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Using two-dimensional hydrodynamic models at scales of ecological importance

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Abstract

Modeling of flow features that are important in assessing stream habitat conditions has been a long-standing interest of stream biologists. Recently, they have begun examining the usefulness of two-dimensional (2-D) hydrodynamic models in attaining this objective. Current modeling practices consider relatively long channel sections with their bathymetry represented in terms of large, macro-scale, topographic features. Meso-scale topographic features, such as boulders, root-wads and other obstructions are typically not considered in the modeling process. Instead, the overall effects of these flow obstructions are captured through increased values in the channel roughness parameters. Such an approach to 2-D modeling allows one to accurately predict average depth and velocity values; however, it is not capable of providing any information about the flow patterns in the vicinity of these obstructions. Biologists though have known that such meso-scale features and the complex velocity patterns generated by their presence, play an important role in the ecology of streams, and thus cannot be ignored. It is therefore evident that there is a need to develop better tools, capable of modeling flow characteristics at scales of ecological importance. The purpose of this study is to expand the utility of 2-D hydraulic models to capture these flow features that are critical for characterizing stream habitat conditions.

There exists a paucity of research addressing what types of topographic features should be included in 2-D model studies and to what extent a boulder or series of exposed boulders can influence predicted flow conditions and traditional useable habitat computations. Moreover, little research has been performed to evaluate the impact mesh refinement has on model results in natural streams. Numerical simulations, based on a natural river channel containing several large boulders, indicate that explicitly modeling local obstructions/boulders can significantly impact predicted flow parameters. The presence of these obstructions create velocity gradients, velocity shelters, transverse flows and other ecologically important flow features that are not reproduced when their geometry is not incorporated into the hydraulic model. Sensitivity analyses show that reducing element sizes in the vicinity of obstructions and banks is crucial in modeling the spatial flow patterns created by meso-scale topographic features. This information, combined with similar data obtained in future studies, can provide guidelines for the placement of fishrocks and other structures often used in stream restoration projects as well as determining what types of meso-scale topographic features might need to be incorporated into habitat suitability studies. Such information may also ultimately allow new spatial habitat metrics to be developed. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Numerical analysis; Bathymetry; Rivers and streams; Aquatic environment; Fish habitat; Spatial variations; Boulders

1. Introduction

Flow through natural channels is typically quite complex. The flow interacts with sediment and the topographic features of the channel bed to create

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complex flow patterns that vary both spatially and temporally (e.g. Diplas, 1994; Wiele et al., 1996; Mosselman, 1998). The dynamic interactions among flow, sediment, and topographic features consequently play a key role in determining current habitat conditions within a river. According to Allan (1995), current and substrate are two of the three most important physical factors in understanding the "functioning of a lotic ecosystem and the adaptations of its denizens". Observations indicate that the wakes and high velocity gradients surrounding boulders create important habitat for trout, invertebrates, and aquatic plants. Trout minimize energy expenditure by using wakes downstream of boulders as velocity shelters, where they can rest in slow water, but can also dart into nearby fast water to feed (Hayes and Jowett, 1994). Likewise, boulders and clusters of rocks create low shear stress zones that play an important role in determining the diversity of periphyton and invertebrates in a stream after a spate (Biggs et al., 1997). Therefore, the local flow patterns induced by boulders and other meso-scale obstructions are critical features in enhancing habitat for flora and fauna within streams.

Ideally, a stream will have a variety and abundance of specific habitats to support the various life stages of all the aquatic organisms native to the stream. Unfortunately, dams, diversion projects, urbanization, agricultural practices, and many other human activities in and around streams can destroy or dramatically change habitat conditions within a stream (e.g. Diplas, 1994; Waters, 1995; Rosgen and Silvey, 1996). When alterations to existing streams are proposed, studies are often performed to ascertain current habitat conditions within the river, and to predict how the project will affect these conditions. Typically, these habitat studies incorporate results from one-dimensional (1-D) flow routing subroutines, such as those used in PHABSIM (e.g. Milhous et al., 1989). However, these 1-D flow models often analyze a river reach by breaking it into discrete cells (or subsections) each having a single depth and velocity value everywhere within it (Bovee, 1978). Any spatial variations in flow, such as velocity gradients and transverse flows, occurring within a cell cannot be modeled.

Recognizing the inability of 1-D models to describe such two-dimensional (2-D) flow patterns, stream biology researchers are beginning to evaluate the usefulness of 2-D hydraulic models as predictive tools in habitat studies (Leclerc et al., 1995; Tarbet and Hardy, 1996; Waddle et al., 1996). Bovee (1996) suggests that, while 2-D models may be superior to traditional 1-D habitat models in several respects, the most promising aspect of 2-D models in habitat studies is their potential to accurately and explicitly quantify spatial variations and combinations of flow patterns important to stream flora and fauna. Such spatial information may provide new and potentially better habitat metrics (Bovee, 1996). Theoretically, 2-D models are capable of reproducing the smallest of 2-D flow features. If such features are to be modeled, channel-bed geometry must be described exactly. Unfortunately, the highly complex channel geometry of a natural stream cannot be described to the minute detail. Consequently, one must identify the features that are necessary to capture the flow patterns important to the phenomenon being studied. In studies where the presence or absence of boulders, rootwads, and other obstructions significantly impact habitat conditions within a reach, bathymetry data on these topographic features must be included in the model. The effects that these objects will have on local flow patterns will ultimately determine the ecological health of the stream. Moreover, to fully capitalize on the spatially explicit output of 2-D hydraulic models requires that the meshes used be capable of reproducing the spatial flow patterns created by the meso-scale topographic features at the resolution important to the aquatic organisms under study.

Prior 2-D modeling efforts have focused on predicting flow patterns over relatively large reaches and have not closely examined the role a single obstruction or a series of obstructions play in local flow patterns and subsequent habitat analyses. Tarbet and Hardy (1996) found that mesh refinement played a significant role in model output in complex channel geometry and Waddle et al. (1996) acknowledge the need for mesh refinement based on topographic criteria. However, few (if any) sensitivity analyses have been performed and there is a paucity of information regarding how local topography (obstructions, boulders, etc.) and mesh refinement affect model results.

This paper presents the results of several numerical simulations, based on actual channel and boulder geometry. The simulations were performed to

determine how to incorporate meso-scale topographic features into 2-D models and whether their incorporation provides significantly different results from those obtained when such features are not considered in the model. Such information provides basic guidelines on the computational effort needed to quantify the degree to which obstructions and other meso-scale topographic features may impact local flow conditions within natural streams. Particular emphasis is placed on the modeling of flows around obstructions, which along with flows near the channel bottom, provide the habitat where most stream organisms live (Allan, 1995). Specifically, the ability and importance of incorporating meso-scale spatial variations into 2-D models is demonstrated by modeling a segment of the North Fork of the Feather River in California, USA, with and without bathymetry information about several large boulders within the study site. To illustrate the influence obstructions/boulders have on habitat conditions within the study site, differences in flow parameters predicted by these two scenarios are evaluated at 10 locations where juvenile rainbow trout were found within the stream. A brief analysis of how the size and location of a single boulder can affect stream conditions is performed. Sensitivity analyses are also performed to provide estimates of the mesh refinement necessary to capture meso-scale flow patterns.

2. Description of the 2-D hydraulic model

RMA-2V, originally developed by King (1990) and now maintained by the Army Corps of Engineers Waterways Experiment Station, is used to model the study site. RMA-2V is a 2-D finite element program that uses the Galerkin method of weighted residuals and a Newton–Raphson scheme to solve the shallow water equations. Linear shape functions are used for depth and quadratic shape functions for velocity. The shallow water equations (a depth-integrated form of the Navier–Stokes equations) consist of an equation for conservation of mass (Eq. (1)) and two equations for the conservation of momentum in the horizontal directions (Eqs. (2) and (3)). These equations can be written as follows:

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}(hu) + \frac{\partial}{\partial y}(hv) = 0, \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\left(\frac{\partial h}{\partial x} + \frac{\partial z_0}{\partial x}\right) - \frac{\epsilon_{xx}}{\rho}\frac{\partial^2 u}{\partial x^2} - \frac{\epsilon_{xy}}{\rho}\frac{\partial^2 u}{\partial y^2} + \frac{gu}{C^2 h}\sqrt{u^2+v^2} = F_x, \tag{2}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\left(\frac{\partial h}{\partial y} + \frac{\partial z_0}{\partial y}\right) - \frac{\epsilon_{yx}}{\rho}\frac{\partial^2 v}{\partial x^2} - \frac{\epsilon_{yy}}{\rho}\frac{\partial^2 v}{\partial y^2} + \frac{gv}{C^2 h}\sqrt{u^2+v^2} = F_y \tag{3}$$

where x and y are the Cartesian coordinates in a horizontal plane; u and v represent the depth averaged velocity in the x- and y-directions; t equals time; h the water depth; ϵ_{xx}, ϵ_{xy}, ϵ_{yx}, and ϵ_{yy} are eddy viscosity coefficients; C the Chezy coefficient; g the gravity; ρ the fluid density; z_0 the channel bottom elevation; and F_x and F_y are optional terms incorporating Coriolis and wind forces acting in the x and y directions. In this study Coriolis and wind forces are considered negligible and not incorporated into the model.

