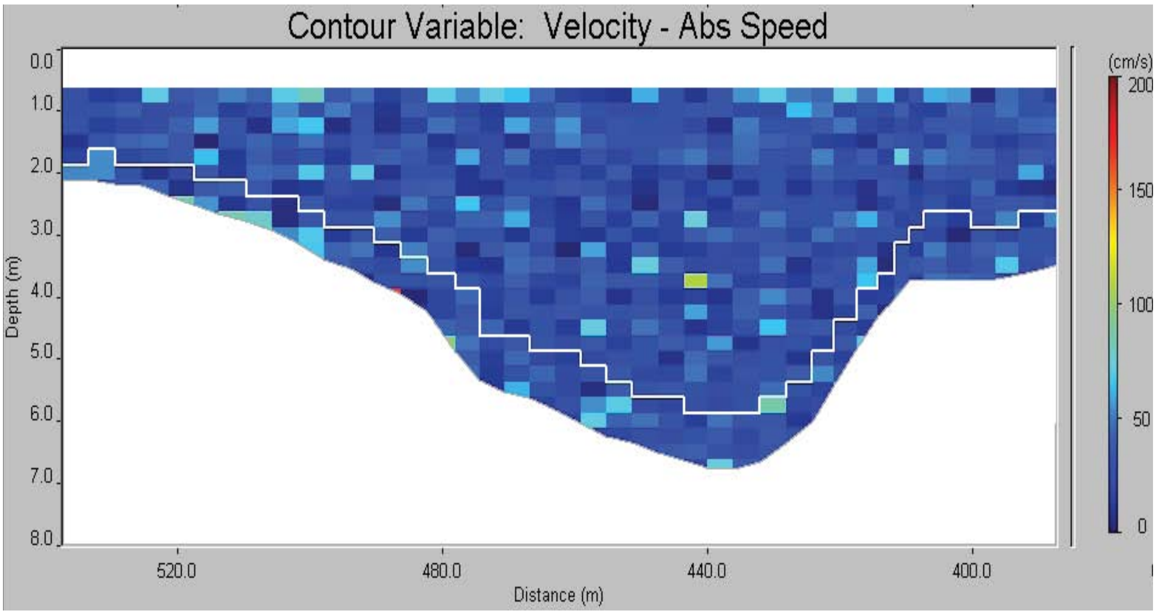


Figure 5.3: Example screen shot from the RiverSurveyor software, through which the ADCP was controlled, showing a cross-section and measured velocity cells.

5.2.2 The reaches

The six reaches, up to 3 km long, were situated along the River Murray, south-east Australia. The three downstream reaches were in close proximity to weirs (weir-affected) (Lock 4 (L4), Lock 5 (L5) and Lock 11 (L11)), while the three upstream sites were "free-flowing" (unaffected by weirs) (Hattah (Hat), Barmah downstream (BDS) and Barmah upstream (BUS)) (Figure 5.4). Further descriptions of the reaches can be found in Chapter 6.

Sampling was conducted on 4-13 April 2006. At each reach, 6–9 cross-sections were located *c.* 250 m apart (Figure 5.4), depending on reach and weather conditions. At each cross-section, the ADCP traversed the same cross-section (as closely as possibly) two to three times. Wood was avoided, where possible, or filtered out of the data (as bad quality data). A laser range-finder was used to measure the width of each cross-section and the position of the boat from the bank when the ADCP started to record data.

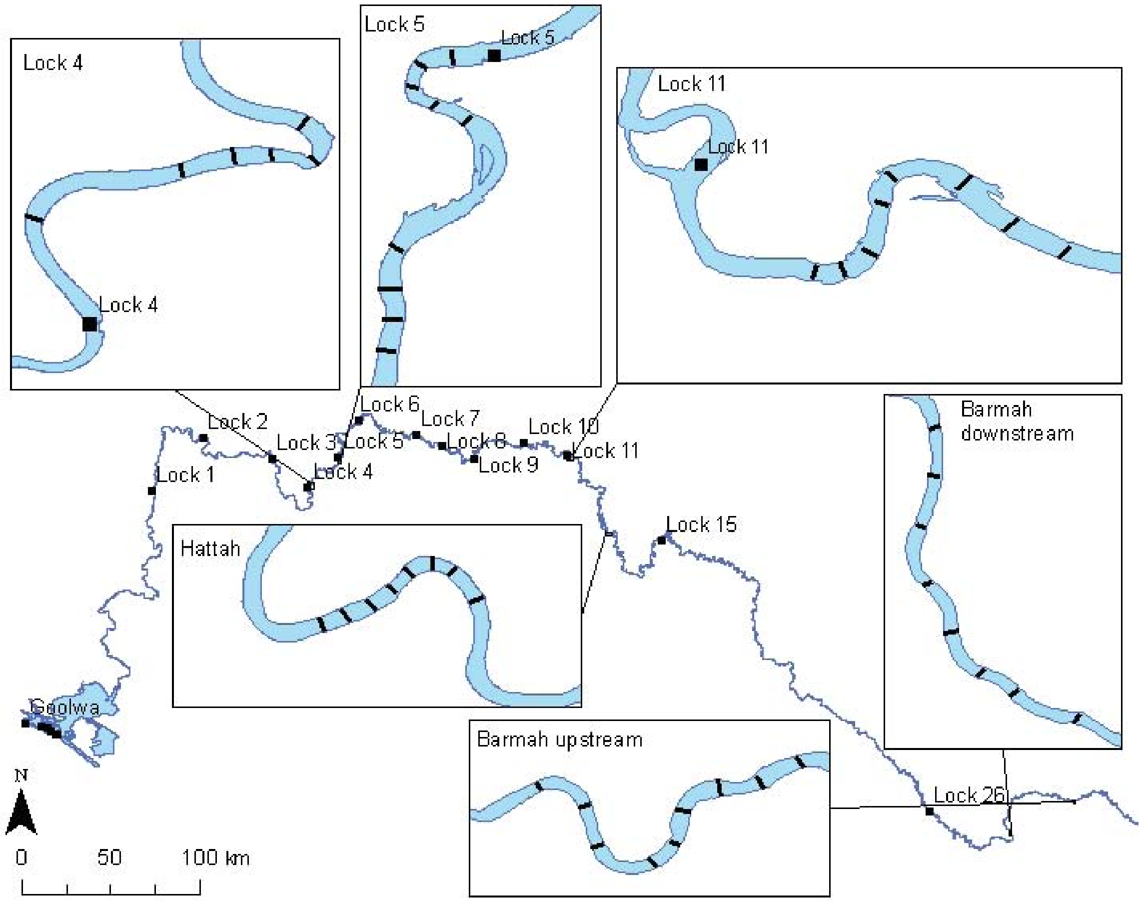


Figure 5.4: The middle and lower tracts of the River Murray, showing the location of the six reaches and cross-sections within the reaches. Flow direction from Lock 26 to Goolwa.

5.2.3 Data processing and analysis

RiverSurveyor output includes location (on a *x-y* grid), depth and depth-averaged velocity for each profile. Data were initially exported to Microsoft Excel to define the profiles for each traverse.

Data *smoothing* is recommended before using the velocity measurements collected from ADCPs (Sime *et al.* 2007). Raw velocity data from moving boat ADCPs are highly irregular due to a combination of instrument noise, operator settings and environmental factors (e.g. water turbulence, particle quality and quantity) (Yorke and Oberg 2002; Muste *et al.* 2004). Thus, the irregularity of the raw data is not due to hydraulic diversity *per se*, but is an artefact of the measurement. Smoothing is applied to the raw ADCP data to obtain relevant mean river velocity fields (Muste *et al.* 2004), and involves the use of a number of suggested procedures that, in effect, spatially and temporally average the raw data. For the depth-averaged velocity, data were smoothed by averaging each profile with the adjacent profiles (i.e. a moving three-sample average).

ViewADP software (SonTek 2000) can access the 3-D data (cf. RiverSurveyor). Raw data were first filtered for low Signal-to-Noise ratio and Data Quality Index, and smoothed using a 3-cell (vertical and horizontal) Gaussian smoothing algorithm. The velocity magnitude was exported from ViewADP for further calculations, including the width-averaged velocity (in Microsoft Excel) and the Kernel density function (using R (R Development Core Team 2007)). The velocity magnitude is a combination of the *x*, *y* or *z* components, and was used because it is the velocity that aquatic biota experience (also the *x* and *y* components are not clearly differentiated due to bends in the reach planform).

RiverSurveyor was used to calculate the discharge. Graphics were compiled using the statistical package R (R Development Core Team 2007).

5.3 Results

A comparison of cross-sectional morphology data from each traverse at each cross-section is shown in Figure 5.5. Note that different extents may be shown for each traverse of a cross-section (e.g. Figure 5.5 (b): L5-CS10), due to variation in the starting and finishing location of good quality data from the ADCP. In general, there is excellent repeatability in the measured cross-sectional shape between most traverses. Where there is not good correspondence (e.g. L4-CS3, L11-CS5, Hat-CS8, Hat-CS10, BDS-CS5, BDS-CS8, BUS-CS5, BUS-CS8), this often is due to the boat being slightly off the original cross-section (perhaps due to poor weather, strong winds or fast flow).

Figure 5.6 shows a comparison of the depth-averaged velocity for each traverse, and the effect of adjacent-profile smoothing. Figure 5.7 depicts the effects of Gaussian smoothing on a cross-section (from ViewADP). Smoothing appears to increase the similarity in the depth-averaged velocity between traverses, by levelling the spikes. This is particularly evident for the free-flowing reaches (Figure 5.6 (d)-(f)), where there is a greater range of velocities across the cross-section. As with the morphology, some of the observed discrepancy could be due to different boat traverses (cf. different traverse morphology for Hat-CS10, BDS-CS5, BDS-CS8).

The width-averaged velocity (an averaged velocity profile) for each traverse in shown in Figure 5.8. As with the depth-averaged velocity, there is reasonable repeatability between the traverses, with the magnitude of the difference increasing at the free-flowing reaches (Figure 5.8 (d)-(f)), as the value of the velocity range increases. Again, some variation between the traverses might be explained by slightly varying boat trajectories (see L11-CS5, Hat-CS10, BDS-CS5, BDS-CS8).

A direct cell-by-cell comparison of the 3-D data is not possible because of the different location and extent of each cell. Therefore, 3-D velocity data from each traverse were pooled, and a Kernel density plot of the distribution calculated (Figure 5.9). For these graphs, the closest repeatability is again noted for the weir-affected reaches (Figure 5.9 (a)-(c)), probably due to the lower range in velocity samples and larger sample size (greater width and depth of cross-section). Again, some variation may be explained by the boat tracking a different traverse (e.g. L11-CS5, Hat-CS8, Hat-CS10, BDS-CS5, BDS-CS8, BUS-CS5).

Note that Figure 5.5 to Figure 5.9 are compiled to facilitate quick comparison between traverses, cross-sections and reaches, and therefore are not presented for detailed inspection.

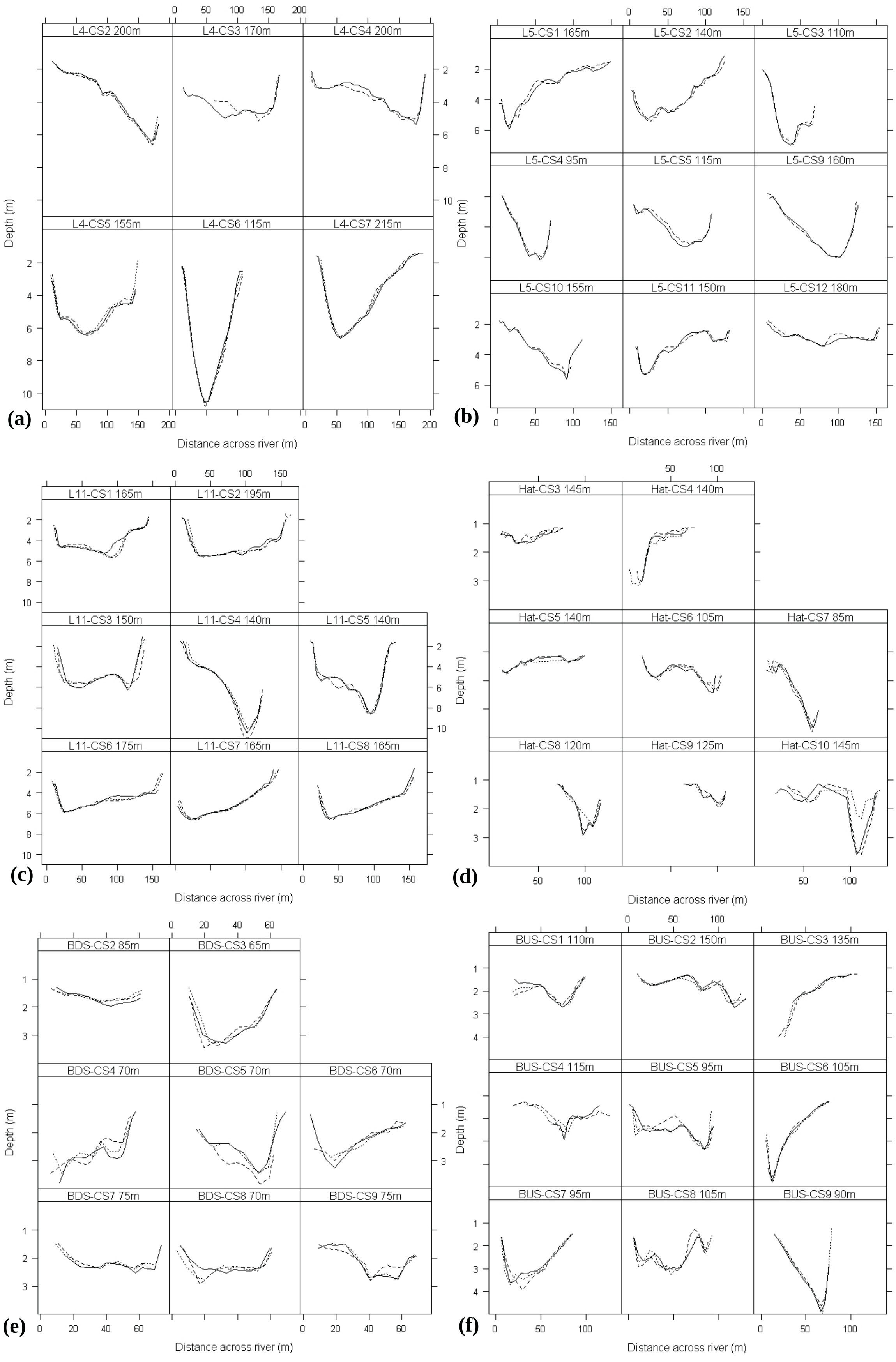


Figure 5.5: Cross-section morphology as measured by the ADCP. Different traverses are shown by different line types. The cross-section width is shown in the plot heading. (a) L4 (b) L5 (c) L11 (d) Hat (e) BDS (f) BUS. Note different depth and width scales.

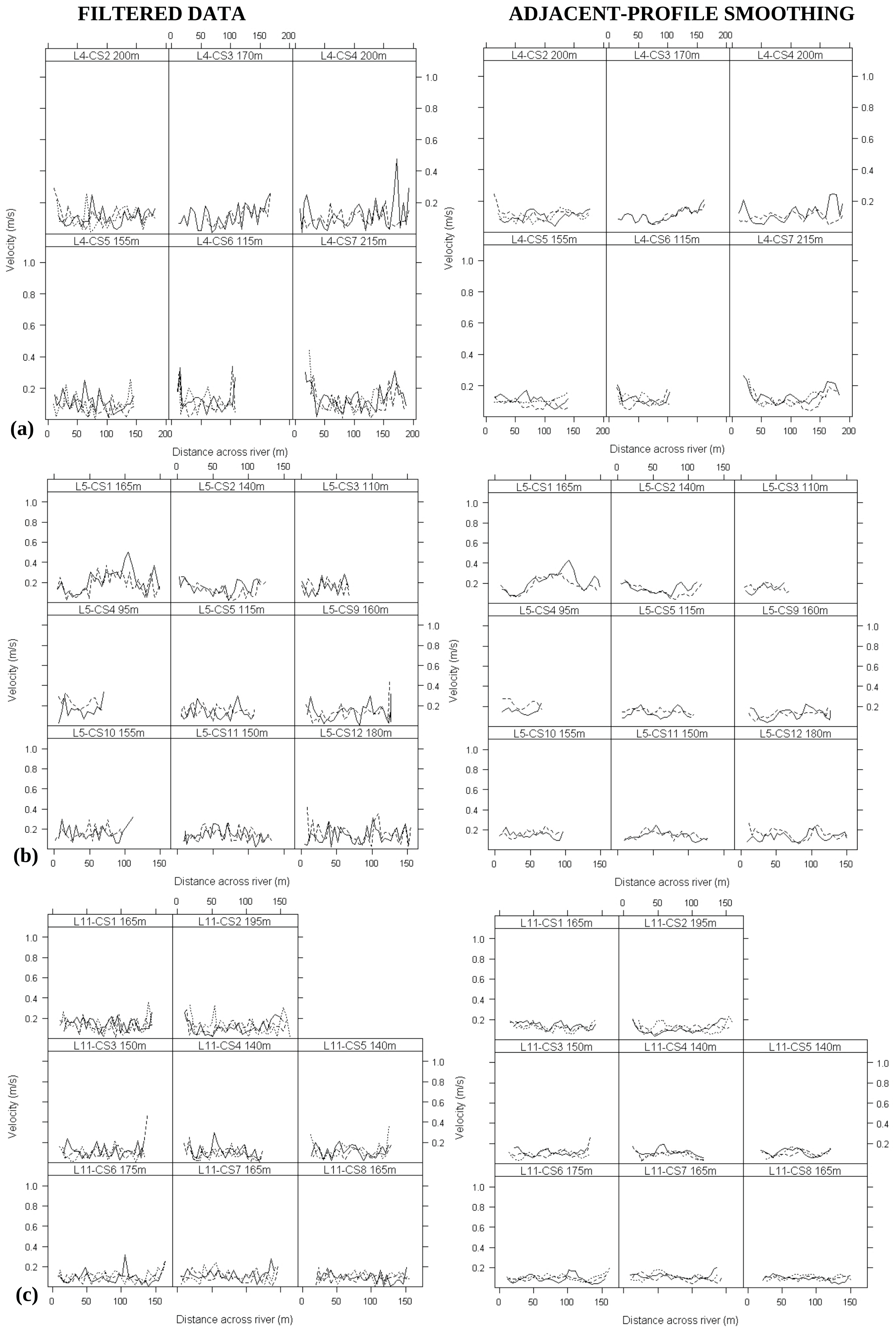


Figure 5.6: Depth-averaged velocity across the cross-section. Cross-section width is shown in the plot headings. Different traverses are shown by different line types. Raw DAV data is shown on the left hand side, and smoothed DAV on the right hand side. (a) L4 (b) L5 (c) L11. Note different width scales.

