Ecohydraulics
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For Katherine, Ben, Joe and Alice.

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Dedicated to Cathrine, Sigurd and Brage.

By Paul Kemp:
Dedicated to Clare, Millie, Noah and Florence.

By Paul Wood:
For Maureen, Connor and Ryan.
Ecohydraulics
An Integrated Approach

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1.1 Introduction

It is well established that aquatic ecosystems (streams, rivers, estuaries, lakes, wetlands and marine environments) are structured by the interaction of physical, biological and chemical processes at multiple spatial and temporal scales (Frothingham et al., 2002; Thoms and Parsons, 2002; Dauwalter et al., 2007). The need for interdisciplinary research and collaborative teams to address research questions that span traditional subject boundaries to address these issues has been increasingly recognised (Dollar et al., 2007) and has resulted in the emergence of new ‘sub-disciplines’ to tackle these questions (Hannah et al., 2007). Ecohydraulics is one of these emerging fields of research that has drawn together biologists, ecologists, fluvial geomorphologists, sedimentologists, hydrologists, hydraulic and river engineers and water resource managers to address fundamental research questions that will advance science and key management issues to sustain both natural ecosystems and the demands placed on them by contemporary society.

Lotic environments are naturally dynamic, characterised by variable discharge, hydraulic patterns, sediment and nutrient loads and thermal regimes that may change temporally (from seconds to yearly variations) and spatially (from sub-cm within habitat patches to hundreds of km² at the drainage basin scale). This complexity produces a variety of geomorphological features and habitats that sustain the diverse ecological communities recorded in fresh, saline and marine waters. Aquatic organisms, ranging from micro-algae and macrophytes to macroinvertebrates, fish, amphibians, reptiles, birds and mammals, have evolved adaptations to persist and thrive in hydraulically dynamic environments (Lytle and Poff, 2004; Townsend, 2006; Folkard and Gascoigne, 2009; Nikora, 2010). However, anthropogenic impacts on aquatic systems have been widespread and probably most marked on riverine systems. A report by the World Commission on Dams (2000) and a recent review by Kingsford (2011) suggested that modification of the river flow regime as a result of regulation by creating barriers, impoundment and overabstraction, the spread of invasive species, overharvesting and the effects of water pollution were the main threats to the world’s rivers and wetlands and these effects could be compounded by future climate change.

The impacts of dam construction, river regulation and channelisation have significantly reduced the natural variability of the flow regime and channel morphology. This results in degradation, fragmentation and loss of habitat structure and availability, with subsequent reductions in aquatic biodiversity (Vörösmarty et al., 2010). Recognition of the long history, widespread and varied extent of human impacts on river systems, coupled with an increase in environmental awareness has led to the development of a range of approaches to minimise and mitigate their impacts. These include river restoration and rehabilitation techniques to restore a more natural channel morphology (e.g. Brookes and Shields Jr, 1996; de Waal et al., 1998; Darby and Sear, 2008), methods to define ways to reduce or mitigate the impact of abstractions and river regulation through the definition and application of instream...
or environmental flows (Dyson et al., 2003; Acreman and Dunbar, 2004; Annear et al., 2004; Acreman et al., 2008), and the design of screens and fish passes to divert aquatic biota from hazardous areas (e.g. abstraction points) and to enable them to migrate past physical barriers, especially, but not solely associated with dams (Kemp, 2012).

Key legislative drivers have been introduced to compel regulatory authorities and agencies to manage and mitigate historic and contemporary anthropogenic impacts and, where appropriate, undertake restoration measures. The EU Water Framework Directive (Council of the European Communities, 2000) requires the achievement of ‘good ecological status’ in all water bodies across EU member states by 2015 (European Commission, 2012). This, in turn, has required the development of methods and techniques to assess the current status of chemical and biological water quality (Achleitner et al., 2005), hydromorphology and flow regime variability, and identify ways of mitigating impacts and restoring river channels and flow regimes where they are an impediment to the improvement of river health (Acreman and Ferguson, 2010). Similar developments have occurred in North America with the release of the United States Environmental Protection Agency guidelines (US EPA, 2006). In Australia, provision of water for environmental flows has been driven by a combination of national policy agreements including the National Water Initiative in 2004, national and state level legislation and government-funded initiatives to buy back water entitlements from water users including the ‘Water for the Future’ programme (Le Quene et al., 2010). Important lessons can be learned from South Africa, where implementation of the National Water Act of 1998 is recognised as one of the most ambitious pieces of water legislation to protect domestic human needs and environmental flows on an equal footing ahead of economic uses. However, Pollard and du Toit (2008) suggest that overly complicated environmental flow recommendations have inhibited their implementation. This provides a key message for ecohydraulic studies aimed at providing environmental flow or indeed other types of river management recommendations (e.g., river restoration) worldwide.

1.2 The emergence of ecohydraulics

During the 1970s and 1980s it was common for multidisciplinary teams of researchers and consultants to undertake pure and/or applied river science projects and to present results collected as part of the same study independently to stakeholders and regulatory/management authorities, each from the perspective of their own disciplinary background. More recently, there has been a shift towards greater interdisciplinarity, with teams of scientists, engineers, water resource and river managers and social scientists working together in collaborative teams towards clearly defined common goals (Porter and Rafols, 2009). Developments in river science reflect this overall pattern, with the emergence of ecohydrology at the interface of hydrology and ecology (Dunbar and Acreman, 2001; Hannah et al., 2004; Wood et al., 2007) and hydromorphology, which reflects the interaction of the channel morphology and flow regime (hydrology and hydraulics) in creating ‘physical habitat’ (Maddock, 1999; Orr et al., 2008; Vaughan et al., 2009).

Like ‘ecohydrology’, ‘eco hydraulics’ has also developed at the permeable interface of traditional disciplines, combining the study of the hydraulic properties and processes associated with moving water typical of hydraulic engineering and geomorphology and their influence on aquatic ecology and biology (Vogel, 1996; Nestler et al., 2007). Ecohydraulics has been described as a sub-discipline of ecohydrology (Wood et al., 2007) although it has become increasingly distinct in recent years (Rice et al., 2010). Hydraulic engineers have been engaged with design criteria for fish passage and screening facilities at dams for many years. Recognition of the need to solve river management problems like these by adopting an interdisciplinary approach has been the driver for the development of ecohydraulics. Interdisciplinary research that incorporates the expertise of hydrologists, fluvial geomorphologists, engineers, biologists and ecologists has begun to facilitate the integration of the collective expertise to provide holistic management solutions. Ecohydraulics has played a critical role in the development of methods to assess and define environmental flows (Statzner et al., 1988). Although pre-dating the use of the term ‘eco hydraulics’, early approaches, such as the Physical Habitat Simulation System (PHABSIM) in the 1980s and 1990s, were widely applied (Gore et al., 2001) but often criticised due to an over-reliance on simple hydraulic models and a lack of ecological relevance because of the way that habitat suitability was defined and calculated (Lancaster and Downes, 2010; Shenton et al., 2012). State-of-the-art developments associated with ecohydraulics are attempting to address these specific gaps between physical scientists (hydraulic engineers, hydrologists and fluvial geomorphologists) and biological scientists (e.g. aquatic biologists and ecologists) by integrating hydraulic and biological tools to analyse and predict ecological responses.
to hydrological and hydraulic variability and change (Lamouroux et al. in press). These developments intend to support water resource management and the decision-making process by providing ecologically relevant and environmentally sustainable solutions to issues associated with hydropower operations, river restoration and the delineation of environmental flows (Acreman and Ferguson, 2010).

The growing worldwide interest in ecohydraulics can be demonstrated by increasing participation in the international symposia on the subject. The first symposium (then titled the 1st International Symposium on Habitat Hydraulics) was organised in 1994 in Trondheim, Norway by the Foundation for Scientific and Industrial Research (SINTEF), the Norwegian University of Science and Technology (NTNU) and the Norwegian Institute of Nature Research (NINA) with about 50 speakers and 70 delegates. Subsequent symposia in Quebec City (Canada, 1996), Salt Lake City (USA, 1999), Cape Town (South Africa, 2002), Madrid (Spain, 2004), Christchurch (New Zealand, 2007), Concepción (Chile, 2009), Seoul (South Korea, 2010) and most recently in Vienna (Austria, 2012) have taken the scientific community across the globe, typically leading to more than 200 speakers and approximately 300 delegates at each meeting.

A recent bibliographic survey by Rice et al. (2010) indicated that between 1997 and the end of 2009 a total of 146 publications had used the term 'ecohydraulic' or a close variant (eco hydraulic, ecohydraulics or eco-hydraulics) in the title, abstract or keywords (ISI Web of Knowledge, http://wok.mimas.ac.uk/). This meta-analysis indicated greater use of the term ‘eco hydraulics’ amongst water resources and engineering journals (48%) and geoscience journals (31%) compared to a more limited use in (21%) biological or ecological journals. By the end of 2011 this figure had risen to 211 publications, with 65 papers being published between 2010 and the end of 2011 (Figure 1.1). This suggests a significant increase in the use of the terms more recently, and strongly mirrors the rapid rise in the use of the term ‘eco hydraulics’, which has been used in the title, abstract or as a keyword 635 times since 1997 (186 between 2010 and 2011). However, bibliographic analysis of this nature only identifies those publications that have specifically used one of the terms and there is an extensive unquantified literature centred on ecohydraulics and ecohydrology that has not specifically used these terms.

