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Flow resistance in natural, turbulent channel flows: The need for a fluvial fluid mechanics

Christopher J. Keylock[1]

[1]Sheffield Fluid Mechanics Group and Department of Civil and Structural Engineering, University of Sheffield, Sheffield, UK

Key Points:

- Conventional hydraulics is inadequate for describing complex fluvial processes
- Fractal descriptions of a forcing may be linked to turbulent dissipation
- Nonequilibrium turbulence modeling can incorporate greater process complexity

Correspondence to:
C. J. Keylock,
c.keylock@sheffield.ac.uk

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Abstract In fluvial environments, feedbacks among flow, bed forms, sediment, and macrophytes result in a complex fluid dynamics. The assumptions underpinning standard tools in hydraulics are commonly violated and alternative approaches must be formulated. I argue that we should question the assumption that classical notions in fluid mechanics provide the foundations for the techniques of the future. Recent work on turbulent dissipation, interscale modulation of the dynamics, intermittency, and the role of complex forcings is discussed. An agenda for future work is proposed that involves improving our characterization of complex forcings and developing better understanding of the behavior of the velocity gradient tensor in complex, fluvial environments. This leads to the formulation of modeling tools relevant to fluvial fluid mechanics, rather than a reliance on methods developed elsewhere. One avenue by which such methods might be developed is suggested based on the stretched spiral vortex as a baseline topology. This would result in a nonequilibrium model for turbulence that has greater potential to capture the dynamics in which we are interested. Although these ideas are raised in the context of a future fluvial fluid mechanics, they are applicable to any situation where turbulent flows are forced in complicated ways.

1. Introduction

Understanding how the boundary conditions and intrinsic dynamics of a turbulent channel flow act to resist the motion of a fluid is the central concern of fluvial hydraulics. In the last few years, a number of papers have reviewed developments in hydraulics and ecohydraulics, as well as the prospect for future research directions [*Nezu*, 2005; *Adrian and Marusic*, 2012; *Nepf*, 2012]. In addition, experimental and eddy-resolving numerical work has highlighted the important role played by coherent flow structures in a variety of fluvial processes [*Adrian and Marusic*, 2012; *Venditti et al*., 2013] and more work could be done to link these to the recent developments in our understanding of boundary layer fluid mechanics [*Ganapathisubramani et al*., 2005; *Marusic et al*., 2010; *Guala et al*., 2011]. Reviews of the potential for eddy-resolving numerical methods in the fluvial sciences have also appeared [*Keylock et al*., 2012a; *Constantinescu*, 2014; *Stoesser*, 2014], highlighting the techniques available and the advances in knowledge necessary in order to formulate methods tailored to hydraulics and geomorphological applications [*King et al*., 2012; *Schmeeckle*, 2014]. Therefore, contemporary fluvial dynamics research has moved beyond time-averaged formulations and toward a more explicitly turbulence-oriented conceptualization of process, although significant gaps in knowledge remain.

For example, in the last decade or so, there has also been a corpus of work developing parameterizations for incorporating the effect of vegetation into the resistance equations adopted in hydraulics. That is, there has been a development of an *ecohydraulics* [*Nepf and Vivoni*, 2000; *Madsen et al*., 2001; *Ghisalberti and Nepf*, 2002; *Nepf*, 2012], often informed by work considering the effect of forest canopies on atmospheric boundary layer structure [*Gao et al*., 1989; *Ikeda and Kanazawa*, 1996; *Raupach et al*., 1996; *Katul et al*., 1997; *Cava and Katul*, 2008; *Belcher et al*., 2012]. Furthermore, research into natural channel flows has maintained significant interest in understanding the resistance induced by bed roughness, be this on the large scale of autogenic bed forms [*Best*, 2005; *Parsons et al*., 2005], or on the smaller scale of roughness patches [*Paola and Seal*, 1995], or individual clasts in a gravel bed [*Lacey and Roy*, 2007; *Hardy et al*., 2007]. Consideration of the vortex dynamics around an individual clast or an isolated object such as a cylinder leads to the elucidation of horseshoe vortex flow structures [*Baker*, 1980; *Kirkil et al*., 2008] that then interacts with the near-wall hairpin vortices and vortex packets [*Adrian et al*., 2000; *Ganapathisubramani et al*., 2003] in complex ways.

Table 1. Approaches to Studying Fluvial Flows Through Vegetation

Scale	Purpose	Framework	Flow Resistance
River and floodplain	Inundation modeling	Shallow-water hydraulic routing	Roughness length
Subreach scale	Large-scale effects of vegetation	RANS modeling	Shear and wake TKE terms
Vegetation stand	Experimental development of process knowledge	Formulating terms to inform RANS modeling	Shear and wake TKE terms
Vegetation stand	*Experimental and DNS development of process knowledge*	*Formulating terms to inform LES modeling*	*Local, anisotropic, dissipation-based*

For example, *Shvidchenko and Pender* [2001] studied the turbulence structure over a mobile gravel bed and found that the flow consisted of a sequence of large-scale eddies that were of geomorphic significance as evidenced by the development of longitudinal troughs and ridges, and preferential transport of bed particles along troughs. Related work lead *Roy et al*. [2004] to propose a model for the development of high and low speed "wedges" in channel flows, and experimental and numerical studies by *Hardy et al*. [2007, 2009, 2010] have provided additional insights into related processes. *Singh et al*. [2010] helped frame these processes in the spectral domain with their identification of a -1.1 low-frequency spectral slope region, the high-frequency limit to which corresponded to the smallest scale bed forms. Separating this region from the inertial regime was a spectral gap bounded by the minimum bed form scale and the integral scale.

Hence, research in the last two decades has provided us with a wealth of knowledge concerning turbulence phenomena in river channels and how these depart from classical notions of an equilibrium, zero-pressure gradient boundary layer. This has resulted in the adoption of modeling methods that explicitly represent the effect of turbulence on the flow. However, the argument advanced in this paper is that the complexity of river channel processes requires a move beyond the direct adoption of tools and methodologies from aeronautical engineering and boundary layer meteorology. It requires the development of bespoke methods, drawing upon both experimental knowledge gained from within the discipline, and recent work in fluid mechanics on the effect of complex flow forcing on both the large and small scales in the flow. This is an important distinction to much of the numerical work in the last decade where, if flow structures are resolved at all, it is usually using a large-eddy philosophy where interest is directed at recirculation phenomena and the very largest vortices. The smaller scales are of less interest and are deemed to be readily parameterizable because of classical scale-separation arguments [*Tennekes and Lumley*, 1972]. For example, as discussed below, this philosophy underpins the large-eddy simulation methods currently used in fluvial dynamics research. This paper argues that what we need instead, is a reconceptualization of what we consider environmental turbulence to be. There are some key theoretical concepts that need to be reexamined in order for numerical modeling methods to be enhanced and it is the aim of this paper to highlight where some of our knowledge gaps are and possible ways in which they may be addressed.

