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Article title: The hydraulic description of vegetated river channels: the weaknesses of existing formulations and emerging alternatives

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Abstract

Currently, many of the methods used to predict the effect of vegetation on river flow suffer from one or both of the following problems: (i) a strong dependence upon parameters that have a poor physical basis and which are only readily determined using empirical means and; (ii) a poor conceptual basis, in terms of the way they represent the effects of vegetation upon the flow, especially in higher dimensionality numerical models. This limits their contribution to problems that extend beyond basic hydraulic prediction (e.g. of water levels) to ecosystem understanding. Here, we show how use of coupled biomechanical–hydraulic models may lead to a much-improved representation of a range of open channel flow processes. Preliminary experiments over hypothetical vegetation canopies are producing very encouraging results, and may provide the means for an improved representation of vegetation in higher dimensionality numerical models which may result in a better justification and more reliable identification of the conveyance parameters needed for both flood identification and the characterisation of habitat.

Introduction

Vegetation is a ubiquitous feature of riverine environments. Whether located on the floodplain, along the banks or in the channel it has a profound influence on the functioning of the fluvial system and has long been the focus of river management activities. This paper focuses on in-channel aquatic macrophytes, which are a fundamental component of many lowland river ecosystems[1, 2]. In-channel vegetation can significantly increase local and boundary flow resistance[3, 4] and traditionally this has been viewed as problematic due to its effect on energy losses. The presence of vegetation may increase flow resistance and energy losses[5]: in turn this leads to a decrease in mean velocity and thus the ability of a river channel to convey a given discharge[4, 6]. To maintain mass conservation, this means that for a given discharge, the cross-sectional area of the river flow must increase; that is the part of a cross-section occupied by the flow. For confined channels, this leads to an increase in depth[7, 8] and consequently may pose a significant flood risk. Historically, it has justified the mechanical removal of vegetation to reduce local flow attenuation and to accelerate the passage of flow [4, 9, 10], even though the reduced attenuation has the potential to increase flooding frequencies downstream[11]. Further, it may be only a short-term solution as certain species (e.g. *Sparganium emersum*) become dominant after cutting[12], with re-growth within six weeks[13]. However, more recently and reversing the logic, vegetation can also be used to actively manage flood risk. By allowing channels in flood-suitable areas to return to their natural vegetated state, the potential for overbank flows increases and therefore flood risk in urban areas downstream may decrease[14]. Therefore within-channel vegetation can be used as a catchment-scale flood management tool.

Over the last few decades, the positive effects of vegetation in terms of ecology have been identified[15, 16]. Vegetation canopies create regions of reduced shear stress[17] that promote sedimentation and retention of particulate nutrients[12, 18]. Furthermore, they may also influence water quality positively through the uptake of heavy metals and nutrients[3] and the production of oxygen in stagnant regions[19]. These factors may enable the development of stable habitats for terrestrial and aquatic wildlife[20-22] and spatial heterogeneity within the flow may encourage a spatial complexity in available habitats, thus promoting biodiversity within rivers[23]. Consequently, vegetation has become central to many river restoration schemes[16].

It is apparent that aquatic vegetation can be seen to have both beneficial and detrimental effects on the river system[24] and exhibits a complex relationship with the flow[25, 26]. However, due to the lack of a full process understanding of flow-vegetation interactions, there is a tension between the positive and negative impacts within river management schemes. There is still a concern that vegetation is a significant driver of flood risk[14], although the abundance and composition of aquatic macrophytes is a key criteria used as an indicator of the ecological status of rivers, and therefore vegetation clearance is discouraged[27]. The debate, as to the trade-off between flood and ecosystem management, is ongoing. Part of this debate may relate to an incomplete transfer of research understanding from that which has focused upon (local) dynamic process interactions to reach-scale predictive tools where empirical relationships still dominate[28, 29].

FLOW THROUGH AQUATIC VEGETATION CANOPIES

Individual vegetation elements within a water flow represent significant sources of drag. At the canopy scale, vegetation can be considered to act as a porous blockage[29, 30] by restricting flow and causing both momentum loss and flow routing. This porous blockage effect creates two very different flow regimes, one above and one within the vegetation canopy. Consequently, the mean velocity profile (Figure 1) within an emergent or submerged vegetated layer does not follow the universal logarithmic law[8, 31] due to the difference in drag magnitude between these two flow regimes.