Porter and Rafols (2009) suggested that interdisciplinary developments in science have been greatest between closely allied disciplines and less well developed and slower for fields with a greater distance between them. This appears to be the case when comparing developments in ecohydrology and ecohydraulics. Ecohydrology has increasingly been embraced by an interdisciplinary audience and even witnessed the launch of a dedicated journal, Ecohydrology, in 2008 (Smettem, 2008), drawing contributions from across physical, biological and social sciences as well as engineering and water resources management. In contrast, publications explicitly referring to ‘eco hydraulics’ predominately appeared in water resources, geosciences and engineering journals and the affiliation of the primary authors remains firmly within engineering and geosciences departments and research institutes. However, the greatest number of papers has appeared in the interdisciplinary journal River Research and Applications (17 papers since 2003). This figure includes five out of ten papers within a special issue devoted to ecohydrodynamics in 2010 (Rice et al., 2010) and two out of nine papers within a special issue devoted to ‘Fish passage: an ecohydraulics approach’ in 2012 (Kemp, 2012), and clearly demonstrates that many authors do not routinely use the term ‘eco hydraulics’. Biologists have been investigating organism responses to their abiotic environments, including the role of fluid dynamics on aquatic communities, for decades and well before the term ‘eco hydraulics’ was coined.
example, from an environmental flow perspective, biological scientists have been involved with determining the relationship between fish (and other biota) and hydraulics since at least the 1970s (e.g. Bovee and Cochnauer, 1978). What this bibliographic analysis highlights is that geoscientists and engineers have more readily adopted the terms than colleagues in biology and ecology.

The dominance of physical scientists and engineers within some studies, many of them using modelling approaches, has been highlighted as a potential weakness of some research. It is argued they rely on faulty assumptions and lack any ecological or biological reality due to inadequate consideration of biological interactions between organisms (inter- or intra-specific), or natural population dynamics (Lancaster and Downes, 2010; Shenton et al., 2012). However, these criticisms have been contested and there is growing evidence that interdisciplinarity is being embraced more widely (Lamouroux et al., 2010; Lamouroux et al., Lamouroux et al., in press). This issue is discussed further in the concluding chapter of this volume.

### 1.3 Scope and organisation of this book

The aim of this research-level edited volume is to provide the first major text to focus on ecohydraulics. It is comprised of chapters reflecting the range and scope of research being undertaken in this arena (spanning engineering, geosciences, water resources, biology, ecology and interdisciplinary collaborations). Individual chapter authors have provided overviews of cutting-edge research and reviews of the current state of the art in ecohydraulics. In particular, authors have been encouraged to demonstrate how their work has been informed by and is influencing the on-going development of ecohydraulics research. The contributions use case study examples from across the globe, highlighting key methodological developments and demonstrating the real-world application of ecohydraulic theory and practice in relation to a variety of organisms ranging from riparian vegetation and instream algae, macrophytes, macroinvertebrates and fish to birds and amphibians. The chapters reflect a spectrum of research being undertaken within this rapidly developing field and examine the interactions between hydraulics, hydrology, fluvial geomorphology and aquatic ecology on a range of spatial (individual organism in a habitat patch to catchment) and temporal scales.

The book is structured into four parts: Part One considers the range and type of methods and approaches used in ecohydraulics research, with a particular focus on aquatic habitat modelling; Part Two considers a range of species–habitat relationships in riverine and riparian habitats; Part Three consists of detailed ecohydraulics case studies that have a clear management application, mostly, but not exclusively, relating to environmental flow determination, fish passage design, river channel and habitat restoration and ecosystem assessment. The final chapter (Part Four) aims to draw together the work contained in the book to outline key research themes and challenges in ecohydraulics and discuss future goals and directions. A number of chapters involve methods, species–habitat relationships and case studies and therefore could have been located in more than one part of the book. The final decision regarding which part to place them in was in some cases clear-cut and in others fairly arbitrary.

We realise that the coverage provided in this volume is not complete and are conscious that the chapters are almost exclusively centred on freshwater, riverine ecosystems. Indeed there has been a considerable volume of research centred on marine (e.g. Volkenborn et al., 2010), estuarine (e.g. Yang et al., 2012) and lentic (lake) ecosystems (e.g. Righetti and Lucarelli, 2010), where equally challenging and exciting ecohydraulic research questions are being addressed. Their exclusion is driven by a desire to keep this book within a manageable size and scope rather than a view that these other parts of the natural environment are somehow less important than riverine ecosystems.

Research currently being undertaken in the arena of ecohydraulics is developing rapidly and is becoming increasingly interdisciplinary, drawing on a range of academic and practitioner traditions and addressing real-world problems. As this interdisciplinary science matures there is a growing demand from river managers and end users to be involved not just at the inception and conclusion, but throughout the studies to enhance the possibility that any management recommendations can be implemented successfully. The occurrence of this would signal a move from interdisciplinarity (between traditional disciplines) to ‘transdisciplinarity’ (that also engages with managers and end users during the research). The editors hope that the realisation of this development will be one mark of this book’s success.

### References


Methods and Approaches
Incorporating Hydrodynamics into Ecohydraulics: The Role of Turbulence in the Swimming Performance and Habitat Selection of Stream-Dwelling Fish

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2.1 Introduction

The complexity and dynamism of river systems, the strength of their biophysical linkages and the need to respond to adverse anthropogenic impacts has led to the emergence of hydroecology as a key area of interdisciplinary research (Hannah et al., 2007). Wood et al. (2007) provide an outline of the target elements of hydroecology in which they emphasise the bi-directional nature of physical-ecological interactions and the need to identify causal mechanisms rather than merely establishing statistical links between biota, ecosystems and environments. Such causal mechanisms operate in the realm of the physical habitat (Harper and Everard, 1998). A sub-discipline of hydroecology known as ecohydraulics has emerged from the scientific literature in recent decades (Leclerc et al., 1996) and, as a contemporary science, has its roots in the hydraulic stream ecology paradigm (Statzner et al., 1988). Ecohydraulics relies on the assumption that flow forces are ecologically relevant (i.e. that they influence the fitness of individual organisms and, therefore, the structure and function of aquatic communities). It lies at the interface of hydraulics and ecology where new approaches to research are required to reconcile the contrasting conceptual frameworks underpinning these sciences, which can be seen respectively as Newtonian (reductionist) and Darwinian (holistic) (Hannah et al., 2007). Harte (2002) has identified elements of synthesis for integrating these disparate traditions which include the use of simple, falsifiable models and the search for patterns and laws. Newman et al. (2006) suggested that hierarchical scaling theory, whereby reductionist explanations are considered at different levels of organisation, could be used to integrate these two approaches. River habitat is structured at a number of scales (Frissell et al., 1986) but it is at the microscale (<10⁻¹ m) of the hydraulic environment where reductionist explanations for ecological phenomena are most often sought (e.g. Enders et al., 2003; Liao et al., 2003a).
Table 2.1 Common terms used to describe the flow environment.

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$</td>
<td>Flow depth</td>
<td></td>
</tr>
<tr>
<td>$y$</td>
<td>Height above bed datum</td>
<td></td>
</tr>
<tr>
<td>$A$</td>
<td>Cross-sectional area of flow</td>
<td></td>
</tr>
<tr>
<td>$P$</td>
<td>Wetted perimeter</td>
<td></td>
</tr>
<tr>
<td>$R$</td>
<td>Hydraulic radius</td>
<td>$= A/P$</td>
</tr>
<tr>
<td>$S$</td>
<td>Longitudinal bed slope</td>
<td></td>
</tr>
<tr>
<td>$\rho$</td>
<td>Fluid density of water</td>
<td>Taken as $1000 \text{ kg m}^{-3}$</td>
</tr>
<tr>
<td>$g$</td>
<td>Acceleration due to gravity</td>
<td>$9.81 \text{ m s}^{-2}$</td>
</tr>
<tr>
<td>$k$</td>
<td>Height of surface roughness elements</td>
<td>Various methods to quantify $k$ provided by Statzner et al. (1988). Typically based on particle size ($D$) distributions for gravel-bed rivers (e.g. $3.5D_{90}$) (Clifford et al., 1992)</td>
</tr>
<tr>
<td>$v$</td>
<td>Kinematic viscosity</td>
<td>$1.004 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ at $20^\circ \text{C}$</td>
</tr>
<tr>
<td>$U$</td>
<td>Mean streamwise column velocity</td>
<td>Measured at $y/h = 0.4$ or depth-averaged</td>
</tr>
<tr>
<td>$Fr$</td>
<td>Froude number $= U/\sqrt{gh}$</td>
<td>$Fr &lt; 1 \rightarrow$ sub-critical flow</td>
</tr>
<tr>
<td>$Re$</td>
<td>Bulk flow Reynolds number $= Uh/v$</td>
<td>$Re &lt; 500 \rightarrow$ laminar flow</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Shear stress (section- or reach-averaged) $= PgRS$</td>
<td>Point measurements can be made using flusswasserstammtisch (FST) hemispheres</td>
</tr>
<tr>
<td>$U_*$</td>
<td>Shear velocity or friction velocity $= \sqrt{\tau/\rho}$</td>
<td>Calculated from point measurements of shear stress or estimated from near-bed velocity profile</td>
</tr>
<tr>
<td>$Re^*$</td>
<td>Roughness Reynolds number $= U_*k/v$</td>
<td>$Re^* &lt; 5 \rightarrow$ hydraulically smooth flow</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Thickness of laminar sublayer</td>
<td>$\delta/k &lt; 1 \rightarrow$ hydraulically smooth flow</td>
</tr>
</tbody>
</table>