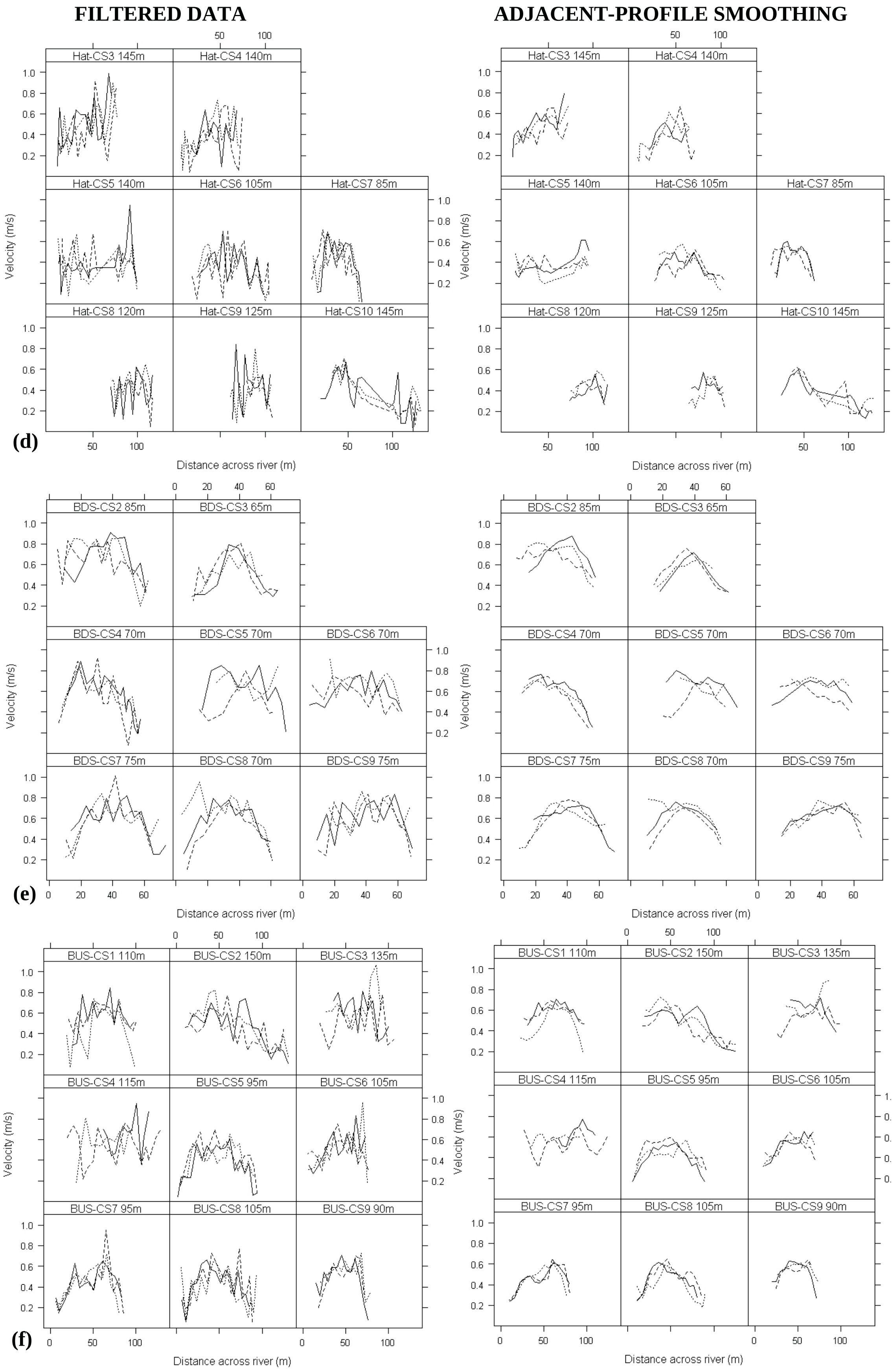


Figure 5.6 cont. Depth-averaged velocity across the cross-section. Cross-section width is shown in the plot headings. Different traverses are shown by different line types. Raw DAV data is shown on the left hand side, and smoothed DAV on the right hand side. (d) Hat (e) BDS (f) BUS. Note different width scales.

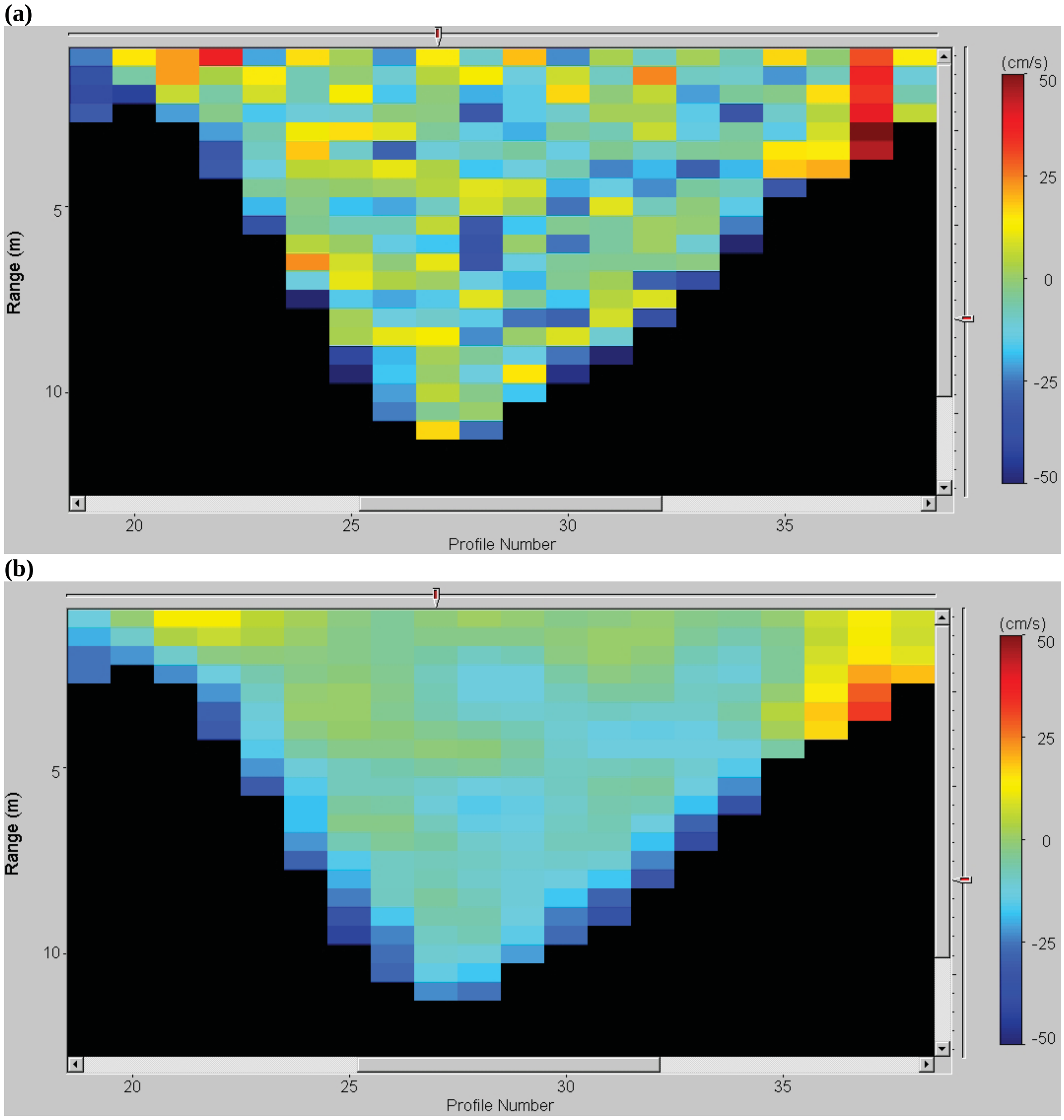


Figure 5.7: A graphic depiction showing the effect of Gaussian smoothing on the velocity within a cross-section, from ViewADP: (a) filtered, (b) filtered and smoothed.

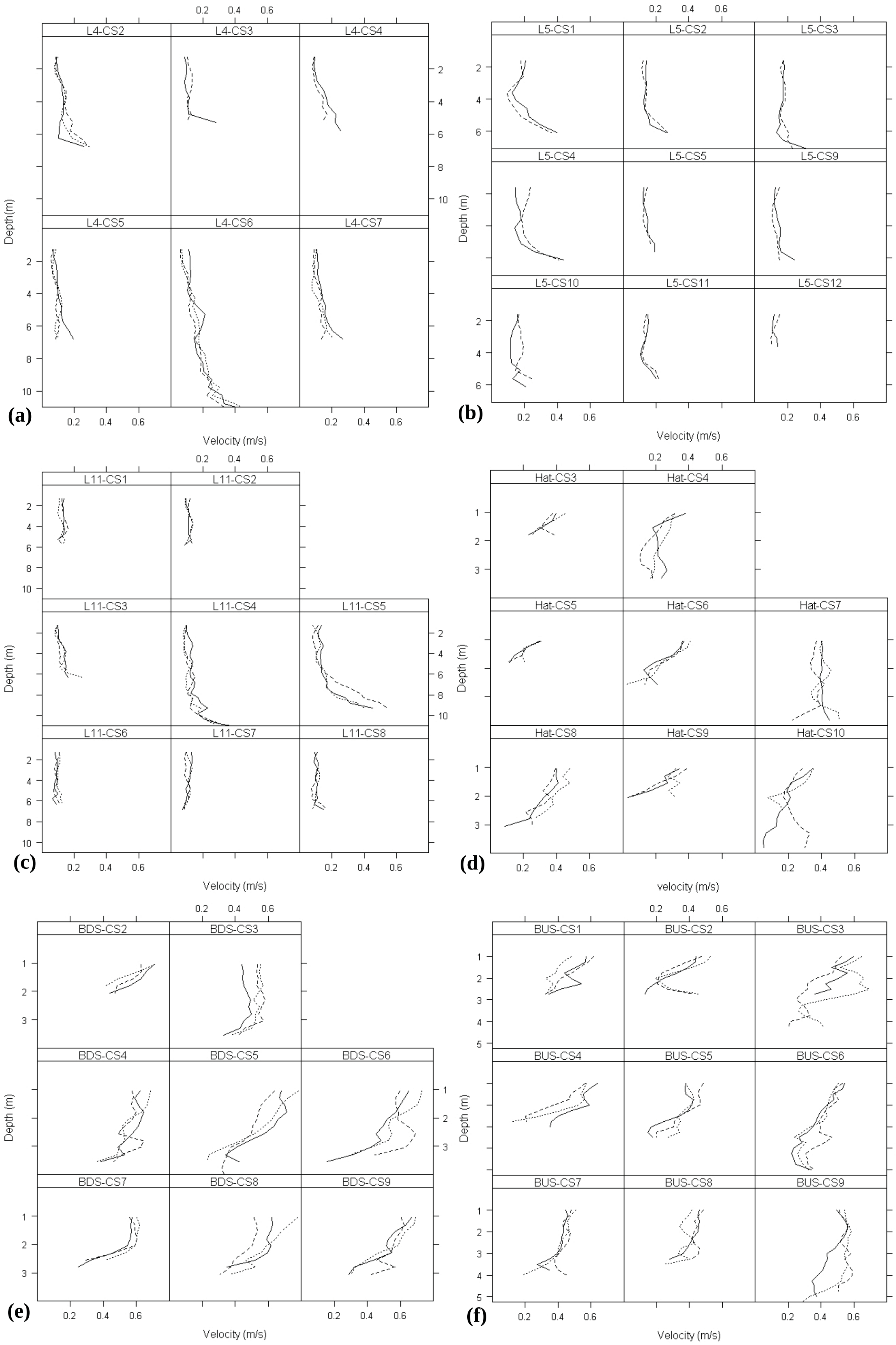


Figure 5.8: Width-averaged cross-sectional velocity (an averaged profile). Different traverses are shown by different line types. (a) L4 (b) L5 (c) L11 (d) Hat (e) BDS (f) BUS. Note the different depth scales.

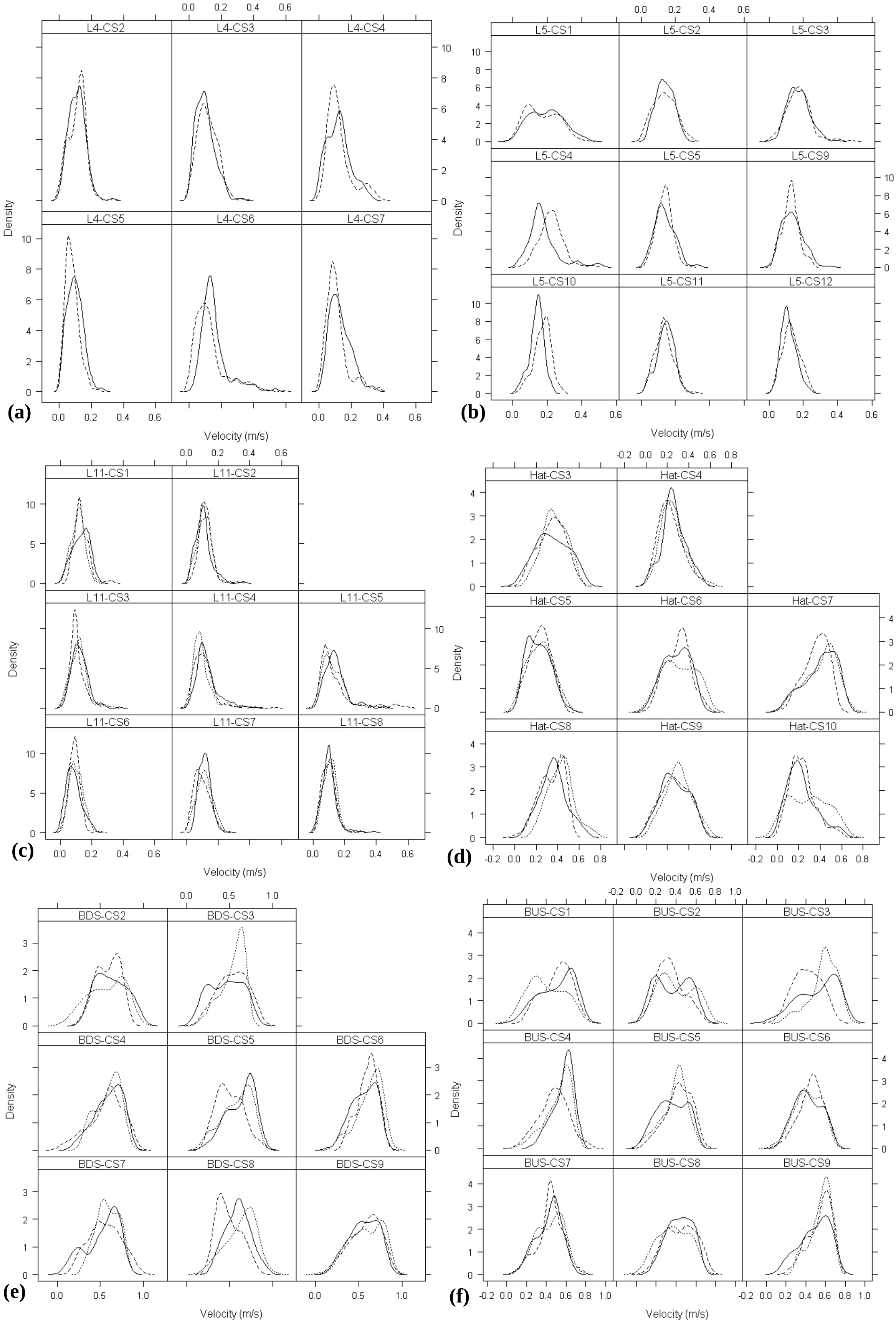


Figure 5.9: Kernel frequency (density) plots for each traverse, shown by different line types. (a) L4 (b) L5 (c) L11 (d) Hat (e) BDS (f) BUS.

A comparison of the discharge calculated for each traverse using RiverSurveyor, with the official discharge reported by the Murray-Darling Basin Commission (MDBC), is shown in Figure 5.10. The discharge calculations show a lot of variation, and although the average discharge appears near the official discharge for the weir-affected reaches (L4, L5 and L11), it generally under-estimates the discharge in the free-flowing reaches (Hat, BDS and BUS).