The first three rows of Table 1 give a simple summary of current work that uses experiments or models to examine water flows through vegetation. At the very largest scale, vegetative resistance is simply added as a displacement height to the one-dimensional or two-dimensional momentum equation in a shallow-water framework. This scale is not considered explicitly in this study. Instead, we focus on the scales where computational fluid dynamics techniques are used, and where studies for the mean flow dynamics (Reynolds Averaged Navier-Stokes, or RANS) have progressed from the simple adoption of standard turbulence closures, to the incorporation of shear and wake turbulent kinetic energy (TKE) production terms in the relevant equations [*López and García*, 2001; *King et al*., 2012]. This has only been possible because of a concerted effort to undertake high-quality experiments at the vegetation stand scale that can inform this progression in modeling [*Ghisalberti and Nepf*, 2002; *Tanino and Nepf*, 2009]. The final row of Table 1 is italicized and highlights the area of primary consideration in this paper: the future use of experiments and direct numerical simulation (DNS) of the Navier-Stokes equations to inform the development of eddy-resolving techniques (such as large-eddy simulation, or LES) for modeling flows through vegetation. This is a field that is, at best, currently embryonic. However, in the same way that bespoke RANS closures for flows through vegetation now exist, and given the increasing use of eddy-resolving methods in fluvial research [*Kang and Sotiropoulos*, 2011; *Keylock et al*., 2012a], it is argued here that bespoke closures for eddy-resolving methods will be required in the future. The primary objective of this paper is, therefore, to suggest some issues with contemporary assumptions in these methods and, hence, to propose some ways forward. Naturally, with such a prospective approach, this extends the scope of the paper beyond the immediate horizons in ecohydraulics to interrogate relevant ideas in fundamental fluid mechanics. However, to contextualize such ideas, it is first useful to consider the basis for the various computational fluid dynamics methods used in the literature.

2. Evolution of Theoretical and Modeling Frameworks

While there would appear to be some use of direct numerical simulation (DNS) of the Navier-Stokes equations in fluvial and hydraulics research [*Williamson et al*., 2012; *Gil Montero et al*., 2014], at any reasonable Reynolds number, to resolve the range of length scales sufficiently to correctly feed energy (and quantities such as helicity) from large to dissipative scales, as well as correctly represent any inverse transfers, means that such studies will be necessarily limited in terms of their spatial extent, complexity of their boundary conditions, or duration of the simulation. Hence, while more such studies might be anticipated to help develop process knowledge (Table 1), practical studies for the foreseeable future will approximate the Navier-Stokes equations by introducing a closure scheme, either within a Reynolds averaged, or an eddy-resolving framework.

2.1. Reynolds Averaged Navier-Stokes (RANS)

The incompressible Navier-Stokes momentum equation may be written as

$$\frac{\partial u_i}{\partial t}+\frac{\partial (u_i u_j)}{\partial x_j}=-\frac{1}{\rho}\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right], \quad (1)$$

where Einstein summation notation is adopted such that indices identify a repeated summation, u is an instantaneous velocity, x is a distance, each of which is oriented along an orthogonal axis i, j, p is pressure, ρ is density, and ν is the kinematic viscosity. This equation, together with the continuity equation for an incompressible fluid, $\partial u_i/\partial x_i=0$ yields the system of Navier-Stokes equations solved with DNS. Introducing the Reynolds averaging operator, $u_i=\bar{u}_i+u_i'$, where the overbar indicates a mean value and the prime the fluctuating component, making this substitution into equation (1), and ensemble averaging gives

$$\frac{\partial\overline{(\bar{u}_i+u_i')}}{\partial t}+\frac{\partial\overline{(\bar{u}_i+u_i')(\bar{u}_j+u_j')}}{\partial x_j}=-\frac{1}{\rho}\frac{\partial\overline{(\bar{p}+p')}}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial\overline{(\bar{u}_i+u_i')}}{\partial x_j}+\frac{\partial\overline{(\bar{u}_j+u_j')}}{\partial x_i}\right)\right], \quad (2)$$

and then using the facts that the mean of a mean is the mean and the mean of the fluctuating terms is zero, gives the Reynolds Averaged Navier-Stokes (RANS) equations, where the action of turbulence emerges from the interaction of the fluctuating velocities in the nonlinear advective term (second term on the left-hand side of equations (1) and (2)):

$$\frac{\partial \bar{u}_i}{\partial t}+\frac{\partial (\bar{u}_i \bar{u}_j)}{\partial x_j}=-\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial \bar{u}_i}{\partial x_j}+\frac{\partial \bar{u}_j}{\partial x_i}\right)-\overline{u_i'u_j'}\right]. \quad (3)$$

Hence, from the perspective of RANS, the closure problem amounts to expressing the variance-covariance tensor (the turbulent, Reynolds stresses) in terms of mean quantities [*Jones and Launder*, 1972; *Launder et al*., 1975; *Speziale*, 1987]. *Rodi* [1980] provided an early introduction and review of the application of RANS in hydraulics. The contributions of Nezu and coworkers over several decades have provided crucial information from experiments and theory regarding the improved parameterization of open channel flow processes in a manner amenable to analysis from a RANS perspective [*Nezu and Nakagawa*, 1993; *Nezu et al*., 1997], and recent work by Nepf and coworkers has furthered this agenda [*Ghisalberti and Nepf*, 2004; *Tanino and Nepf*, 2009].

Because sudden changes in topography in open channel flows generate adverse pressure gradients, resulting in flow separation, a well-developed boundary layer cannot necessarily be assumed. Hence, it is useful to compare the performance of different RANS closure schemes in such circumstances. *Lien and Leschziner* [1994] studied a backward-facing step flow (a paradigmatic case of flow separation and recirculation), revealing some of the deficiencies of simpler RANS closures. *Kang and Sotiropoulos* [2012] examined the effectiveness of simple RANS closures for the flow in meandering channels and showed that they struggled

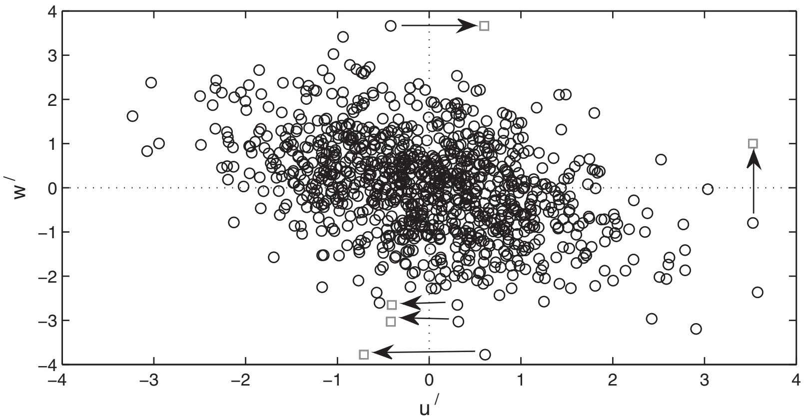

Figure 1. One thousand hypothetical instantaneous measurements of u' and w' in a boundary layer (hence, with a correlation, $R(u,w) \sim -0.4$) are shown as circles. A modified data set, also considered in the text, consists of 995 of the values represented by circles, and five that are transformed variants of the original data (moving the original circle positions to the locations of the squares as shown by the arrows). In all cases, the arrows indicate a datum has moved from an even quadrant (positive contributor to mean Reynolds stress) to an odd-numbered quadrant (negative contributor to mean Reynolds stress).

to represent key features of the dynamics such as shear layers on the inner and outer banks, the secondary cell at the outer bank, and the inner bank horizontal recirculation zone. The reason for this was that such models failed in regions of high-turbulence anisotropy, indicating the difficulties of adopting isotropic RANS models in regions of complex dynamics. As a consequence, eddy-resolving methods were deemed preferable.