2.1.1 'Standard' ecohydraulic variables

Much research has focused on the relationship between instream biota and the 'standard' ecohydraulic variables of flow depth ($h$), mean streamwise velocity ($U$) and combinations of these. These simple hydraulic quantities, and indices derived from them (e.g. Froude number, $U:h$), have traditionally been used to classify a range of mesoscale ($10^{-1} - 10^1 \text{ m}$) units of instream habitat (e.g. channel geomorphic units, hydraulic biotopes, functional habitats) for habitat assessment and design purposes (Jowett, 1993; Padmore, 1997; Wadeson and Rowntree, 1998; Kemp et al., 2000). $U$ is typically measured at 'point six' depth ($y/h = 0.4$, where $y$ is height above the bed) and (ensemble) averaged over 10–60 s. Other commonly used variables describing the bulk flow are the Froude number ($Fr$, ratio of inertial to gravitational forces) and the Reynolds number ($Re$, ratio of inertial to viscous forces) (Table 2.1). These are dimensionless variables representing gradients from tranquil (sub-critical) to shooting (super-critical) and laminar to fully developed (turbulent) flow respectively. Because the flow environment experienced by benthic organisms living very close to the bed differs markedly to that farther up in the water column (Statzner et al., 1988), the inner region (see Figure 2.1) has often been characterised by

Figure 2.1 Co-ordinate system for three-dimensional flows and structure of flow over rough, permeable boundaries.
a different set of variables. They include bed shear stress ($\tau$), shear velocity ($U_s$), roughness Reynolds number ($Re^*$) and the thickness of the laminar sublayer ($\delta$). $U_s$ is related to $\tau$ (Table 2.1) which, in turn, is responsible for the appearance of a mean gradient in the vertical velocity profile. $U_s$ can be interpreted as a velocity scale for flow statistics in the inner region. $Re^*$ describes the ‘roughness’ of the near-bed flow environment. Finally, $\delta$ approximates the thickness of the laminar sublayer where viscous forces predominate over inertial forces. In rivers with coarse bed material (i.e. gravel-bed rivers) which are characterised by hydraulically rough flow ($Re^* > 70$), however, $\delta$ is typically very small in comparison to roughness size ($k$) (Davis and Barmuta, 1989; Kirkbridge and Ferguson, 1995), rendering it irrelevant to the study of all but the smallest organisms (Allan, 1995).

Flow forces are reported to be the dominant factors influencing the processes of dispersal, reproduction, habitat use, resource acquisition, competition and predation in river ecosystems (Table 2.2). The passive dispersal of benthic organisms is controlled by the same mechanisms as sediment transport (Nelson et al., 1995; McNair et al., 1997), although many invertebrates actively enter the water column and are able to swim back to the substrate (Waters, 1972; Mackay, 1992). Hydraulic limitations to fish migration are related to body depth and maximum sustained and burst swimming speeds $V_{\text{max}}$, which vary considerably between species and with water temperature (Beamish, 1978). $h$ and $U$ are key factors in the segregation of rheophilic species (e.g. Bisson et al., 1988), whilst the distribution of benthic organisms has been related to $\delta$, $Fr$, $\tau$ and $Re^*$ (e.g. Statzner, 1981a, 1981b; Scarsbrook and Townsend, 1993; Brooks et al., 2005). Most instream biota exhibit a subsidy-stress response to flow as resources (e.g. food, nutrients, oxygen) may be limiting at low $U$, whilst at high $U$ drag disturbance and mass transfer may be the limiting factors (Hart and Finelli, 1999; Nikora, 2010). Thus, for example, the energetic cost of swimming for juvenile Atlantic salmon ($Salmo salar$) is negatively related to $U$, whilst prey delivery is positively related to $U$ (Godin and Rangeley, 1989). Some of these examples offer mechanistic explanations for flow–biota interactions on which predictive models may be built (e.g. Hughes and Dill, 1990) but ecohydraulic research more often relies on correlative techniques to describe abundance–environment relationships. Whilst correlative approaches may represent a pragmatic compromise in the absence of detailed mechanistic knowledge (Lamouroux et al., 2010), ecohydraulics should strive to establish a more ecologically realistic foundation for modelling the response of populations to environmental change and management interventions (Lancaster and Downes, 2010; Frank et al., 2011).

In this chapter we argue that the inclusion of higher order (turbulent) properties of the flow constitutes a more complete and ecologically relevant characterisation of the hydraulic environment that biota are exposed to than standard ecohydraulic variables alone. The use of turbulent flow properties in ecohydraulics, therefore, has the potential to contribute towards achieving river research and management goals (e.g. river habitat assessment, modelling, rehabilitation) but more information on the mechanisms by which turbulence affects biota is required before this potential can be realised. After outlining the theory, structure and measurement of turbulent flow in open channels we focus on the swimming performance and habitat selection of stream-dwelling fish as an example of how the hydrodynamics of river ecosystems may affect resident biota. The discussion is biased towards salmonids ($S. salar$, $S. trutta$, $Oncorhynchus mykiss$) as most research has focused on these species due to their ecological (Wilson and Halupka, 1995; Jonsson and Jonsson, 2003) and socio-economic (e.g. Murray and Simcox, 2003) importance and our ability to measure turbulence at the focal point of these organisms, although the turbulent flow properties discussed are likely to be relevant to a range of other aquatic biota. Our scope is generally confined to small to medium (second–fourth order) lowland gravel-bed rivers, although there may well be wider applicability both in terms of river size and type. We acknowledge that many factors (e.g. physico-chemical, biological) make up the multidimensional niche of biota (e.g. Köhler, 1992; Sweeting, 1994; Lancaster and Downes, 2010) but ecohydraulics serves to emphasise the physical environment, which many have cited as the dominant factor in the ecology of lotic communities (e.g. Statzner et al., 1988; Hart and Finelli, 1999; Thompson and Lake, 2010). The discussion, therefore, is restricted to the hydraulics of river habitats.

### 2.2 Turbulence: theory, structure and measurement

Turbulence in fluid flows was recognised by Leonardo Da Vinci as early as 1513 and is a ubiquitous phenomenon in river ecosystems, where $Re \gg 500$ (Davidson, 2004). Despite this, however, there is still no formal definition of turbulence, although a number of key qualities have been identified. Turbulent flow exhibits seemingly random
### Table 2.2 Some examples of flow-biota links identified in the ecohydraulics literature.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Variable(s)</th>
<th>Species/community/process influenced by variable</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dispersal and reproduction</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silvester and Sleigh (1985); Reiter and Carlson (1986); Biggs and Thomsen (1995)</td>
<td>$\tau$, $U_*$</td>
<td>Positively correlated with loss of biomass of filamentous and matt-forming algal communities</td>
</tr>
<tr>
<td>Stevenson (1983); Peterson and Stevenson (1989)</td>
<td>$U$</td>
<td>Negatively correlated with diatom colonisation rates on clean ceramic tiles</td>
</tr>
<tr>
<td>Deutsch (1984); Becker (1987) cited in Statzner et al. (1988)</td>
<td>$Re$, $Fr$</td>
<td>Oviposition sites of certain caddis fly (Trichoptera) genera correlated with $Re$ and $Fr$</td>
</tr>
<tr>
<td>McNair et al. (1997)</td>
<td>$U_*$</td>
<td>Transport distance positively related to Rouse number ($= V_s/\tau$, where $V_s$ is settling velocity)</td>
</tr>
<tr>
<td>Beamish (1978); Crisp (1993); Hinch and Rand (2000)</td>
<td>$h$, $U$</td>
<td>Fish migration inhibited when $h \ll \text{body depth}$ and/or when $U &gt; V_{max}$</td>
</tr>
<tr>
<td><strong>Habitat use</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biggs (1996)</td>
<td>$U$</td>
<td>Growth rate and organic matter accrual of periphyton and macrophytes enhanced at intermediate $U$</td>
</tr>
<tr>
<td>Scarsbrook and Townsend (1993); Lancaster and Hildrew (1993)</td>
<td>$\tau$</td>
<td>Macroinvertebrate community structure related to spatial and temporal variation in $\tau$</td>
</tr>
<tr>
<td>Statzner (1981a)</td>
<td>$\delta$</td>
<td>Body length of freshwater snails (Gastropoda) and shrimps (Gammarus) positively correlated with $\delta$</td>
</tr>
<tr>
<td>Statzner (1981b)</td>
<td>$\delta$, $Fr$</td>
<td>Abundance of <em>Odagmia ornata</em> (Diptera:Simuliidae) negatively correlated with $\delta$ and positively correlated with $Fr$</td>
</tr>
<tr>
<td>Statzner et al. (1988)</td>
<td>$Re &gt; U &gt; \delta &gt; Re_\tau &gt; Fr$</td>
<td>Order of best explanatory variables to predict distribution of water bug <em>Aphelocheirus aestivalis</em></td>
</tr>
<tr>
<td>Brooks et al. (2005)</td>
<td>$Re_\tau$</td>
<td>Strongest (negative) correlation with macroinvertebrate abundance and species richness</td>
</tr>
<tr>
<td>Bisson et al. (1988); Lamouroux et al. (2002); Moir et al. (1998, 2002); Sagnes and Statzner (2009)</td>
<td>$h$, $U$, $Fr$</td>
<td>Fish species and life stages segregated by hydraulic variables due to morphological and ecological traits</td>
</tr>
<tr>
<td><strong>Resource acquisition, competition and predation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wiley and Kohler (1980); Eriksen et al. (1996); Stevenson (1996)</td>
<td>$U$, $\delta$</td>
<td>$U$ controls the delivery of limiting resources. Laminar sublayer ($\delta$) limits rate of molecular diffusion.</td>
</tr>
<tr>
<td>Godin and Rangeley (1989); Hayes and Jowett (1994); Heggenes (1996)</td>
<td>$U$, $h$</td>
<td>$U$ positively correlated with prey delivery and negatively correlated with capture rates for salmonids; velocity gradients determine energetic costs of drift-feeding by insectivorous fish; high $h$ provides refuge from predators and competition</td>
</tr>
<tr>
<td>Peckarsky et al. (1990); Malmqvist and Sackman (1996); Hart and Merz (1998)</td>
<td>$U$</td>
<td>High $U$ serves as a refuge from predators for blackflies (Simuliidae) and stoneflies (Plecoptera)</td>
</tr>
<tr>
<td>Poff and Ward (1992, 1995); DeNicola and McIntyre (1991)</td>
<td>$U$</td>
<td>Negatively correlated with rates of algal consumption by snails and certain caddis flies (Trichoptera)</td>
</tr>
<tr>
<td>Matczak and Mackay (1990); Hart and Finelli (1999)</td>
<td>$U$</td>
<td>Higher $U$ reduces competition and increases carrying capacity of filter-feeding macroinvertebrates</td>
</tr>
</tbody>
</table>
behaviour, has three-dimensionality and rotationality and is intermittent in time and space over a range of scales (Nikora, 2010). Turbulent fluctuations in flow velocities have been implicated in suspended sediment transport (e.g. Bagnold, 1966), bedload transport and the development of bed morphology (e.g. Best, 1993), mixing of dissolved and particulate substances (e.g. Zhen-Gang, 2008), and root-mean-squared turbulence intensity may be characterised in a number of ways, including standard deviation ($\sigma_{u,v,w}$), relative turbulence intensity ($TI_{u,v,w}$), and root-mean-squared (RMS$_{u,v,w}$) values:

\[
\begin{align*}
RMS_u &= \sqrt{\frac{1}{n}(u_1^2 + u_2^2 + \cdots + u_n^2)}, \\
RMS_v &= \sqrt{\frac{1}{n}(v_1^2 + v_2^2 + \cdots + v_n^2)}, \\
RMS_w &= \sqrt{\frac{1}{n}(w_1^2 + w_2^2 + \cdots + w_n^2)},
\end{align*}
\]

where $n$ is the number of individual observations within a velocity time series. RMS values reflect the normal Reynolds stresses included in the final term of Equation (2.1), whilst the diagonal Reynolds shear stresses ($\tau_{ij}$) are given by:

\[
\tau_{uv} = \rho u'v', \quad \tau_{uw} = \rho u'w', \quad \tau_{vw} = \rho v'w'.
\]

These represent the turbulent flux of momentum within a fluid which is related to force by Newton’s second law.

\[\rho \frac{\partial U_i}{\partial x_j} = \rho g_i - \bar{f}_i + \frac{\partial}{\partial x_j}\left[-p \delta_{ij} + \mu \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) - \rho \bar{u}_i \bar{u}_j\right] \]

where $\bar{f}$ is body force per unit volume of fluid (N m$^{-3}$) and $p$ is isotropic hydrostatic pressure force (N m$^{-3}$). According to Reynolds decomposition, the instantaneous velocity (time series) at a point can be separated into mean and fluctuating components in the streamwise ($u$), vertical ($v$) and spanwise ($w$) directions:

\[u = U + u', \quad v = V + v', \quad w = W + w'.\]

Research in the past century has focused on two complementary frameworks within which to study turbulence in open channel flows. The statistical framework treats turbulence as a random phenomenon and focuses on descriptions of the bulk statistical properties of the flow (Richardson, 1922; Kolmogorov, 1941), whereas the deterministic framework emphasises the structural coherency of turbulent flows at a number of spatiotemporal scales (Robinson, 1991).

\[TI_u = \sigma_u/U, \quad TI_v = \sigma_v/V, \quad TI_w = \sigma_w/W.\]

\[2.2.1 \text{ Statistical descriptions of turbulence}\]

Water behaves as an incompressible, homogenous, Newtonian fluid in rivers and its flow is governed by equations describing the conservation of mass, momentum and energy. These mass–momentum (Navier–Stokes) and energy equations are set out by Tonina and Jorde (see Chapter 3). The basic principles underlying fluid mechanics are described in any introductory-level text on hydraulics (e.g. Kay, 2008). The full set of equations describing turbulent flow is provided by Nezu and Nakagawa (1993) and several other research-level texts. The turbulence intensity $\bar{u}'\bar{u}'$ is a vector quantity, with each component ($u_i = u, v, w$) derived from the three normal Reynolds stress terms ($\rho u'v', \rho v'w', \rho w'u'$) in the Reynolds-averaged Navier–Stokes (RANS) equation:

\[2.1\]

where $\bar{f}$ is body force per unit volume of fluid (N m$^{-3}$) and $p$ is isotropic hydrostatic pressure force (N m$^{-3}$). According to Reynolds decomposition, the instantaneous velocity (time series) at a point can be separated into mean and fluctuating components in the streamwise ($u$), vertical ($v$) and spanwise ($w$) directions:

\[u = U + u', \quad v = V + v', \quad w = W + w'.\]

where $U, V$ and $W$ are time-averaged velocities and primes denote turbulent fluctuations. Reynolds decomposition requires strict stationarity of the mean so that the fluctuating components only describe turbulence and do not include variation of the mean flow. Turbulence intensity may be characterised in a number of ways, including standard deviation ($\sigma_{u,v,w}$), relative turbulence intensity ($TI_{u,v,w}$), and root-mean-squared (RMS$_{u,v,w}$) values:

\[RMS_u = \sqrt{\frac{1}{n}(u_1^2 + u_2^2 + \cdots + u_n^2)}, \quad RMS_v = \sqrt{\frac{1}{n}(v_1^2 + v_2^2 + \cdots + v_n^2)}, \quad RMS_w = \sqrt{\frac{1}{n}(w_1^2 + w_2^2 + \cdots + w_n^2)}\]

where $n$ is the number of individual observations within a velocity time series. RMS values reflect the normal Reynolds stresses included in the final term of Equation (2.1), whilst the diagonal Reynolds shear stresses ($\tau_{ij}$) are given by:

\[\tau_{uv} = \rho u'v', \quad \tau_{uw} = \rho u'w', \quad \tau_{vw} = \rho v'w'.\]

These represent the turbulent flux of momentum within a fluid which is related to force by Newton’s second law.
A summary of overall turbulence is given by Turbulent Kinetic Energy (TKE):

\[
TKE = 0.5(RMS_u^2 + RMS_v^2 + RMS_w^2)
\]  
(2.6)

which, as a scalar quantity, is a useful descriptor of turbulence in complex three-dimensional flows. The order \( RMS_u > RMS_v > RMS_w \) has been found to hold throughout the water column with the following ratios (Nezu and Nakagawa, 1993; Song and Chiew, 2001):

\[
\frac{RMS_w}{RMS_u} = (0.71 - 0.75), \quad \frac{RMS_v}{RMS_u} = (0.5 - 0.55).
\]  
(2.7)

The above quantities used to describe turbulence intensity are often non-dimensionalised by dividing through \( U \) or \( U_\ast \). Nezu and Nakagawa (1993) derived semi-empirical equations to describe the distribution of turbulence intensities and TKE throughout the flow depth:

\[
\frac{\sigma_u}{U_\ast} = 2.30 \exp(-y/h), \quad \frac{\sigma_v}{U_\ast} = 1.27 \exp(-y/h), \quad \frac{\sigma_w}{U_\ast} = 1.63 \exp(-y/h), \quad \frac{TKE}{U_\ast^2} = 4.78 \exp(-2y/h).
\]  
(2.8)

These semi-theoretical curves (Equation (2.8)) are based on flows at a range of \( Re \) and \( Fr \) and provide a good fit when limited to the intermediate flow region (\( 0.1 < y/h < 0.6 \)) of fully developed flows.

An essential feature of turbulent flows is that they are rotational or, in other words, they are characterised by non-zero vorticity. Vorticity (\( \omega \)) describes the curl (curve) of the velocity vector and is equal to twice the angular velocity (rate of rotation of the fluid at a point). An eddy can be defined as a region of flow with finite vorticity (Webb and Cotel, 2010). The fundamental concept underpinning the statistical description of turbulence is the eddy or energy cascade (EC). The EC states that turbulence is initiated in the production range at an external scale of the flow (i.e. \( h \)). The depth of the largest eddies (\( L_y \)) in open channel flows, therefore, is comparable to \( h \). The largest eddies are anisotropic and, when point sampled velocity time series data are available, their integral length scale (\( L_x \)) must be determined by integrating the autocovariance function, to give the integral time scale (ITS), and applying Taylor’s (1935) frozen turbulence approximation (Clifford and French, 1993a), which states that:

\[
L = Ut \quad \text{(2.9)}
\]

where \( L \) is length and \( t \) is time scale. The large eddies are unstable and transfer their energy to successively smaller eddies in the inertial subrange until eddies become so small that viscous forces in the dissipation range finally cause kinetic energy to be dissipated to heat at Kolmogorov’s micro-scale (\( \eta \)):

\[
\eta = (v^3 \varepsilon)^{1/4}
\]  
(2.10)

where \( v \) is kinematic viscosity and \( \varepsilon \) is the rate of turbulent energy dissipation, which should ideally be estimated from the scaling of velocity spectra in the inertial subrange (Pope, 2000) but is more often estimated by assuming isotropic tendency:

\[
\varepsilon = 15v \left( \frac{\partial u}{\partial x} \right)^2 = 15v \left( \frac{RMS_u}{\lambda} \right)^2
\]  
(2.11)

where \( \lambda \) is the Taylor microscale denoting the boundary between the inertial and dissipation ranges.

