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Effectiveness of 1D and 2D hydraulic models for instream habitat analysis in a braided river

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ABSTRACT

There is considerable interest in the use of 2D hydraulic models for the prediction of instream habitat especially for complex hydraulic situations such as those found in braided rivers. The general assumption is that the greater spatial resolution of 2D models and their hydraulic modeling will give better predictions of instream habitat. We apply a 1D model and two 2D models to a section of braided river and compare measured and predicted water depths and velocities at two flows, as well as habitat predictions over a range of flows. The correlation between predicted and measured depths and velocities was higher for the 1D than for the 2D models. Practical limitations on topographic definition and the subjectivity associated with 2D calibration resulted in errors in predicted water levels that could cause braids to either flow or stop flowing. All three models generally predicted similar trends in habitat (weighted usable area) variation with flow, although there were differences in the magnitudes, location of maxima and changes in gradient. The differences between the 1D and 2D model predictions could not be attributed to the greater spatial resolution of 2D models, because there was as much difference between 1D and 2D habitat–flow relationships as between the two 2D models. The difficulty in acquiring sufficient and accurate bed topography and the skill required in calibrating 2D models is a practical limitation to their utility, and it cannot be assumed that they are better simply because they require more data and the time and effort required to develop a good 2D model is not warranted in many situations. The main advantage of 2D models over 1D models is that they should provide more accurate predictions outside the calibration range of 1D models, especially at high flows in braided rivers, but improved calibration and validation techniques are required.

1. Introduction

Instream habitat models are used to predict habitat changes with flow and to assist decisions on an acceptable flow regime, usually with an emphasis on minimum flow requirements. The habitat models use hydraulic models to predict water depth and velocity for a range of flows, and then evaluate habitat suitability at these flows, where habitat suitability is usually, but not necessarily, defined in terms of water depth, velocity, substrate composition and cover. Hydraulic models vary in complexity, from simple models based on hydraulic geometry (Jowett, 1998) to those based on 2D and 3D hydraulic equations (Leclerc et al., 2003; Olsen and Stokseth, 1995; Pasternack et al., 2004). As the computational power and availability of computers has increased, so has the availability of more complex hydraulic models, and the use of 2D hydraulic models has been advocated for instream habitat analysis (Leclerc et al., 1995).

Practitioners must decide on the form of hydraulic model that best suits their purpose and budget. An important difference between the models is the spatial resolution; an hydraulic geometry model predicts the mean cross-section depth and velocity, a 1D model predicts the depth and mean vertical velocity at points across the river, a 2D model predicts the depth and magnitude and direction (*X*,*Y*) of mean vertical velocity at points, and a 3D model predicts the depth and magnitude, direction, and vertical distribution (*X*,*Y*,*Z*) of velocity at points. Water levels in 1D models can be predicted by three methods; a water surface profile (WSP) model, an "IFG-4" model and MANSQ. A WSP method is based on energy conservation and predicts water surface levels from mean cross-section geometry. The "IFG-4" and MANSQ methods are largely empirical. The former predicts water surface levels from a stage–discharge relationship derived by a log–log fit to calibration

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measurements of stage and discharge. The latter uses calibration measurements of stage and discharge to predict the relationship between Manning's *N* and discharge and then uses Manning's equation to determine the stage–discharge relationship for individual cross sections. For all three methods, the transverse distribution of velocity is predicted using water levels and conveyance (Milhous et al., 1989; Mosley and Jowett, 1985).

The type of habitat suitability criteria may determine the hydraulic information required and this can limit the choice of model. For example, if habitat suitability is defined by average water depth and velocity over a section of river (e.g., Tennant (1976) method), any of the hydraulic models could produce this information. However, if habitat suitability is calculated at individual points and integrated over a section of river, models with greater spatial resolution than hydraulic geometry models are required. Similarly, if habitat suitability is defined in terms of the vertical velocity distribution, a 3D model is the only model that could be used.

Minimum data requirements increase with the complexity of the hydraulic models. Crowder and Diplas (2000) showed that a 2D model was able to predict small-scale velocity patterns, such as velocity shelters behind obstructions and transverse flows and it has been claimed that 1D models do not capture habitat patterns at reach and sub-reach scales (Wheaton et al., 2004). Although 1D models are not normally applied in a spatially explicit manner, there is no reason why 1D surveys and model predictions cannot be made at the spatial resolutions used for 2D models, if necessary. For example, the RHYHABSIM 1D program calculates habitat suitability by interpolating between transverse measurement points; longitudinal interpolation is achieved through the use of streamlines and the results have been used in the spatially explicit trout energetics model of Hayes et al. (2007). The advantage of 2D models over 1D models is that they predict current directions, and changes in the pattern of velocity distribution. 3D models will also predict the vertical velocity distributions. However, most habitat suitability criteria are based on point values of depth, mean vertical velocity and substrate composition, although individual-based fish models (Railsback and Dixon, 2003) and models based on energetic concepts (Addley, 1993; Guensch et al., 2001; Hayes et al., 2007) have been developed to the stage where they could be used for flow assessment.