Given that the dominant direction of shear in a boundary layer is the vertical variation of the longitudinal velocity, there is an understandable emphasis on the $-\rho\overline{u'_1 u'_3} \equiv -\rho\overline{u'w'}$ component of the Reynolds stress in the literature. The linear correlation between u and w, $R(u,w)=\overline{u'w'}/\sigma(u)\sigma(w)$, where $\sigma(\ldots)$ is the standard deviation, is $R(u,w) \sim -0.4$ in a boundary layer [*Nakagawa and Nezu*, 1977], meaning that $-\rho\overline{u'w'}$ is positive. However, the correlation is sufficiently weak that the turbulence activity is not always in the negative quadrants (Figure 1), which causes a profound difficulty with any assumption that the velocity covariance is sufficient to describe turbulence for many water research applications and, thus, any RANS closure: strong instantaneous activity in the positive quadrants may mean that a flow with a lower value for $|\overline{u'w'}|$ has at least as great a mean instantaneous activity, $\overline{|u'w'|}$ and is, as a consequence, more turbulent. That is, with the vertical lines indicating the absolute magnitude of a quantity, we contrast the magnitude of the mean coupling (the absolute covariance) in the first instance, with the mean of the magnitude of the pairwise interactions (the instantaneous, fluctuating stresses) in the latter case. For example, $R(u,w)=-0.402$ for the circles in Figure 1, with $\overline{u'w'}=-0.44$ (thus, $|\overline{u'w'}|=0.44$) and $\overline{|u'w'|}=0.75$. Conversely, if we replace five of the circles with the squares as indicated by the arrows in Figure 1, then for these new data, while $\overline{|u'w'|}=0.75$ again, the Reynolds stress-proportional term has dropped in magnitude to $\overline{u'w'}=-0.42$ ($|\overline{u'w'}|=0.42$). Thus, moving 0.5% of the points causes a 5% change in the Reynolds stress, while maintaining the mean magnitude of the instantaneous stresses. Hence, without engaging at all with the issues in RANS concerning the representation of the average effect of transient flow structures, a difficulty with models predicated on Reynolds stresses as *the* representation for turbulence can be demonstrated.

While positive Reynolds stress emphasizes quadrants 2 and 4, quadrant 1 has been shown to have an important influence in sediment transport processes as highlighted by *Heathershaw and Thorne* [1985] and *Nelson et al*. [1995]. The former authors showed that bed load transport was correlated to $u' > 0$ events, while the latter studied sediment entrainment during boundary layer recovery, downstream of the reattachment point of a backward-facing step flow. They showed that the most efficient quadrants for bed load transport were the quadrant 1 outward ejections although, because they are more common, quadrant 4 sweeps transported the majority of bed load. Hence, an important deficiency of the RANS framework emerges for sedimentological studies: locations on the bed with $\overline{u'w'}$ close to zero, but with significant outward ejections, may be more able to mobilize bed load than those where the exerted Reynolds stresses are much higher.

2.2. Eddy-Resolving Methods

Given the difficulties with using the RANS framework to represent these processes effectively, numerical modeling of the Navier-Stokes equations that retains more information on the flow dynamics is required. Eddy-resolving simulation techniques such as large-eddy simulation (LES) and detached eddy simulation (DES), or lattice Boltzmann methods, then become necessary. The utility of eddy-resolving methods has been demonstrated by the explosion of the number of studies in the last few years, with applications to flow around channel obstacles and their associated scour holes [*Kirkil et al*., 2008; *Koken and Constantinescu*, 2009], flow through vegetation [*Kim and Stoesser*, 2011], as well as sediment transport [*Nabi et al*., 2012, 2013a; *Schmeeckle*, 2014] and flow over bed forms [*Nabi et al*., 2013b; *Chang and Constantinescu*, 2013; *Omidyeganeh and Piomelli*, 2013], and flow through channel confluences [*Constantinescu et al*., 2011a]. See *Keylock et al*. [2005] for an early introduction to the use of LES in channel flow hydraulics and *Keylock et al*. [2012a] for a similar introduction and review of DES.

2.2.1. Detached Eddy Simulation (DES)

Detached eddy simulation [*Spalart and Allmaras*, 1994] aims to model those vortices away from boundaries explicitly, while treating those near to, or attached to surfaces in a statistical sense. It is based on a one equation closure obtained from the total derivative of a modified eddy viscosity. Production is a function of the vorticity magnitude, while destruction is a function of distance from solid surfaces [*Baldwin and Barth*, 1991]. DES modifies this distance function so that it is the minimum of the computational mesh dimension and the distance to the nearest surface. The consequence of this is that DES operates in a RANS-like mode near boundaries and a LES-like mode in the far field, providing a seamless means to model flow near complex boundaries without having to go to the computational expense of a full LES simulation, which requires very small filter scales near boundaries to resolve the flow. Indeed, *Constantinescu et al*. [2011b] showed, in a fluvial context, that DES could out-perform a LES that uses wall functions to span the distance from a boundary to the first computational node (i.e., it did not fully resolve the flow). The numerical experiment was undertaken in a meander bend with bed deformation mimicking the typical higher depths on the outer side of the bend. In this configuration, a RANS treatment near the wall that can approximate the mean velocity vectors and turbulence production in this region is better than imposing a velocity profile to span the gap to the center of the first node. Because turbulence production occurs preferentially near boundaries, and because the topography of the meander bend means that flow on the inner bank, in particular, is relatively shallow, capturing such phenomena, even in an average sense, leads to a better representation of the dynamics overall.

Refinements to DES have improved its capacity for modeling the flow near complex boundaries [*Aupoix and Spalart*, 2003] and with complex mesh designs [*Spalart et al*., 2006]. *Spalart* [2009] concluded his review of the state of the art in DES with four key future issues, the key theoretical component being the need to establish the link between a resolved DES flow field and the exact flow field in a similar fashion to a priori LES studies [*Vreman et al*., 1995; *Akhavan et al*., 2000]. Without such a connection, while DES represents a highly effective, practical tool, and research into optimal ways to represent environmental processes in DES is a sorely needed development, such enhancements will lack theoretical justification.

2.2.2. Large-Eddy Simulation (LES)

The LES equations are obtained from Navier-Stokes by applying a spatial filtering operator such that the full dynamics at the filter scale and larger are resolved. Hence, the closure problem now consists of writing a model for the effect of the subfilter scales (dissipation of energy, straining, and potential inverse cascade effects of the small scales on the large). Traditionally, the scale chosen for the filter, Δ, equated to the mesh or grid used to model the equations, meaning that one spoke of "the grid scale" and "subgrid scales." However, contemporary methods mean that the filtering scale can be defined independently of the mesh, meaning that "subfilter scales" is the more appropriate expression. The standard closure for LES is to adopt an eddy viscosity approach, with the length scale given by the filter [*Smagorinsky*, 1963; *Muschinski*, 1996]. The Smagorinsky coefficient, C_s, couples the eddy viscosity, ν_e, to the resolved strain rate tensor, $\hat{S}_{ij}$ and, thus, the deviatoric stress:

$$\tau_{ij}-\frac{1}{3}\delta_{ij}\tau_{kk}=-2\nu_e\hat{S}_{ij}, \tag{4}$$

$$\nu_e=[C_s\Delta]^2\sqrt{2\hat{S}_{ij}\hat{S}_{ij}}. \quad (5)$$

Its value is dependent on the mesh aspect ratio and turbulence anisotropy [*Horiuti*, 1993], meaning that a test filtering procedure is commonly used to vary this coefficient dynamically [*Germano*, 1992].