The extent of the inertial subrange can be defined by application of the Kolmogorov law describing the one-dimensional energy spectrum, which states that the frequency spectrum of eddies decays according to a power law of \(-5/3\) in the inertial subrange (Figure 2.2). This subrange loosely corresponds to the intermediate region where energy generation (\( G \)) and \( \varepsilon \) are in quasi-equilibrium. \( G > \varepsilon \) in the inner region whereas \( G < \varepsilon \) in the free-surface region. Turbulence is therefore said to be exported from near the bed towards the surface (Nezu and Nakagawa, 1993).

Figure 2.2 Power spectrum for the vertical velocity component in the wake of a submerged boulder showing production range and inertial subrange as defined by Kolmogorov’s \(-5/3\) power law. F. Breton (unpublished data).
Average eddy frequency \((f_{u,v,w})\) can be determined from a time series by fitting a second order autoregressive model of the form:

\[
\begin{align*}
    u_t &= a_1 u_{t-1} + a_2 u_{t-2} + e_t
\end{align*}
\]  

(2.12)

where \(a_1\) and \(a_2\) are coefficients of the velocity at a given time lag and \(e_t\) is a random component (Clifford and French, 1993a). Alternatively, dominant eddy frequencies can be identified through examination of peaks in velocity power spectra (Figure 2.2) or from the results wavelet analysis (e.g. Torrence and Compo, 1998; Hardy et al., 2009). These frequencies may be converted to dominant or average eddy dimensions \((L_{u,v,w})\) by applying Equation (2.9).

2.2.2 Coherent flow structures

Another description of turbulence based on coherent flow structures (CFSs) has emerged due to the fact that most statistical descriptions ignore the presence of quasi-periodic patterns of coherent motion in the flow (Robinson, 1991). Nikora (2010, p. 373) broadly defines a CFS as 'a three-dimensional flow region over which at least one fundamental flow variable exhibits significant correlation with itself or with another variable over a range of space and/or time'. Research into CFSs has progressed through flow visualisations (e.g. Kline et al., 1967; Shvidenko and Pender, 2001), direct numerical simulations (e.g. Hardy et al., 2007) and analysis of turbulent flow time series in the space and/or time (frequency) domains (e.g. Buffin-Bélanger and Roy, 1998; Lacey and Roy, 2007). CFSs contain most of the turbulent energy and are generally found in the productive subrange (Nezu and Nakagawa, 1993). They can be categorised into two broad scales. At a relatively small scale, CFSs are generated by vortex shedding from protuberant roughness elements (e.g. pebble clusters) and the separation zones in lee of them. The basic forms of such CFSs are horseshoe and hairpin vortices as well as the Kármán vortex street, a region with alternating passages of clockwise and anti-clockwise eddies rotating on a vertical axis (Figure 2.3). At a larger scale, turbulent fluctuations are manifested in high- and low-speed wedges occupying the full depth of the flow.

Clifford and French (1993b) provided evidence that dominant eddy frequencies in gravel-bed rivers could be linked to bed particle sizes by means of the Strouhal relationship, which states that:

\[
    S_l = \frac{SU}{f}
\]  

(2.13)

where \(S_l\) is the diameter of a theoretical body responsible for vortex shedding, \(S\) is the Strouhal number and \(f\) is the frequency of interest. Assuming \(S = 0.2\) (Schlichting, 1979), it was found that values of \(S_l\) associated with peaks in the power spectrum were of the same order of magnitude as roughness characteristics derived from bed particle size \((D)\) distributions, including \(3.5D_{84}\) which reflects typical pebble cluster dimensions. Harvey and Clifford (2009) provided support for this relationship, this time relating average eddy frequencies to particle size distributions in two reaches of a mixed-bed river. Lacey and Roy (2008) used \(S = 0.18\) (Achenbach, 1974) and found that the predicted eddy shedding frequency was in good agreement with the frequency (1 Hz) of small-scale vortices observed using flow visualisation in the wake of a submerged pebble cluster. In addition to this high frequency mode, lower frequency fluctuations caused by the intermittent interaction and amalgamation of small-scale vortices were identified, a phenomenon also reported from wavelet analysis of flow over a naturalised gravel bed in the laboratory (Hardy et al., 2009). Tritico and Hotchkiss (2005), on the other hand, found that \(S = 0.2\) gave estimates of \(f\) which were an order of magnitude lower than the frequency of vortices observed to shed from emergent boulders. The Strouhal relationship, however, may only apply to submerged roughness elements (Franca and Lemmin, 2007). Even in these cases, there is much doubt as to the universality of the scaling in natural settings or naturalised flows in the laboratory, with reported values of \(S\) ranging from 0.1 to 0.25 (Venditti and Bauer, 2005).
A number of studies in gravel-bed rivers have shown that roughness elements such as pebble clusters are associated with distinct zones of turbulent flow conditions (e.g., Buffin-Bélanger and Roy, 1998; Lawless and Robert, 2001a; Lacey and Roy, 2007) (Figure 2.4), which do not closely correspond with the structures illustrated in Figure 2.3 due to the depth-limited nature and high $Re$ of flow over rough gravel beds. These zones may be considered CFSs. In addition to the streamwise and vertical patterns of flow over roughness elements identified by Buffin-Bélanger and Roy (1998), Lawless and Robert (2001b) found that flow around pebble clusters recreated in a laboratory flume was also associated with spanwise flow perturbations, resulting in patterns of flow divergence and convergence. Given that pebble clusters may comprise as much of 10% of the area of the bed (Naden and Brayshaw, 1987), one would expect them to have a substantial effect on reach-scale turbulence characteristics. Other microbedforms (e.g., transverse ribs, stone cells) typical of gravel-bed rivers (Hassan and Reid, 1990; Tribe and Church, 1999) may also be expected to influence turbulence at the reach scale. Lamarre and Roy (2005) and Legleiter et al. (2007), however, found that the effects of such bedforms on distributions of turbulent flow statistics were only localised ($<25D_h$ downstream), with reach scale turbulence largely influenced by gross channel morphology (e.g., pool-riffle sequences, meander bends). Despite this, pebble clusters have a considerable localised effect on the magnitude of turbulent flow properties (Lacey et al., 2007). Working in a gravel-bed river, for example, Buffin-Bélanger et al. (2006) found that $TKE$, $RMS_v$, and $RMS_w$ were 100%, 80% and 30% greater respectively with a pebble cluster than without it. Lacey and Roy (2008) reported over a fourfold increase in $TKE$ and $\tau_{uv}$ values in the wake region of a pebble cluster compared to background levels. The effects of pebble clusters may persist for a downstream distance of $8.5h_s$ (Buffin-Bélanger et al., 2006) to $15h_s$ (Buffin-Bélanger and Roy, 1998), where $h_s$ is bedform height, in lee of the topographic high.

A parallel strand of research into CFSs has focused on larger-scale structures which take the form of alternating high- and low-speed fluid wedges inclined at an angle to the bed. Though they occur over both rough and smooth beds, the mechanism by which they are formed may be different in each of these environments. Over smooth beds they are thought to originate from the bursting of streamwise streaks of low-speed fluid in the viscous sublayer into the outer region, which triggers a subsequent high-speed sweep towards the bed (Nezu and Nakagawa, 1993). Flow visualisations and direct numerical simulations have shown them to be formed by the concatenation of hairpin vortices which induce regions of coherent flow velocities over the whole flow depth (Adrian, 2007). Since a viscous sublayer does not form over rough (e.g., gravel) beds, their origin in such cases is uncertain. Nevertheless,
numerous studies have shown that they do exist in flows over rough beds (e.g. Shvidenko and Pender, 2001; Roy et al., 2004), where they are known as ejections (low-speed, upward motion) and sweeps (high-speed, downward motion). Flow visualisations over a uniform gravel bed by Shvidenko and Pender (2001) suggest that they are caused by the passage of large, macroturbulent eddies rotating on a spanwise axis (Figure 2.5). These structures interact with CFSs in the wake of submerged roughness elements, causing the vertical expansion (ejections) or contraction (sweeps) of the recirculation zone (Buffin-Bélanger and Roy, 1998; Buffin-Bélanger et al., 2001; Lacey and Roy, 2008). Ejections, sweeps and other flow events are traditionally detected using conditional sampling techniques (e.g. Lu and Willmarth, 1973; Blackwelder and Kaplan, 1976; Keylock, 2007). One commonly applied method technique is that of Lu and Willmarth (1973), known as quadrant analysis. This involves attributing events to one of four quadrants (e.g. $Q_2$) depending on the joint variation of $u'$ and $v'$ around the mean (Figure 2.6), usually with an amplitude threshold value or 'hole size' (e.g. $2\sigma_{uv}$; Harvey and Clifford, 2009) so that only the stronger events are detected. Several variables may be derived from such analyses, including time in each quadrant for a given hole ($H$) size (e.g. $T_{Q2}$ $T_{H2}$), event frequency (e.g. $f_{Q2}$ $T_{H2}$) and fractional contribution to Reynolds shear stress (e.g. $\tau_{uv}Q2$ $T_{H2}$) (Lacey et al., 2007; Harvey and Clifford, 2009; Roy et al., 2010).