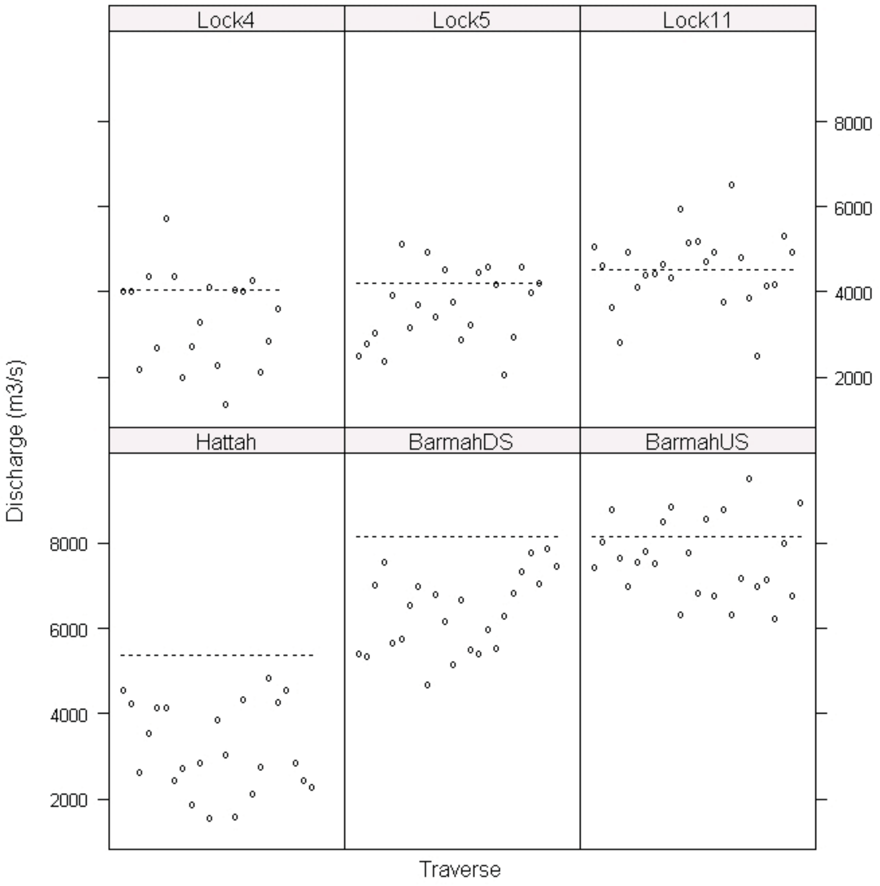


Figure 5.10: Comparison of the discharge calculations from RiverSurveyor (circle symbol, o) and the discharge reported by the Murray-Darling Basin Commission (line symbol, -).

5.4 Discussion

The aim of this study was to assess the reliability and suitability of an ADCP to collect velocity and depth data in a large lowland river, for use in ecohydraulic studies. To be considered reliable, the ADCP should collect similar velocity and depth data on different traverses of the same cross-section (that is, show good repeatability). The suitability of the ADCP is assessed on both its practical application (in the field) and the measured data.

Reliability

In this study, the ADCP demonstrated excellent repeatability of depth measurements between traverses of the same cross-section (except, obviously, where the boat followed a slightly different course), and therefore can be considered reliable for this purpose. Similarly, the bottom-tracking function (which records the boat location) performed well.

Variability between traverses was recorded for the velocity measurements, the magnitude of which could significantly affect the potential hydraulic habitat for organisms. As mentioned, some of the variation observed may come from slightly different boat trajectories. Another source of variation may be the processing of the data, particularly the inclusion and exclusion of valid data cells in a profile. For example, the depth-averaged velocity reported here is an average of the measured filtered data, and does not include estimates of velocity in the blanking or bottom zones (SonTek 2005). The number of valid data cells can vary with each profile, thus affecting the reported value. This factor is likely to have a greater effect on shallow profiles, where there are fewer cells, and therefore the inclusion and exclusion of cells will have a significant influence on reported values. This is likely to have contributed to the observed differences in the depth-averaged velocity profiles for the different traverses in the shallower, free-flowing reaches.

Removing the random noise associated with ADCP measurements by smoothing, to obtain more reliable velocity estimates, is highly recommended (Dinehart and Burau 2005a; Sime *et al.* 2007). As smoothing is essentially a process of spatially and temporally averaging the measured data, the amount of smoothing applied is a balance between achieving large-scale, reliable data, and retaining some of the smaller-scale hydraulic variability. A number of smoothing algorithms have been proposed (Muste *et al.* 2004), but the method used, and amount of smoothing, are dependent on the study aims and researcher’s preferences. The smoothing functions used here (adjacent-profile averaging for the depth-averaged velocity, and the Gaussian smoothing algorithm for the 3-D data) appear adequate for smoothing the random noise, while retaining hydraulic diversity.

There was a lot of variation in the discharge calculated by RiverSurveyor, which generally underestimated the reported MDBC discharge in the free-flowing reaches, but approached it at the weir-affected reaches. RiverSurveyor calculates discharge by using the measured data and estimating the velocity of the unmeasured sections of a cross-section (the edges, surface and bottom layers). While distances to the bank were measured as accurately as possible, the sampling was not designed to calculate discharge, and therefore edge inaccuracies may have been introduced. It is also likely that the relatively shallow and narrow nature of the channel at the free-flowing reaches (and therefore smaller sampling size and proportion of cross-section actually sampled) significantly influenced the discharge calculations. It is also possible that the MDBC discharge was not actually the discharge experienced at the time of sampling, due to: inaccuracies in MDBC measurement techniques; the distance from sampling reach to MDBC measurement location; the difference in time of day between MDBC measurements and ADCP sampling; and daily variations caused by lock operation and irrigation pumping schedules.

Suitability

The 1000 kHz ADCP used in this study could not collect data from shallow areas (<1.5 m), vegetated areas, and around fallen wood. As many sections of the reaches measured, particularly the free-flowing reaches, contained shallow areas and/or vegetation and wood, the ability of the ADCP to capture the range of hydraulic conditions in those reaches is limited, which needs to be considered when interpreting results. Higher frequency, mini ADCPs are better able to measure shallow water (<0.5 m) and negotiate narrow channels and obstacles (e.g. a Sontek RiverCat).

Moving-boat ADCP measurements are spatial and temporal averages of instantaneous velocities over a finite area (Muste *et al.* 2004; Shields and Rigby 2005), and therefore do not capture small-scale hydraulic features. Measurements with current meters, and output hydraulic models, are also temporal and spatial averages of conditions. ADCPs measure hydraulic conditions somewhere between instantaneous fluctuations (that aquatic organisms experience), and longer-term averages (including smoothing processes), so it has been suggested they give a better indication of habitat conditions than conventional measurements (Shields and Rigby 2005).

The ADCP was efficient at collecting 3-D data over a large reach. Three-dimensional data can be used to better understand the hydraulic environment of a reach (Stewart *et al.* 2005), but processing 3-D data is complicated. A number of techniques have been used to reduce data to comprehensible form, including: specific examples of depth profiles (e.g. Booker *et al.* 2001; Booker 2003; Wilson *et al.* 2006) or cross-sectional contours (e.g. Kondolf *et al.* 2000; Daniels and Rhoads 2003; Daniels and Rhoads 2007); reduction of data to two-dimensions (e.g. Kostaschuk *et al.* 2004; Dinehart and Burau 2005b; Dinehart and Burau 2005a; Kostaschuk *et al.* 2005; Chen *et al.* 2007); or density analysis of pooled data (e.g. Booker 2003; Clifford *et al.* 2005; Wilcox and Wohl 2007). Variations of some of the above were used in this study: data were reduced to two dimensions in two directions (depth-averaged and width-averaged velocity), and data were pooled for the Kernel density curve. Given the aim of assessing the repeatability of measured ADCP data, this is considered adequate. Note, however, that further information can be extracted from the ADCP; only the velocity magnitude (average speed of the three-directional components) was used, not the individual x, y and z components.

The limited operating range of the ADCP, and the large (*c.* 5 m) profile width, mean the application of ADCP data to fish-habitat (including hydraulic-preference) studies is limited (Shields *et al.* 2003). For example, many species of fish inhabit the littoral zones or the top layer of water in large rivers. However, reach-scale ADCP data have been collected to calculate metrics (Crowder and Diplas 2000a; Crowder and Diplas 2006) of fish habitat quality (Shields *et al.* 2003; Shields and Rigby 2005), and have been used to investigate hydraulic flow patterns in the path of migrating fish (Dinehart and Burau 2005b; Dinehart and Burau 2005a).

Therefore, the potential of ADCPs for ecohydraulic studies lies in its ability to measure reach-scale hydraulic conditions (e.g. Thoms *et al.* 2006). ADCPs provide more data than one average measurement, but less detailed data than that required for smaller-scale fish (individual)-habitat interactions. Thus, data from ADCPs are better suited to examine community or population responses, or ecosystem processes, to reach-scale hydraulic condition (Shields *et al.* 2003; Thoms *et al.* 2006). The potential use of ADCPs is greatly increased with the development of higher-frequency mini-ADCPs, but work on data collection protocol and processing is still needed (Dinehart and Burau 2005a; Shields and Rigby 2005).

6 USING VARIOGRAMS AND AN ADCP TO IDENTIFY SPATIAL AND TEMPORAL DIFFERENCES BETWEEN REACHES

6.1 Introduction

Spatial hydraulic diversity is an attribute of a healthy river ecosystem (Mann and Bass 1997; Zeug and Winemiller 2008, Chapter 3) and is influenced, at the reach-scale, by discharge, channel form, and obstacles such as vegetation, wood and regulating structures (Chapter 4). Measuring the hydraulic environment at the reach-scale is problematic, however, particularly in large lowland rivers.

In approaching this problem, Chapter 4 explored different methods to characterise reach spatial hydraulic diversity, using artificial (virtual) reaches. Variograms, the only method used that incorporated spatial arrangement, were recommended. Chapter 5 assessed the reliability and suitability of an Acoustic Doppler Current Profiler (ADCP) to measure hydraulic conditions for ecohydraulic purposes. The ADCP was shown to be a reliable and suitable instrument to measure hydraulic conditions at the reach-scale.

This chapter extends the investigation by considering whether variograms may be used to elucidate spatial and temporal differences in the hydraulic features of reaches, using data from an ADCP.

6.2 Methods

6.2.1 The reaches

The River Murray (Figure 6.1) is highly regulated by dams and diversions, mainly to supply irrigation needs (Walker 1992). Downstream of the Darling River Junction, 830 km from the river mouth near Goolwa, there are 10 closely-spaced, 3 m high weirs, so that the lower Murray essentially is a cascading series of pools (Walker 2006).

NOTE:
This figure is included on page 88 of the print copy of the thesis held in the University of Adelaide Library.

Figure 6.1: The Murray-Darling Basin, south-eastern Australia, and the six reaches (L4, L5, L11, HAT, BDS, BUS) (adapted from Murray-Darling Basin Commission 2003).

Six study reaches were chosen along the Murray (Figure 6.2). The three downstream reaches are in weir pools (the "weir-pool" reaches), and the three upstream reaches are less affected by weirs (the "free-flowing" reaches). A summary of the reach dimensions is in Table 6.1.

Reach Lock 4 (L4), 2.7 km upstream of Lock 4, is characterised by a wide channel, steep edges and a fairly flat ("*U*" shape) cross-section *c.* 5 m deep. The reach also contains a distinctive sharp bend, where the depth increases to 15 m, and the cross-section shape changes to a "*V*" shape. Littoral vegetation is dominated by emergent macrophytes (particularly *Phragmites australis*, *Typha* spp.), willows (*Salix* spp., mainly *S. babylonica*) and planted grasses. A cliff was present around the bend.

Reach Lock 5 (L5) is 2 km downstream of Lock 5, in the Lock 4 weir pool. Being the upstream end of the weir pool, conditions were shallower than in Lock 4. Emergent macrophytes also dominated the littoral vegetation, but some submerged vegetation, and bare steep banks with exposed tree roots, were also present.

Reach Lock 11 (L11) is 1.6 km upstream of Lock 11, next to the rural city of Mildura. It is a deeper reach than Lock 5, and contains two bends. The banks of this reach were lined with lawn grass, emergent macrophytes, house boats and a paddle-steamer dock.

The free-flowing reaches retain more of their pre-regulation character, and are flanked by eucalypt woodlands (river red gum: *Eucalyptus camaldulensis*, black box: *E. largiflorens*).

Reach Hattah (HAT) is a shallow, free-flowing reach, with one bend. The banks of this reach are primarily bare, either consisting of a shallow sand bar, or <4 m earthen cliff with exposed roots, and fallen trees.

Reach Barmah downstream (BDS) is in a narrower part of the river. The reach contains many shallow bends, but no sharp bends. The littoral zone comprised variously of submerged and emergent macrophytes, fallen wood and <4 m earthen cliffs with exposed tree roots.

Reach Barmah upstream (BUS) has a slightly wider channel, and contains a couple of sharper bends. Again, the littoral zone is comprised of a variety of submerged and emergent macrophytes, fallen wood, and <4 m earthen cliffs with exposed tree roots.

Sampling was conducted over two periods, 4-12 September 2006 and 17-22 April 2007. Discharge was considerably lower in April 2007, due in part to the basin-wide drought forcing water restrictions and a reduction in irrigation water being channelled down the river (Table 6.1). While this also affected the water level at the free-flowing reaches (the river appeared to be *c.*1 m lower), weir operations ensured that the water level in the weir-pool reaches remained relatively constant.

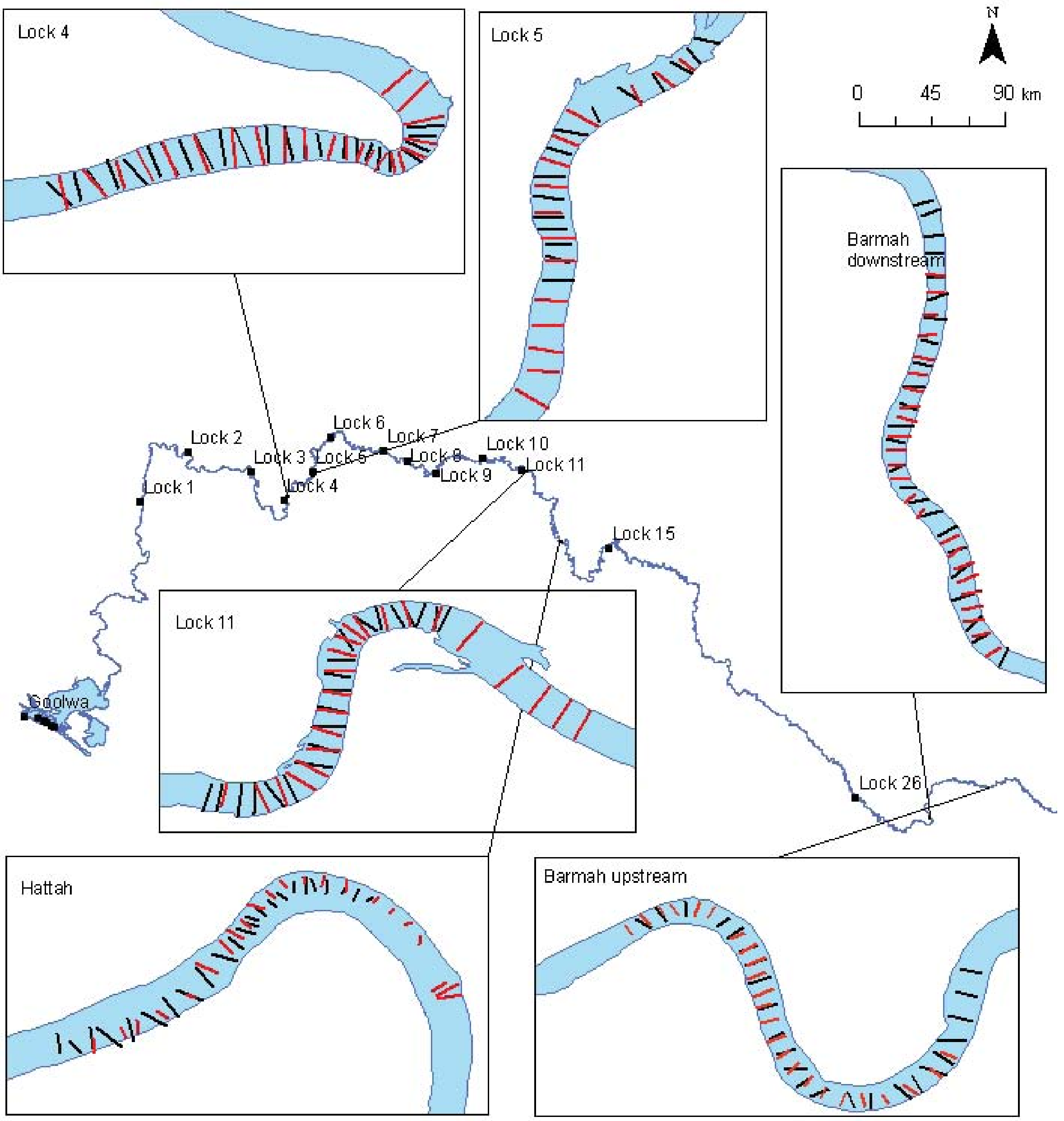


Figure 6.2: The middle and lower tracts of the River Murray, showing the locations of the six reaches and the cross-sections within the reaches.
Black line: September 2006; Red line: April 2007.
Flow from Lock 26 to Goolwa.

Table 6.1: Discharge and stage for the six reaches over the two sampling times. Discharge and water level difference taken from daily Murray-Darling Basin Commission reports.

	Length	Width (m)		Discharge (ML/day)		Water level
Reach	(km)	Min.	Max.	2006	2007	Difference (m)
Lock 4 (L4)	1.9	110	215	3,670	1,345	+0.03
Lock 5 (L5)	2.1	120	215	3,150	724	0.00
Lock 11 (L11)	2.4	130	200	6,100	1,870	0.00
Hattah (Hat)	1.8	60	125	6,500	2,200	*c.1**
Barmah DS (BDS)	1.6	55	75	8,025	3,750	*c.1**
Barmah US (BUS)	2.4	70	125	10,500	4,000	*c.1**

**Approximate, from observation*

6.2.2 ADCP sampling

A Sontek 1000 kHz three-beam ADCP (SonTek 2000) was mounted in the downward facing position to a 3.7 m semi-v hulled boat with an adjustable aluminium pole. The ADCP was controlled through an onboard laptop, using the Sontek program RiverSurveyor (SonTek 2005). The ADCP was initialised with the following settings: ping rate 0 s (the maximum); profile interval 5 s (equivalent of ~5 m per profile); cell size 0.25 (free-flowing reaches) or 0.5 m (weir-pool reaches); blanking distance 0.5 m; and bottom-tracking on. An overview of the principles of operation can be found in Chapter 5, with further details in Muste *et al.* (2004) and Kostaschuk *et al.* (2005).