It is in an extension of the basic test filtering method where one can see how environmental fluid mechanics can make fundamental contributions to the field, rather than being dependent on developments in mainstream fluid mechanics and mechanical/aerospace engineering. *Porte-Agel et al*. [2000] introduced the triple filtering philosophy to permit scale dependence in C_s. They argued that a crucial limitation in the dynamic formulation that is particularly relevant for wall-bounded flows is the assumed scale invariance between the value for C_s at the test filter and actual filter scales. By adopting a power law scaling (i.e., $C_s(\Delta)\sim\Delta^{\vartheta}$) and combining this subfilter scale model with a Lagrangian averaging formulation, *Bou-Zeid et al*. [2005] were able to obtain high-quality results for flow over surfaces with sudden changes in roughness characteristics. More specifically, turbulence dissipation was shown to be represented more effectively and because of the sensitive dependence of C_s upon roughness, the more physically relevant Lagrangian approach was found to give better results than the more arbitrary planar averaging approach. While these ideas have been used in water research, it has generally been in the context of water vapor transport by atmospheric flows over variable roughness terrain [*Bou-Zeid et al*., 2004]. Validation and development of such methods for flow over complex river topography, combined with some form of immersed boundary method [*Lane et al*., 2004; *Ge and Sotiropoulos*, 2007] is an interesting avenue to pursue further.

2.3. The Utility of Eddy-Resolving Methods

A number of comparisons of RANS, DES, and LES techniques exist in the fluvial sciences, sometimes complemented by experimental data [*van Balen et al*., 2010; *Constantinescu et al*., 2011b; *Keylock et al*., 2012a]. None of these are yet sufficiently comprehensive that all methods can be evaluated in a comparable fashion for a full-set of fluvially related boundary conditions. Hence, the work considered here permits some conclusions to be drawn, although there is further potential for developing benchmarking of methods. Here we focus on two studies that consider vegetative flows and meandering channels, respectively.

Kim and Stoesser [2011] took an applied numerical modeling approach to flow through emergent vegetation, comparing RANS and a coarse LES utilizing wall functions. They showed that RANS modeling is highly dependent on bespoke, empirical parameterization of the closure scheme representing the forcing due to vegetation, highlighting both the importance of experimental work on salient processes [*Nepf*, 1999; *Nepf and Vivoni*, 2000] and the need to consider fluvial RANS closures from a fresh perspective, informed by experiment and theory [*King et al*., 2012]. The multiple relevant length scales (flow depth, stem diameter, plant height, and canopy scales) and the development of turbulence by mean shear and interactions with the canopy, highlight the complexity of the forcing and the possible need to consider alternative means of conceptualizing the physics (see below). Because of its improved physical representation of (some of) these phenomena, *Kim and Stoesser* [2011] found that LES was less dependent upon parameterization in the closure. The agreement with experimental data was acceptable for low density canopies as a consequence of an improved modeling of velocity gradients and recirculation zones.

In a further comparison of RANS (actually, unsteady, isotropic RANS) and LES, mentioned briefly above, *Kang and Sotiropoulos* [2012] performed simulations through a field-scale meandering channel using the same mesh and numerical method for both approaches. This provides in one sense, a true comparison between methods, although differences in the modeled physics mean that RANS simulations could be undertaken on a coarser mesh. While the isotropic RANS closure was able to capture the secondary flow structure induced by planform curvature, it could not resolve inner and outer bank shear layers, a secondary circulation cell at the outer bank secondary cell, or the inner bank horizontal recirculation zone; all of these were resolved by LES (see also *Keylock et al*. [2012a, Figure 2] for a similar result). The difference was attributed to such features arising in regions of significant stress anisotropy and, while conventional RANS formulations are isotropic in nature, conventional LES only assumes isotropy at small scales. This permits a more accurate representation of flow structure, even if not a fundamentally correct one, an issue returned to below.

2.3.1. Coupled Simulations of Flow and Sediment

While an ideal numerical model should incorporate two-way coupling between the flow and transported sediment [*Schmeeckle*, 2014], the large number of particles of a small size makes this computationally

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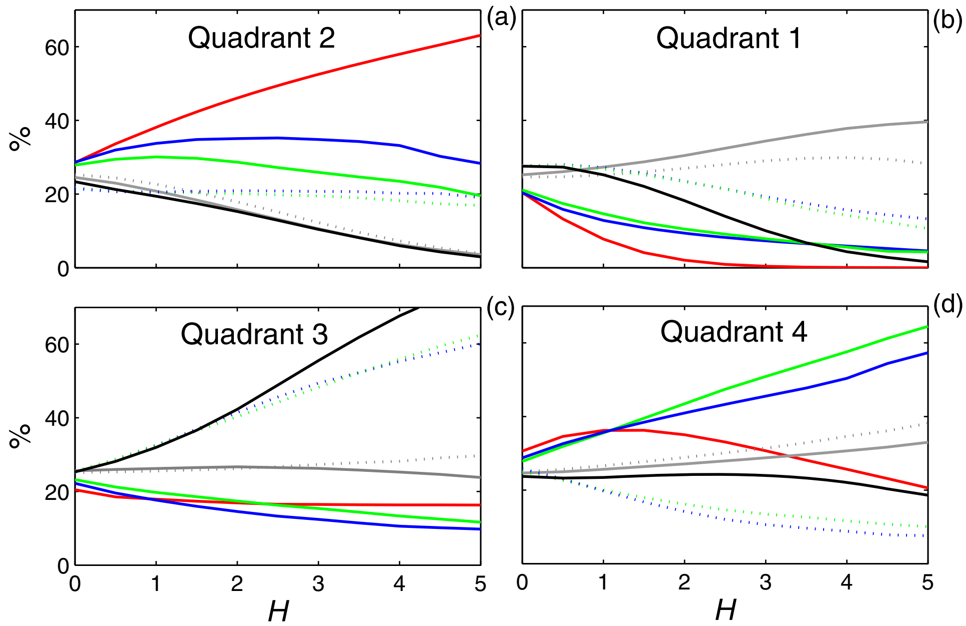

Figure 2. An analysis of velocity-intermittency-based quadrants. Results for flow over mobile gravel bed forms (a laboratory experiment performed by *Singh et al*. [2009, 2010]) are shown as a solid black line. Other results are from the centerline of a turbulent jet [red; *Renner et al*., 2001], data in the far-wake of a cylinder with incoming velocities of 8.5 m s^{-1} (gray dotted) and 24.3 m s^{-1} (gray) [*Stresing and Peinke*, 2010], and data near the wall ($<$200 wall units, solid lines) and higher into the flow ($>$700 wall units, dotted lines) at 6 m s^{-1} (blue) and 8 m s^{-1} (green) for a rough wall boundary layer (the inlet flow from *Keylock et al*. [2012c]). This figure is taken from *Keylock et al*. [2013] (copyright American Geophysical Union) and is reproduced with the permission of the AGU.