The assumptions made in deriving these equations and within the solution procedure limit RMA-2V to solving subcritical flows with a free surface and hydrostatic pressure distributions (King, 1990). The finite element method used in RMA-2V solves Eqs. (1)–(3) for u, v, and h at each node within a finite element mesh, and allows velocity and depth values to be interpolated across elements such that the model's output represents a continuous field of flow depth and velocity.

The program RMA-2V provides two options for the wetting and drying of elements. The first option, used in this study, is elemental elimination. In this process, the user specifies a minimum depth. If any node on a previously wet element has a computed depth less than this value, the whole element is considered dry and no flow passes through the element. The user also specifies a second depth. If the computed depths at all nodes on a previously dry element exceed this second value, the element becomes wet and carries the element's full flow volume. The second option, "Marsh Porosity", provides a means of allowing the amount volume of flow passing through an element to be gradually increased or decreased between fully wet and dry states (USACE, 1996).

The data required to run RMA-2V consist mainly of

four things: bathymetry data describing the channel geometry, boundary conditions, channel-bed roughness coefficients (Chezy or Manning) and eddy viscosity values. Bathymetry data is collected in the form of *XYZ* coordinates. Roughness values are assigned to a particular element based on the material properties visually observed at that element's location within the study reach. Similarly, one can specify eddy viscosity values that are characteristic of each bed material and assign viscosity values for each element depending on the bed material found at that element's location. One can also assign eddy viscosity values such that each element has a specified Peclet number (USACE, 1996). The typical, but not only, means of applying boundary conditions in RMA-2V is to specify a total flow rate at the upstream boundary and a water surface elevation at the downstream boundary.

Of the data described above, bathymetry data is the most important. According to USACE (1996), 80% of the ability to produce accurate model results depends on using appropriate bathymetry data, mesh design, and boundary conditions. The amount of time needed to collect this information, particularly the bathymetry data, depends on the complexity of the channel's geometry.

3. Study methodology

3.1. Site description

A 400-m reach on the North Fork of the Feather River near Belden, California, USA, is selected as the study site. The river, like many of the rivers in the area, is regulated by an upstream dam. This regulation provides steady flows within the study site. Specifically, the study site has a flow rate of approximately 4.25 m^3/s in the summer and 2.10 m^3/s in winter. The channel width varies between 15 and 20 m, while the average slope is 0.012. A typical mountainous trout stream, the river contains a variety of pools, riffles, runs, and small cascades. Maximum channel depth ranged from approximately 0.4 m in the riffles and runs to 1.5 m in the pools. The channel's bottom consists almost entirely of cobble and boulder sized rocks. The larger boulders often create complex flow patterns and potentially good habitat.

3.2. Bathymetry data

Bathymetry data for the study site was collected in the form of *XYZ* coordinates, using a Leica TC 600 total station. Coordinates were surveyed primarily along 25 cross-sections throughout the 400-m reach. The distance between cross-sections depended on how fast channel geometry was changing. The faster it changed, the closer cross-sections were spaced. The minimum distance between cross-sections was 6 m, while the maximum was 36 m. Additional *XYZ* coordinates between cross-sections were surveyed to describe obstructions such as large boulders and scour holes that significantly impacted local flow patterns. The process of determining what constituted an obstruction relied on subjective judgement. The authors decided to incorporate only obstructions that protruded (or, at the lower discharge, could protrude) above the water surface and visibly altered flow conditions around the object. Bathymetry data on an obstruction was typically collected with five *XYZ* coordinates; four surveyed at the base of the obstruction, and one surveyed at the top. Additional *XYZ* coordinates were later added around the obstruction's bases to prevent the creation of artificial bars. The crude representation of the boulders is meant only to capture, to some degree, the significant velocity gradients, velocity refuges, lateral flows, and other local 2-D flow patterns triggered by the presence of the boulders. The obstructions in this case were boulders that had basal areas ranging from 0.56 to 4.10 m^2 and heights ranging from 1 to 2 m. A few additional *XYZ* coordinates were surveyed within the flood plains. Over 600 spot elevations were collected. The time it took to collect this data was approximately 200 person hours.

3.3. Boundary conditions and model parameters

Boundary conditions for the study site were established by measuring discharge at the upper most cross-section and surveying water surface elevations at the lower most cross-section for two separate discharges. Discharges were 2.18 and 4.24 m^3/s, respectively. Since no tributaries joined the modeled section of the stream, discharge was assumed to be constant throughout the study site. Channel bed roughness was estimated based on a Manning's *n*

roughness value table. Moreover, as distinct differences in bed material were difficult to identify within the study reach, a Manning's coefficient of 0.05 was used throughout the reach. The boundary conditions measured during the 4.24 m^3/s discharge were used in all the model simulations presented here. Specifically, the upstream boundary condition was given as a flow rate (4.24 m^3/s) and the downstream boundary condition was given in the form of head (water surface elevation equal to 721.13 m). Eddy viscosity was assumed to be isotropic and allowed to vary on an element by element basis as described by USACE (1996). Specifically, RMA-2V was set to automatically assign eddy viscosity values such that each element would have a specified Peclet number. The Peclet value chosen was 20.

Typically, when performing 2-D hydraulic model studies roughness and turbulence parameters are adjusted to calibrate the model so that model results match measured depth and velocity values taken in the field as closely as possible. Such an approach, however, can lead to the assignment of unrealistic parameter values that mask the influence of meso-scale flow patterns. Here, it was decided not to calibrate the model and attempt to duplicate the exact flow conditions at the study site, but to assign roughness and eddy viscosity values representative of natural streams and observe how the addition of meso-scale topographic features to the modeled channel geometry influence model output. The model results should, therefore, be indicative of the influences that individual boulders and other topographic features have in other natural streams, particularly as 80% of the ability to produce accurate model results depends on using appropriate bathymetry data, mesh design, and boundary conditions USACE (1996).

3.4. Fish location data

Fishery personnel studying the site collected the locations of juvenile rainbow trout at the 4.24 m^3/s discharge. Fish locations were obtained by snorkeling the entire reach and marking the precise locations of young trout with flagged bolt washers. The fish locations were then surveyed. Knowing the exact fish locations within the reach provided a means of determining the effects that the presence or absence of obstruction data has on predicted flow conditions at the trout locations.

3.5. Model reach

While bathymetry data was collected to model the entire 400-m study reach, only the lower 61 m (or approximately four channel widths) of the study site has been modeled to date. Reasons for modeling this section of river are, first, flow is sub-critical throughout the reach; second, a variety of macro- and meso-scale flow patterns are present; and third, 10 juvenile trout were located within the reach. Sub-critical flow is necessary in order to run RMA-2V. Model results confirm subcritical flow conditions and estimate a maximum Froude number of 0.64 for the modeled reach. The macro- and meso-scale flow patterns are ideal for studying the ability of the model to predict meso-scale flow patterns. The 10 juvenile trout locations provide a means of determining the effect the inclusion or exclusion of boulder geometry has on predicted habitat conditions at actual fish locations. The modeled area represents the upstream portion of a large pool. Several large boulders near the head of the pool create a variety of localized flow patterns. These features include a transverse flow from the west bank to the east bank and a velocity refuge immediately downstream of the boulders' position (along the west bank). A top view of the modeled reach along with the fish locations, and *XYZ* coordinates is shown in Fig. 1.

3.6. Mesh preparation

The study site was modeled using a variety of finite element meshes which were designed to investigate three items: (1) the effect that mesh refinement has on model results, particularly when obstructions are introduced; (2) the effect that the presence, or absence, of meso-scale obstruction data can have on flow conditions within a river; and (3) the effect that size and location of a single obstruction can have on flow conditions within a stream. This section describes how the various meshes were generated and used to investigate these issues. The next two sections describe the results generated from these meshes.