Often the requirement for high spatial resolution of topographical data for 2D models limits their application for instream habitat assessment to reaches a few kilometers or so in length; however, they have been used to assess longer reaches; Hardy et al. (2006) and Bowen et al. (2003) modeled a total of 9 and 26.3 km of river, respectively. If the purpose of the hydraulic model is to represent conditions in a longer section of river, as is often the case, the "representativeness" of the reach that is selected can be questioned. Morhardt et al. (1983) suggested a stratified-random design as a means of achieving better representation in 1D models, whereby cross-section locations are randomly selected within sampling units (usually habitats such as pools, runs, and riffles). This method, commonly known as habitat mapping, requires that the various sampling units to be defined and mapped to quantify their proportions in the section of river. Because cross-sections can be widely spaced, it is not possible to use water surface profile modeling to determine water levels, and water levels are instead determined from empirical stage–discharge relationships. In PHABSIM (Milhous et al., 1989), the method based on stage–discharge relationships was called "IFG-4" to distinguish it from alternative 1D modeling procedures.

There is a tendency to believe that more sophisticated and expensive models will produce better and/or different results. Theoretically, the flow physics of 2D models are better able to model flow patterns over a complex river bed, such as obstructions, islands and meanders (Katopodis, 2003). In complex rivers, a 2D model allows transverse variations in water level so that features such as diagonal riffles can be modeled, whereas a 1D model assumes that a flow change will result in a constant change in depth across the cross-section. However, 2D models do not necessarily predict water velocities accurately (e.g., Guay et al., 2000, 2001; Tarbet and Hardy, 1996; Williams, 2001), nor do they necessarily predict depths and velocities more accurately than 1D models, although they can predict changes in complex flow situations (Waddle et al., 2000). In braided or multi-channel rivers, 2D models can predict braiding patterns and the proportion of flow in each of the channels. The 1D modeling program RHYHABSIM (Clausen et al., 2004) has the facility to predict instream habitat in braided or multi-channel rivers using empirical methods.

In this study, we compare the depth and velocity predictions made using RHYHABSIM with predictions made by two 2D models, one with a rectangular grid (Hydro2de, Beffa, 1996; Beffa and Connell, 2001) and the other with a variable-size triangular grid (River2D, Ghanem et al., 1996; Waddle et al., 2000). We also compare the habitat predictions made by the three models. The field measurements and modeling were part of an actual field survey and analysis and we assess the various models on this practical basis.

2. Method

2.1. Study site and survey

The Hurunui River flows from the Southern Alps of South Island, New Zealand, to the sea on the east coast. Like many other South Island east coast rivers, it is confined to a single channel as it flows through hill country, then braids as it flows across plains. A study reach was selected in the braided section of river after viewing the river from the air (Fig. 1). The braided nature of the reach was the primary criterion for selection, and the number of braids and total water surface width in the selected reach was about average for the section of river considered in the study. Other issues considered were access and the requirement for the reach to have a single thread at its upstream end to simplify 2D modeling. At the study site, the basin area is 1640 km^2, with a mean flow of about 70 m^3/s and average annual low flow of 19 m^3/s. The number of braids varied between 1 and 5 with an average of 3. The reach dimensions were 600 m across stream and 1295 m down stream with an average water surface width of 71 m and gradient of 0.055. The survey was carried out over three days when the flow varied from 26 m^3/s to 45 m^3/s. Surface substrate was sampled using the Wolman (1954) method where a standard template with square holes in half phi increments from 8 mm to 256 mm was used to assess the grading of at least 100 clasts. The median particle size (d_{50}) was 23.5 mm and the armor size (d_{84}) was 72 mm.

2.2. 1D survey

We established 24 transects for the 1D model at approximately 50 m intervals along the study reach (Fig. 1). There were between one and five separate channels at each transect. Each stream channel intersected by the transect was then treated as a single cross-section for the purposes of the 1D model. Water depths, velocities, and substrate composition were measured at intervals (0.3–2 m) across the cross-section, with additional measurements at abrupt changes in bed level and/or water velocity, so that the model assumption of linear interpolation between points was valid. The average spacing of points was 1.6 m across