exorbitant if one's intention is to run a dynamic and fully resolved LES for sufficient duration to examine bed evolution. Hence, it is more typical for one-way coupling of the flow onto the sediment to be adopted, such as in the study by *Escauriaza and Sotiropoulos* [2011]. However, another way to overcome this difficulty is to assume that the particles in suspension have a negligible impact upon flow momentum, but contribute to stratification effects through a Boussinesq term that is added to the momentum equations [*Khosronejad et al*., 2011]. These are then solved in a LES framework using the dynamic Smagorinsky approach, with the suspended sediment flux and volume fraction modeled by an advection-diffusion equation [*Zedler and Street*, 2001], with an appropriate entrainment scheme [*Van Rijn*, 1993; *Chou and Fringer*, 2008]. Because bed load occurs in a thin layer, near the bed, it too is assumed to have a negligible coupling to the flow field. Given appropriate fluxes for suspended and bed load, the bed evolution can then be determined using the nonequilibrium Exner-Polyna equation for sediment continuity [*Paola and Voller*, 2005]. The success of this method can be seen in its application by *Khosronejad and Sotiropoulos* [2014] to an experiment by *Venditti and Church* [2005] on the initiation of bed forms from a planar sand bed. This case is challenging numerically because of the planar initial condition and the need for the flow field to evolve with the geometry in order to correctly capture the bed form development. That such a case can be modeled successfully (see *Khosronejad and Sotiropoulos* [2014, Figure 15] for a quantitative comparison and their Figures 12 and 14 for the development of bed defects in the simulation) highlights why the eddy-resolving framework provides a much better process representation than is attainable with RANS.

2.4. Prospects

The work highlighted above shows there has been significant progress in modeling fluvial problems in the decade since *Keylock et al*. [2005, p. 297] stated that "While large-scale studies of flow and sediment transport in rivers are unlikely to benefit from the direct application of LES due to the high computational cost, small-scale process modelling should benefit directly." However, that such work draws upon dynamic Smagorinsky formulations [even if scale dependence is introduced, *Porte-Agel et al*., 2000; *Bou-Zeid et al*., 2005] means that progress has been primarily computational and numerical. Modeling work has not directly benefited from a careful examination of the physics of boundary layers or separated flows and developing environmental flow-specific (nonequilibrium and anisotropic) closures as a consequence. This is what we examine next in order to suggest a pathway for such work.

In much the same way that experimental work by Nezu, Nepf and their coworkers has enhanced our understanding of how to parameterize fluvial processes effectively from within a RANS framework, experimental studies of flow, vegetation, sediment transport, and bed forms that consider the action of flow structures [*Best*, 1992; *Nelson et al.*, 1995; *Lelouvetel et al.*, 2009; *Nepf*, 2012; *Keylock et al.*, 2014a], as well as more theoretical work [*Keylock et al.*, 2012b; *Vassilicos*, 2015] may all be drawn upon to suggest appropriate research directions.

3. New Emphases for a Turbulent, Fluvial, Fluid Mechanics

3.1. Turbulent Dissipation

A RANS closure such as $k-\epsilon$ [*Jones and Launder*, 1972] explicitly involves the mean turbulent energy dissipation rate, ϵ. Both the Spalart-Allmaras closure for DES [*Spalart and Allmaras*, 1994] and the Smagorinsky model for LES [*Smagorinsky*, 1963] are based on the eddy viscosity, ν_e, approach to energy dissipation, although the former relates it to vorticity magnitude while the latter is based on strain rates (equations (4) and (5)). In addition, there is an underpinning assumption of equilibrium in these classical closure schemes. This can be seen by considering that ν_e is taken to be similar to UL, where U and L are the velocity and length scales that characterize the turbulence. This provides a direct connection to ϵ if, following *Tennekes and Lumley* [1972] one assumes $\epsilon \sim U^3/L$, given $\epsilon = \nu \langle S_{ij}^2 \rangle$, where the braces indicate some form of averaging and ν_e is deemed to act in a similar fashion, in principle, to the molecular kinematic viscosity, ν. This is the equilibrium assumption introduced by *Kolmogorov* [1941a], who assumed that because small scales in the flow evolve rapidly, their evolution is in equilibrium with what is happening at a larger length scale $r \sim L$. Because there is then a scaling range (popularly known as the inertial range) where the rate of energy transfer is given by ϵ independent of r, dimensional analysis leads to the 2/3 "law" for the second moment of the spatial velocity gradients (the second-order structure function):

$$\langle (u_{x+r} - u_x)^2 \rangle = C_K (\epsilon r)^{2/3}. \qquad (6)$$

This also leads to $\epsilon = C_\epsilon U^3/L$, where the constant C_ϵ is independent of Reynolds number [for a sufficient Reynolds number, *Sreenivasan*, 1984]. Hence, the turbulence closures used in fluvial research assume $\nu_e \sim C_\epsilon U^4/\epsilon$, unless density/stratification effects are included as an additive term to give a modified eddy viscosity.

Significant research in the last decade has focused on examining this equilibrium assumption and the consequences of its relaxation [see *Vassilicos*, 2015, for recent discussion of this matter]. This is a crucial issue for an improved fluvial fluid mechanics as we assume that turbulence theory is "known" and that our role is to examine how complex boundary conditions generate large-scale vortices that control momentum, sediment, and pollutant fluxes. But what does it mean to validate a model against experiment if the basis for the closure in the model is predicated on inappropriate assumptions? If the answer is that such considerations are irrelevant *because* of our focus on larger scale turbulence (i.e., $r \geq L$) then such an argument falls down owing to it invoking the very same scale-separation argument used to derive the equilibrium formulation! As a discipline, we need to understand the flow at all scales and develop closures that respect our measurements of how dissipation actually behaves in environmental flows with all their complexity.

3.2. Supplementing Formulations of Length Scales for Complex Turbulent Processes

One way in which interesting dissipation behavior can be observed is to change the turbulence forcing from a conventional, single large scale to the multiple scales more likely to be seen in the environment. For example, numerical simulations of periodic turbulence in a box with a power law forcing scheme [*Mazzi and Vassilicos*, 2004; *Kuczaj et al.*, 2006] and experiments of the wake generated behind fences immersed in a boundary layer with fractal and regular spacing [*Keylock et al.*, 2012c] have shown that, estimating dissipation using $\epsilon = 2\nu \int \kappa^2 E(\kappa) d\kappa$, where κ is the wave number and $E(\kappa)$ is the spectral energy, there is apparent dissipation occurring within what, from the Fourier spectrum, looks like a Richardson-Kolmogorov cascade, where dissipation should be negligible over these scales. For example, *Keylock et al.* [2012c] compared results for four fences of the same height, and varying number and organization of fence struts, as well as

Table 2. Attributes of the Fences Used in the Study by *Keylock et al.* [2012c], Where D_f is the Linear Fractal Dimension[a]

Porosity (%)	Number of Structures	Mean (Standard Deviation) of Structure Spacing (mm)	D_f
50	5	10.00 (0.0)	1.000
50	9	5.00 (0.0)	1.000
50	9	5.00 (4.4)	0.842
60	9	6.25 (5.5)	0.774

[a]Calculations exclude the 10 mm bottom gap that was present for all fences.

porosity (Table 2). While an analysis based on mean velocities and their variance scaled with porosity as expected (i.e., a length scale based on spatial occupancy), the values for the proportion of dissipation arising over the length scales bounding the scaling region were double those for the two fractal fences than the single-scale fences despite their difference in porosity and the varying number of struts for the two single-scale fences. These effects persisted at least 10 fence heights downstream where boundary layer recovery was beginning to be observed.