Four meshes with different degrees of refinement were created to investigate the impact mesh refinement

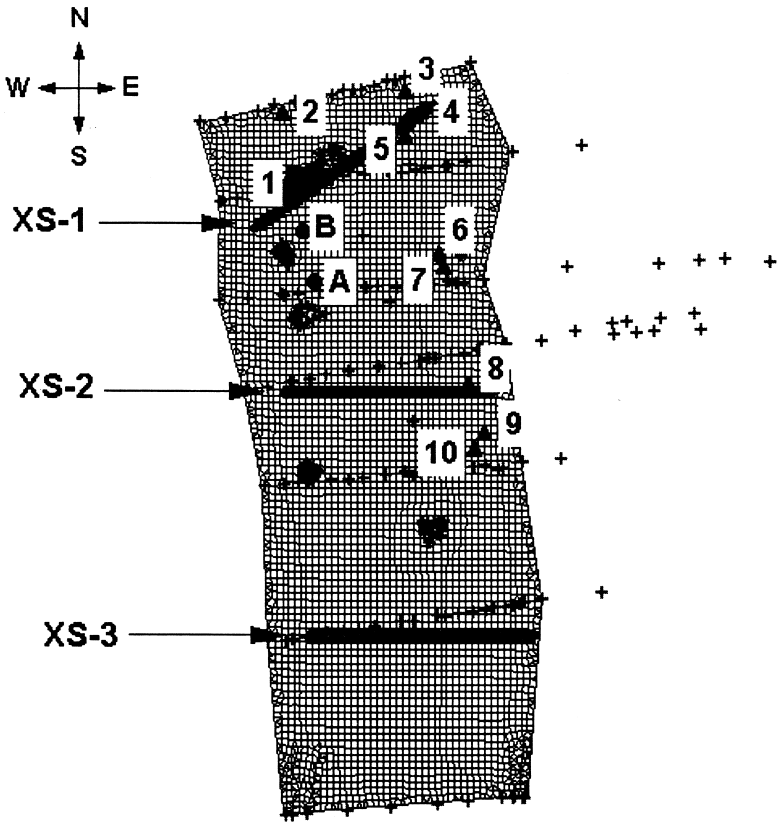

Fig. 1. Top view of the modeled site. The second coarsest finite element mesh is shown here. The plus signs are the locations of the surveyed *XYZ* coordinates. The clusters of *XYZ* coordinates represent the locations of boulders. The triangles represent positions where juvenile trout were found in the pool. XS-1, XS-2, and XS-3 are the locations of cross-sections used to help determine the influence boulder geometry and mesh refinement has on model output. XS-2 is 20 m downstream of XS-1 while XS-3 is 40 m downstream of XS-1.

has on model output. Each mesh was created using an adaptive tesselation algorithm within BOSS' SMS (a commercially available pre- and post-processor for RMA-2V). Mesh node elevations were then interpolated to each of the four meshes using two different data sets. The first interpolation data set consisted of all the bathymety data collected within the modeled area excluding data on obstructions. The second data set consisted of all the data points from the first data set plus *XYZ* coordinates describing boulder/obstruction geometry. Table 1 summarizes the number of elements, nodes, average element size near the boulders and average element size far away from the boulders in each of the four meshes. The first mesh did not use refine points at the boulder locations and created a fairly uniform mesh. Meshes 2–4, however, had refine points on the boulders and created meshes that had smaller elements in the vicinity of the boulders and larger elements far away from them. Figs. 1 and 2 show the second coarsest and most refined meshes, meshes 2 and 4, respectively.

Interpolating each data set to a specific mesh assigns different elevations to the nodes in the mesh, but keeps the number and position of the elements the same. Consequently, when two meshes of the same refinement are compared, any differences in model output are a result of the differences in bathymetry data. Such a comparison is made later, using the most refined mesh (mesh 4 in Table 1) to study what effect the presence or absence of obstruction bathymetry data has on predicted habitat conditions within the study site.

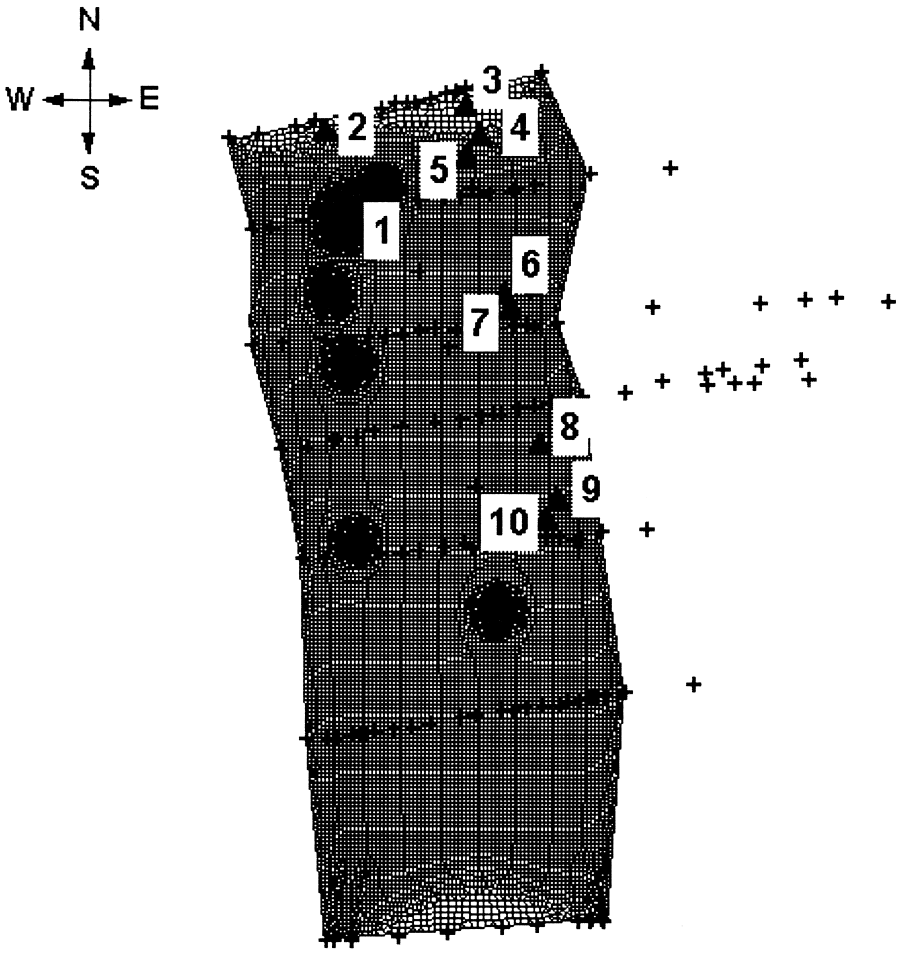

Fig. 2. Most refined finite element mesh. The plus signs are the locations of the surveyed *XYZ* coordinates. The triangles represent positions where juvenile trout were found in the pool.

Meshes that contain information on more than one boulder will generate flow fields that reflect the combined effects of all the boulders in the study site. Four additional meshes, as described in Table 2, were generated to determine how a single obstruction's size and location might impact local flow conditions within a river. These meshes differed slightly from one another in the exact number and position of elements, but were designed to have about the same mesh refinement as that used in Mesh 4. The

Table 1
Meshes used to model the site with and without obstructions being present

Mesh	Number of elements	Number of nodes	Average element size near boulders (m^2)	Average element size away from boulders (m^2)
1	1182	3595	1.252	1.270
2	4776	14 237	0.175	0.327
3	16 927	50 598	0.076	0.082
4	19 321	57 462	0.025	0.082

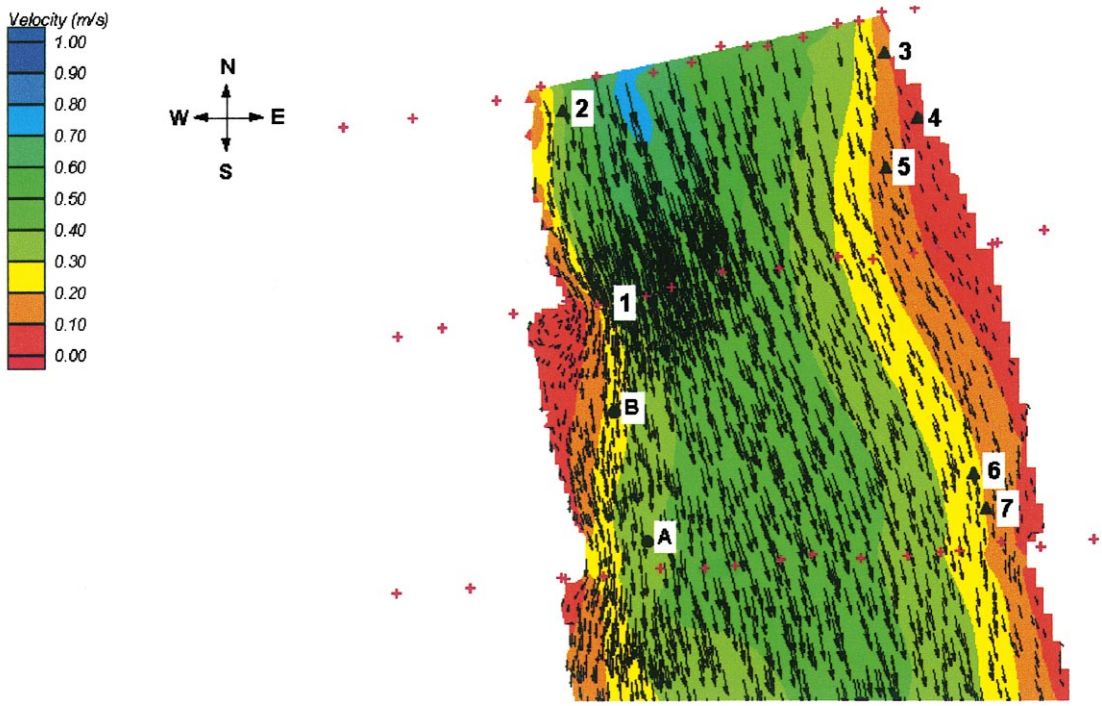

Fig. 3. Model velocity output for the pool when boulders are not present. Arrows represent the direction of flow and are scaled to velocity magnitude. Color contours give the magnitude of the velocities within the pool. Triangles represent locations within the pool where young trout were located and local model velocity gradients were calculated. Circles represent additional locations were model velocity gradients were calculated. Mesh #4 is the underlying mesh.

first three meshes (meshes 5–7) focus on the role obstruction size has on local flow conditions. The fourth mesh (mesh 8) highlights how a single obstruction's location can impact local flow conditions.