At each reach, 15-24 cross-sections were measured. Cross-sections were spaced 50-150 m apart (Figure 6.2), depending on conditions at the reach: wood, house boats, sand bars were avoided to get the most complete cross-section. However, in many cases the shallow conditions meant that only part of the cross-section could be sampled (Lock 5, Hattah and the Barmah reaches particularly). GPS coordinates were taken at the start and end of each cross-section, and the distance to the bank from where the ADP started collecting valid data was measured with a laser range-finder.

6.2.3 Data processing and analysis

RiverSurveyor was used to define the start and finish profile of each cross-section, and to coordinate profile locations with GPS measurements. The ADCP files were then imported to ViewADP (SonTek 2000), where data were filtered for bottom-tracking, low Signal-to-Noise-Ratio and Data Quality Index, and smoothed using the 3-cell (vertical and horizontal) Gaussian algorithm. Data were then exported to Microsoft Excel.

In Excel, the depth-averaged velocity (DAV) measurements were smoothed by averaging adjacent profiles, as recommended in Chapter 5 (note, the Gaussian smoothing algorithm did not affect the depth-averaged velocity data). The velocity used for all calculations was the *velocity magnitude*; a combination of the *x*, *y* and *z* velocity components. This was chosen because it reflects the velocity experienced by aquatic organisms, and, due to the many bends in the reaches, the relative contributions of the *x* and *y* components vary within a reach. Therefore, the velocity magnitude offers a consistent measurement, regardless of the relative direction of the reach.

The local Froude Number was calculated for each profile in Excel, using Equation 6.1:

$$Fr = \frac{V}{\sqrt{gD}} \tag{6.1}$$

where Fr = Froude Number
V = depth-averaged velocity magnitude of the profile (m s^{-1})
g = gravitational constant (9.81 m^2 s^{-1})
D = depth of the profile (m)

R statistical software (R Development Core Team 2007) was used to test the depth and DAV samples of each reach for normality, using the Shapiro-Wilk Test ($\alpha = 0.05$). The depth-DAV correlation and all graphics were also created in R.

Directional (across-channel and down-channel) empirical variograms were also calculated in R (see Chapter 4 for more details on the calculation of variograms). For analysis, the profile coordinates were converted from the x and y coordinates measured. The reach was first ‘straightened’: the distance between consecutive cross-sections was measured along the thalweg (in ArcGIS), and this distance was taken as constant for the whole cross-section. Then, the distance between banks was converted from metres to percentage distance from the true left bank. This conversion allows for the comparison of streamlines, and ensures that the distances between cross-sections are measured in river kilometres, not on the straight-line distance (particularly relevant for reaches with sharp bends).

Variograms were calculated for the DAV, depth and Froude Number for 2006 and 2007, and for the velocity at different depths for 2006.

6.3 Results

6.3.1 Hydraulic conditions

Table 6.2 shows the DAV and depth profile measurements from the six reaches in September 2006 and April 2007. Higher velocities, and a greater velocity range, were measured in the free-flowing reaches (Hattah, Barmah downstream and upstream). Velocities were greatest in September 2006, when discharge was highest (Table 6.1).

Depths were greater in the weir-pool reaches (Locks 4, 5 and 11) than the free-flowing reaches. Note that the minimum measured depth for all reaches is >1 m, reflecting the operating range of the ADCP, and taking into consideration that the shallowest measurement (often on the edge of the cross-section) has been excluded by the 3-profile smoothing. Depths in the weir-pool reaches stayed relatively constant between 2006 and 2007, reflecting the precise management of weir-pool water levels. The maximum depth fell in both Barmah sites, as observed in the field. The maximum depth at Hattah appears to have increased, although water level was observed to have fallen. This is due to the inclusion of a different cross-section within the reach (upstream end; Figure 6.2), where there was a scour hole.

Figure 6.3 shows the depth-DAV scatter-plots (one point for each profile) for each reach. The weir-pool reaches show a low range of DAV over a wide range of depths. Conversely, the free-flowing reaches have a restricted range of depths, but a wider range of velocities. Between 2006 and 2007 there is little change shown in Locks 4 and 5, but Lock 11 shows a restricted range of velocities. The free-flowing reaches show a restricted range of DAVs and depths from 2006 to 2007 (except for Hattah, with the inclusion of the new cross-section increasing the depth range).

The Shapiro-Wilk Test indicated that the depth and DAV distributions for each reach over the two sampling times were not Normal ($p < 0.05$). Therefore Kendall's correlation was used for the depth-DAV correlation. The Barmah reaches had the lowest correlation over both sampling periods.

Figure 6.4 shows that a variety of cross-sectional shapes were present at each reach (2006 sampling). The DAV distributions within cross-sections also varied within each reach, as demonstrated by Figure 6.5 (depth-DAV scatter-plots for each cross-section) and Figure 6.6 (example of velocity contours within a cross-section), for September 2006.

Table 6.2: The range, mean and median of depth-averaged velocity (cm s^{-1}), depth (m) and Kendall's correlation measured at each reach.

Reach	Cross-secs		Min	Max	Mean	Median	Kendall's Corr.
Lock 4	24	*DAV 06*	2.0	28.7	9.7	9.4	06: -0.207
	22	*DAV 07*	2.0	26.1	9.9	9.4	07: -0.356
		Depth 06	1.63	15.24	5.35	4.59	
		Depth 07	1.51	15.08	5.55	4.74	
Lock 5	15	*DAV 06*	4.6	32.7	14.4	14.0	06: -0.228
	15	*DAV 07*	2.5	27.4	12.9	12.6	07: -0.413
		Depth 06	1.27	6.43	3.52	3.37	
		Depth 07	1.19	6.66	3.19	2.94	
Lock 11	22	*DAV 06*	4.7	34.8	15.0	14.6	06: -0.109
	22	*DAV 07*	2.1	21.2	9.4	8.9	07: -0.184
		Depth 06	1.26	11.07	5.39	5.39	
		Depth 07	1.82	11.58	5.55	5.32	
Hattah	24	*DAV 06*	15.1	85.6	46.7	45.8	06: 0.162
	22	*DAV 07*	2.7	65.5	28.7	28.7	07: -0.343
		Depth 06	1.26	4.54	2.16	2.03	
		Depth 07	1.14	5.59	2.05	1.74	
Barmah DS	24	*DAV 06*	23.0	98.4	68.0	70.4	06: -0.085
	24	*DAV 07*	4.8	83.6	48.8	49.3	07: -0.063
		Depth 06	1.30	4.12	2.62	2.73	
		Depth 07	1.17	3.24	1.93	1.90	
Barmah US	24	*DAV 06*	13.9	98.6	56.3	57.3	06: -0.058
	24	*DAV 07*	9.0	78.7	42.5	43.0	07: -0.127
		Depth 06	1.15	5.21	2.60	2.47	
		Depth 07	1.14	4.54	1.90	1.66	

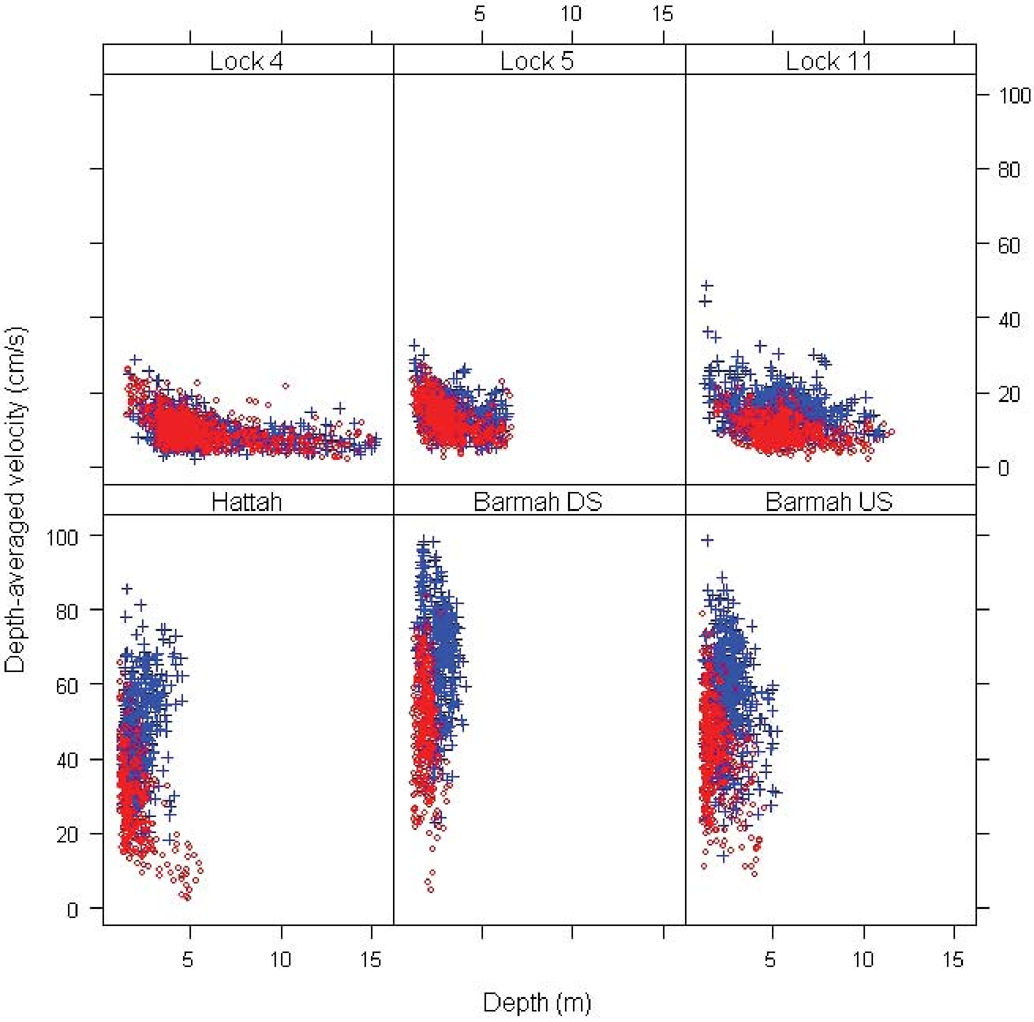


Figure 6.3: Depth-averaged velocity-depth scatter-plots for the six reaches. Blue cross: September 2006; Red circle: April 2007.

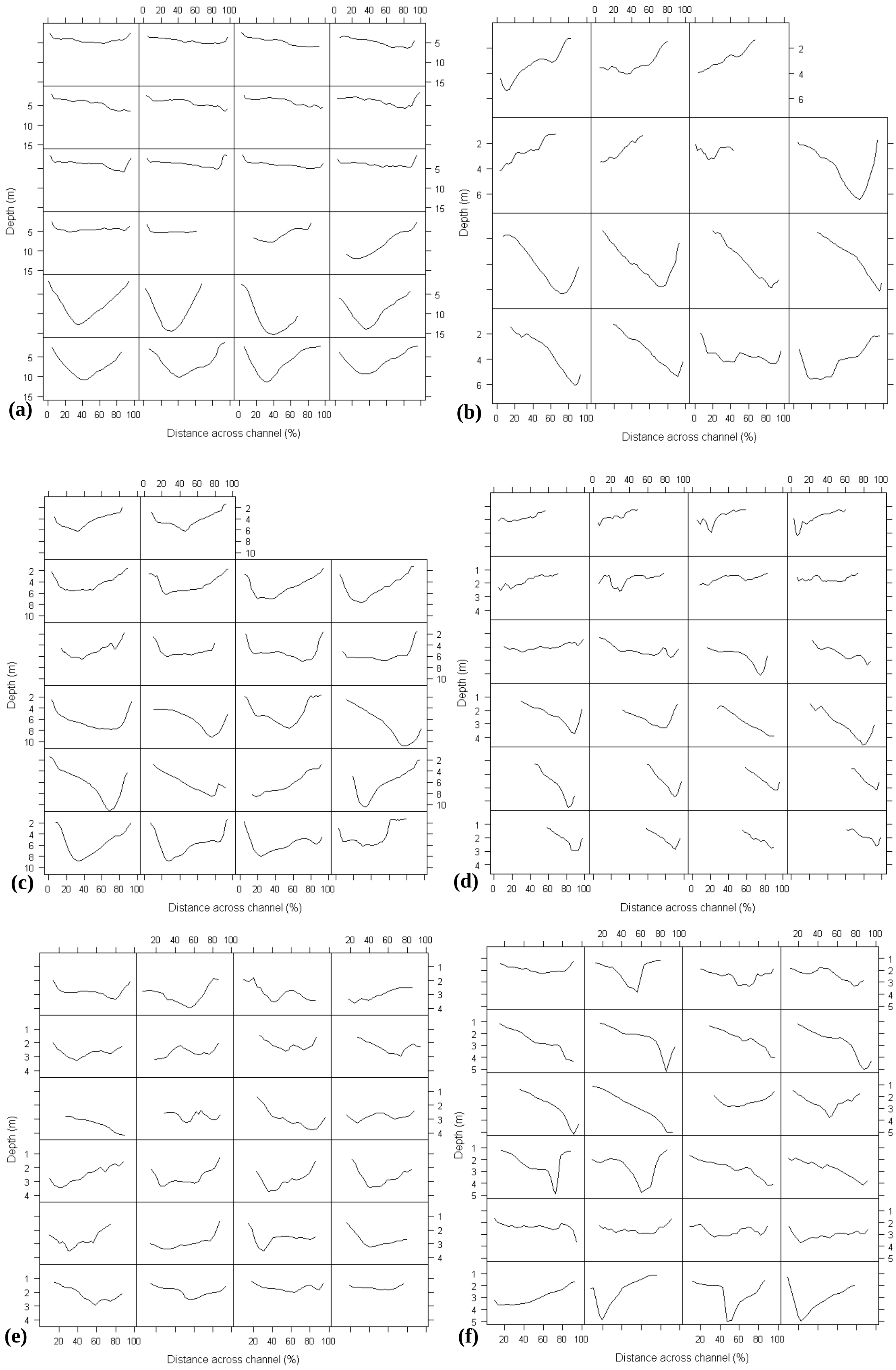


Figure 6.4: Cross-sections at the six reaches in September 2006. Percentage distance across from the true left. Note different depth scales. (a) L4 (b) L5 (c) L11 (d) HAT (e) BDS (f) BUS.

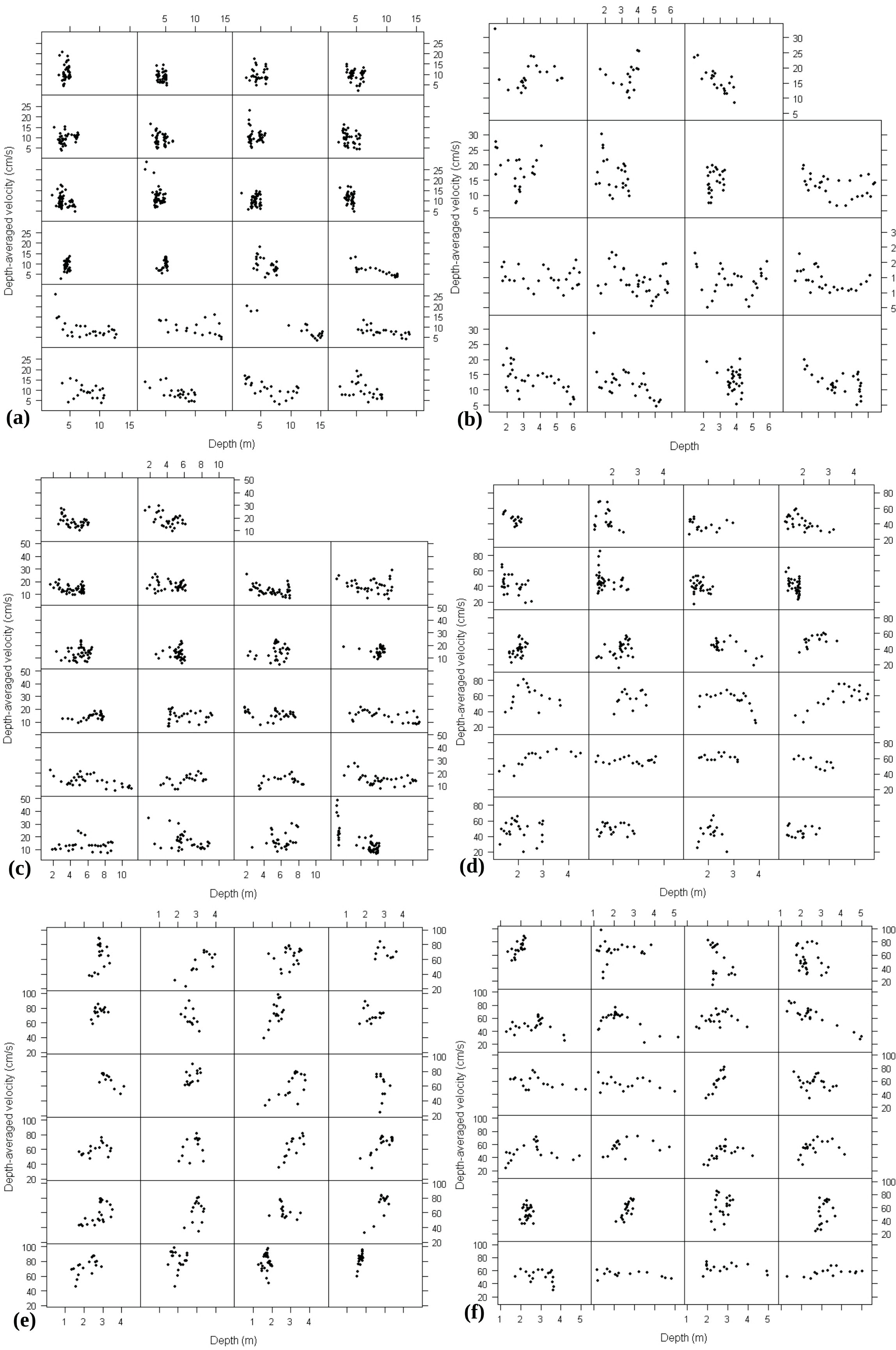


Figure 6.5: Depth-averaged velocity-depth scatter-plots for cross-sections within the six reaches for September 2006. From top left is cross-section 1 to *n* for each reach. (a) L4 (b) L5 (c) L11 (d) HAT (e) BDS (f) BUS.