The importance of macroturbulent structures lies in the fact that they dominate energy production, with ejections and sweeps contributing most to Reynolds shear stress (Williams et al., 1989; Clifford and French, 1993b; Roy et al., 2004). Ejections have been found to dominate fractional contributions to $\tau_{uv}$ except in the roughness sublayer (Dancey et al., 2000), the near-wake region immediately in lee of roughness elements (Lacey and Roy, 2008) and in relatively shallow flow, whereas the strength of both ejections and sweeps may be reduced in relatively deep areas (Hardy et al., 2007). The spatial and temporal organisation of high-magnitude events leads to patterns of scour due to bedload transport (Best, 1992; Shvidenko and Pender, 2001). An understanding of the dynamics and dimensions of macroturbulent structures, therefore, is crucial to our understanding of bedform development and possible implications for biota. Studies in a wide range of flow conditions have found that these structures scale with $h$ (Table 2.3). Working in a gravel-bed river, for instance, Roy et al. (2004) found that scalings were very similar to those reported from laboratory studies over smooth beds. Furthermore, they calculated that the spatial persistence of high- and low-speed wedges was over $5.6h$ and that they were advected downstream at a velocity close to $U$, with the convective velocity ($U_c$) of high-speed wedges approximately 10% higher than low-speed regions.
Table 2.3 Dimensions of macroturbulent structures from laboratory experiments (except *). Dimensions scaled by flow depth \((h)\).

<table>
<thead>
<tr>
<th>Reference</th>
<th>(Re)</th>
<th>Length</th>
<th>Width</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nakagawa and Nezu (1981)</td>
<td>4200–12 000</td>
<td>1.5</td>
<td>—</td>
<td>0.5–1</td>
</tr>
<tr>
<td>Inamoto and Ishigaki (1987)</td>
<td>6100–7800</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Komori et al. (1989)</td>
<td>11 000</td>
<td>2</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Yalin (1992)</td>
<td>Not given</td>
<td>6</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Shvidenko and Pender (2001)</td>
<td>12 000–98 000</td>
<td>4–5</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Liu et al. (2001)</td>
<td>10 756–59 870</td>
<td>1–2</td>
<td>—</td>
<td>0.25</td>
</tr>
<tr>
<td>Roy et al. (2004)*</td>
<td>150 000–200 000</td>
<td>3–5</td>
<td>0.5–1</td>
<td>1</td>
</tr>
</tbody>
</table>

### 2.2.3 Measuring turbulence in the field

At least four key aspects of the measuring device and sampling protocol are fundamental to the accuracy and completeness of turbulence measurements which are to be studied within both of the complementary frameworks outlined above: the degree of disturbance introduced into the flow; the digitisation rate; the size of the sampling volume; and the record length. Any device which measures flow around or in close proximity to a physical sensor will interfere with the flow (e.g. Lane et al., 1993). Devices which are able to record flow velocities in a remote volume of fluid, therefore, are preferable.

The digitisation rate \((f_D)\) determines the highest frequency of velocity fluctuation that can be resolved, which is equal to the Nyquist frequency \((f_N)\):

\[
f_N = 0.5 f_D
\]

(2.14)

in order to avoid aliasing effects (Bendat and Piersol, 2000). Nezu and Nakagawa (1993) provide an estimate of minimum \(f_D\) based on turbulence theory:

\[
f_D > \frac{(50/\pi)}{(U/h)}
\]

(2.15)

An approximation of maximum useful digitisation rate beyond which additional data will be redundant is given by C. M. Garcia (personal communication):

\[
f_D < \frac{U_C}{D_S}
\]

(2.16)

where \(D_S\) is the characteristic length (maximum dimension of the sampling volume). 20 Hz is often used as a minimum \(f_D\) for in situ measurements of turbulence (Buffin-Bélanger and Roy, 2005), as recommended by Clifford and French (1993a). According to Equations (2.15–2.16), however, this may not always be sufficient to resolve higher frequency fluctuations in rivers and there is scope for the use of much higher \(f_D\), depending on \(D_s\), which limits the maximum useful \(f_D\) due to spatial averaging effects.

If \(D_S > \eta\) then the device will fail to resolve turbulence down to the dissipation range. \(\eta\) may be estimated according to (Nezu and Nakagawa, 1993):

\[
\eta \approx \frac{h}{Re^{0.75}}
\]

(2.17)

Nikora (2010) asserts that \(\eta\) in a typical river may be as large as 3 mm. Devices which have sampling volumes with maximum dimensions greater than 3 mm, therefore, are unlikely ever to resolve the finest turbulent structures in rivers. As larger scales of the flow contain most of the turbulent energy (Davidson, 2004), however, resolution of the smallest scales may not be necessary to obtain accurate measurements of certain turbulence quantities (e.g. \(TKE\), \(\tau_{uv}\)).

Whilst \(f_D\) and \(D_s\) limit the finest detail that can be resolved from turbulence measurements, record length \((RL)\), a function of \(f_D\) and time series duration \((t)\):

\[
RL = f_D t
\]

(2.18)

determines the largest flow structures that can be detected and influences the precision of the resulting turbulent flow statistics. Buffin-Bélanger and Roy (2005) provided an empirical assessment of optimum \(RL\) by performing a bootstrapping technique on 19 long time series (24 000 time steps) to derive sample time series of various lengths. They defined the optima as the point at which the standard error of turbulence statistics levelled off. The overall mean optimum \(RL\) was 1300 time steps, whereas 3500 was sufficient to encapsulate optima for all turbulent flow properties (Figure 2.7). Given a typical \(f_D\) of 20–25 Hz the optimal time series duration to achieve low standard errors with minimum sampling effort was recommended as 60–90 s.
and proportion of time spent in ejections (Clifford and French, 1993b; Harvey and Clifford, 2009) using electromagnetic current meters (ECMs) (e.g. Tritico et al., 2007; Liao et al., 2009). Instead, field investigations have often relied on point measurements (e.g. Tritico et al., 2007) and acoustic Doppler velocimeters (ADVs). More recently, particle imaging velocimeters (PIVs) have emerged as a useful tool in laboratory studies. PIVs provide information on the flow field by recording the displacement of particles suspended in a region of fluid (Raffel et al., 2007), thus avoiding the need to rely on Taylor’s frozen turbulence approximation (Equation 2.9) and allowing direct measurement of eddy dimensions. The aforementioned devices, however, are difficult to deploy in the field due to their high sensitivity to environmental variation or the requirement for careful positioning and orientation relative to the boundary (Nezu and Nakagawa, 1993; Nezu, 2005), although submersible miniature PIVs have been developed and tested in a limited range of environmental conditions (e.g. Tritico et al., 2007; Liao et al., 2009). Instead, field investigations have often relied on point measurements using electromagnetic current meters (ECMs) (e.g. Clifford and French, 1993b; Harvey and Clifford, 2009) due to their physical robustness, yet these devices are intrusive and modify flow patterns in the vicinity of the probe. Furthermore, they are not capable of simultaneous measurement of three-dimensional velocity components and do not satisfy the criteria for $f_D$ and $D_S$ outlined in the above section.

Originally developed for use in the laboratory, ADVs have become an appealing alternative for turbulence measurement in natural river settings since the 1990s (Lane et al., 1998) as data on all three velocity components are recorded in a small sampling volume which is remote (50–100 mm) from the sensing probe, thus minimising the effects of flow intrusion (Kraus et al., 1994). Commercially available second generation ADVs are capable of digitisation rates of up to 200 Hz, have maximum sensor dimensions of 6 mm (Rusello et al., 2006) and can provide reliable estimates of turbulence quantities at distances less than 10 mm from a solid boundary (P. Rusello, personal communication). Despite these obvious advantages, ADV measurements are subject to a number of errors that are controlled by probe positioning, instrument settings and local flow properties (McLelland and Nicholas, 2000). Close attention to instrument settings and carefully designed data collection and processing procedures, therefore, are critical to obtaining reliable results with ADVs. Probe positioning and orientation in relation to local site coordinates may be particularly important if field data are collected for certain purposes (e.g. model validation), in which case an appropriate surveying method should be incorporated into the data collection process (e.g. Lane et al., 1998). For ecohydraulic studies it may be sufficient to rotate the data during post-processing so that $V = W = 0$. As with any measurement of turbulence in potentially unsteady flows, the stationarity of the mean must be tested using an appropriate method, such as a reverse arrangement test (Bendat and Piersol, 2000), and non-stationary time series detrended using linear or low order polynomial regressions before residuals are calculated (Clifford and French, 1993b).