Meshes 5–7 were generated by adding the geometry of a single square obstruction to the bathymetry data used to model the site without any obstructions present. The dimensions of the each obstruction are different. Mesh 5 incorporates the geometry of a $0.914 \times 0.914 \times 0.51$ m^3 obstruction; meshes 6 and 7 contain obstructions with dimensions of $1.83 \times 1.83 \times 1.02$ and $2.74 \times 2.74 \times 1.53$ m, respectively. Each of the obstruction's lower left corner is located at the same coordinates in each mesh (near fish location 1 in Figs. 1–3). The larger the obstruction, the further it extended toward the center of the channel. Table 2 lists the number of elements, average element size used near the boulders, and nodes used in each mesh. Mesh 8 represents the geometry of the largest boulder found in the study site. The boulder is located

Table 2
Meshes used to model single obstruction scenarios

Mesh	Obstruction base dimensions (m)	Obstruction height (m)	Elements in mesh	Nodes in mesh	Average element size near boulders (m^2)	Average element size away from boulders (m^2)
5	0.914×0.914	0.51	17 447	52 194	0.031	0.082
6	1.83×1.83	1.02	17 449	52 202	0.030	0.082
7	2.74×2.74	1.53	17 479	52 280	0.030	0.082
8	2.26×2.11	1.99	16 828	50 362	0.034	0.082

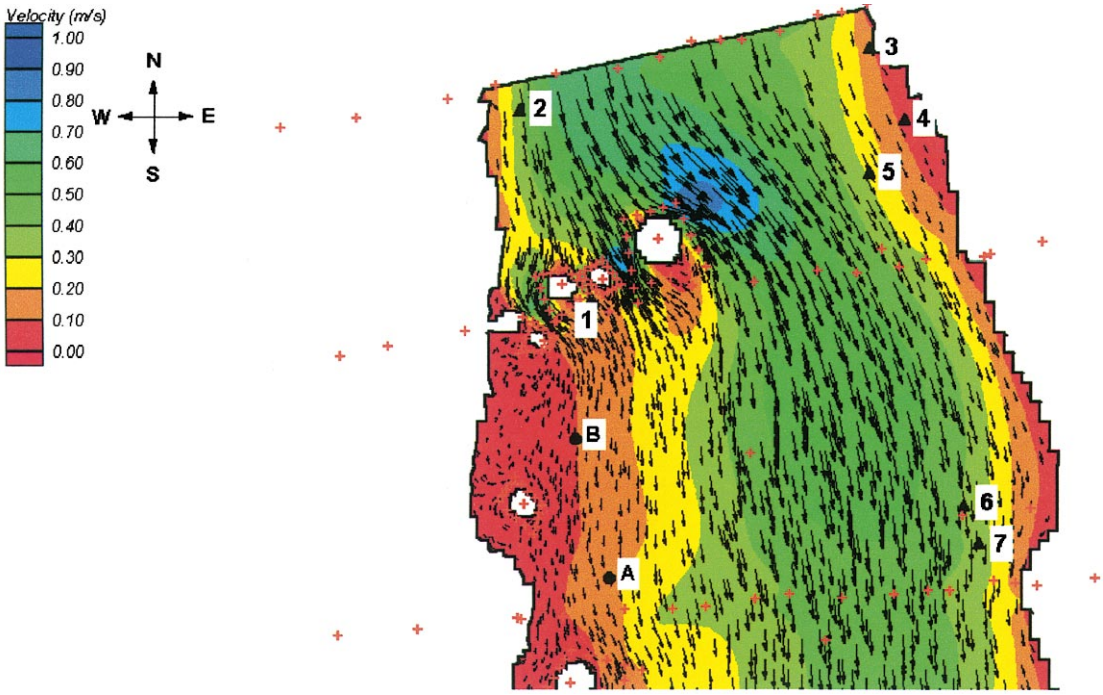

Fig. 4. Model velocity output for the pool when boulders are incorporated into the model's bathymetry. The six boulders shown here appear as white shapes completely surrounded by the flow. Mesh #4 is the underlying mesh.

near the boulders in meshes 5–7, but further out in the channel. The approximate dimensions of the boulder, the number of elements used in mesh 8 and the elements average size used near the boulder are listed in Table 2 as well.

4. Results

4.1. Obstruction analysis

An evaluation of how the presence of obstructions affects predicted flow patterns and their subsequent habitat conditions is provided here. Specifically, model output from the most refined mesh (mesh 4) without obstruction data is compared to model output from mesh 4 with obstruction data. An analysis of model output from meshes 5–8 is also provided to evaluate the influence the size and location of a single obstruction have on a stream's local flow patterns.

Results of modeling the study site without and with all the boulders included in the bathymetry data are shown in Figs. 3 and 4, respectively. In the absence of boulders, flow remains largely parallel to the channel banks. The current is slightly swifter on the west (left) bank than on the east (right) bank. When the boulders are incorporated into the model, a substantial transverse flow near the top of the pool is predicted. The current now becomes much swifter near the east bank than the west bank and the maximum velocity in the pool increases by 21%. Immediately downstream of the boulders complex flow patterns are predicted. These intricate flow patterns have areas with velocity values up to 96% less than those predicted without boulders. Moreover, these low velocity areas are surrounded by steep velocity gradients also not previously predicted. The conditions modeled with the boulders present are much more indicative of the flows visually observed at the model site.

The degree to which a specific point's predicted velocity, depth, and velocity gradients change due to the presence, or absence, of obstructions depends on the point's relative location to the boulders. Fig. 5 depicts the change in velocity magnitude that occurs

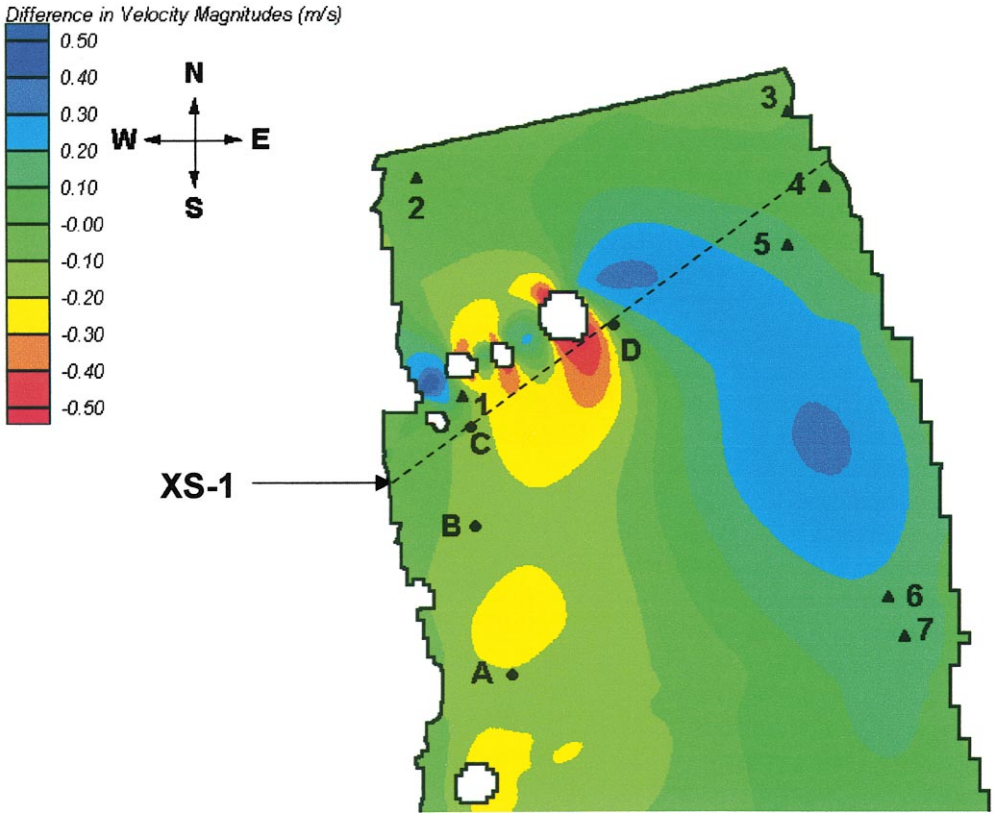

Fig. 5. Contour plot showing the differences in velocity magnitudes predicted by modeling the site with and without obstructions in the bathymetry data. Positive values show the areas that the presence of the boulders increase predicted velocity values. Negative values show the areas that experience decreases in velocity due to the presence of the boulders. Mesh #4 is the underlying mesh.