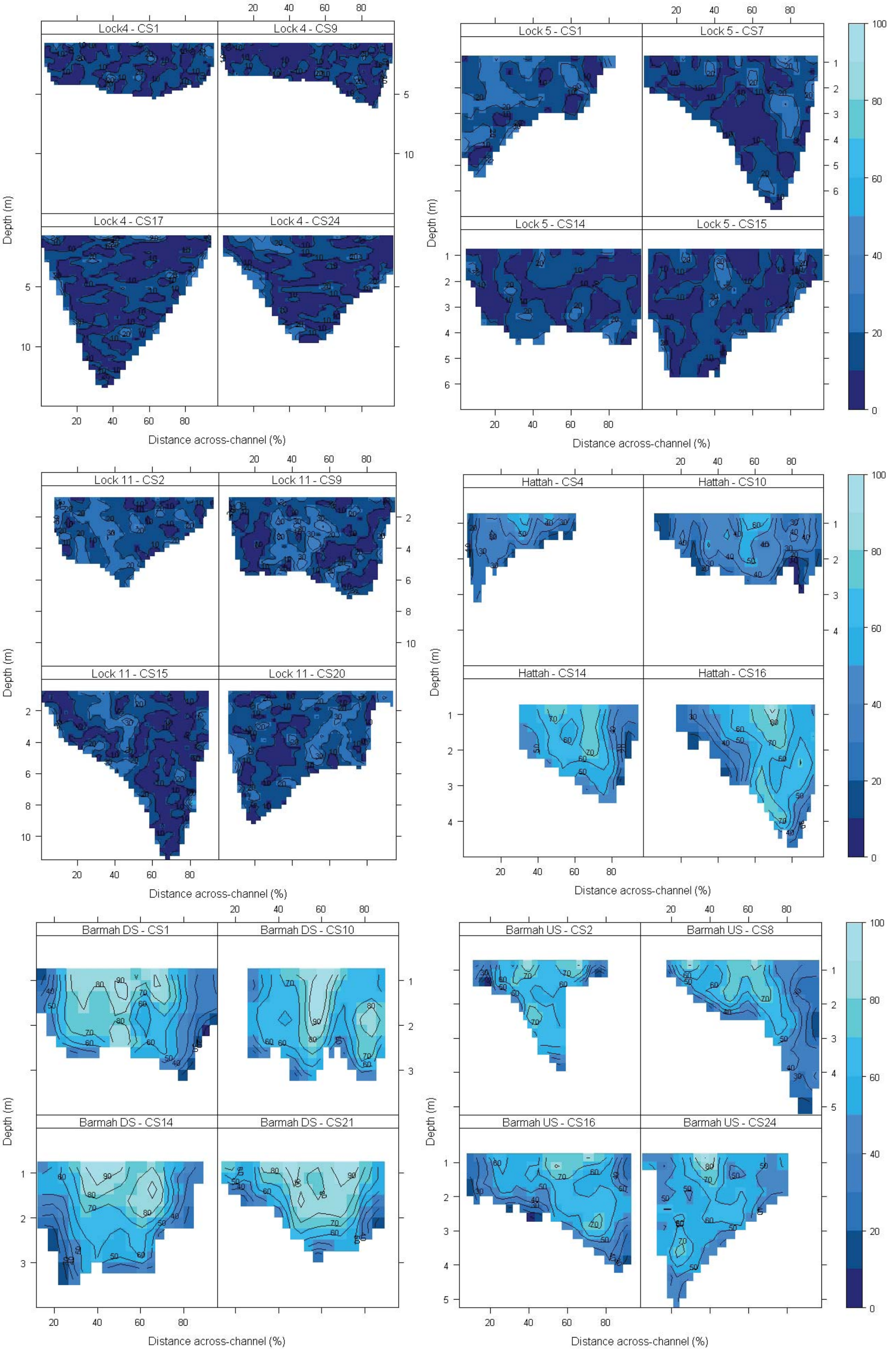


Figure 6.6: Four cross-section velocity contours from each reach. Velocity scaling is shown in the colour key on the right, in cm s^{-1}. Note different depth scales. Reach shown in plot heading.

6.3.2 Reach characterisation - variograms

Spatial differences between reaches

Directional (across- and down-channel) variograms for the DAV, depth and Froude Number for the six reaches for 2006 are shown in Figure 6.7, Figure 6.8 and Figure 6.9, respectively.

Both across- and down-channel DAV variograms show that the free-flowing reaches have a much greater semivariance. Within the weir-pool reaches, Lock 4 has the lowest semivariance both across- and down-channel, while Lock 11 has the greatest semivariance across-channel, but is similar to Lock 5 down-channel. There is little difference between the shape and size of variograms between the Barmah reaches across-channel, but Hattah has about half their semivariance across-channel. Down-channel the semivariance and variogram shapes are closer, although Barmah downstream has the highest semivariance, followed by Barmah upstream and Hattah, respectively.

Across- and down-channel depth variograms highlight the difference in the depth between the weir-pool and free-flowing reaches: the deeper weir-pool reaches have higher semivariances. The highest semivariance was calculated for Lock 4 down-channel, where a deep bend (*c.*15 m) is present (Table 6.2).

Across- and down-channel Froude Number variograms also show the difference between the weir-pool and free-flowing reaches. The free-flowing reaches have a greater semivariance than the weir-pool reaches. The Froude Number variogram shapes show a similar pattern of differentiation between reaches as for the DAV variograms.

Variograms of the velocity at five depths within a reach are compared to the DAV, for across- (Figure 6.10) and down-channel (Figure 6.11) (September 2006 data). The DAV semivariance is the lowest in all reaches, as the 3-profile smoothing reduces variability. For the weir-pool reaches (particularly Lock 4, both directions) the shallowest layer (at 0.87 m depth) has most semivariance. There is little distinction between the different layers at the free-flowing reaches. Note, however, that the variogram depths are closer together.

Temporal changes

Variograms for across- and down channel for DAV, depth and Froude Number from September 2006 and April 2007 are shown in Figure 6.12 to 6.17. For ease of comparison, each reach is shown separately.

The change in the calculated DAV variograms between the two sampling times differs between reaches. Across-channel (Figure 6.12), Lock 11 is the only reach to show a slight decrease in semivariance with distance from 2006 to 2007; the other reaches show no change. Down-channel (Figure 6.13), Lock 11 again shows a slight decrease in semivariance from 2006 to 2007, as do the free-flowing reaches.

The depth semivariance increased across-channel in Lock 4 and Hattah, decreased in Locks 5 and 11, and stayed constant in the Barmah reaches from 2006 to 2007 (Figure 6.14). Down-channel depth variograms showed no appreciable difference between the two sampling times, but overall showed more semivariance than across-channel (Figure 6.15).

Across-channel, Froude Number semivariance between 2006 and 2007 decreased slightly in Lock 11, increased in the Barmah reaches, and stayed constant at Locks 4 and 5 and Hattah (Figure 6.16). The changes in variograms were different down-channel: between 2006 and 2007 the Froude Number semivariance decreased slightly in Lock 11 and Barmah downstream, increased in Hattah and Barmah upstream, but again stayed constant at Locks 4 and 5 (Figure 6.17). The changes in semivariance were the same for the Froude Number and DAV in the weir-pool reaches, but not the free-flowing reaches.

Note that Figure 6.7 to Figure 6.17 have been displayed to facilitate easy comparison between reaches, not for detailed inspection.

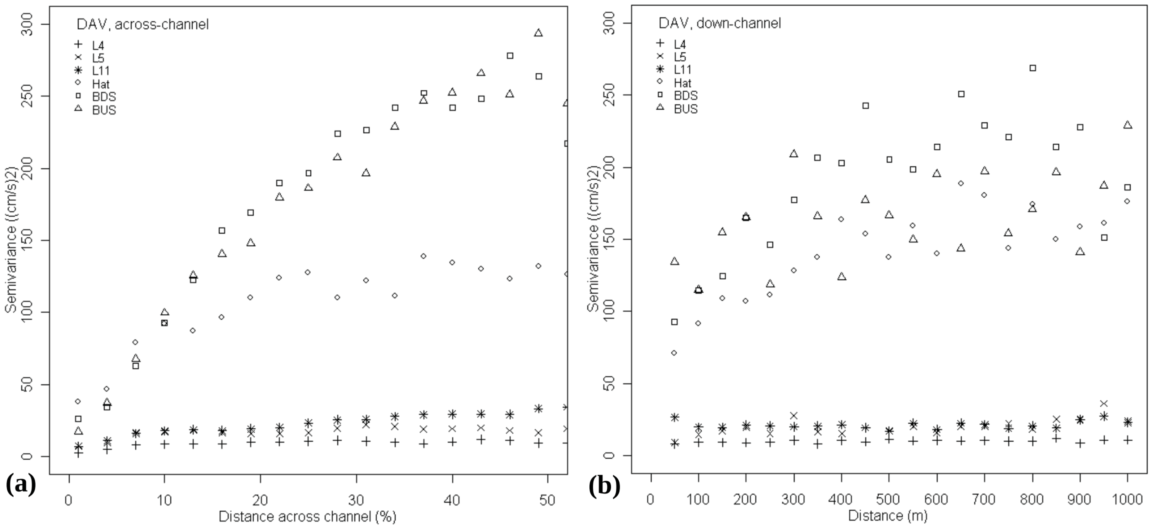


Figure 6.7: Directional depth-averaged velocity variograms for the six reaches (see legend), September 2006. (a) across-channel, (b) down-channel.

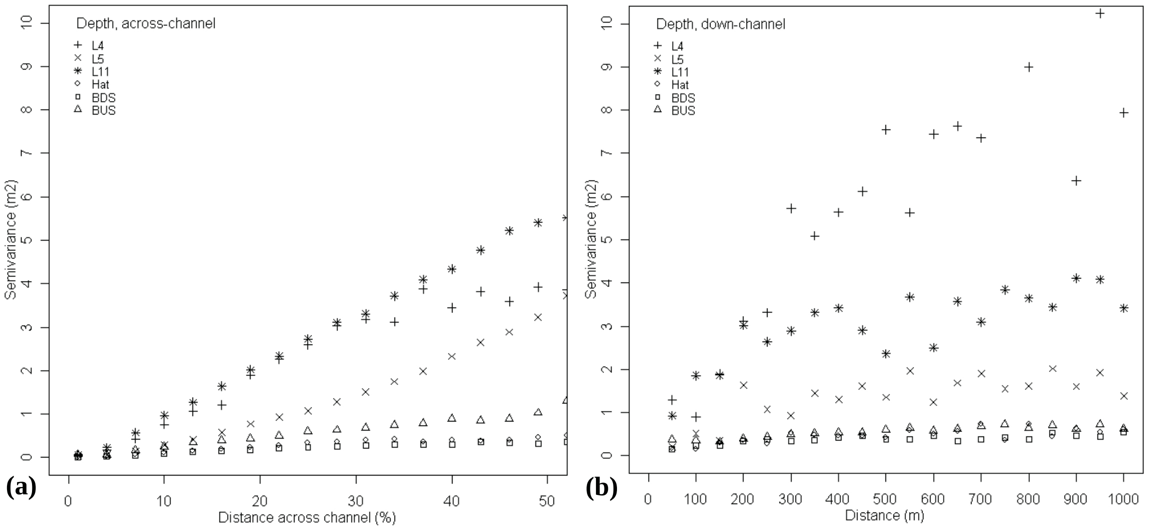


Figure 6.8: Directional depth variograms for the six reaches (see legend), September 2006. (a) across-channel, (b) down-channel.

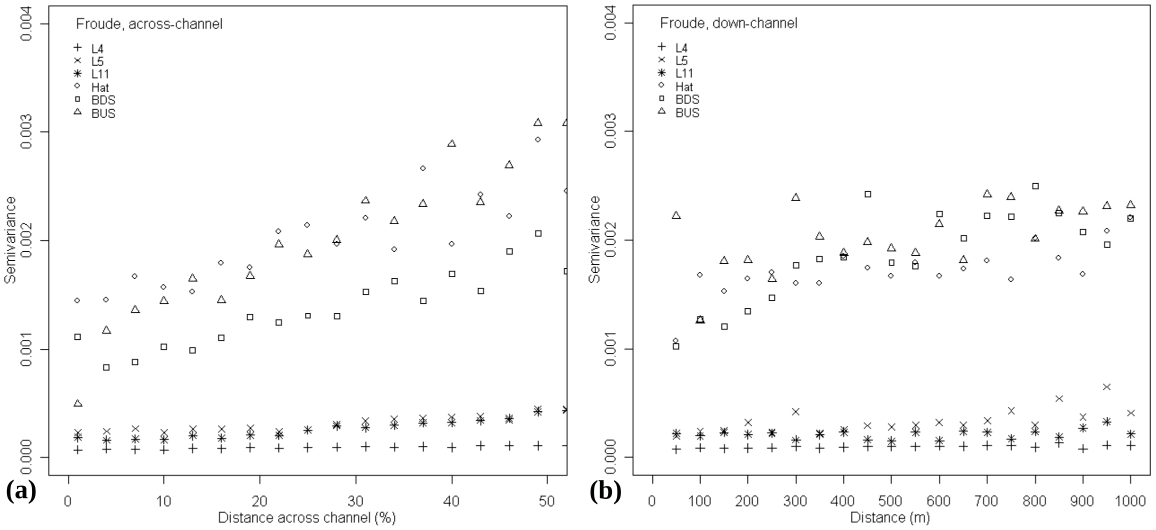


Figure 6.9: Directional local Froude Number variograms for the six reaches (see legend), September 2006. (a) across-channel, (b) down-channel.

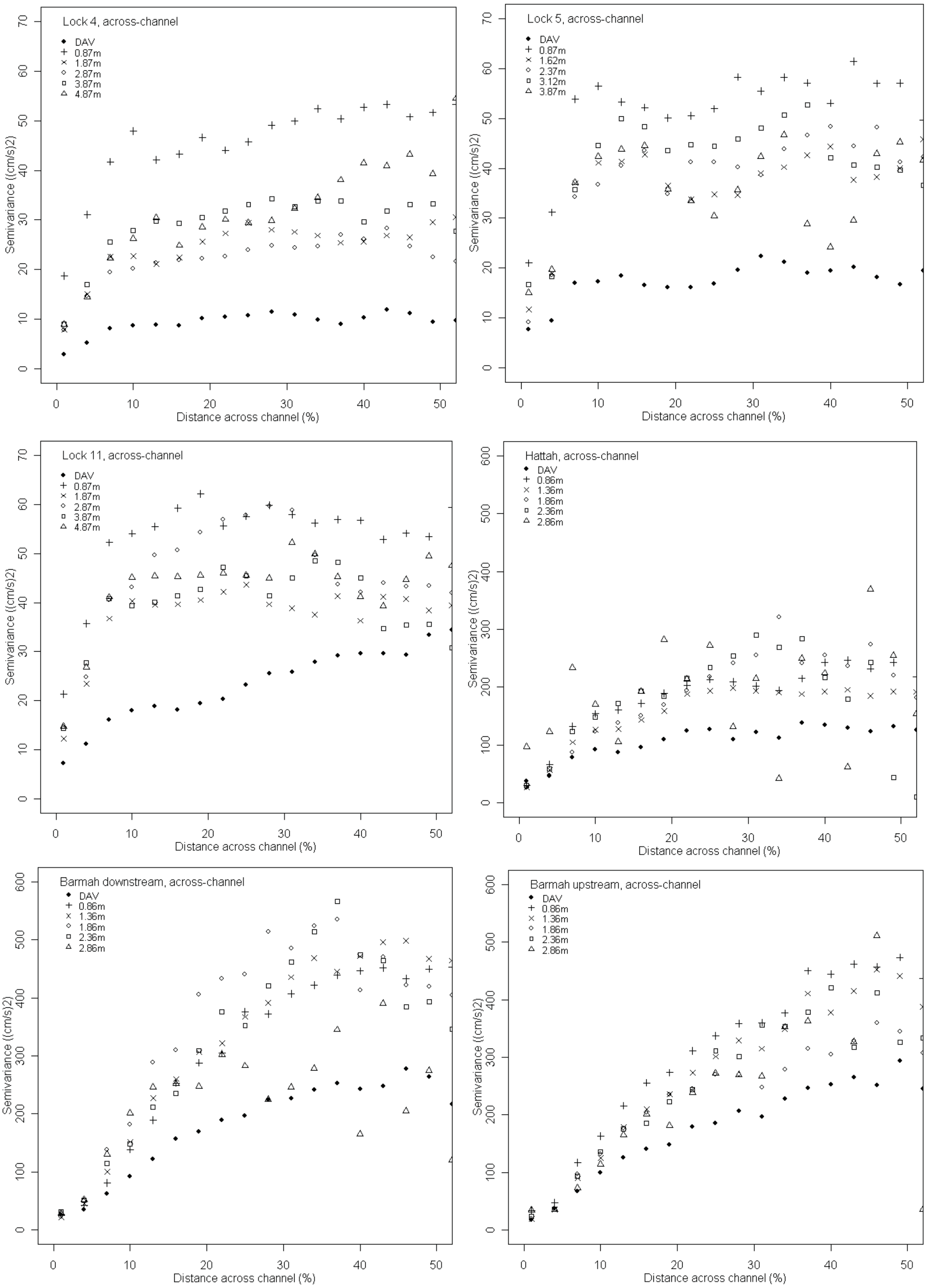


Figure 6.10: Across-channel directional variograms of the depth-averaged velocity and velocity from other selected depths (see legend) for the six reaches, September 2006. Reach shown in the top left of each plot.