This has implications for the philosophy underpinning the parameterization of complex forcings acting on a flow field. In a large river channel, one might need to consider the grain, ripple, dune, and channel depth scales as well as intrinsic variability of each. As already noted, for flow through and over vegetation, one must consider flow depth, stem diameter, plant height, and canopy scales. All or some subset of these effects, combined with an appropriate weighted averaging might provide one with a length that scales velocity profiles and the velocity variance. However, to understand dissipation a more careful consideration of the organization of the various elements is needed that goes beyond porosity. These need to be parameterized in some way, and it is suggested here that, based on recent work in the literature [*Hurst and Vassilicos*, 2007; *Seoud and Vassilicos*, 2007; *Nagata et al*., 2013; *Keylock et al*., 2012c] the fractal dimension of the forcing object provides a starting point. This then needs to be complemented by lacunarity and succolarity of the forcing [*de Melo and Conci*, 2013]. That is, one adopts measures for the scaling of the lengths inducing the forcing, the extent to which this fills the space or volume of concern, and the tortuosity for a laminar flow map through the object (i.e., one considers direction). Characterization of our experiments in these terms may well aid the understanding of dissipation under complex forcings, leading to improved numerical models, whether eddy resolving or not.

With reference to section 3.1, it was experiments using fractal grids [*Hurst and Vassilicos*, 2007; *Valente and Vassilicos*, 2011] that revealed issues with the equilibrium relation $\epsilon = C_\epsilon \; U^3/L$ [*Mazellier and Vassilicos*, 2010], leading to nonequilibrium approaches [*Valente and Vassilicos*, 2012; *Vassilicos*, 2015] based on both a global, Re_G, and local Reynolds number, Re_L, where the former uses the bulk mean velocity and the length scale of the forcing and the latter uses the root mean square of the longitudinal velocity and its integral scale. *Valente and Vassilicos* [2012] found that $C_\epsilon \sim Re_G^m / Re_L^n$ with $m, n \sim 1$, This formulation fits logically with the above discussion concerning the definition of complex objects as we can define the appropriate length scale for the forcing in Re_G, and then attempt to predict variation in Re_L and, thus, C_ϵ from the fractal dimension, etc. of the forcing.

Hence, conventional work in (eco)hydraulics based on the global Reynolds number (even with a clever definition of the length scale to incorporate the potential multiscale nature of the forcing) may not be adequate. On the other hand, the local Reynolds number, reflecting as it does the nature of turbulence from point-to-point, captures aspects of the flow field that perhaps reflect the fractal dimension, lacunarity, and succolarity of the forcing object, leading to a better understanding in fluvial fluid mechanics. Our suggested approach provides an alternative means of conceptualizing these effects, with the potential to complement the conventional methodology [*Nepf*, 2012], which considers a drag length scale for the canopy flow given by

$$L_{\mathrm{drag}} = (C_{\mathrm{drag}} a)^{-1}, \tag{7}$$

where a is the leaf area index and C_{drag} is the drag coefficient, while closer to the bed, the length scale is dominated by wakes that scale with the smaller of the stem diameter or vegetation spacing. As acknowledged by *Ghisalberti and Nepf* [2004] this approach is currently limited by an appropriate understanding of the drag coefficient within the canopy. Measures of fractal dimension, lacunarity, and succolarity, coupled to a richer understanding of dissipation, should allow us to define drag coefficients as a function of geometry much more effectively, although significant work in this area is required.

3.3. Coupling Across Scales in Boundary Layers and Other Relevant Flows

The traditional scale-separation argument that underpins the LES philosophy and Kolmogorov's ideas [*Kolmogorov*, 1941a] does not strictly hold for homogeneous isotropic turbulence owing to the nature of the forcing [*Yeung and Brasseur*, 1991], triad interactions [*Ohkitani and Kida*, 1992], and variations in dissipation as a function of large scales [*Mazellier and Vassilicos*, 2008]. However, there is even stronger cross-scale connectivity in boundary layers [*Hutchins et al*., 2011], something that goes back to Townsend's formulation of the attached eddy hypothesis [*Townsend*, 1956]. The modulation of the small scales by the large has recently been shown to affect all three velocity components in a turbulent boundary layer [*Tallaru et al*., 2014], and has been modeled empirically using simple formulae. For example, *Marusic et al*. [2010] proposed that

$$u_p(z^+) = u_{ideal}(z^+)(1+\beta_{amp}u_{OL}) + \beta_{supp}u_{OL}, \tag{8}$$

where u_p^+ is the predicted velocity signal at a given height (expressed in wall units, z^+), $u_{univ}(z^+)$ is the ideal signal at a given z^+ in the absence of the modulation, and u_{OL} is the velocity in the outer layer that modulates the near-wall flow. The coefficients β_{amp} and β_{supp} parameterize the amplitude modulation by the large scale as well as any direct superposition effects. More work is needed to understand how equation (8) can be better understood and the extent to which such effects differ under complex, environmental boundary conditions. For example, *Singh et al*. [2010] identified a scaling region in the velocity spectrum at larger scales than the inertial regime that corresponds to the scale of the bed forms in their experiment. Do such effects result in any modulation, or does equation (8) need to be generalized to a set of equations each of which characterizes the amplitude modulation of small scales by a particular part of the larger scale forcing? Investigating the physics of modulation is important irrespective of the extent to which improved computational power permits improved, dynamic meshing around bed forms for two reasons:

1. Without an understanding of how any such modulation arises, it is not clear that the criteria for refining the mesh will target the regions where such effects are important.
2. If such effects propagate across scales and are not captured by the closure scheme adopted, the issue will remain irrespective of the mesh adopted until the limit of the Taylor or perhaps even Kolmogorov scale is approached.

The absence of a clear scale separation in boundary layers, highlighted in the work discussed here, demonstrates the importance of a deeper understanding of the fluid mechanics of complex fluvial flows. A closure scheme for modeling such phenomena will struggle to represent the near-bed flow correctly if it is based on inappropriate assumptions. The near-bed region is critical for understanding sediment transport, pollutant dispersal and, thus, river management and fluvial ecological issues [e.g., salmon spawning grounds and the near-bed habitats that lead to ecological diversity, *Fernandes et al*., 2004]. Hence, development of approaches containing a physics that is particular to fluvial fluid mechanics phenomena is likely to increase our applied capacities significantly.

3.4. Nonequilibrium Turbulence as a Consequence of Velocity-Intermittency Coupling

In addition to the scale-separation assumption, there is another crucial assumption in classical work that tends to have been ignored, although it was recognized as a weakness by Kolmogorov in both his original phenomenologies for turbulence [*Kolmogorov*, 1941b] and in the modified variant that introduced intermittency [*Kolmogorov*, 1962]. This is the assumption of independence between the velocity increments, the study of which underpins classical theory (e.g., the second-order structure function in equation (6)) and the velocity itself. The modulation results discussed in the previous section suggest that this might not be the case in a boundary layer, while both theoretical and experimental studies have shown that this is also not the case for other flow types [*Hosokawa*, 2007; *Stresing and Peinke*, 2010]. Hence, the deficiencies of simple closures are to ignore intermittency (whether formulated in terms of convex scalings for the velocity increments [*Kolmogorov*, 1962], multifractal spectra [*Muzy et al*., 1991], or scalings that themselves evolve as a function of scale [*Renner et al*., 2001; *Stresing et al*., 2010; *Keylock et al*., 2015] and to assume that there is a universality to the energy cascading process that has no dependence on the large-scale velocity.