within the upper 20-m of the study reach when boulders are added to the model's bathymetry data. The color contours indicate that over half of this region experiences velocity changes of 0.10 m/s or greater. A change in velocity of 0.10 m/s corresponds to 12% of the maximum predicted flow velocity or 37% of the average predicted flow velocity. These changes in velocity are largely positive toward the east bank and negative along the west bank. The largest of these changes, in excess of 0.50 m/s, occur in the immediate vicinity of the boulders. Moreover, Fig. 5 illustrates that these changes are both positive and negative and exhibit spatial arrangements that tend to significantly increase the velocity gradients in the vicinity of the boulders. To demonstrate the effect that the presence of boulders has on local velocity gradients, the lateral velocity profiles generated immediately downstream of four boulders (cross-section XS-1 in Fig. 5) for the two scenarios were compared in Fig. 6. Point C reflects the location along cross-section 1, XS-1, which has the largest velocity gradient when boulders are not explicitly modeled. Point D reflects the location of the maximum velocity gradient occurring along XS-1 when the boulders are present. The velocity gradients for these two points are 0.184 and 0.537 s^{-1}, respectively. Thus, the presence of the boulders creates velocity gradients 2.92 times greater than predicted in the absence of boulder geometry. It should also be emphasized that the velocity profile generated with the incorporation of boulder geometry is far more sinuous than that produced without boulder geometry. Capturing such spatial variability is particularly important. The velocity refuge produced by the boulders (found at distances of 0–6.0 m along XS-1) is a potential location where periphyton and invertebrates might

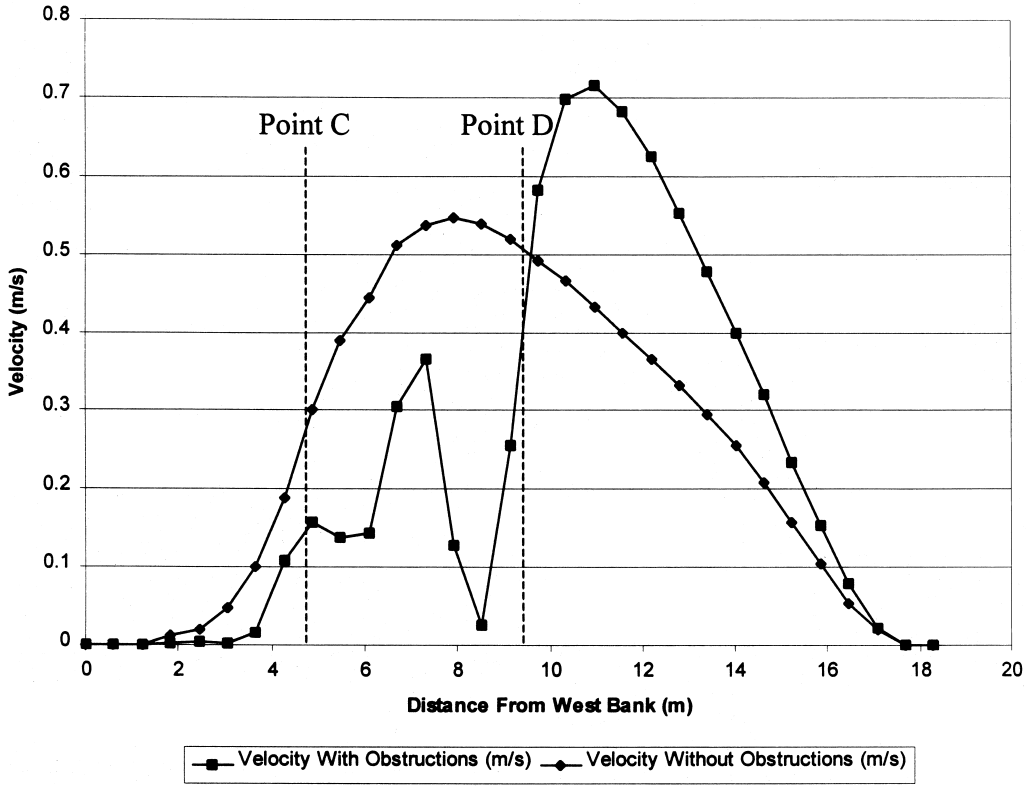

Fig. 6. Velocity profiles along XS-1 (shown in Fig. 5). The dashed lines represent the locations where points C and D cross the profiles. Point C refers to the location having the maximum velocity gradient when boulder geometry is not incorporated into the model. Point D is the location having the maximum velocity gradient when boulders are incorporated into the model.

receive some protection from high flows. Likewise, the low velocity values surrounded by high velocity gradients found between 7.5 and 9.0 m along XS-1 are indicative features of a trout feeding station.

Table 3 tabulates the predicted velocity, and lateral velocity gradients (with and without obstructions) at each fish location, points C and D, and two arbitrary locations (points A and B) shown in Figs. 3–5. On average the 10 fish locations experience a 33% change in velocity and a 22% change in the velocity gradients surrounding them. Locations 2, 3, 9, and 10 experience little change in predicted velocity values, but experience significant changes in velocity gradient. Points 1, 4–8, and A experience significant changes in velocity, and velocity gradient values. Points A and B experience an average decrease of 57% in velocity and 18% in velocity gradient. As drag force increases with velocity squared, fish located at points 5–7 experience nearly 3.25 times the drag predicted by the model not incorporating boulders. Whether or not changes of this magnitude actually influence juvenile habitat selection remains unknown. The observation that most of the trout were located within the region influenced by the boulders' presence suggests that the boulders and the changes in flow patterns they induce may be significant. Table 4 shows that the presence or absence of the boulders does not significantly change average flow-conditions within the pool. Consequently, if local velocity gradients and velocity refuges are important to aquatic habitat, average flow conditions cannot be used to describe habitat conditions within a study reach, even if the model incorporates local topography.

The above results clearly demonstrate that the presence of the boulders significantly affects predicted flow and habitat conditions within the pool. However, the arrangement of the boulders near the head of the pool masks the relative importance of a single

Table 3
Comparison of flow parameters at locations within the modeled reach

Location	Without obstructions		With obstructions	
	Velocity (m/s)	Velocity gradient (m/s/m)	Velocity (m/s)	Velocity gradient (m/s/m)
1	0.249	0.238	0.218	NA
2	0.387	0.152	0.360	0.233
3	0.141	0.066	0.132	0.148
4	0.048	0.084	0.075	0.076
5	0.151	0.072	0.279	0.128
6	0.218	0.092	0.387	0.108
7	0.190	0.079	0.347	0.124
8	0.184	0.082	0.241	0.099
9	0.145	0.065	0.142	0.090
10	0.218	0.103	0.212	0.075
A	0.372	0.108	0.178	0.062
B	0.243	0.055	0.096	0.058
C	0.171	0.184	0.147	0.083
D	0.512	0.045	0.424	0.537

boulder. To examine the influence of single obstructions, model output from meshes 5–8 (described in Table 2) was compared to the model output generated with no obstructions present (mesh 4 without obstructions). Specifically, velocity output from these five different scenarios was analyzed along the three cross-sections (XS-1, XS-2 and XS-3) shown in Fig. 1. XS-1 is located immediately downstream of the four boulders at the upper portion of the study site. The single obstruction in meshes 5–8 was similarly placed near the west bank just upstream of XS-1. The other two cross-sections (XS-2 and XS-3) are approximately 20 and 41 m downstream of XS-1, respectively. These distances can also be described as approximately 9 and 18 times the diameter of the largest boulder. Fig. 7 shows the resulting velocity profiles measured across XS-1. The presence of a single obstruction placed near the bank creates higher velocity gradients near the banks, shifts the velocity profile to the right, and increases the maximum velocity. The larger this obstruction the more pronounced these effects become. The fourth obstruction, located further out in the stream, forces the velocity to increase substantially on both sides of the obstruction and creates a pronounced wake. At XS-2, shown in Fig. 8, all four velocity profiles are very similar to each other. In each case, the obstruction is shifting the velocity profile slightly to the right of the profile generated by the exclusion of boulders. Consequently, the presence of a single obstruction, regardless of size or location, is not significantly impacting flow conditions this far downstream. At XS-3 velocity profiles (not shown here) are virtually identical.