The velocity profile can be sub-divided into three distinct zones (Fig. 1): i) a relatively quiescent canopy zone within the vegetation, where flow velocity is low and fluid mixing is diminished; ii) a mixing zone close to the canopy top where flow is sheared and is generally faster and more turbulent; and iii) a log-law zone above the canopy, with free-stream flow often characterized by positive vertical velocity gradients, which decrease to zero at the free surface. This mean velocity profile pattern was first described and approximated as S-shaped by Inoue[32] and has been observed across a range of aquatic canopy flows[33, 34] . The exact shape of the velocity profile is determined by the drag exerted by the vegetation, which in turn depends on plant and canopy properties such as stem density and cross-sectional area[4, 10].

In addition to exerting drag on the flow, the vegetation itself is also subject to several reciprocal forces: i) a buoyancy force; ii) a drag force; iii) a virtual mass force; iv) the Basset force [35] induced by a lagging boundary layer generated through turbulence and; v) the Saffman lift force[36] due to asymmetric plant shape. These forces are counteracted by vegetation forces dependent on characteristics of the vegetation: i) the rigidity of the plant; ii) the plant area exposed to the flow; iii) its height relative to the flow depth and; iv) the distribution horizontally and vertically in plant density[6]. Dependent on the ratio of these two sets of forces, vegetation can exhibit four different motion characteristics when exposed to a flow: i) erect with no movement; ii) gently swaying; iii) strong, coherent swaying and; iv) prone[31]. Here, categories (ii) and (iii) differentiate between motion relating to singular events or ambient flow and those caused by the passage of canopy-scale vortices. Therefore, plant canopies as well as acting as a porous blockage are also a potentially dynamic blockage, further restricting flow, leading to momentum loss and impacting upon flow routing.

Plant motion can impact upon the velocity profile. The velocity profile is governed by momentum transfer through turbulent shear produced by the canopy[37], and moving canopies can absorb up to 40% more momentum than rigid canopies[38]. Complex cyclical feedbacks also exist between foliage and momentum absorbing area and thus drag. The drag will initially increase with foliage density[16], but flow forcing will cause foliage reconfiguration through streamlining, which will subsequently reduce the form drag. This has been shown to be more important in drag reduction than stem bending and enables plant survival through either static or dynamic reconfiguration during extreme flow events[39]. Reconfiguration of the canopy into streamlined low-porosity blockages can also impact upon the drag mechanism, with viscous friction drag dominating over form drag[40].

The inflection point in the velocity profile at the top of the canopy is important as it represents a highly unstable region, which acts as the main driver for canopy shear layer turbulence, producing Kelvin-Helmholtz and Görtler-type vortices. The vortices are generated through shear instability and evolve with both distance and time[41], generally scaling on the drag generated by the canopy, to a finite thickness dependent on the space between the top of the canopy and the free surface[38]. These vortices develop into a range of complex flow structures, including transverse and secondary vortices in the form of rolls and ribs[42], hairpin vortices[43] and shear layers dominated by Kelvin-Helmholtz vortices[44, 45]. In addition, there are two other broad turbulence regimes: the boundary layer, and wakes. At the wake scale, mean kinetic energy is converted into wake-generated turbulent kinetic energy at the scale of the plant stems[8, 41]. Physically scaled experiments using cylinders as an analogue for plants have shown that applying a scaling relationship between the flow Reynolds number and the plant stem diameter ($Re_d = Ud/v$, where v = kinematic viscosity (m^2s^{-1}); U = velocity (ms^{-1}); d = stem diameter (m)) produces vortex shedding at $Re_d \approx 50$, but it is not until $Re_d > 200$ that vortex instability causes the wake to become fully turbulent[38]. However, aquatic vegetation is seldom found in isolation[46], making these relationships far more complex than the experiments can consider. For example, forces on individual plants can be reduced due to sheltering and through the reduced canopy velocity due to energy extraction by upstream plants. For depth-limited shallow aquatic flows, there is usually little evidence of boundary layer turbulence, and instead the shear-scale Kelvin-Helmholtz vortices dominate[10]. These vortices can generate up to 80% of the momentum transport between the canopy and the open flow[30].