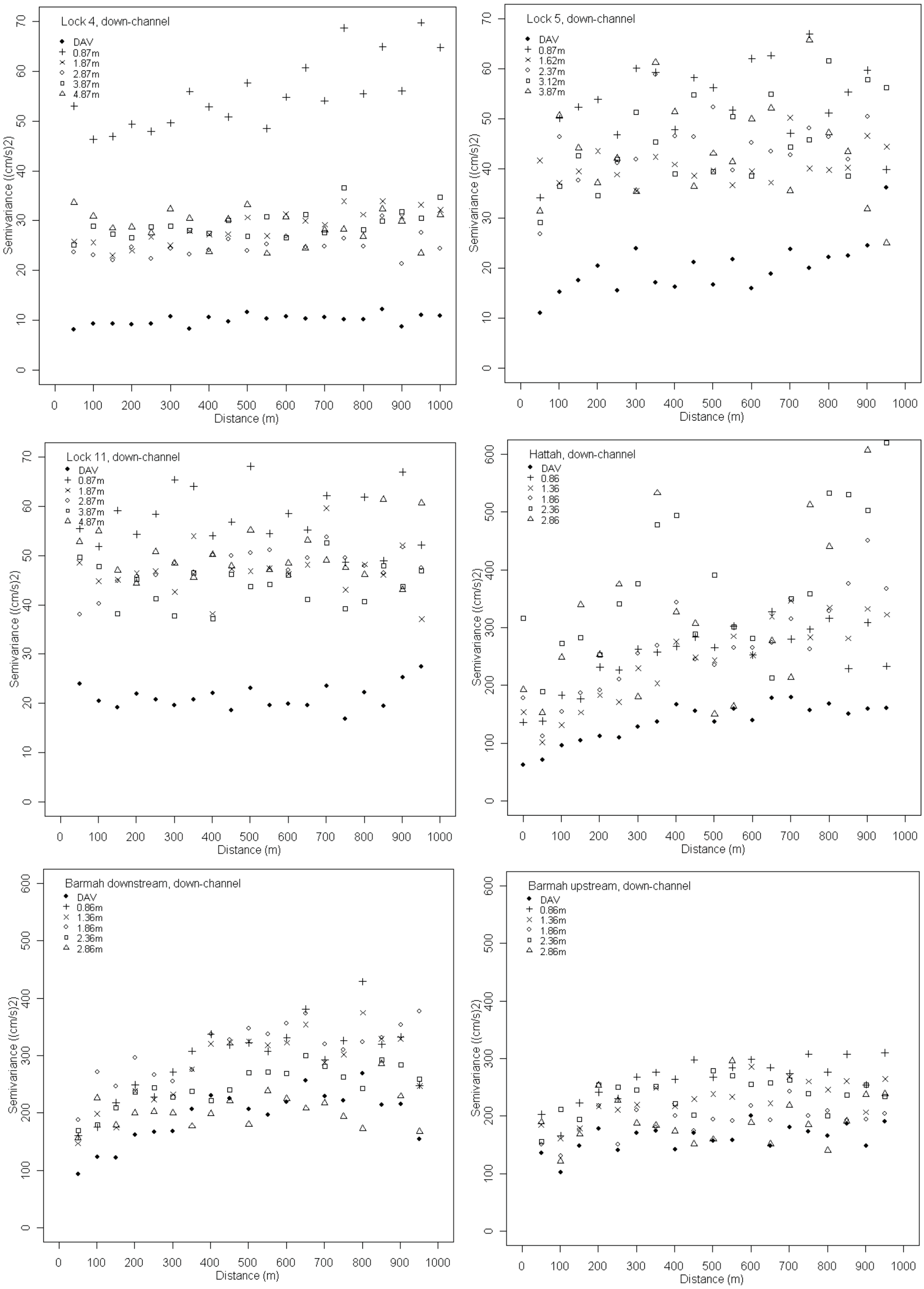


Figure 6.11: Down-channel directional variograms of the depth-averaged velocity and velocity from other selected depths (see legend) for the six reaches, September 2006. Reach shown in the top left of each plot.

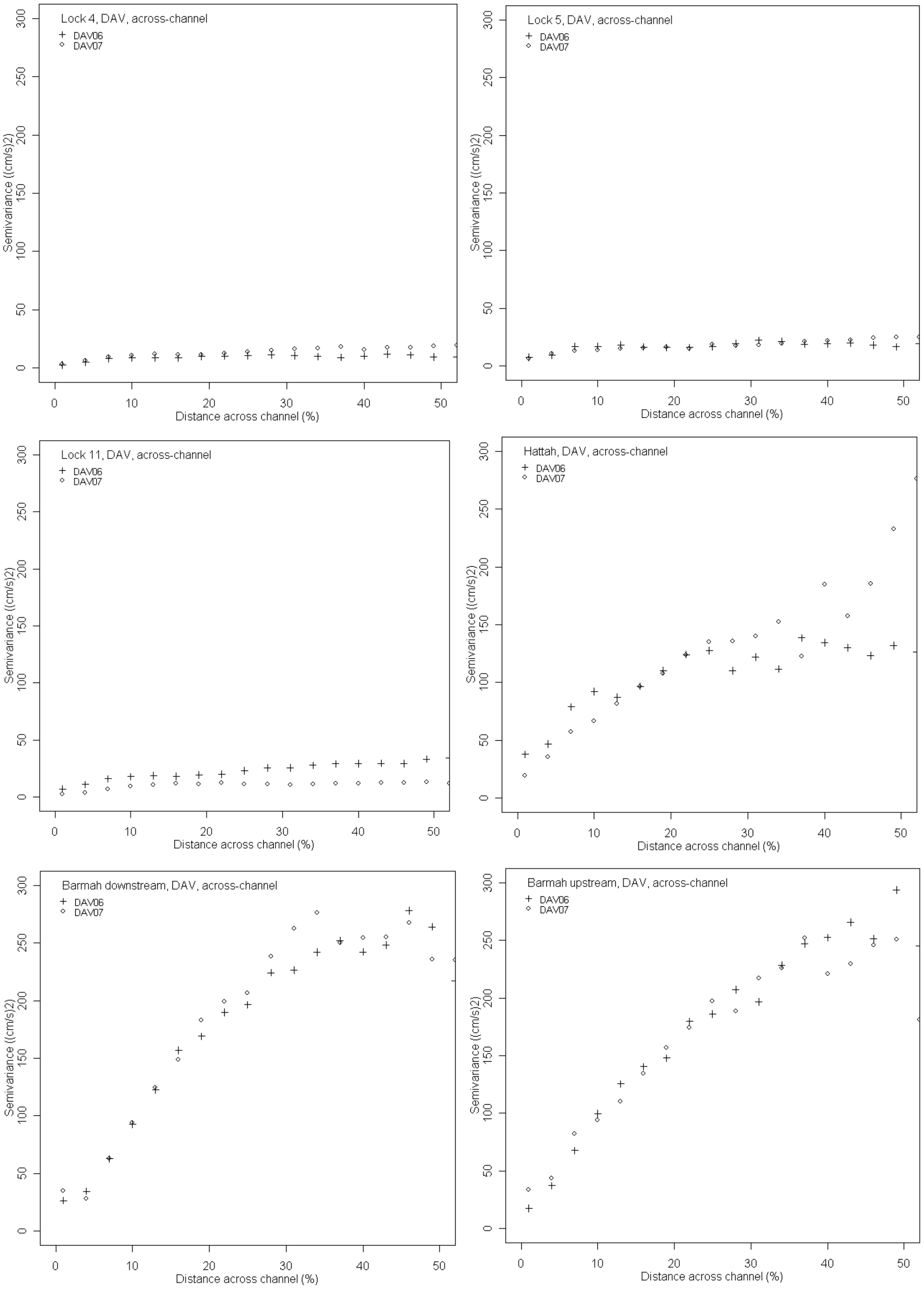


Figure 6.12: Across-channel directional depth-averaged velocity variograms for the six reaches from September 2006 and April 2007. Reach shown in the top left of each plot.

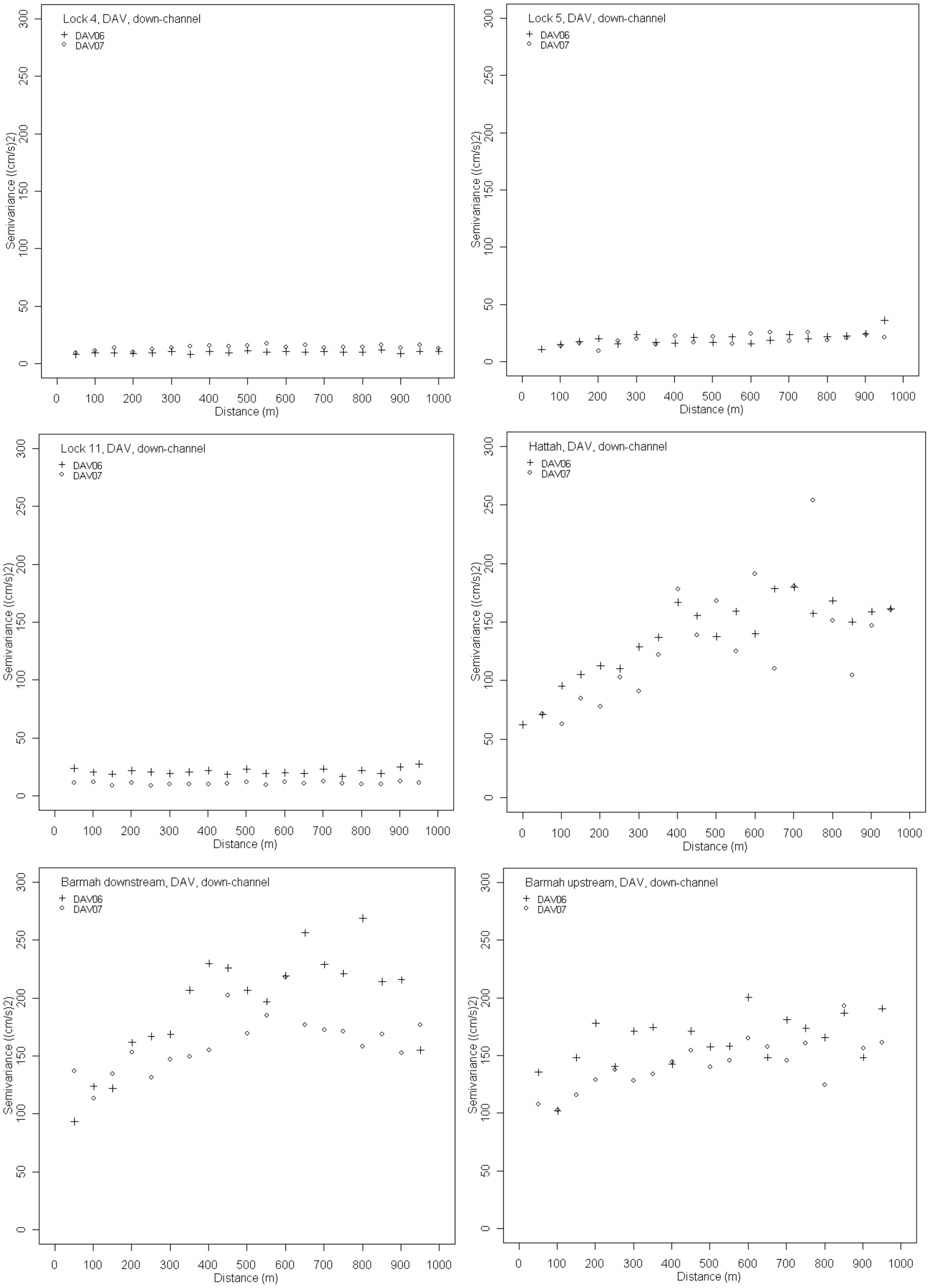


Figure 6.13: Down-channel directional depth-averaged velocity variograms for the six reaches from September 2006 and April 2007. Reach shown in the top left of each plot.

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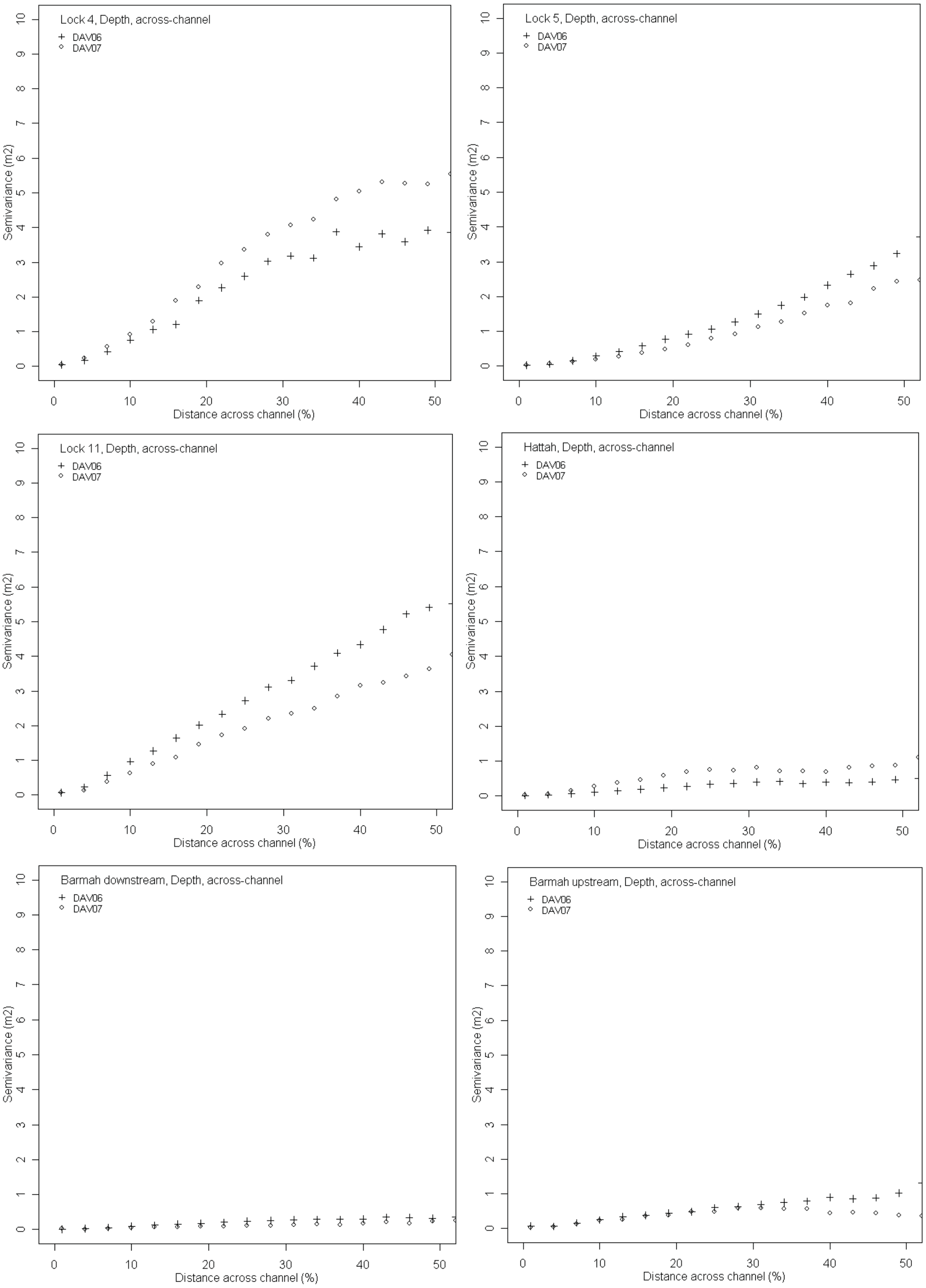

Figure 6.14: Across-channel directional depth variograms for the six reaches from September 2006 and April 2007. Reach shown in the top left of each plot.