A single obstruction need not influence a large portion of the river to significantly impact a river's habitat conditions. Fig. 9 depicts the same portion of the study site modeled three ways: without obstructions (mesh 4) and with a single obstruction (meshes 6 and 8). Observations from Figs. 7–9 indicate that a

Table 4
Model average nodal results using most refined mesh

Model conditions	Maximum depth (m)	Maximum velocity (m/s)	Average depth (m)	Average velocity (m/s)	Average water surface elevation (m)
Without obstructions	1.50	0.71	0.78	0.28	721.140
With obstructions	1.49	0.86	0.77	0.27	721.137

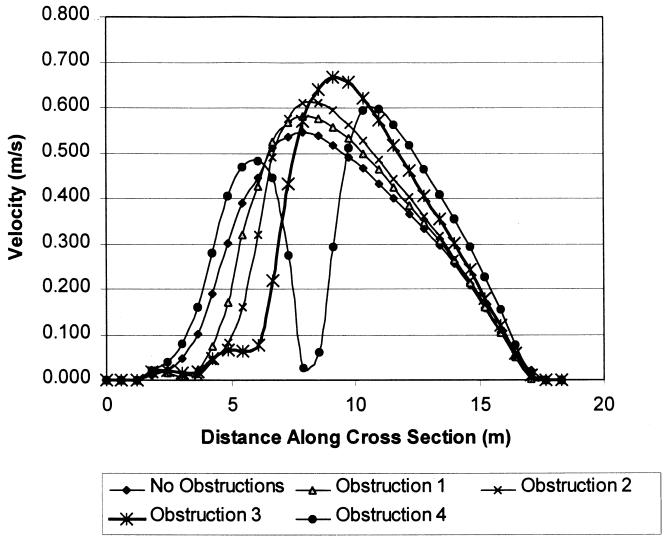

Fig. 7. Velocity profiles along XS-1 that were generated by the meshes having a single obstruction incorporated into their bathymetry data. Obstructions 1–3 correspond to meshes 5–7 in Table 2, which have square obstructions of increasing size at the same location. Obstruction 4 corresponds to mesh 8, which incorporates bathymetry data on the location and dimensions of a boulder found farther out in the stream than obstructions 1–3.

single obstruction appreciably impacts downstream flow conditions only to a distance of about 6–8 times the obstruction's diameter. These localized flow patterns, however, have unique features that may provide important habitat. Suppose that an aquatic organism prefers to live in slow eddies that have velocities between 0 and 0.10 m/s (shown in dark red). Fig. 9a and b demonstrates that by adding

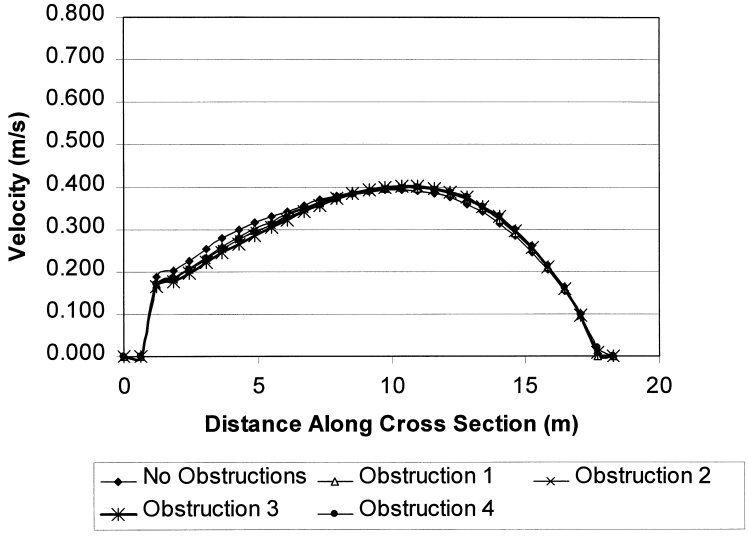

Fig. 8. Velocity profiles along XS-2 that were generated by the meshes having a single obstruction incorporated into their bathymetry data. Obstructions 1–3 correspond to meshes 5–7 in Table 2, which have square obstructions of increasing size at the same location. Obstruction 4 corresponds to mesh 8, which incorporates bathymetry data on the location and dimensions of a boulder found farther out in the stream than obstructions 1–3.

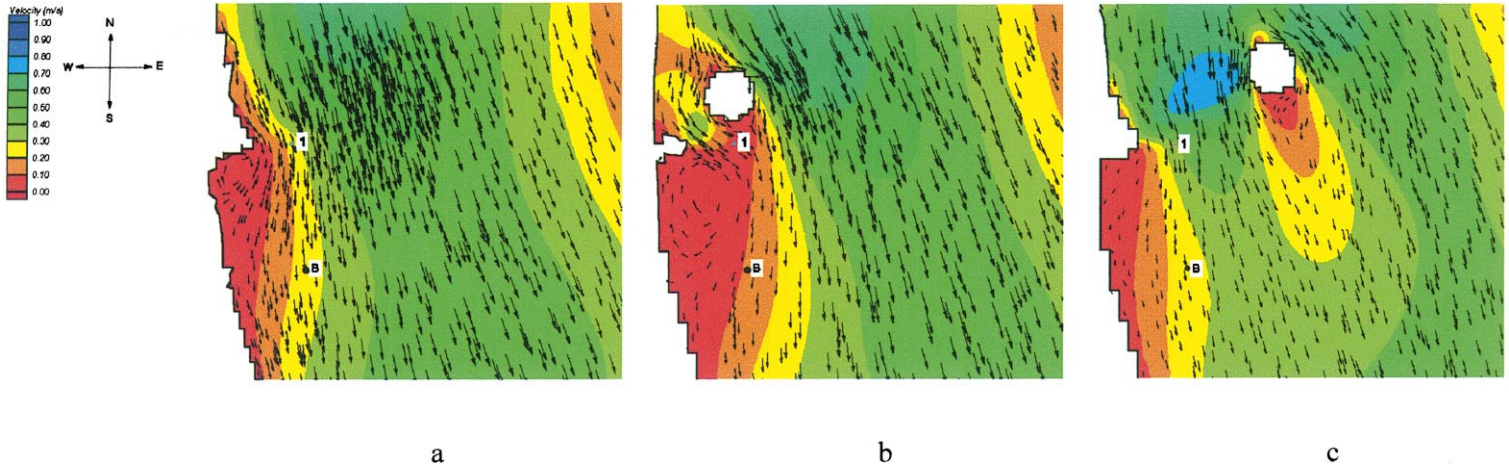

Fig. 9. The effect obstruction size and placement has on local habitat conditions. The plots represent enlarged views of habitat conditions near the obstructions. Velocity conditions without any obstruction present are shown in (a). (b) Reflects the influence of a 1.83×1.83 m^2 obstruction placed near the bank. (c) Depicts the flow conditions produced by a single 2.26×2.11 m^2 boulder placed further out in the stream.

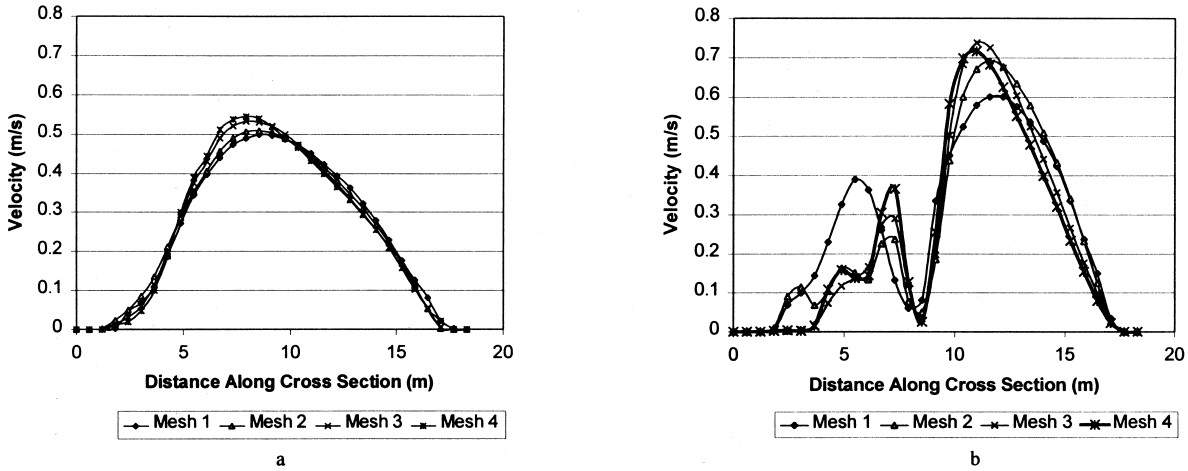

Fig. 10. The effect of mesh refinement on velocity profiles at XS-1. Meshes 1–4 refer to the meshes described in Table 1. Profiles generated with meshes not containing data on boulder geometry are shown in (a). Velocity profiles generated with meshes containing information on the presence of boulders are shown in (b). Distance is measured from the left (west) bank.

just a single obstruction (Fig. 9b) into the model the area exhibiting these conditions can double. Consequently, the actual useable habitat could be substantially underestimated by ignoring a number of isolated obstructions creating these features. Likewise, if biologists were to determine that velocity shelters surrounded by steep velocity gradients were indicative of good trout habitat, Fig. 9c would probably be a far better indicator of actual habitat conditions than Fig. 9a.