Thus, the nature of turbulence in the presence of vegetation will be dependent upon three factors: i) the amount of blockage caused by the vegetation canopy; ii) the plant and foliage reconfiguration under hydrodynamic loading; and iii) the flow Reynolds number. The first factor accounts for patch size, stem density and plant form/morphology while the second is a function of the plant biomechanical properties. These factors govern the processes that generate flow resistance and it has been shown that i and iii are important in determining the magnitude of vegetative drag[47, 48]. These findings have been deduced using rigid cylinders as an analogy for vegetation, and it is suggested here that for (more) natural vegetation similar deterministic relationships and functionalities can be derived for the biomechanical properties which control reconfiguration (ii). The implication of this brief review is that we now have a good process understanding of vegetation-flow interactions but as discussed below this process understanding has yet to be transferred to predictive methods for understanding vegetation-flow interactions.

CURRENT METHODS FOR PREDICTING THE INFLUENCE OF VEGETATION ON FLOW

The above section has provided a synopsis highlighting the complex flow hydraulics generated when there is water flow through a plant canopy. However, the current tools used to predict the effect of vegetation on flow have not incorporated this process understanding. As discussed below, in applying both empirical predictive methods and more sophisticated numerical models, the focus has been on using a classical parameterisation of vegetation blockage and momentum loss effects by means of a roughness parameter in a ‘black box’ approach.

Empirical Approaches

Despite the complexity of flow-vegetation interactions highlighted above, the representation of vegetation in either predictive equations or flood models is still commonly incorporated in bulk roughness parameters. These approaches are structured on semi-empirical formulae to obtain a prediction of flow magnitude (e.g. the Manning or Darcy-Weisbach equations) that parameterizes energy losses through a bulk friction parameter so as to reproduce the correct relationship between flow and water level. The Manning’s (n) parameter is therefore effective[49, 50], and has to be, because it represents several processes that contribute to energy loss (e.g. momentum loss, dispersion associated with secondary circulation & diffusion) which are not explicitly represented in hydraulic models. It is justified by the fact that most of such models are one-dimensional, where tests show that model predictions of water level are commonly the most sensitive to Manning’s n as compared with other parameters. Despite fundamental concerns over the behaviour of this parameter (such as its depth-dependence[51]), Manning’s n is still the most frequently used roughness parameter[6] found in most 1D hydrodynamic models used for conveyance estimation (e.g. ISIS, MIKE11, HEC-RAS).

Approaches to determining the most appropriate values of Manning’s n vary and a history of this usage is provided in Lane[52]. As n cannot be measured directly, it has to be estimated. One way to do this is to use inverse methods, such as where Manning’s n is estimated by inverting the Manning equation:

$$n = \left(\frac{R^{2/3}}{V}\right) s^{1/2} \qquad (1)$$

where: R is the hydraulic radius ($R=A/P$ where A is the section area and P is the wetted perimeter), V is the section-averaged velocity and s is the water surface slope. Equation 1 distinguishes between a component that is by definition dynamic in space and time (in brackets) and a component that is commonly simplified to the local river reach slope. Whilst the water surface slope may be assumed to be stationary under certain restricted cases, the component in brackets should normally be dynamic. As water level rises during a flood event, it is common for V to increase at a faster rate than $R^{2/3}$ and for n to fall: that is n has a flow dependence according to Eq. 1; and this is for good reason because of flow submergence effects. Thus, Eq. 1 implies that n should have at least some flow dependence, more commonly described as a depth dependence. As the object of most hydraulic modelling studies is the estimation of flow parameters, back calculation from flow parameters is not a realistic option. As a result, a series of methods have been developed to aid the specification of n, in which back-calculations of n are related to readily measurable information. This has included:

1. look up tables where qualitative descriptors of the vegetation characteristics are assigned n values[53];
2. look up photographs[45], where n values can be estimated from photographs of rivers where n has been back-calculated;
3. n-Re relationships[54] where n is correlated with Re for different plant species, even though this may have no physical justification[55]; and
4. empirical scaling relationships[56, 57] including the amount of vegetation in the channel (e.g. $n=0.0043B^X-0.0497$, where B^X is the proportion of vegetation in the cross section[56]), even if these parameters are reach-specific and can even predict a negative, unphysical value of n for low values of B^X.

In practice, research into how hydraulic modelling is practiced has shown that even when modellers use such relationships, the value of n that is estimated may still not be effective: it does not reproduce measured water levels[52]; and when used in optimization, the determined roughness values may differ significantly from their measured or estimated values[49]. For example in a recent flood model study of a 1 in 1000 year flood event non-unique n values have been shown to provide optimum levels of model agreement[58].