Keylock et al. [2012b] introduced a new method for studying the (potential) coupling between velocity and increments that appears to yield robust results for relatively short datasets [*Keylock et al*., 2014b]. The concept underpinning the method stems from the Frisch-Parisi conjecture:

$$D(\alpha) = \min_n (\alpha n - \xi_n + 1), \tag{9}$$

where n is the moment order of the velocity increments (it is 2 in equation (6)) and ξ_n is the associated scaling exponent on r, which is $\frac{2}{3}$ in equation (6) because Kolmogorov's 1941 theory yields $\xi_n = \frac{n}{3}$. Departures from this scaling are due to intermittency [*Kolmogorov*, 1962; *Frisch et al*., 1978], implying (at the very least) a non-Gaussian distribution underpinning the energy cascade [*Kolmogorov*, 1962; *She and Leveque*, 1994] and multifractality in the velocity statistics [*Meneveau and Sreenivasan*, 1991] as represented by the singularity spectrum, $D(\alpha)$ in equation (9). That is, rather than the Hölder exponent (which captures the local standard deviation, or "roughness," of the time series) being constant at all times, $\alpha(t) = \bar{\alpha}$, it varies locally, and $D(\alpha)$ captures the degree of variation.

It was shown by *Keylock* [2008] that the values for $\alpha_u(t)$ were highly correlated with those for the other velocity components ($\alpha_v(t)$ and $\alpha_w(t)$). Hence, assuming that u dominants the mean flow and turbulence statistics, if we characterize the relation between $u(t)$ and $\alpha_u(t)$, we can incorporate a proportion of the departures from $\bar{\alpha}$ into our turbulence treatment without the need for a fully stochastic approach. The classical quadrant method is illustrated in Figure 1 and described in section 2.1. *Keylock et al*. [2012b] changed the definition such that quadrants were formed from the fluctuating longitudinal velocity component, $u'^*(t)$, and the fluctuating Hölder exponent, $\alpha_u'^*(t)$, where the asterisk indicates a normalization by the standard deviation, σ, i.e., $u'^*(t) = u'(t)/\sigma(u)$. In the same way that conventional quadrant analysis adopts a threshold "hole size" to isolate the more significant events [*Bogard and Tiederman*, 1986], introducing such a threshold and counting the proportion of the dataset in each quadrant as a function of H was found to clearly discriminate between different flow types (Figure 2) and to show that environmental flows may have rather unusual characteristics: The black line in Figure 2 is for the flow over a mobile gravel bed [*Keylock et al*., 2013], a result that was replicated for a flow over fixed bed forms by *Keylock et al*. [2014b], and clearly differs to that for jets, wakes and boundary layers.

Using Figure 2, one can see that for the extreme events (high H) associated with $u' < 0$, a jet flow (red line) is preferentially in quadrant 2, i.e., the slower moving fluid is relatively smooth (higher than average value for α). In contrast, outer layer boundary layer flows and the flow over a gravel bed exhibit a dominance at high H in quadrant 3. Following the argument in *Frisch et al*. [1978] that it is the low α "events" that correspond to the advection of vortical flow structures through the probe because they increase the local standard deviation of the velocity signal (an argument used in *Keylock* [2008] to identify flow events from single-point measurements), then in the types of flow of greater relevance to the fluvial community (boundary layers, bed form-influenced flows), flow structures away from the wall are correlated with $u' < 0$. Thus, knowledge of u' permits us to predict some of the variation in α, providing a means to generate conditional models for dissipation that reflect the organization of flow structures. A deficiency of a turbulence closure that does not incorporate intermittency is that dissipation is imposed in too uniform a fashion. By using larger scale velocity information to account for some of the variation in α, small-scale intermittency can be better represented in subfilter scale closures, leading to more physically realistic results. This is revisited at the end of the next section where we discuss fluctuations in the dissipation rate and the topology of stretched spiral vortices.

3.5. A Route to a Nonequilibrium Modeling Framework

We still have a fundamental problem. How does the flow know it is a jet or a boundary layer, or the consequence of the amalgamated shedding of wakes from clasts of variable size on a heterogeneous gravel bed? We need this information to select an appropriate velocity-intermittency template. The answer is that the velocity-intermittency results are providing an insight, from just single-point data, into the structure of the velocity gradient tensor (VGT), which is given by

$$A_{ij} = \begin{pmatrix} \partial u_1/\partial x_1 & \partial u_1/\partial x_2 & \partial u_1/\partial x_3 \\ \partial u_2/\partial x_1 & \partial u_2/\partial x_2 & \partial u_2/\partial x_3 \\ \partial u_3/\partial x_1 & \partial u_3/\partial x_2 & \partial u_3/\partial x_3 \end{pmatrix}, \tag{10}$$

and from which we may obtain the strain and rotation (and, hence, vorticity) tensors:

$$S_{ij} = A_{ij} + A_{ij}^{\mathsf{T}}, \tag{11}$$

$$\Omega = A_{ij} - A_{ij}^{\mathsf{T}}, \tag{12}$$

10.1002/2015WR016989

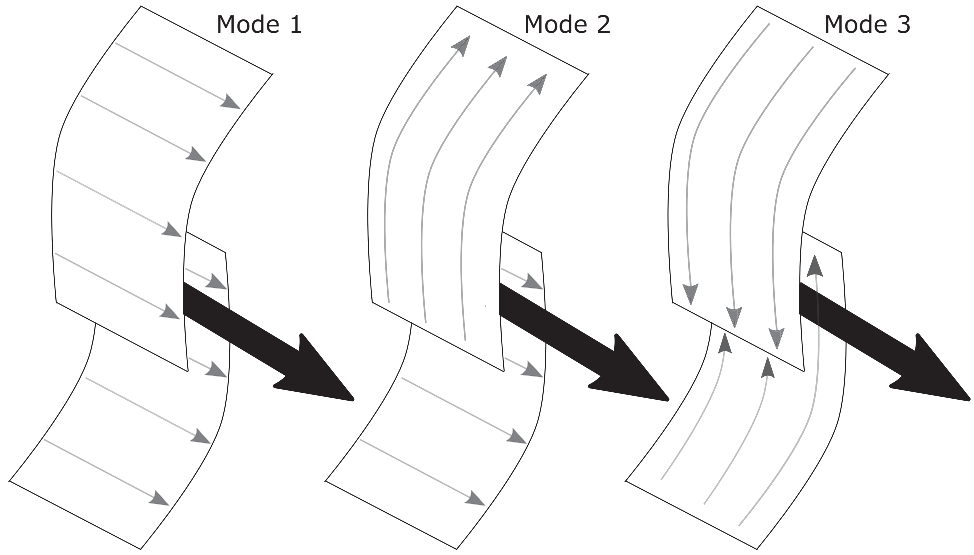

Figure 3. The stretched spiral vortex model and the three modes of behavior. The large arrow shows the vortex tube and the gray arrows the vorticity vectors along the vortex sheets.