4.2. Sensitivity analysis

While coarse mesh elements reduce computer time and allow the modeling of larger river segments, they may also prevent the model from accurately quantifying important local flow features that influence stream habitat. Consequently, when modeling meso-scale flow patterns one must not only assure that the bathymetry data is capable of reproducing flow patterns of interest, but that the numerical model's mesh is capable of accurately quantifying these patterns. One common means of assessing a model's numerical accuracy is to compare the results of the original (coarse) mesh to a second, more refined mesh. If significant changes in model results occur, then an even more refined mesh is needed, if not, the original mesh is sufficiently refined.

Such sensitivity analyses were performed using the meshes summarized in Table 1 to determine the effects that the presence of boulder geometry and mesh size have on numerical accuracy. Specifically, velocity profiles produced by meshes 1–4 (with and without obstructions) were evaluated at cross-sections XS-1, XS-2, and XS-3 (shown in Fig. 1). Fig. 10a and b graphs the magnitude of these velocity profiles at XS-1. The velocity profiles generated in the absence of boulders differ modestly with increasing refinement. The maximum velocity increases by 8% and shifts 0.61 m toward the west bank of the river with increased refinement. More pronounced changes in the velocity profile occur with the presence of boulders (Fig. 10b). Mesh refinement increases the maximum velocity by 19% and causes the two highest peaks in the velocity profile to undergo lateral shifts. The first peak shifts 1.8 m toward the east bank; the second shifts 0.6 m toward the west bank. Increasing mesh refinement also substantially alters the shape of the velocity profiles in the immediate vicinity of the boulders (2–10 m from the west bank). The profile changes from having two local maximum points to a profile having three local maximum points. The velocity at 5.5 m from the left bank decreases 64% with mesh refinement. It should also be emphasized that at 8.5 m from the bank the velocity obtained using mesh 4 with obstructions is 96% less than the velocity predicted using mesh 4 without boulders present. Such changes in the velocity profile demonstrate the

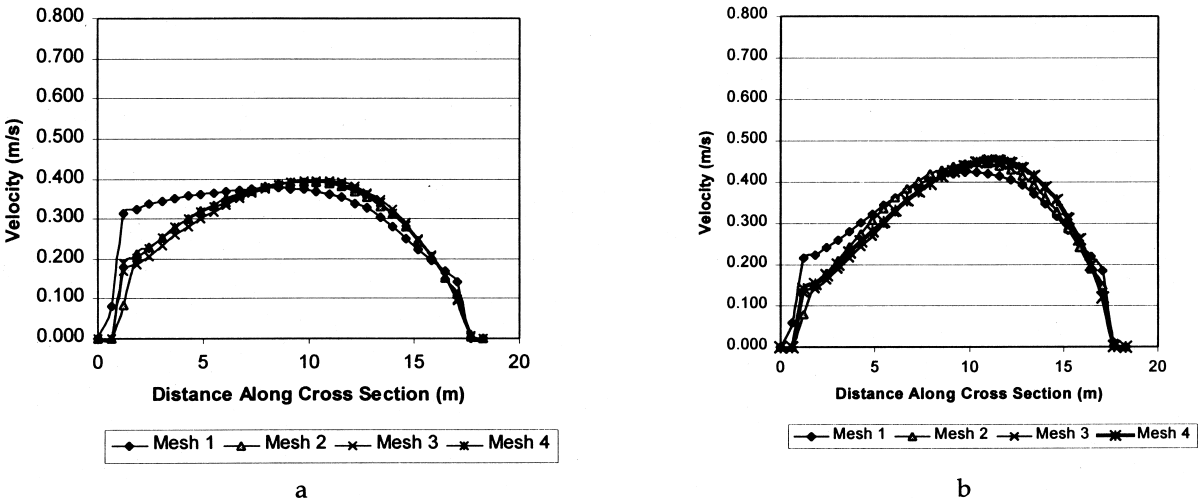

Fig. 11. The effect of mesh refinement on velocity profiles at XS-2. Meshes 1–4 refer to the meshes described in Table 1. Profiles generated with meshes not containing data on boulder geometry are shown in (a). Velocity profiles generated with meshes containing information on the presence of boulders are shown in (b). Distance is measured from the left (west) bank.

importance of incorporating boulders into the channel geometry and reducing mesh size in the immediate vicinity of the boulders. However, even the coarsest mesh incorporating boulder geometry is far more representative of actual field conditions than the most refined velocity profile containing no information on the boulders.

Fig. 11a and b demonstrates that, unlike the single obstruction in meshes 5–8, the boulders in mesh 4 are still significantly influencing the flow patterns at XS-2. This additional influence over downstream flow conditions is due to the four closely spaced boulders that act much like a single large obstruction. The boulders shift the velocity profile to the right and increase the maximum velocity. However, the velocity shelters and velocity gradients found in the immediate vicinity of the boulders are no longer present at XS-2. Mesh refinement causes the velocity profiles (with and without boulders) to shift toward the east bank and increase the maximum velocity slightly. Without boulders, this velocity increase is 4.8%; with boulders, the velocity increase is 6.4%. In both cases, the coarsest mesh provides substantially different velocities near the west bank. Such deviations near the bank can be expected and are an indication that meshes should be refined near banks where steep slopes and velocity gradients often exist.

The velocity profiles at XS-3 (not shown here) change very little with increased mesh refinement. In both cases, only the velocity profiles of the coarsest mesh differ significantly with the more refined mesh profiles and these differences are restricted to areas close to the west bank. Moreover, unlike at XS-1 and XS-2, not only are the velocity profiles not changing with mesh size, but also the profiles with boulders are very similar to profiles without boulders. Hence, the presence or absence of the boulders at the top of the pool is not impacting flow conditions at XS-3 as they were at XS-1 and XS-2. If one assumes that the four boulders upstream of XS-1 act as a single obstruction having an effective width of 4.7 m (the width across the four boulders), the boulders influence downstream flow patterns to a distance of approximately 4–8 times the effective width.

While Figs. 10 and 11 cannot provide information on how dense a mesh should be in a particular instance, they demonstrate the importance of using finer meshes in the vicinity of steep velocity and bathymetry gradients. An unfortunate consequence of needing small elements to accurately capture velocity gradients, particularly in narrow channels having numerous boulders, is that these small element sizes may prevent substantially larger elements from being used throughout the rest of the study site. To avoid

Table 5
Comparison of mesh sizes used in various studies

Study	Channel parameters			Mesh size parameters		
	Flow rate (m^3/s)	Average width (m)	Length (m)	Number of elements	Number of nodes	Average area per element (m^2)
Waddle et al. (1996)	4.0–21.0	35–50	315	6508	3302	4.05
Leclerc et al. (1995) (two sites)	90–330	–	102 (site 1)	1114 (site 1)	2382 (site 1)	–
		152	402 (site 2)	800 (site 2)	1700 (site 2)	76.0
Ghanem et al. (1996)	14.6	50	245	1516	853	8.08
Present study	4.24	15	61	1182–19 321	3595–57 462	1.27–0.082

large errors and instabilities finite element meshes are required to increase or decrease element sizes slowly throughout a mesh. Consequently, when automated meshing programs are employed to increase element sizes in areas away from the refine points (as was done in this study), mesh elements may not get particularly large. Here, mesh 1 was an almost uniform mesh having element sizes of about 1.27 m^2 or $(1.46d)^2$, where d is the average flow depth within the pool. Mesh 4 used element sizes varying from 0.025 m^2 or $(0.20d)^2$ in the vicinity of the boulders to 0.082 m^2 or $(0.37d)^2$ in regions outside the influence of the boulders. As all the velocity profiles except the coarsest mesh are nearly identical at XS-3, the elements near XS-3 in mesh 2 are small enough to adequately capture the velocity profiles away from the presence of the boulders. These elements have areas of approximately 0.33 m^2 or $(0.75d)^2$.

The necessity of using small element sizes to accurately capture meso-scale flows patterns may dictate adopting finer meshes than those previously used in flow modeling studies. Table 5 compares the average mesh properties used here to average mesh properties used by some previous researchers. A more appropriate approach would be to compare the average element size used in the vicinity of obstructions within these meshes. Unfortunately, such a comparison cannot be made as previous studies did not report the exact sizes of individual obstructions surveyed (if any) or the degree to which mesh refinement was employed near such obstructions. However, Table 5 does provide an indication of the computational power needed to capture the meso-scale flow patterns studied here as compared to other studies.