In vegetated river channels, the basic problem with these treatments is that whilst plant related flow blockage and momentum losses may occur throughout the flow, dependent upon the distribution of plant material and its interaction with the flow, the losses are being represented by assuming that they occur only at the interface between water and the river bed[59].

A more physically-based approach is to use the empirical drag equation:

$$F_D = \frac{1}{2}\rho C_D A U^2 \tag{2}$$

which calculates the total drag force exerted by the blockage, based upon the mean velocity (U), the fluid density (ρ), the frontal area (A) and the drag coefficient (C_D). This equation has been used extensively to calculate momentum loss terms within hydrodynamic models ranging from large-scale bulk 1D models [60, 61] through to reach-scale 3D models [20, 62]. However, this approach also has its limitations. There is debate about how best to define the frontal area of the plant, especially given difficulties in measuring natural plant characteristics as well as plant motion and associated changes to area[63, 64]. Primarily however, these limitations relate to the role of the drag coefficient. While values for the drag coefficient are well understood for simple geometric shapes (e.g. cylinders) they are less well understood for complex geometries often associated with natural vegetation canopies. In many studies, cylindrical vegetation (C_D=1) has been assumed. However, for all but the simplest reeds and grasses this represents a significant simplification of plant form. Furthermore, through streamlining, aquatic macrophytes reconfigure into more hydrodynamically ideal shapes. Therefore, the drag coefficient as well as the projected area will vary with plant reconfiguration[28].

One approach that has been used to account for drag on flexible bodies is the Vogel exponent. The Vogel exponent[65, 66], ψ, quantifies the drag reduction through a power law dependence with flow velocity ($F \propto U^{2+\psi}$), where ψ ranges from -0.2 to -1.2[67]. Thus, a Vogel exponent of 0 reduces the power law to Eq. 2. Recent experiments with prototype and real vegetation have suggested a value of ψ=-0.66-1 for flexible vegetation[67-70]. However, while providing an empirical relationship the Vogel exponent is not dimensionally correct and therefore cannot be used to calculate the drag force and subsequent energy loss within vegetated rivers.

In physical terms, the Vogel exponent is an alternative statement of the idea that the frontal area and drag coefficient are a function of both velocity and plant characteristics. A number of authors have sought to utilise this approach, by developing parameters which link the velocity, raised to the Vogel exponent, to geometric and biomechanical plant parameters which together define the plant reconfiguration[71]. For example, the Vogel exponent approach has been used to characterise bulk vegetative resistance terms (e.g. Manning's *n*) with the inclusion of separate foliage and stem components[72] and species-specific drag coefficients[73, 74] which represent an increase in process representation from the rigid cylinder approaches.

However, when applied at a bulk scale, these enhanced drag treatments do not represent flow blockage and still rely upon the assumption of homogeneous plant form across the canopy and no sheltering effects within the canopy. It is not surprising, then, that they fail to quantify the spatial (and temporal) variation in drag and roughness due to plant and patch characteristics[27, 54]. Further, if we are interested in wider ecosystem parameters (suspended sediment, pollutants, erosion and deposition processes) understanding the spatial heterogeneity of flow within and around vegetation is crucial.

Higher dimension numerical modelling

Even when model dimensions have been increased to either 2D or 3D predictions of flow to improve the process representation, a similar philosophy for representing vegetation has been applied to the one discussed above: a focus upon empirical parameters or simple models that represent vegetation effects on energy losses. In the initial approaches, as in the roughness parameterisation approaches, vegetation was considered to be a sub-grid scale effect and models were designed to focus upon larger scale turbulent structures. Following this logic, bulk source and sink terms are added to the mass conservation equations, for example by adding a drag term into a steady Reynolds Averaged Navier Stokes (RANS) model with a κ-ε[20, 62] or κ-ω turbulence closure[20]. The drag force term in these applications is based on plant density and the assumption of rigid, cylindrical vegetation. These models reproduce mean and turbulent quantities well, although when Defina and Bixio[75] applied the same κ-ε model alongside an analytical model they found that they could not effectively predict the quantitative detail of turbulence. These models predict neither the spatial heterogeneity of flow nor the turbulence within the vegetation canopies, at shear and wake scales[75], which drives many canopy processes.