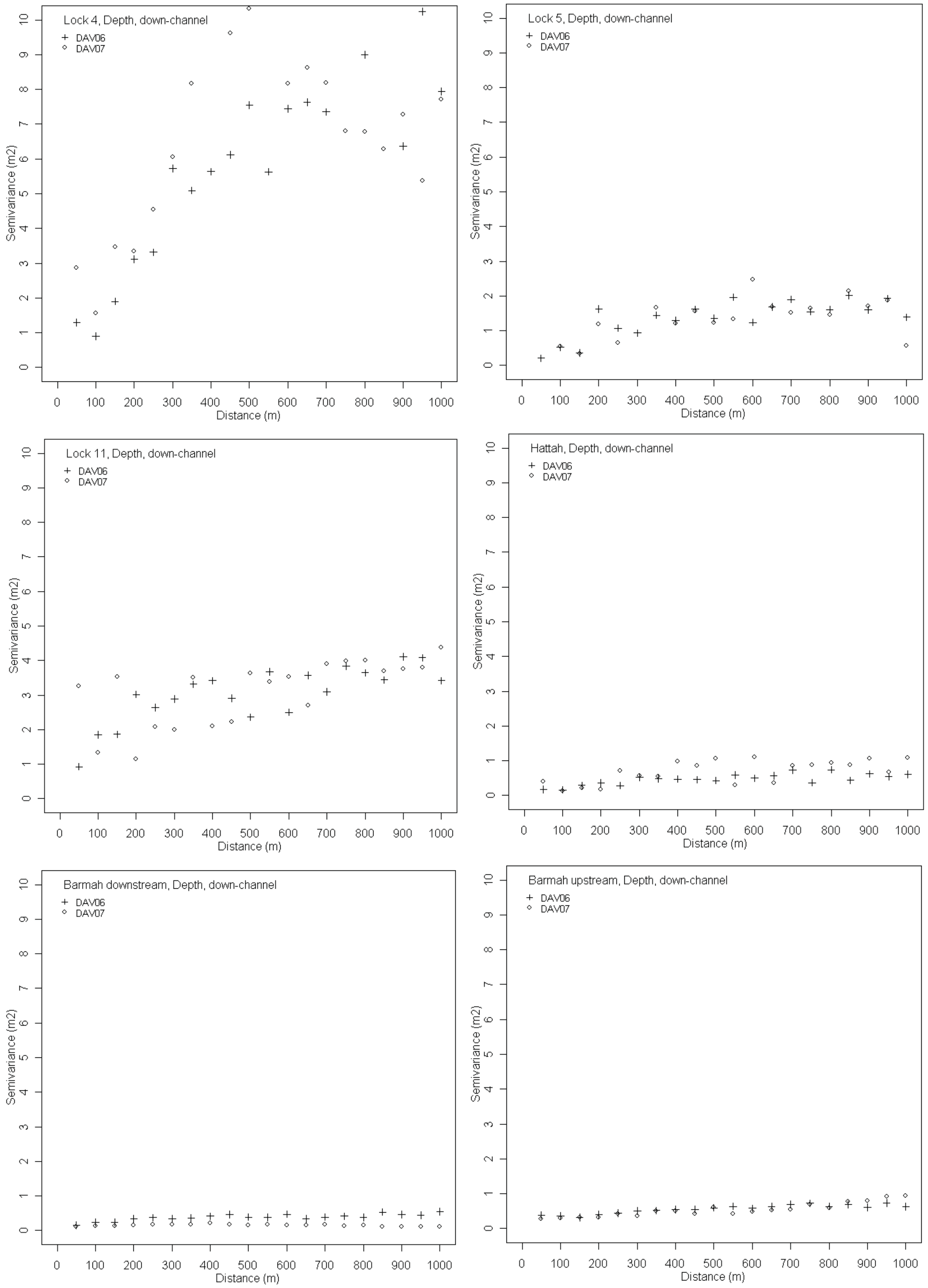

Figure 6.15: Down-channel directional depth variograms for the six reaches from September 2006 and April 2007. Reach shown in the top left of each plot.

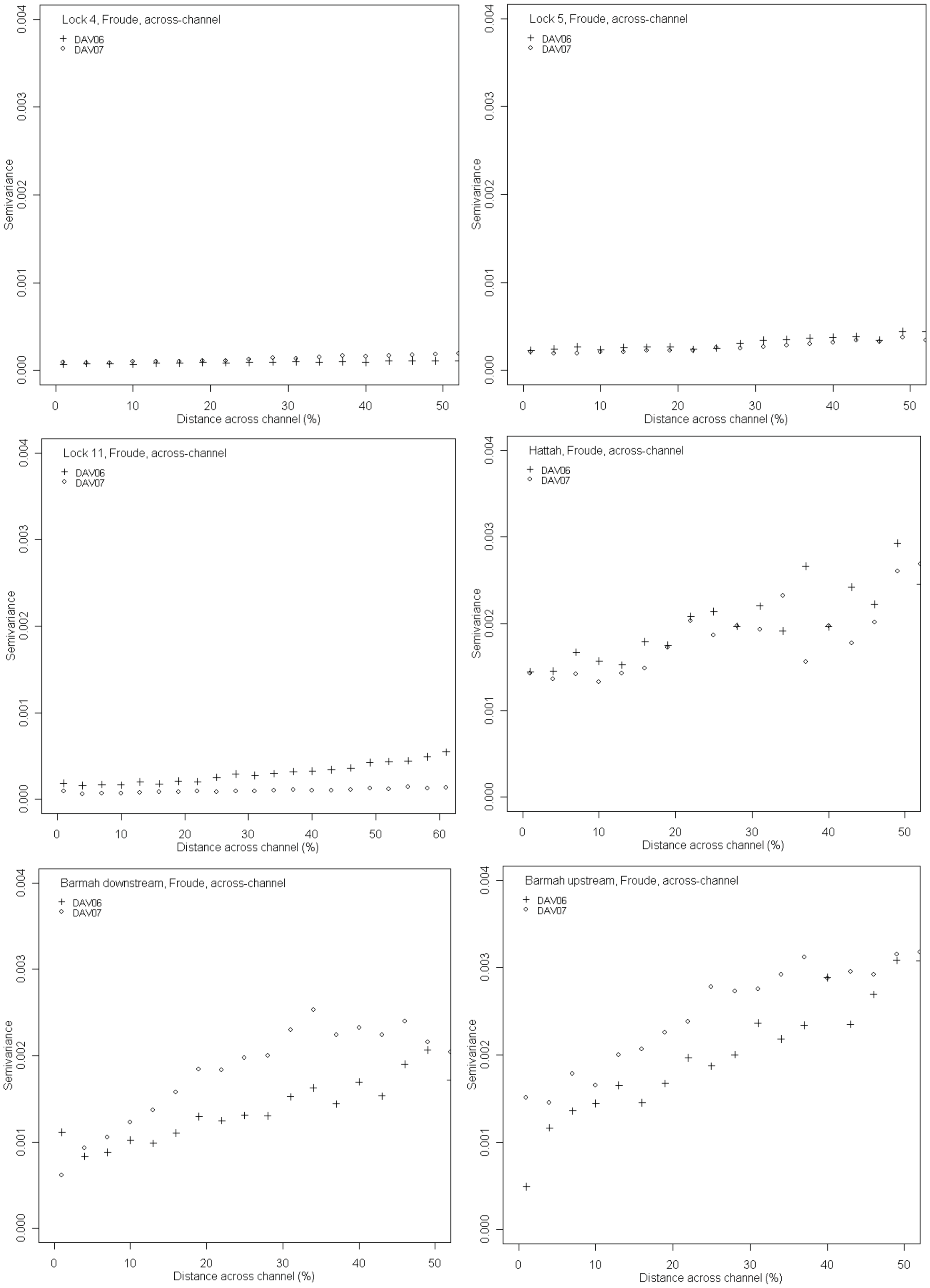

Figure 6.16: Across-channel directional local Froude Number variograms for the six reaches from September 2006 and April 2007. Reach shown in the top left of each plot.

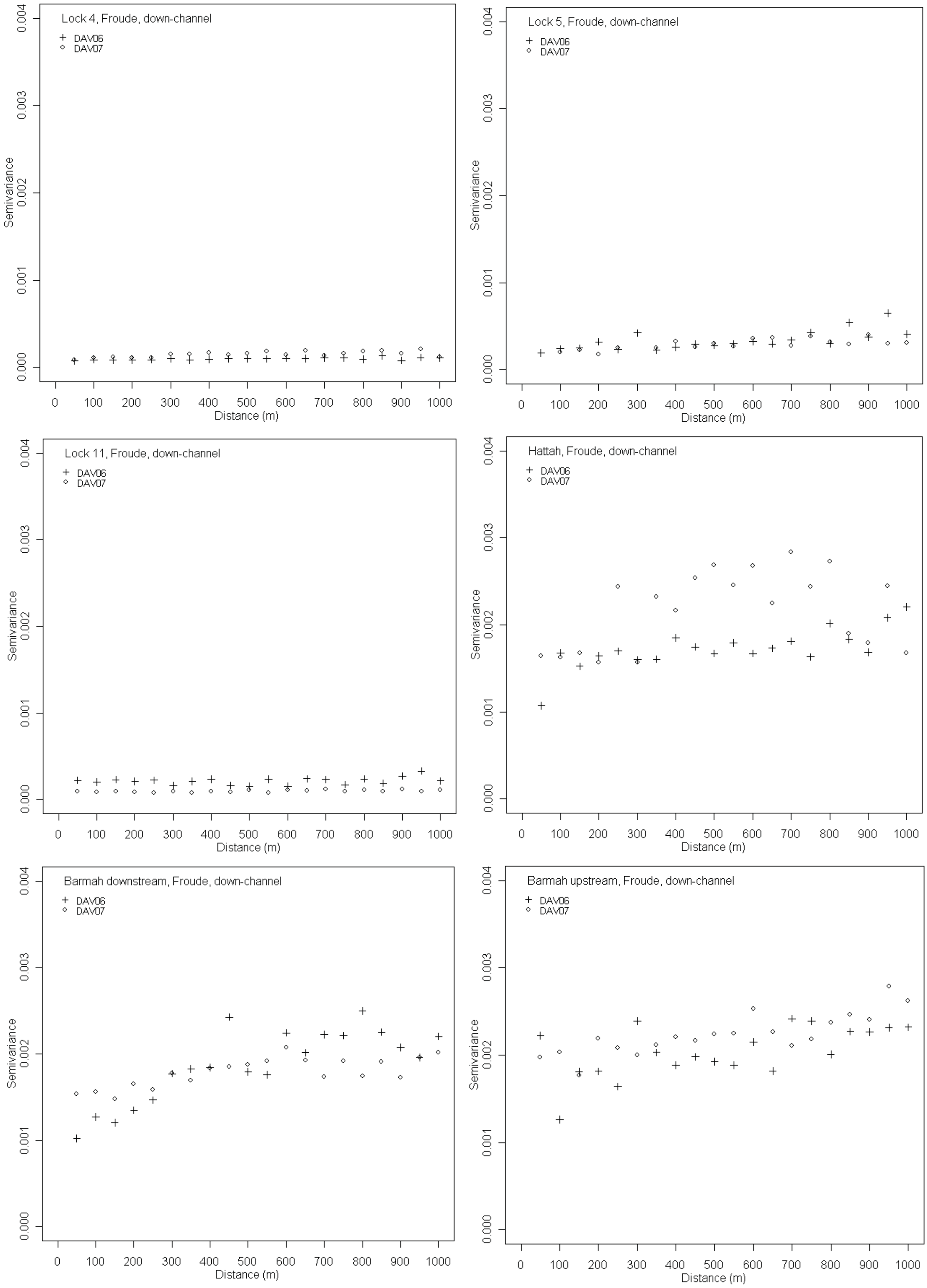

Figure 6.17: Down-channel directional local Froude Number variograms for the six reaches from September 2006 and April 2007. Reach shown in the top left of each plot.

6.4 Discussion

The aim of this chapter was to investigate whether variograms can be used to identify spatial and temporal differences between reaches in a large, lowland river, from data measured with an ADCP.

Data collection and processing

The suitability of ADCPs to collect ecohydraulic data has been discussed in Chapter 5, but a few points are worth restating, as they affect the observed variability of the reaches. The ADCP used here was a 1000 kHz instrument, built for deep-water situations. This had little effect on sampling the deeper weir-pool reaches (except part of Lock 5), but it meant that, particularly in April 2007, many sections of the free-flowing reaches could not be sampled. This, and problems with some features, such as shallow edges in littoral vegetation and wood, meant that the full extent of hydraulic conditions could not be measured. Higher frequency, mini-ADCPs that can work in water <0.5 m are available, and are recommended for future work in these, and similar reaches.

This study used a sampling design of 15-24 cross-sections (perpendicular to the flow), spaced 50-150 m apart. The sampling pattern was chosen as a balance between the size of the reach, the scale of the data measured (that is, the size of a profile), the logistics of ADCP use, and the proposed analysis (specifically, the use of variograms). Other sampling patterns may be equally valid (e.g. Shields and Rigby 2005; Thoms *et al.* 2006). A consistent sampling approach within a study (as used here) is the most important for reliable interpretation of the results, if not for comparison with other studies.

Spatial differences between the reaches – September 2006 data

The summary statistics, scatter-plots, contour plots, and variograms all differentiate between the weir-pool and free-flowing reaches: the weir-pool reaches are deeper and slower, the free-flowing reaches shallower and faster.

Of the weir-pool reaches, Lock 11 had the greatest DAV semivariance both across- and down-channel, followed by Lock 5 and then Lock 4, although the actual difference between the variograms is slight. Lock 4 had a slightly lower median and range of DAVs, which may contribute to this. Interestingly, at all the weir-pool reaches, both across- and down-channel, the velocity varies the most (has a greater semivariance) in the shallowest depth layer measured. Water flows *over* the weirs at Locks 4, 5 and 11, and it is possible that the ADCP is therefore measuring the effects of a top layer of water moving semi-independently of deeper layers.

The higher across- and down-channel depth semivariance for the weir-pool reaches reflects, in part, the deeper conditions within these reaches compared to the free-flowing reaches. Locks 4 and 11 had similar depth semivariances for across-channel, but Lock 5 had a lower semivariance, due to the shallower conditions. Down-channel there was more differentiation between the weir-pool reaches: Lock 4 had the highest depth semivariance, due to the deep bend, and then Lock 11, and then Lock 5, the shallowest weir-pool reach. This indicates that the variograms are sensitive to the range of sample values, and can differentiate how this variability occurs across- or down-channel.

The overall higher DAV semivariances at the free-flowing reaches is due in part to the wider range of (faster) velocities measured. Hattah has approximately half the across-channel DAV semivariance of both the Barmah reaches (still *c.* 4 times the weir-pool reaches), but has only slightly less semivariance down-channel than the Barmah reaches. The DAV was slighter slower in Hattah (lower range, mean and median), which accounts for some of this differentiation. The DAV semivariance was slightly higher down-channel than across-channel in Hattah, which is likely caused by the deeper, faster-flowing bend within the flatter, slower sections of the reach. There is little to distinguish the DAV semivariance between the Barmah reaches. The Barmah reaches are not characterised by one feature (such as a bend), and thus, their down-channel semivariance is slightly lower than their across-channel variance.

The lower depth semivariances in the free-flowing reaches are due in part to the shallower channels. There is little differentiation in the across- and down-channel depth semivariance between the free-flowing reaches.

Spatial differences in potential fish habitat

The magnitude of the velocity in the weir-pool reaches averaged *c.* 0.12 m s^{-1}, and, based on the swimming ability of the fish species tested in Chapter 2, would provide good hydraulic habitat for species including the Australian smelt (*Retropinna semoni)*. The free-flowing reaches had patches of slower velocity, but also large patches of faster flowing velocity (maximum *c.* 1 m s^{-1}) , and thus it would be expected that the abundance of Australian smelt would be greater in the weir-pool reaches than the free-flowing reaches. This is consistent with field data from these reaches (Engeldow 2005; Matveev 2007).

There was a greater range of velocities and hydraulic patches in the free-flowing reaches (as described by the range and semivariance) than the weir-pool reaches, and therefore the free-flowing reaches could potentially cater for the hydraulic preferences of a wider range of fish species than the weir-pool reaches. The increase in the range of hydraulic patches must be a compensated for by a decrease in the abundance of each hydraulic patch type (limited spatial extent), thus the diversity of the fish species could potentially be higher, but the abundance of some species lower (such as the Australian smelt), in the free-flowing reaches.

Temporal changes between reaches, September 2006 to April 2007

Discharge was reduced by >50% at all the reaches between September 2006 and April 2007. This affected the water level at the free-flowing reaches, but not the weir-pool reaches.

The weir-pool reaches appear to have responded differently to the reduced discharge. The DAV across- and down-channel semivariance decreased slightly for Lock 5 but stayed constant for Locks 4 and 11. The reduced discharge decreased the median DAV for Locks 5 and 11, but DAV stayed constant for Lock 4. This indicates that the DAV range within the reaches is not exclusively responsible for the calculated variogram; i.e. the variogram does reflect patchiness.

The down-channel depth variograms for Locks 4, 5 and 11 stayed constant, but perhaps unusually, given the same water-level, the across-channel depth semivariance increased slightly for Lock 4, and decreased slightly for Locks 5 and 11. The change could be due to the change in location of the cross-sections measured – for Lock 4 there were *c.* 2 more cross-sections through the deep bend in 2007 than 2006, increasing the across-channel semivariance, whereas for Locks 5 and 11 there may have been comparatively more flat ("*U*") shaped cross-sections included.

In all the free-flowing reaches, across-channel DAV semivariance stayed constant between 2006 and 2007, but decreased down-channel. The DAV median and range decreased at all these reaches in that time. This indicates that, although the across-channel variability was conserved with the reduced discharge, the down-channel variability is more sensitive to the absolute range of DAV.

There is little change in the depth variograms between 2006 and 2007 at the free-flowing reaches, despite the large drop in water level. An exception is the slight increase in the across-channel semivariance at Hattah, likely due to the inclusion of the cross-sections through the scour hole. This again indicates that the calculation of depth variability using variograms is a characteristic of the reach, and independent of the water level, but sensitive to the inclusion of distinguishing features such as deep holes.

Using variograms to characterise spatial and temporal differences between reaches

The variograms calculated here were clearly able to differentiate DAV and depth spatial conditions between the weir-pool and free-flowing reaches, and, to a lesser extent, within those reaches.

Depth variograms were independent of water level, but sensitive to the inclusion of extraordinary reach features. This indicates that variograms were suitable for characterising the geomorphic diversity of the reach; they were responsive to the variability between samples, not just the absolute value. The directional variograms were able to describe from which direction the diversity was coming, therefore allowing for identification of specific reach features (such deep holes). The use of directional variograms may complement other measures developed specifically to describe geomorphic diversity (e.g. Western *et al.* 1997; Bartley and Rutherfurd 2005).

The response of DAV diversity within reaches to a change in discharge varied between reaches, as has been found in other studies (Clifford *et al.* 2002a; Emery *et al.* 2003; Dyer and Thoms 2006; Thoms *et al.* 2006): some reaches retain more of their characteristic velocity patchiness with changes in discharge than others. Each reach may have a different threshold discharge, where patchiness may change dramatically (Dyer and Thoms 2006), depending on the underlying channel form (Shields and Rigby 2005). The variograms calculated here further suggest that DAV does not change evenly within a reach with discharge: the slower flow conditions affected the down-channel, but not across-channel, DAV diversity in the free-flowing reaches.