Four further sources of error can contaminate the signal and introduce bias into the resulting turbulent flow statistics (Voulgaris and Trowbridge, 1998). First, Doppler noise caused by random scattering motions in the sampling volume is intrinsic to ADVs. As this noise is normally distributed, it has no effect on mean velocities. Vertical stress components are also relatively unaffected due to the sensor’s geometrical characteristics but horizontal components and $TKE$ will be biased high (Lane et al., 1998; Nikora and Goring, 1998). The frequency at which the signal is dominated by Doppler noise, termed the noise floor, can be seen as a flattening in the power spectra at high frequencies and may be as low as 4–10 Hz.
(Nikora and Goring, 1998). Several methods have been proposed to detect and filter out Doppler noise (e.g. Lane et al., 1998; Nikora and Goring, 1998; Voulgaris and Trowbridge, 1998; McLelland and Nicholas, 2000). Second, due to internal spatial and temporal averaging, ADVs produce a reduction in all of the even moments in the velocity signal (Garcia et al., 2005). Despite these potential sources of error, Garcia et al. (2005) have shown that ADVs yield a good description of turbulence when:

$$\frac{f_{\delta h}}{U_C} => 20$$  \hspace{1cm} (2.19)

Third, errors due to phase shift uncertainties, when the phase shift between outgoing and incoming pulses lies outside the range $-180^\circ$ to $+180^\circ$, results in intermittent spikes in the time series when flow velocities approach or exceed the velocity range set by the user. This type of error, commonly known as phase wraparound, can bias estimates of mean and turbulent flow statistics and methods to detect, filter and replace spikes (e.g. Goring and Nikora, 2002; Parsheh et al., 2010) are required to minimise its effects. Finally, velocity shear in the sampling volume may contribute a significant proportion of the overall measurement error close to the boundary (McLelland and Nicholas, 2000). As an indication of the overall quality of data at the time of collection, ADV user interfaces report the average and instantaneous velocity correlation ($R^2$) between successive radial velocities for each receiver as well as the signal-to-noise ratio (SNR), which is related to the concentration and quality of seeding particles in the flow. Commonly applied quality control thresholds for the estimation of turbulent flow statistics in ecohydraulic studies are average $R^2 > 0.7$ and SNR > 20 (e.g. Smith et al., 2006; Enders et al., 2009).

### 2.3 The role of turbulence in the swimming performance and habitat selection of river-dwelling fish

Research into the link between fish and turbulence has focused on swimming performance and habitat selection. Swimming stability and kinematics have been used as surrogates for the energetic costs of swimming in turbulent flow in order to supplement the few studies that have measured energetics directly. Field studies evaluating the role of turbulence in the habitat selection of fish are extremely rare and currently limited to brown trout and Atlantic salmon, although several large-scale flume experiments have the potential to contribute towards a greater understanding in this area. Lacey et al. (2012) have emphasised the need to consider four aspects of turbulent flow (intensity, periodicity, orientation and scale) when examining the links between fish and turbulence (Table 2.4).

#### 2.3.1 Swimming performance

Some early experimental research into fish-turbulence links was reviewed by Pavlov et al. (2000). They reported that critical $U$ thresholds at which fish were displaced downstream for gudgeon (Gobio gobio), roach (Rutilus rutilus) and perch (Perca fluviatilis) were negatively related to $TI_u$. Furthermore, larger fish of a given species had higher critical $U$ thresholds for a given $TI_u$. Linear regression revealed a significant ($p < 0.002$) relationship between eddy length ($L_u$) and critical $U$ threshold. The critical $L_u$ was equal to 0.66$t$, where $t$ is fish body length. The mechanism behind this relationship was cited as the distribution of hydrodynamic forces acting on the body of a fish. When $L_u \ll t$, the moments of the forces were evenly distributed along the body of the fish. When $L_u > 0.66$t$, fish were destabilised and actively moved their pectoral fins to correct their position, thus creating greater hydrodynamic resistance and presumably increasing energy expenditure. This result was confirmed by Lupandin (2005) in the case of perch. Pectoral fins are also known to be important in the swimming stability of salmonids (McLaughlin and Noakes, 1998; Drucker and Lauder, 2003) and are a particularly distinctive feature of the station-holding behaviour of Atlantic salmon parr.

<p>| Table 2.4 The IPOS framework for studying fish-turbulence links. Modified from Lacey et al. (2012). |</p>
<table>
<thead>
<tr>
<th>Relevant turbulent flow properties</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intensity</strong></td>
</tr>
<tr>
<td>$\sigma_{u,v,w}$</td>
</tr>
<tr>
<td><strong>TI</strong></td>
</tr>
<tr>
<td><strong>RMS_{u,v,w}</strong></td>
</tr>
<tr>
<td><strong>$\tau_{uv}$</strong>, <strong>$\tau_{uw}$</strong></td>
</tr>
<tr>
<td>Vorticity ($\omega$)</td>
</tr>
<tr>
<td>Eddy maximum angular momentum ($\Pi_e$)</td>
</tr>
<tr>
<td><strong>Periodicity</strong></td>
</tr>
<tr>
<td>$f_{u,v,w}$</td>
</tr>
<tr>
<td><strong>ITS</strong></td>
</tr>
<tr>
<td>Spectral peaks and flatness</td>
</tr>
<tr>
<td><strong>Orientation</strong></td>
</tr>
<tr>
<td>Axis of eddy rotation ($x$-$y$, $x$-$z$, $y$-$z$)</td>
</tr>
<tr>
<td>Vector of dominant flow fluctuation ($x$, $y$, $z$)</td>
</tr>
<tr>
<td><strong>Scale</strong></td>
</tr>
<tr>
<td>Average eddy dimensions ($L_{u,v,w}$)</td>
</tr>
<tr>
<td>Integral scales ($L_{x,y,z}$)</td>
</tr>
<tr>
<td>$Re$</td>
</tr>
</tbody>
</table>
(Arnold et al., 1991), which have larger pectoral fins than other salmonids allowing them to maintain position in lower velocities on the substrate rather than in the water column.

Two essential features of an eddy, its orientation and intensity, are ignored by the Pavlov et al. (2000) model. The orientation of perturbations (e.g. eddies) is a critical factor in the swimming stability of fish (Webb, 2004; Liao, 2007), yet Pavlov et al. (2000) only considered eddies rotating on a horizontal axis. Tritico and Cotel (2010) found that the swimming stability of creek chub (Semotilus atromaculatus) in a flume was related to both eddy size and orientation. Instances where fish lost postural control (spills) were not observed until the 95th percentile of eddy diameter, determined using PIV, reached 0.76$bl$. Spills were more than twice as frequent and lasted 24% longer in flow fields dominated by eddies rotating on a horizontal axis. The resumption of steady swimming after disturbance from horizontal eddies required additional rolling movements in comparison to recovery from vertical eddies. It has been suggested that susceptibility to destabilisation from eddies of different orientation is related to body morphology, with laterally and dorso-ventrally compressed fish more susceptible to horizontal and vertical eddies respectively (Lacey et al., 2012). In addition to $L_u$ and eddy orientation, several commentators have suggested that the potential for an eddy to destabilise a fish is also a function of the ratio of eddy momentum to fish momentum (Webb et al., 2010; Webb and Cotel, 2010; Lacey et al., 2012). Tritico and Cotel (2010) quantified the maximum angular momentum of eddies ($\Pi_e$), given by:

$$
\Pi_e = \frac{m_e \Gamma_e}{4\pi}
$$

(2.20)

(where $m_e$ is eddy mass), and found that the occurrence of spills increased as a function of $\Pi_e$ above a threshold of 30 000 g cm$^2$ s$^{-1}$.

Though they have been cited with respect to juvenile salmonids (e.g. Enders et al., 2005a) the findings of Pavlov et al. (2000) and Lupandin (2005) may have limited relevance for this species and life stage. The reason for this relates to the eddy sizes and orientation covered in the studies. Given a typical $bl$ of Atlantic salmon parr of 70–150 mm (Gibson and Cutting, 1993), for instance, and the fact that their habitat preference typically means that $h \gg bl$ (Crisp, 1993; Armstrong et al., 2003), the dominant energy-containing (macroturbulent) eddies rotating on a horizontal axis (Figure 2.5) are likely to be much larger than $bl$ if the scalings provided in Table 2.3 are correct. Webb and Cotel (2010) postulated that when $L_u \gg bl$ fish perceive the flow as rectilinear, responding only to a variation of the mean flow vector. Enders et al. (2005b) found that the feeding behaviour of Atlantic salmon parr was not related to the passage of macroturbulent structures, suggesting that they do not respond to the largest horizontal eddies. Furthermore, the station-holding microhabitat of juvenile salmonids is typically in lee of a home rock (Cunjak, 1988; Guay et al., 2000) where eddies are shed on a vertical axis in the Kármán vortex street (Figure 2.3b). By simplifying this microhabitat in a smooth-walled laboratory flume, Liao et al. (2003b) showed that rainbow trout could attune their swimming kinematics (body amplitude, tail-beat frequency) to the frequency of vertical eddies ($0.25 < L_u/bl < 0.5$) shed from a cylinder. They termed this swimming behaviour ‘Kármán gaiting’ and Liao (2006) found that four fish spent the majority of time in locations of the flume where this gait was possible (Figure 2.8).

Using electromyography, Liao et al. (2003a) and Liao (2004) revealed that the Kármán gait was associated with lower muscle activity in rainbow trout swimming in the Kármán vortex street than those swimming in the free stream with no cylinder (Figure 2.9). The $Re$ of flows used in these experiments was not reported but calculations based on reported flume dimensions and discharges...
Figure 2.9 Time series (1–6) illustrating that red axial muscle activity measured in a flume using electromyography differed between rainbow trout \( (Oncorhynchus mykiss) \) swimming in the free stream (a) and behind a cylinder (b). Circles denote electrode positions with no (open), intermediate (grey) or high (closed) muscle activity. From Liao et al. (2003a). Reprinted with permission from American Association for the Advancement of Science.