Process representation has been developed by dividing the drag into stem drag and leaf drag components in a Large Eddy Simulation (LES)[76]. In this approach stem drag is modelled as basic cylinder drag, whereas leaf drag is modelled using an estimated leaf area index. The model was compared against a standard canopy drag treatment and it was shown that both models predicted the same spectral slope, but that the standard canopy drag treatment under-predicted the RMS velocity, effectively damping the canopy instability. Furthermore, the dual drag approach showed good agreement with PIV data[76] and proved to be a reliable tool for investigating turbulence and momentum transport over canopies. This approach however still does not account for heterogeneity in plant form within canopy flows.

Thus, whilst there has been progress in vegetation representation within 2D and 3D models, they remain predominantly focused upon development of bulk friction parameters that are incommensurate with the increased physical complexity of such models as compared with their 1D counterparts rather than developing ways of representing vegetation blockage and momentum losses at the within-section scale in a way that is, in effect, distributed.

THE NEED FOR A DISTRIBUTED APPROACH TO DESCRIBING FLOW HYDRAULICS

The most promising approach to date appears to be to model the plant canopies as porous blockages and at a scale at which the vegetation diameter significantly exceeds the cell width of the model. Because of the high model resolution that this implies, and the computational demands that result, most models have focused upon stem-scale processes involving smaller canopies and have not considered larger or highly submerged canopies. This approach was originally proposed by Stoesser *et al.,*[77] who performed LES experiments on an array of submerged cylinders. Comparison with experimental results showed good agreement and they were able to replicate classical vortex regimes (e.g. horseshoe, von Karman, rib and roller vortices as well as trailing vortices from the vegetation tops). An important development with this representation of the vegetation is that pressure and friction drag are directly calculated[78], removing the need for empirical drag coefficients. This approach has subsequently evolved to consider larger domains, enabling patch-scale analysis whilst retaining stem-scale resolution. Stoesser *et al.,*[48] conducted experiments on a patch of emergent vegetation considering different vegetation densities and showed changes to wake turbulence patterns caused by changes in vegetation density. Finally, Kim and Stoesser[79] developed a low resolution method that reproduced the results from the validated high resolution model with reasonable accuracy, including the streamwise and spanwise velocity gradients, wake structure and secondary currents[79]. While these stem scale models are capable of capturing the fine turbulence structure with great accuracy, it is worth noting that they do not include any treatment of flexible vegetation. They are therefore unable to capture the complex feedbacks between flow and vegetation, which may influence canopy processes[10, 80].

Various models have previously been developed to incorporate flexible vegetation[81-84], but none have been incorporated into a full 3D model. Therefore, these models are unable to capture either the complex turbulence structure within and around the canopy or the plant's response to that turbulence. Marjoribanks *et al.*[85] have recently developed a combined biomechanical-LES model. This study applied Nikora's[39] classification of aquatic vegetation characterising it as either 'tensile' or 'bending'. As such, two separate biomechanical vegetation models were developed in order to represent vegetation across a range of plant forms and incorporated into a Computational Fluid Dynamics model to simultaneously predict vegetation-flow interactions at high spatial and temporal resolutions. This new approach allows high resolution investigation into both canopy flows and the dynamic plant response to canopy-flow. For example, it is possible to investigate the evolution of turbulent structures along the canopy top (Figure 2). Figure 2 shows that a shear-layer forms along the canopy top and a roller vortex develops approximately 0.9 m downstream from the leading edge of the canopy and lifts into the free flow. These vortices are key controls on mass and momentum transport within the canopy and therefore quantifying their occurrence and characteristics will improve our ability to predict transport processes within the canopy. Similarly it is possible to identify wake-scale vortices (Figure 3) that are forming around each individual plant stem. Here, individual wake structures can be seen behind the base of each individual stem which are consistent with the necklace vortices which originate at the base of cylinders[77, 86], but the reattachment length scales of the structures is greater than the spacing between the individual wakes and as such coalescence occurs generating larger-scale turbulent patterns. This simple application demonstrates the heterogeneity within the flow field that is generated by the presence of vegetation.