$$\omega_i = e_{ijk}\Omega_{jk}, \tag{13}$$

and e_{ijk} is the Levi-Civita symbol. The characteristic equation for the velocity gradient tensor is $A_{ij} = \lambda_i^3 + P\lambda_i^2 + Q\lambda_i + R = 0$, where λ_i are the eigenvalues of A. Incompressibility means that $P=0$, while both Q and R have a clear physical interpretation. The former gives the relative importance of strain and vorticity/enstrophy [*Hunt et al*., 1988; *Dubief and Delcayre*, 2000] and, consequently, is now used commonly in numerical studies of fluvial processes for flow structure identification [*Kirkil et al*., 2009; *Chang and Constantinescu*, 2013]:

$$Q = \sum \delta_{ij}\lambda_i\lambda_j \equiv -(A^2) \equiv \frac{1}{4}(\omega^2 - 2S^2), \tag{14}$$

where for example, $\omega^2 = \omega_i\omega_i$. On the other hand, R concerns the balance between strain and enstrophy production [*Ooi et al*., 1999; *Lüthi et al*., 2009]:

$$R = \prod \lambda_i \equiv -\frac{1}{3}S_{ij}S_{jk}S_{ik} - \frac{1}{4}\omega_i\omega_j S_{ij}. \tag{15}$$

Detailed consideration of the invariants of A_{ij} and their meaning for flow topology has been given by *Vieillefosse* [1984], *Perry and Chong* [1987], *Chong et al*. [1990], and *Nakayama* [2014]. Because such work requires joint consideration of Q and R, and because the latter has not been investigated in detail for complex, vegetative forcings, it follows that this represents a big unknown in fluvial fluid mechanics research, and without it we cannot link topology and dissipation without postulating some form of similarity to the classical behavior considered in these references. Such work has shown that local dissipation takes place near vortex tubes but is organized into sheet-like structures [*Kerr*, 1985]. A template model for this phenomenon is the stretched spiral vortex [*Lundgren*, 1982] shown in Figure 3. Evidence for the existence of this system of vortex tube, with associated vortex sheets has been found in homogeneous isotropic turbulence [*Horiuti and Fujisawa*, 2008], shear flows [*Horiuti and Ozawa*, 2011], and boundary layers [*Pirozzoli et al*., 2010]. Crucially, however, the relative frequency of different modes of behavior of the stretched spiral vortex differed for these cases, which is highly suggestive of a means to place the above results on velocity-intermittency and modulation of the small scales on a process-based footing: the manner by which vortical structures are coupled to larger scales depends upon the stretched vortex modes present (Figure 3) and their mutual interaction. As this is something that is completely unknown for complex environmental flows, it would seem to be a profitable avenue to explore in the future because a mechanistic basis for hydraulic parameterizations of turbulence dissipation would be potentially realizable by this route.

How could such information inform model development? The Smagorinsky closure described in section 2.2.2 is an equilibrium closure—dissipation at subfilter scales takes place without any history or lag effects, despite what is implied in the modulation and velocity-intermittency results described above. The triple filtering approach of *Porte-Agel et al*. [2000] helps in that there is greater information available on the variation in the local flow field permitting the Smagorinsky coefficient's value to approximate the local flow structure more accurately. However, history effects that are clearly of significant importance still cannot be modeled if the base model is an absolutely dissipative and equilibrium formulation.

The Smagorinsky model may be derived by assuming that the subfilter scale spectrum follows the Kolmogorov $-5/3$ model. A perturbation expansion about the baseline $-5/3$ spectrum reveals a $-7/3$ spectrum due to fluctuations in the dissipation rate and these two spectra may be linked to the topology of the stretched spiral vortices [*Horiuti and Ozawa*, 2011]. Hence, an alternative modeling framework is to work with a transport equation for the subfilter scale kinetic energy and to incorporate topological effects through their consequences for the spectrum. This will then reflect the topology of the flow under consideration, permitting phase lags as a consequence of local variations in dissipation. Perhaps more importantly for representing complex processes, it will, as a consequence, permit reverse cascades of energy whereby subfilter scale energy generation can sustain large-scale oscillation, which is more realistic than the absolutely dissipative Smagorinsky approach [*Horiuti and Tamaki*, 2013]. Such a model may also be implemented within the dynamic framework [*Ghosal et al*., 1995] and, hence, the triple filtering approach of Porte-Agel and coworkers [*Porte-Agel et al*., 2000; *Bou-Zeid et al*., 2005] described above, providing significant greater flexibility in the evaluation of the modeling coefficients.

4. Conclusion

In a recent position paper, *Vaughan et al*. [2009] argued for an "ecohydromorphology" as a means to integrate fluvial geomorphic and ecological understanding to effect improved river management. The contention of this paper is that, this may very well be appropriate for large-scale problems where an understanding of detailed process mechanics is not necessarily of first order importance. However, real progress on our understanding of the relevant physics means we not only move beyond consideration of how to parameterize processes from a RANS perspective, but reconsider the work on the importance of coherent flow structures for ecofluvial dynamics from a fresh fluid mechanics perspective. In this way, we have a more appropriate starting point to examine the representation of the salient dynamics, which opens up the potential to formulate coarser scale, potentially RANS-based parameterizations, which have a correct physical basis.

Quite simply, we need a *Fluvial Fluid Mechanics* that is developed with reference to the theories that permit nonequilibrium formulations of turbulent phenomena. Hence, there needs to be an engagement with new work on turbulent dissipation [*Vassilicos*, 2015], the role of complex forcings [*Hurst and Vassilicos*, 2007; *Nagata et al*., 2013; *Keylock et al*., 2012c] and the modulation of small scales by the large [*Ganapathisubramani et al*., 2003; *Hutchins et al*., 2011]. These phenomena exhibit connections to older work on interscale coupling [*Ohkitani and Kida*, 1992] and intermittency [*Kolmogorov*, 1962], as well as more recent studies of velocity-intermittency coupling [*Stresing and Peinke*, 2010; *Keylock et al*., 2012b].

Therefore, all of the exciting work published by *Water Resources Research* in the last decades, which has enriched our understanding of fluvial flow dynamics greatly, can potentially be driven forward to a new level, where the current phenomenologies are placed on a more fundamental footing. In this paper, it has been suggested that an improved understanding of the nature of the velocity gradient tensor for fluvial flows with a complex forcing would be an appropriate starting point. From this, using the stretched spiral vortex model [*Lundgren*, 1982] as a candidate topology to frame our thinking, a potential modeling direction based on large-eddy simulation and a nonequilibrium closure that incorporates information on the small-scale vortical structure has been proposed. This argument is at a sufficiently fundamental level that it has generic relevance to any domain where turbulent flows are forced in a complex fashion. Hence, the call here for a fluvial fluid mechanics is part of a wider plea for a greater engagement with such concepts in environmental and industrial fluid mechanics. As more and more groups develop the modeling and experimental capacities to study the turbulent fluid mechanics of fluvial processes in the manner described in this paper, it is anticipated that these goals will become closer to reality. No doubt *Water Resources Research* will continue to chronicle and to catalyze these developments as they emerge.

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