The computer used to run the RMA-2V simulations in this study was a DELL XPSR450 with 256 MB of RAM. The time it took for the computer to complete one iteration was about 2 s for mesh 1. This number increased to approximately 560 s for mesh 4. The number of time steps and iterations necessary to complete a simulation can vary dramatically. In addition to the number of elements in a mesh, factors such as the flow conditions at the study site, the wetting-drying options used and whether the simulation is steady or unsteady influence the total computation time. In the present model simulations, the total run time ranged from 10 s to 50 min.

Figs. 10 and 11 demonstrate how mesh refinement is a scale issue in habitat studies. The degree of mesh refinement needed depends on two items: (1) the accuracy and resolution needed in the model as determined by stream biologists and flow modelers; and (2) the degree to which the channel-bed geometry changes and has been described in the model. If the model's bathymetry data fails to incorporate the topographic features creating the flow patterns of interest, model output will not reproduce the meso-scale flow patterns they create regardless of mesh refinement. Using overly large elements in areas of rapidly changing topography will provide poor resolution of the meso-scale flow predictions.

5. Discussion

An important step in performing a hydraulic modeling study is determining what flow parameters are pertinent to the study and what type of model is needed to obtain this information. For example, the most important parameter in flood plain analyses is

river stage. The river's stage will determine how much area is inundated. Accurate description of velocity gradients and spatial variations in flow is not of primary concern and a 1-D model is sufficient for obtaining river stage. In aquatic habitat studies, selecting the appropriate model is not so simple. Factors such as the species and life stages of the aquatic organisms being studied dictate to what degree and accuracy depth, velocity, velocity gradients, and localized flow patterns need to be described. A 1-D model may suffice for a habitat study requiring only an accurate description of the river's macro-scale flow patterns. Alternatively, a 2-D model excluding information on topographic features could be used to describe the macro-scale flow features. However, a 2-D model that incorporates obstructions into the bathymetry may be necessary for a habitat study requiring an accurate description of both macro- and meso-scale flow patterns. Likewise, a 3-D model may be required to study macro-invertebrate habitat where the flows around submerged obstructions may be important. Consequently, a key step in using hydraulic models in habitat studies is for biologists, ecologists and flow modelers to jointly determine the spatial flow patterns, parameters, resolution, and accuracy that need to be achieved with the model. Only then can steps be taken to select the most efficient and appropriate model for a study. Such information may also provide new and improved habitat metrics based on better defined local and spatial parameters.

Another important consideration in model selection is the labor and computational costs involved with a specific study site. Both the computational cost and data necessary to describe the channel geometry and flow characteristics increase with model dimensionality. Lower dimensional models are better suited to model longer stretches, but sacrifice spatial resolution. Observations by Leclerc et al. (1995), Ghanem et al. (1996), and Waddle et al. (1996) suggest that in certain cases the data needed for input into 2-D models may require less time to collect than the data needed to perform PHABSIM simulations. However, no controlled studies have been performed to directly compare the labor requirements. The main advantage of using 2-D models in habitat studies is their ability to sufficiently reproduce spatial variations that 1-D models cannot adequately predict, but may be too costly to obtain with 3-D models.

Two streams with similar depths, average velocities, and slopes can produce entirely different habitat conditions. Often, the difference in habitat conditions lies in the availability of certain spatial variations in depth and velocity within the river reach. Consequently, the topographic features that create these important spatial variations in natural streams need to be incorporated into models. Crowder and Diplas (2000), building on the modeling results described here, propose spatial habitat metrics that characterize such flow patterns and provide stream biologists a potentially better means of locating and quantifying suitable habitat. The incorporation of medium size topographic features into 2-D models is not straightforward. One must decide which feature sizes to incorporate and which sizes to exclude based on the study's needs. This selection will determine the extent to which bathymetry will need to be surveyed. Researchers need to clearly state what types of features were surveyed and how these features were surveyed so that the influence of channel topography on model output can be more thoroughly evaluated.

Sensitivity analyses play an integral role in 2-D habitat modeling, even in the absence of boulders. Mesh refinement, particularly near the banks, may significantly impact wetting and drying processes and velocities near the bank. Consequently, even channel topography which can be accurately described with spot elevations taken every 20 m may require element sizes much smaller than $20 \times 20\ m^2$. Sensitivity analyses are also needed to properly calibrate a model. If calibration is performed without a sensitivity analysis, the adjusted channel roughness and eddy viscosity values may be compensating for low numerical accuracy and not variations in actual roughness and eddy viscosity values. For example, increasing roughness coefficients near channel banks to compensate for using a coarse mesh may result in unrealistic roughness coefficients near the banks and thus inappropriate velocity values. Similarly, when obstructions are not included in a model's bathymetry data, the boulders are viewed simply as channel roughness, instead of as part of the channel topography. Any local effects the boulders create are not modeled. Instead, the local effects of the boulders are diffused throughout the modeled stream section via roughness and eddy viscosity values. Consequently, unrealistic roughness coefficients and eddy

viscosity parameters may be assigned during the calibration of the model in an attempt to duplicate the flow velocities and depths induced by the presence of the obstructions.

The exact extent to which topographic features and mesh refinement will affect model predictions will depend on the individual site. Different flow conditions and arrangements of obstructions will affect model results differently. Regardless of the study site, proper description of the channel and mesh development is crucial to obtaining accurate numerical results. The steep velocity gradients, velocity shelters, and other complex flow patterns, found in the immediate vicinity of the boulders cannot be modeled without incorporating boulder geometry into a model's bathymetry data. Moreover, accurate quantification of such flow patterns requires substantial mesh refinement in the vicinity of the boulders and channel banks. The precision to which model results incorporating local topographic features and adequately refined meshes can duplicate actual field conditions needs to be established under a variety of different field conditions. Sources of model error include bathymetry errors (due to either collection or interpolation), insufficient mesh refinement, field measurement errors, and errors in turbulence modeling. Isolating and determining the magnitude of such errors is difficult and makes model calibration and validation problematic.

Two-dimensional models have predictive abilities that may provide crucial information in stream restoration projects. According to Connor (1991), an important step in estimating the scour and deposition that occurs around fishrocks is to visualize and predict how the placement of fishrocks will change the stream's flow patterns. Successfully reproducing the major flow patterns within the study site by incorporating boulder geometry into the channel bathymetry suggests that 2-D models may be useful in determining the placement of fishrocks and other structures needed to create habitat that is self-sustaining and does not require periodic restocking.

6. Conclusions

The use of 2-D models to predict localized flow patterns important to aquatic habitat consists primarily of three steps: (1) determining the type and scales of flow patterns important to the study; (2) collecting bathymetry data at a resolution that allows the model to reproduce the spatial variations important to the study; and (3) refining the model's mesh to a level that provides a solution within acceptable resolution. Numerical simulations based on actual channel and boulder geometry show that the presence or absence of bathymetry data on a series of boulders can significantly influence predicted flow patterns, especially in the vicinity of the obstructions. Flow patterns were affected up to a distance of approximately 4–8 times the width across four closely spaced obstructions at the top of a pool. The boulders had heights ranging from $1.25d$ to $2.80d$ (d is the average flow depth) and had average basal areas ranging from $(0.97d)^2$ to $(2.63d)^2$. The presence of the boulders increased the maximum predicted flow velocity in the reach by 21%. The average predicted velocity and velocity gradients at ten fish locations increased by 33 and 22%, respectively. Steep velocity gradients and local velocity shelters in the immediate vicinity of the boulders were not predicted when boulder geometry was not incorporated into the model.

Mesh refinement played an important role in model resolution especially when obstructions were incorporated into the model's bathymetry data. Reducing mesh element areas from $(1.45d)^2$ to $(0.20d)^2\ \mathrm{m}^2$ in the vicinity of boulders significantly altered the shape of predicted velocity profiles in the immediate vicinity of obstructions. Element areas of $(0.74d)^2$ were needed to describe the flow outside the influence of the boulders. Even the coarsest mesh reproduced much more realistic flow conditions when bathymetry data on the boulders was included in the model than a more refined mesh containing no information on the boulders. Individual obstructions influenced downstream flow patterns up to a distance of approximately 6–8 times the obstruction's diameter and created unique localized flow patterns. If ignored, the abundance of suitable habitat within a reach may be significantly under or overestimated.

The results of the numerical simulations presented here reasonably predicted the meso-scale flow patterns visually observed in the field when boulder geometry was explicitly incorporated into the model. Moreover, they provide information on the

computation cost and types of model resolution one might hope to gain from incorporating meso-scale topographic features into 2-D models. Such information is a first step in the modeling of spatially varying flow patterns and developing spatial habitat metrics that better quantify stream habitat conditions.

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