Another key advantage of high-resolution numerical models over flume or field-based methods is they allow us to fully quantify processes within the canopy. For example, it is possible to evaluate variables such as turbulent kinetic energy (Figure 4) and bed shear stress (Figure 5) which are essential when considering sediment dynamics[12, 18, 87]. The spatial heterogeneity demonstrated in Figures 4 and 5, which could have a significant impact on local sediment and nutrient transport processes as well as habitat creation, would not be predicted if either an empirical parameterisation or bulk source approach was applied as these would only modify the local velocity profile rather than predict the correct flow heterogeneity. As such, this method provides increased knowledge of preferential flow paths, areas of erosion and potential habitat development compared to that which can be gained using a canopy-scale model. Furthermore, comparison between the time-averaged and instantaneous turbulent kinetic energy results (Figure 4) indicates that a time-averaged approach may not be sufficient for predicting sediment transport caused by high magnitude but low frequency events within the canopy. Such an example is demonstrated in Figure 4b where a localised region of high turbulent kinetic energy, in the order of three times the mean, can be identified covering a region of 4 vegetation stems. These localised peaks are caused by penetration of large-scale turbulent structure into the canopy and occur throughout the canopy. Therefore, estimates of erosion and sediment transport based upon the mean turbulent kinetic energy values may significantly under-predict actual erosion values. Similarly, Figure 5b identifies regions of high Reynolds stress at the bed, which are only captured using a spatially distributed and time-dependent method.

If this kind of approach can be developed, then it may start to provide us with a new understanding of what happens within macrophyte canopies within flowing streams. Macrophytes have been identified as a refuge from predators[88-90], as hosts for predators[91, 92] and as sources of food[88, 91]. Positive and negative impacts on water quality, such as dissolved oxygen[90] have been observed in relation to instream fauna. Complex effects of macrophytes on trophic interactions within aquatic ecosystems have been reported[92, 93] including how habitat is used by macroinvertebrates and fish[93]; even if there is also debate as to precisely what the effects of aquatic plants are upon, for example, predator-prey relationships[89, 94]. This large body of work aside, there is much less understanding of the relationship between the flow hydraulics within such canopies, how it mediates the characteristics of the refuge including flow velocity, sediment accumulation and water quality, and then what effects the presence such refugia have during flow extremes, both high flow and low flow. Biggs *et al.*[95] consider the potential effects of flow variability upon ecosystems in relation to flow velocity variations and show how small scale flow fluctuations within and around plant canopies can have a critical effect on mass transfer processes, notably in relation to the suitability of habitat for invertebrates and food availability. This lack of research may be addressed with the kind of modelling described in this paper if it can provide detail within plant canopies and around individual plant stems, for a range of flow events. This has proved to be extremely difficult using either field instrumentation or laboratory scale models.

Conclusion

The aim of this paper has been to highlight the basic limitations of traditional treatments of vegetation in mathematical models of river channels. Many of the methods used to deal with vegetation suffer from one or both of the following problems: (i) a strong dependence upon parameters that have a poor physical basis and which are only readily determined using empirical means and; (ii) a poor conceptual basis, in terms of the way they represent the effects of vegetation upon the flow, especially in higher dimensionality numerical models. The use of coupled biomechanical–hydraulic models may lead to a better representation of a range of open channel flow processes. Preliminary experiments over hypothetical vegetation canopies are producing very encouraging results, and may provide the means for an improved representation of vegetation in higher dimensionality numerical models. However, they still require further development. Problems of determining the characteristics of plants will inevitably mean that application of these methods in many practical situations may prove to be unfeasible. There is therefore a need to classify both the biomechanical properties of the plant (flexural rigidity, buoyancy) and the geometric characteristics (the plant shape, foliage density, leaf area index) for a range of common macrophytes.

There is also a need to improve the model representation of the plant to include foliage and plant-plant interaction. Such developments need to be run in parallel to developments in experimental and field measurements of canopy flow. Recent work by Marjoribanks *et al.*[85] demonstrated the difficulty in collecting data within the canopy at a spatial and temporal resolution sufficient to validate these current biomechanical-LES models. However, the approach outlined above may enable a distributed representation of hydraulics and energy losses within rivers.

Such models are becoming increasingly applicable at the reach-scale, due to advances in computational resources. However, such high-resolution models are not always appropriate. Therefore, a key area for development is the inclusion of such high resolution process information within bulk models. In particular, physically based drag approaches which include parameterisations of plant form and biomechanics may provide a mechanism for incorporating flow and vegetation heterogeneity. It is suggested that experimental investigation of river channel processes using a numerical biomechanical-LES approach will enable recalculation of the spatially distributed canopy scale drag, and may result in a better justification and more reliable identification of the conveyance parameters needed for flood identification and habitat characterisation.