Evidence for the opposite relationship between turbulence and swimming energetics to that suggested by Liao et al. (2003a; 2003b) has emerged from experiments in respirometers. Using four combinations of \( U \) and \( \sigma_u \), Enders et al. (2003) found that swimming costs (rate of oxygen consumption) for Atlantic salmon parr increased significantly \( (p < 0.05) \) with \( \sigma_u \) for a given \( U \) (Figure 2.10). This relationship was also reported by Enders et al. (2005a), who found that \( \sigma_u \) contributed 14\% of the explained variation in swimming costs in a model which included temperature (2\% of variation), fish body mass (31\%) and \( U \) (46\%). They also reported that existing bioenergetic models based on forced swimming (e.g. Boisclair and Tang, 1993) underestimated swimming costs under highly turbulent conditions \( (\sigma_u = 10 \text{ cm s}^{-1}) \) by a factor of 14. Underlining the equivocal nature of the evidence further, Nikora et al. (2003) found that turbulence had no effect on the swimming performance (time-to-fatigue) of inanga \( (Galaxius maculatus) \). Turbulence in these studies, however, was produced using pumps or artificial structures and may not be comparable to the conditions created by Liao et al. (2003a; 2003b) in terms of intensity, orientation and scale, having no effect on fish or possibly impeding rather than enhancing swimming performance (Lacey et al., 2012).

2.3.2 Habitat selection

Very few studies have examined fish habitat selection with respect to turbulence. These have most often been
undertaken in artificial settings in the laboratory. Smith et al. (2005), for instance, recorded the microhabitat positions of juvenile rainbow trout in a flume with cover provided in the form of bricks. By measuring mean \((U, V, W)\) and turbulent \((\text{RMS}_{u,v,w}, \text{TKE}, \tau_{uv,aw}, L_x, L_y)\) flow properties at focal positions taken up by fish and those available throughout the flume, they found that fish selected positions with significantly lower \(V\) \((p = 0.01)\) and \(L_x\) \((p < 0.01)\) than available during a low-discharge treatment and lower \(U\) \((p < 0.01)\), \(\tau_{uv}\) \((p < 0.01)\) and \(L_x\) \((p = 0.03)\) during a separate high-discharge treatment. This study was performed with individual fish in each trial, thus ignoring the effects of competition. In the same flume, this time with three cover treatments to create varying levels of turbulence and three discharge treatments \((0.03–0.11 \text{ m}^3 \text{ s}^{-1})\), Smith et al. (2006) placed 30 fish in the test section for each of four replicate trials. The number of individuals that chose to remain in the test section after 24 hours was better predicted by \(\text{TKE}\) than \(U\) (Figure 2.11). The reason cited for this was that \(\text{TKE}\) was more sensitive to the experimental treatments. Smith and Brannon (2007) subsequently found that turbulent flow properties \((\text{RMS}_{u,v,w}, \text{TKE})\) were better able to detect the presence of cover types used by fish \((\text{boulders, woody debris, scour holes})\) than \(U\) in four gravel/cobble-bed rivers. The intensity of turbulence in these flume studies, however, was not comparable to that typically found in gravel-bed rivers. Maximum values of \(\text{TKE}\) and \(\tau_{uv}\), for instance, were an order of magnitude lower than those found by Tritico and Hotchkiss (2005) in lee of a boulder.

Flume experiments examining the routes taken by fish during migration through artificial structures have begun to reveal a highly species-specific relationship between turbulence and habitat selection. Russon et al. (2010) found that most \((63.3\%)\) approaches by downstream migrating adult European eels \((\text{Anguilla anguilla})\) towards bar racks designed to screen fish from hydroelectric power turbines were associated with zones of highest \(\tau_{uv}\). Conversely, Kemp and Williams (2008) reported that downstream migrating Chinook salmon \((\text{Oncorhynchus tshawytscha})\) smolts preferred a smooth culvert with significantly lower \(\tau_{uv}\) \((p < 0.001)\) to treatment culverts augmented with corrugated sheet and cobbles. Silva et al. (2011) similarly found that migrants avoided highly turbulent conditions, in this case by observing Iberian barbel \((\text{Luciobarbus bocagei})\) moving upstream through orifices associated with an experimental pool-type fishway. Most barbel used areas of lowest \(U\) and \(\text{TKE}\) and there were negative correlations between turbulent flow properties and fish transit time, with the most significant being \(\tau_{uv}\) \((p < 0.001)\) and \(\text{TKE}\) \((p < 0.01)\). Fish were observed to use pectoral fins for postural control more frequently under the most turbulent conditions. For lamprey, which lack paired fins to facilitate control, turbulence is likely to present a greater challenge to swimming stability. Kemp et al. (2011) presented indirect evidence suggesting that upstream migrating river lamprey \((\text{Lampetra fluviatilis})\) were able to pass experimental weirs under highly turbulent conditions by altering swimming trajectories to closely follow the substrate and channel walls. This strategy allowed lamprey to hold station by using the oral disk to attach to the structure, possibly as part of a burst-and-attach swimming strategy.

Field studies of fish habitat selection with respect to turbulence are limited to two examples focusing on salmonids. At the microscale in a third-order sand-bed stream, Cotel et al. (2006) observed the locations of brown trout by snorkel surveying at summer low flow over three

![Figure 2.11](image-url)  
**Figure 2.11** Comparison of models to predict volitional rainbow trout density in response to experimental treatments in a flume. Reproduced from Smith et al. (2006) by permission of The American Fisheries Society.
Ecohydraulics has suffered from an overreliance on correlative approaches based on relatively simple, mean characteristics of the flow, yet turbulence is a ubiquitous phenomenon in rivers. The inclusion of turbulent flow properties in ecohydraulic research, therefore, should enhance our mechanistic knowledge of physical-ecological interactions. The hydrodynamic environment is composed of a range of turbulent structures of varying intensity, periodicity, orientation and scale from across the EC. The development of ADVs as field tools has helped to advance our knowledge of these structures in natural settings (e.g. Lacey and Roy, 2008; Roy et al., 2010) but great care must be taken to ensure that ADVs provide a reliable description of the turbulence (Garcia et al., 2005). Information on the flow field using PIVs (Tritico et al., 2007; Tritico and Cotel, 2010) and two- or three-dimensional hydrodynamic models (e.g. Crowder and Diplas, 2002, 2006; see also Chapter 3 in this volume), rather than point measurements of turbulence, could represent the next major step forward in our understanding of how turbulence affects instream biota. Work in the laboratory as well as the field is likely to be useful in this regard, but flume studies must ensure that the relevant characteristics of turbulent flow are recreated to closely mimic the hydraulic habitat of target biota (Lacey et al., 2012).

The mechanisms by which turbulence may affect the fitness of individual fish have been quantified in several ways, including critical eddy length (e.g. Pavlov et al., 2000) and the energetic costs of swimming in turbulent flow (e.g. Enders et al., 2003). These mechanisms may, in turn, influence the structure of fish communities by determining habitat preference with respect to turbulence (e.g. Cotel et al., 2006; Smith et al., 2006). Hydraulic research has highlighted two scales of turbulence – scaling with $h$ (Roy et al., 2004) and the size of microbedforms (Clifford and French, 1993b; Lacey and Roy, 2008) respectively – which could be particularly relevant to stream-dwelling fish. Laboratory work with a limited number of species suggests that high-magnitude spanwise (macro-turbulent) eddies may, depending on the ratio of eddy size and momentum to fish body length and momentum, destabilise fish and result in increased energetic costs (Pavlov et al., 2000; Lupandin, 2005; Tritico and Cotel, 2010), whereas smaller, vertically oriented eddies could enhance swimming efficiency (Liao et al., 2003a; Liao, 2006). Research with Atlantic salmon parr has revealed a negative relationship between swimming costs and turbulence in a highly artificial setting (Enders et al., 2003) and field observations on the summer habitat preference of brown trout in a sand-bed stream suggest that this could influence position choice at the microscale (Cotel et al., 2006). A tagging study found no relationship between turbulence and the summer habitat preference of Atlantic salmon parr at the reach scale of a gravel-bed river (Enders et al., 2006). Though statistically significant differences between available and used distributions of $\sigma_u$ and TKE were found for some fish in one or more of the study years, the sign of the relationship was not consistent (Figure 2.12(b)), leading the authors to conclude that there was no link between Atlantic salmon parr habitat selection and turbulence at the reach scale.

![Figure 2.12](image-url)

**Figure 2.12** Relationships between turbulence and salmonids in rivers. (a) Turbulence intensity ($T_{Iu}$) and nose velocity ($U$) for various locations with brown trout (closed symbols) and similar locations with no fish (open symbols). Reproduced from Cotel et al. (2006), by permission of The American Fisheries Society; (b) reach-scale habitat availability (grey boxes) and locations of four tagged Atlantic salmon parr (open boxes) in relation to $\sigma_u$ over two years. Vertical bars represent upper and lower 5th percentiles. Reproduced from Enders et al. (2009), by permission of The American Fisheries Society.
important turbulent flow properties to focus on. Diameter and momentum are likely to be among the most dominant axes of eddy rotation and metrics describing eddy rehabilitation targeted at fish and other biota. Distinct ecological variable in river research and management is needed before turbulence can be integrated as a key research priority which has received little attention (but see Enders et al., 2005b). More detailed information is needed before turbulence can be integrated as a distinct ecological variable in river research and management activities (e.g., habitat modelling, assessment and rehabilitation) targeted at fish and other biota. TKE, dominant axes of eddy rotation and metrics describing eddy diameter and momentum are likely to be among the most important turbulent flow properties to focus on.

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