Froude Number is often calculated in stream hydraulics, and has been described as an important habitat metric (Kemp *et al.* 2000). The Froude Number represents "*the ratio of inertial forces to gravitational forces*" and is a good descriptor of bulk flow characteristics (the interaction between depth and velocity) (Gordon *et al.* 2004). Froude Number has been shown to be a good discriminator between flow-types (Kemp *et al.* 2000; Howes and Stewardson 2005) and habitats (Shields *et al.* 1994). Here the Froude Number variograms were similar to the DAV variograms: they showed the same spatial differentiation between the reaches, and the same response to the change in discharge for the weir-pool reaches. The DAV and Froude Number variograms only differed in the response to the change in discharge at the free-flowing reaches. Froude Number requires careful interpretation: very different velocity and depth combinations can exhibit similar Froude Numbers (Clifford *et al.* 2006), particularly within reaches where depths and velocities can vary significantly (see Equation 6.1). Given the ambiguity in the interpretation of Froude Numbers, the little additional information gained in this study, and its debatable biological relevance, it is suggested that it is not relevant for future use in describing spatial hydraulic diversity in large rivers.

One advantage of using variograms to measure spatial diversity is that variograms do not rely on the designation of hydraulic categories or patches (cf. Kemp *et al.* 1999; Emery *et al.* 2003; Clifford *et al.* 2004a; Dyer and Thoms 2006; Thoms *et al.* 2006). Assigning hydraulic measurements to categories that have no, or limited, biological meaning, can introduce bias in the diversity calculations, and their interpretation. Another advantage of the variogram is the ability to identify how the diversity differs across- and down-channel, which enables variograms to identify aspects of hydraulic field that other parameters can not (Legleiter *et al.* 2007).

By focussing on the value of the semivariance, and not the variogram shape (such as the nugget and range values, which can be calculated from models fitted to the empirical variogram curve), this study used only part of the possible interpretative ability of variograms (see Chapter 4 for further detail on the anatomy of a variogram). Using the semivariance only was sufficient to identify spatial and temporal differences between reaches, but this does highlight that variograms can provide further information on how hydraulic diversity changes with discharge within a reach. For example, only the DAV semivariance decreased down-channel for the free-flowing reaches, not the range, indicating that some spatial structure was retained, despite the reduction in median DAV conditions possibly influencing the lower semivariance (sill) value.

Describing the spatial diversity of a reach does not replace other parameters developed to look at specific aspects of habitat quality, such as turbulence (Smith and Brannon 2007) or velocity gradients (Crowder and Diplas (2000a; 2002; 2006)). Measurements of spatial diversity are not designed to investigate direct fish-habitat interactions. Rather, they can assist understanding of community level biodiversity responses to reach-scale spatial hydraulic diversity (e.g. Stewart *et al.* 2005). The variogram is suitable for measuring and describing aspects of reach-scale spatial hydraulic diversity, and therefore is recommended for future use.

7 GENERAL DISCUSSION

7.1 Overview

Understanding the nature of the hydraulic diversity – biodiversity relationship underpins efforts to increase biodiversity in river reaches through channel rehabilitation and environmental flows. This thesis has contributed by:

- exploring the factors that create hydraulic diversity, and the ways that fish respond to a diverse hydraulic environment;
- developing the variogram as a new method to characterise the spatial hydraulic diversity of a reach;
- using the variogram to describe temporal and spatial changes between reaches;
- demonstrating the use of hydraulic modelling for comparing reaches; and
- assessing the Acoustic Doppler Current Profiler (ADCP) for describing the range of hydraulic conditions in a large, lowland river, the River Murray.

These points are reviewed below, following a brief recapitulation of the significance of spatial hydraulic diversity.

7.2 Reach-scale spatial hydraulic diversity

‘Environmental flows’ describe the quantity and quality of water allocated for river ecosystem conservation and/or restoration (Petts 1996; Pretty *et al.* 2003; Tharme 2003). Many approaches focus solely on the provision of water, describing the timing, frequency and magnitude of high flows or other features of the hydrograph (Poff *et al.* 1997; Richter *et al.* 1998; Arthington and Pusey 2003). However, a successful conservation or restoration programme is determined not just by the provision of water, but by the physical habitat (Boulton 1999; Maddock 1999).

A diverse physical habitat caters for a wide range of organisms, and thus promotes biodiversity and ecological ‘health’ (Gore 1996; Biggs *et al.* 1997; de Nooij *et al.* 2006; Eros 2007). It includes hydraulic features, such as velocity, depth and turbulence. Given the key role that these conditions play in determining the distribution and abundance of lotic organisms (Statzner and Higler 1986; Grift *et al.* 2003), and the potential range of habitat requirements (for different species, activities, life-stages etc.), reach-scale hydraulic diversity ought to be a primary issue in river restoration and conservation (Beebe 1996; Kondolf *et al.* 2000).

7.3 Fish and spatial hydraulic diversity

To promote spatial hydraulic diversity, it is necessary to know how fish and other aquatic biota respond to hydraulic conditions. This thesis used two approaches: the commonly used swimming ability test, and a novel fish behaviour study.

7.3.1 Fish swimming ability

Chapter 2 described a modified incremental swimming ability procedure to test the swimming ability of two pelagic (common galaxias: *Galaxias maculatus*; Australian smelt: *Retropinna semoni*) and one demersal species (flathead gudgeon: *Philypnodon grandiceps*). The demersal species was the weaker swimmer, consistent with the expectation that ecological habit and body form is related to swimming ability.

Caution is needed in interpreting the results in an ecological context (cf. Nikora *et al.* 2003). For example, the flathead gudgeon apparently is the weakest swimmer, but during testing the fish had the ability to seek out small patches of slower velocity. This indicates that swimming ability alone may not determine distribution and abundance.

7.3.2 Fish behaviour

Chapter 3 described an experiment to investigate how fish use a diverse hydraulic environment. Two species with contrasting ecological habits (pelagic *versus* demersal) were chosen. Individuals were placed in a sinuous constructed channel providing a range of hydraulic conditions and potential habitats. Over three discharges, behaviour was recorded *via* cameras, and activity and habitat choices were analysed. This is a novel experiment—the first time that fish movement and behaviour within a flume have been quantified within a specific time period (cf. Holm *et al.* 2001).

During a three-hour recording period, both species visited a number of habitats, and the levels of activity and times spent differed. The differences reflected the species' habits, as expected: across the three discharges the common galaxias favoured the pelagic habitat, and spent 20-60% of the time cruising, whereas the flathead gudgeon preferred the demersal habitat and spent <6% of the time cruising.

The preferred habitat for each species was consistent over the range of experimental discharges, but their ability to access their preferred habitat differed. The flathead gudgeon's preferred habitat was underneath boulders, which they could access at all discharges, while the common galaxias' preferred habitat was the inflow zone, which they could not access (constrained by their swimming ability) during the high discharge. This suggests that while their preferences are dictated primarily by their ecological habit, their realised habitat is subject to the hydraulic conditions.

Other factors, such as the presence of drift feed and other fish, are likely to affect behaviour. In this study, both species were influenced by the presence of other fish of the same species, but in different ways. Common galaxias generally were in a group that followed one fish's choice of habitat, whereas the flathead gudgeons chose habitats independently (but were sometimes affected by the territorial behaviour of other fish). The contrasting behaviour was a reflection of their social interaction—common galaxias are a schooling species, and flathead gudgeons are solitary.

The effect of social interaction was also noted for the Australian smelt, another pelagic, schooling species. Observations of nine Australian smelt (60 ± 3 mm TL, mean ± SD) in the constructed flume showed that the school rarely split during the three-hour recording period (at low discharge). Their preferred activity and habitat were holding positions between the downstream wood and outflow zone (cf. the inflow zone for the common galaxias).

Behaviour is also likely to be influenced by the presence of other fish species. Non-piscivorous fish may have little effect, or they may intimidate other fish, particularly in shared habitat. Piscivorous fish are likely to be influential, causing some species to seek cover and to not explore the environment freely.

This experiment showed how fish use a number of habitats over time, how the activity levels vary between species, and how the hydraulic conditions affect the habitat preferences of fish. Adding behaviour to habitat prediction models is a complex task, but these results show that behaviour, as determined by ecological habit, can play an important role in fish distribution and abundance, and should be considered. The results also support the promotion of hydraulic diversity as a tool for maximising biodiversity.

7.4 Measuring spatial hydraulic diversity

A reach was described in Chapter 1 as "a stream- or river-section with large-scale homogeneous geomorphic and hydrologic conditions, i.e. it contains no easily observable discontinuities such as a waterfall, change in slope, or tributary junction". The physical length of a reach is dependent on the size of the river and the research or management aims. They are a commonly used unit of study because they can contain a variety of smaller-scale homogeneous habitat patches (as perceived by the study organism), and they can be the ideal scale for implementing management actions.

There is no standard method to characterise reach-scale spatial hydraulic conditions. Because organisms may use different habitats for different purposes (e.g. fish may use slow-velocity patches for resting and faster velocity patches for feeding (Mitchell *et al.* 1998; Deschênes and Rodríguez 2007)), the spatial arrangement of habitat patches in reaches is likely to be important (Shields and Rigby 2005). Any characterisation of reach hydraulic environment should therefore consider the spatial arrangement of hydraulic conditions (Crowder and Diplas 2000a; Booker *et al.* 2004; Crowder and Diplas 2006).

7.4.1 Reach characterisation

Chapter 4 investigated methods to describe reach hydraulic diversity, by comparing the spatial diversity of eight model reaches with different hydraulic features (channel form, wood and vegetation).

An average reach value gives an indication of the scale of the reach (short, long, fast, slow etc.), but does not describe the diversity. Measurements of the range and coefficient of variation indicate the spread of data, but not the equitability (evenness). Shannon's and Simpson's indices do so, but are sensitive to the ways that data are categorised. Graphical methods such as histograms and scatter-plots are useful for description, but are difficult to compare objectively. None of these methods considers spatial arrangement.

The variogram is a plot of semivariance (half of the mean of the squared difference between sample pairs) against the distance between sample pairs (Brooker 1991). By considering the distance (and, optionally, the direction) between sample pairs, it incorporates one feature of the spatial arrangement of samples. In Chapter 4, the calculated directional variograms were able to differentiate between the reaches, and provided information about differences across- and down-channel. This is the first time that variograms have been used explicitly to characterise reach spatial hydraulic diversity (cf. Clifford *et al.* 2005; Rivas-Casado *et al.* 2005; Legleiter *et al.* 2007).

The variogram proposed here can be used: (a) to indicate the habitat quality of a reach, (b) as a tool for comparison of reaches, (c) as a guideline for the design of river rehabilitation projects and (d) to quantify the benefits of rehabilitation.

7.4.2 Reach modelling

The reliability of variograms increases with the number of data points. Hydraulic modelling can be used to estimate many data points within a reach, as well as having other ecohydraulic applications, including assessing flow requirements (Bovee 1986; Stewardson and Gippel 2003; Stewart *et al.* 2005), resolving detailed flow and habitat patterns and exploring the relationship between flow processes, sediment transport and channel morphology (Lane *et al.* 1999; Clifford *et al.* 2005).

As highlighted above, the spatial arrangement of hydraulic patches, and an ability to describe the range of conditions within a reach, are important. For these purposes, 3-D hydraulic modelling is appropriate (Stewart *et al.* 2005). In Chapter 4 it was demonstrated that the 3-D Computational Fluid Dynamics model SSIIM (Lane 1998; Olsen 2007) was able to successfully model a range of features, including wood, vegetation and variable channel form. Thus, SSIIM can be used to model different management scenarios in river rehabilitation projects, and the management options may be comprehensively compared. SSIIM has successfully modelled real reaches (Booker *et al.* 2001; Clifford *et al.* 2002a; Clifford *et al.* 2002b; Booker 2003; Clifford *et al.* 2004b; Clifford *et al.* 2005; Wilson *et al.* 2006), and preliminary modelling of the River Murray, conducted as part of this study, proved promising, despite the relatively large size of the modelled reach.

7.4.3 Field sampling

Modelling can provide insights into water movement and compare different management scenarios, but field measurements are essential for understanding reach hydraulic conditions. Measuring reach-scale hydraulic diversity can be logistically difficult and time-consuming, particularly in ‘non-wadeable’ rivers (Shields *et al.* 2003). ADCPs can be deployed from a moving boat, rapidly sampling the depth and 3-D velocity (Muste *et al.* 2004), but their use in ecohydraulic studies has been limited (cf. Shields *et al.* 2003; Shields and Rigby 2005; Thoms *et al.* 2006).

Chapter 5 assessed the reliability and suitability of ADCP for use in a large, lowland river, the Murray. Results from three sequential traverses of the same cross-section, at 48 locations across six reaches, were compared. The ADCP proved to be reliable in measuring the morphology and diversity of velocity within a cross-section, as required for ecohydraulic and habitat studies. However, consideration needs to be given to the processing of the raw data—the use of ADCP would be enhanced by clear guidance/standards on data processing (Dinehart and Burau 2005a).

The suitability of ADCPs for use in the River Murray depended on the reach. Because of the frequency of the instrument used, shallow areas (*c.* <1.5 m) were not accessible, and in a few reaches shallow areas accounted for a large portion of the cross-sections sampled. Thus, the ADCP missed out on sampling the full diversity of hydraulic conditions. Higher frequency, mini-ADCPS are available and can sample in shallower environments (<0.5 m), and may be more suitable. Nevertheless, the ADCP used was still able to rapidly and adequately sample a variety of hydraulic conditions within all the reaches.

7.4.4 Field characterisation – identifying spatial and temporal variation

Sampling and characterisation methods should be able to detect spatial and temporal changes. The aims of Chapter 6 were to develop ADCP sampling data and directional variograms as a method to identify spatial and temporal variations between reaches on the Murray. Spatial variation was provided by six reaches and temporal variation by two sampling periods.

Variograms were able to differentiate spatially between the two categories of reaches sampled (weir-pool and free-flowing), and to a lesser extent within those categories. If the ADCP data had been more comprehensive (cf. high-frequency ADCP), the spatial differences within categories may have been clearer. Nonetheless, the variogram was able to identify specific features of the reaches, such as unusually deep sections.

Temporal changes within the reaches were less well-defined, although the discharge differed by >50% between sampling periods. This was expected for temporal changes in channel form (depth), and indicates that using ADCP data and variograms is a reliable method for sampling and characterisation. Temporal changes in the depth-averaged velocity variograms were reach-dependent, as shown in other studies (Clifford *et al.* 2002a; Emery *et al.* 2003; Thoms *et al.* 2006).

7.5 Recommendations for future work

Research investigating the different types, scales and levels of hydraulic diversity, and what is beneficial for different kinds of aquatic organisms, and what is not, is recommended. For example, river regulation often decreases spatial hydraulic diversity by turning free-flowing reaches into lentic environments, but a weir could also be seen to increase spatial diversity by creating a slower-velocity environment upstream and faster-velocity environment downstream. Thus, there are likely to be beneficial and harmful degrees and types of hydraulic diversity. There may be an optimal level of reach diversity, beyond which more physical diversity is detrimental to biodiversity (cf. Intermediate Disturbance Hypothesis: Fox and Connell 1979).

Two approaches to investigating the different types of spatial hydraulic diversity are recommended. Firstly, the experimental procedure developed in Chapter 3 (fish behaviour), specifically the use of multiple video cameras and timed analysis, should be used to investigate the responses of fish (or other aquatic organisms) to different types of hydraulic diversity and habitat. The effects on behaviour of the presence of drift-prey, other organisms and predators should also be considered.

Secondly, the variogram should be developed as a tool for characterisation, comparison and design. The variogram comprises a number of components (e.g. the nugget, range and sill) and potentially could be used to characterise different types and levels of hydraulic diversity. Other points needing consideration in variogram development include the number of data points required for a reliable variogram (for spatial hydraulic diversity characterisation), and the optimal data spacing and pattern required to capture different scales of spatial hydraulic diversity.

Chapters 5 and 6 demonstrated the potential of ADCPs to quickly measure a range of hydraulic conditions within a reach. The 1000 kHz ADCP used in this study was better suited for deeper conditions, and therefore the next step is to test a higher frequency ADCP, particularly in shallow reaches and around features such as rocks, vegetation and wood, in order to capture as much of the hydraulic diversity as possible. As well as work needed on guidelines for the processing and analysing of collected data (see above), research is needed to provide sampling protocols for the collection of data for the purpose of capturing hydraulic diversity. For example, this study used evenly-spaced cross-sections to characterise the reach, but differently spaced cross-sections, or sampling patterns (e.g. Thoms *et al.* 2006), are also likely to affect the perceived spatial hydraulic diversity.

SSIIM can be used to complement field data collected by ADCPs by allowing more detailed hydraulic analysis of specific features or potential habitats that ADCPs can not measure, such as around wood and vegetation, and shallow, edge regions. The ADCP data collected are well suited to the development of SSIIM models as the depth data can be used to develop the base grid, and the velocity data to calibrate the model. The models can then be used to demonstrate reach spatial hydraulic changes for a number of river management options, including a range of discharges.

Empirical data comparing levels of hydraulic diversity to biodiversity are needed. A lack of a method to measure hydraulic diversity is likely to be one reason for the lack of data, and another is that data can be logistically difficult to obtain (particularly in large rivers). One idea is to simultaneously measure the reach hydraulic environment and fish stock in the River Murray using an ADCP and split-beam hydroacoustics (Matveev 2007), respectively. This idea was trialled as part of this thesis, but results were inconclusive because of the mismatch in instrumentation. With technological advancements and procedural changes, however, there are interesting opportunities for large-scale data collection.

In smaller, ‘wade-able’ streams, it may be logistically easier to sample a range of aquatic organisms, and describe the biodiversity. High-frequency ADCPs could then be used to sample the hydraulic conditions, and variograms to characterise them. For the most incisive studies of the link between hydraulic diversity and biodiversity, data comparisons should be made between reaches, and then, ideally, after reach manipulation (i.e. placement of wood).

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