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Figures

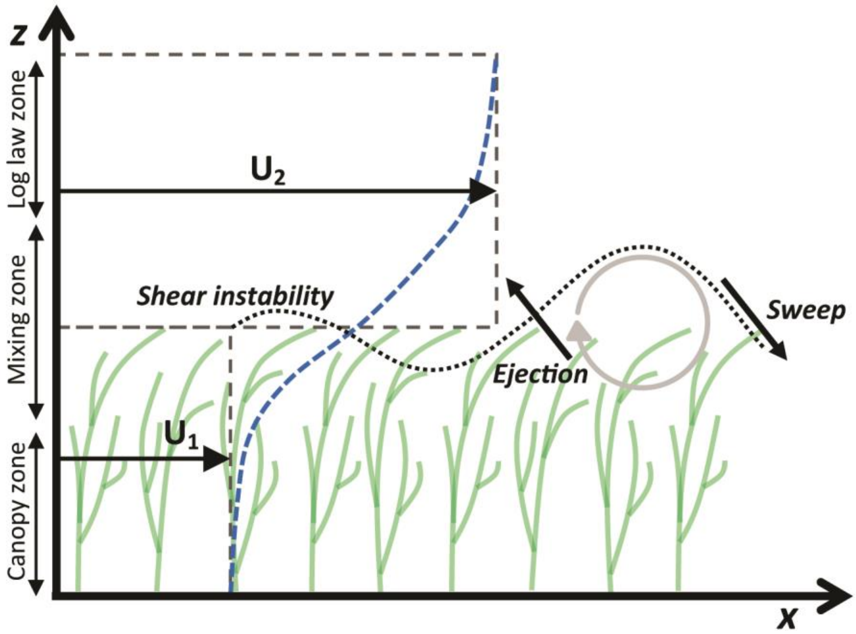

Figure 1: Schematic model of canopy flow showing the development of the characteristic canopy velocity profile (blue, dashed line) and associated turbulence structure, due to the difference in above-canopy (U_2) and within-canopy (U_1) flow velocities.

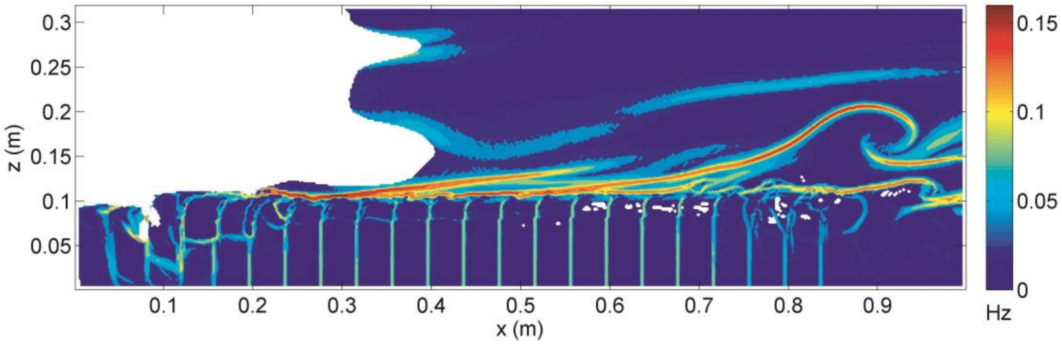

Figure 2: The predicted vortex structures identified by FTLE[96] down the midline of a hypothetical vegetation canopy. Vortex structures have been tracked for 1 second. As the variable increases (tends towards red) the vortex attractors are stronger demonstrating vortex tracks. A roller vortex can be seen to be developing as the structure moves off from the top of the canopy. Flow is from left to right.

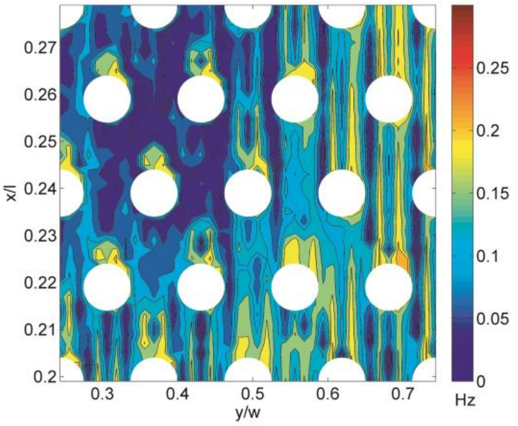

Figure 3: A plan view of the vortex structures at ~0.02 z/h calculated using FTLE. Individual wake structures can be observed forming around individual stems but the reattachment length is greater than the separation distance between stems forming larger scale turbulent structures. Flow is from bottom to top.

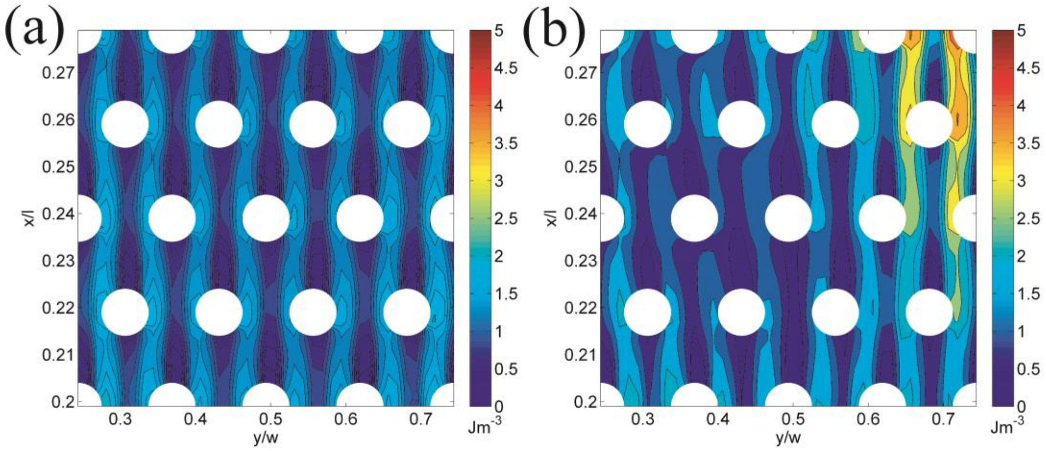

Figure 4: A plan view of the Turbulent Kinetic Energy (TKE) calculated at 0.02 z/h. a) Represents the time averaged TKE and b) represents the instantaneous TKE calculated from a Large Eddy Simulation predicting flow at a resolution of 50 Hz, Flow in these images is from bottom to top.

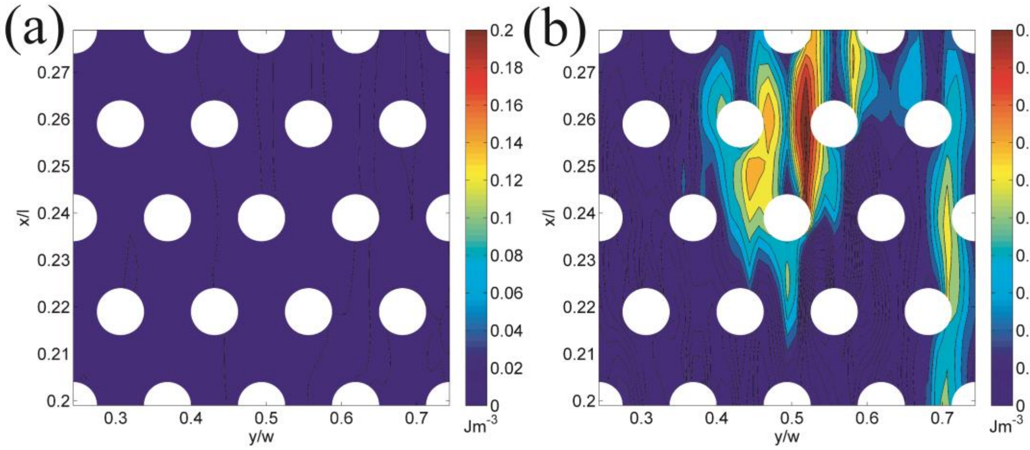

Figure 5: A plan view of the near-bed Reynolds stress calculated at 0.02 z/h. a) Represents the time averaged Reynolds stress and b) represents the instantaneous Reynolds stress calculated from a Large Eddy Simulation predicting flow at a resolution of 50 Hz, Flow in these images is from bottom to top.