Reproducing and Quantifying Spatial Flow Patterns of Ecological Importance with Two-Dimensional Hydraulic Models

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Doctor of Philosophy
in
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April 25, 2002

Blacksburg, VA

Keywords: Two-Dimensional Models, Hydraulic Models, Spatial Flow Patterns, Reproducing and Quantifying Flow Patterns, Ecologically Important Flow Patterns

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(ABSTRACT)

Natural streams typically have highly complex flow patterns. Velocity gradients, circulation zones, transverse flows, and other flow patterns are created in the presence of topographic features (e.g. exposed boulders, bars). How flow complexity influences a stream's ecological health and morphological stability, as well as how flow complexity responds to changes in hydrologic conditions, is poorly understood. One-dimensional (1-D) hydraulic models and two-dimensional (2-D) models that do not explicitly incorporate meso-scale topographic features are not capable of adequately reproducing the flow patterns found in channels having complex topography. Moreover, point measurements of depth and velocity, which are used to describe hydraulic conditions in habitat suitability studies, cannot be used to characterize spatially varying flow patterns of biological importance.

A general methodology for incorporating meso-scale topography into 2-D hydraulic models is presented. The method provides a means of adequately reproducing spatial flows of interest to riverine researchers. The method is developed using 2-D model simulations of a reach of the North Fork of the Feather River in California. Specifically, the site is modeled with and without bathymetry data on exposed boulders found within the site. Results show that the incorporation of boulder topography and an adequately refined mesh are necessary for reproducing velocity gradients, transverse flows, and other spatial flows.

These simulations are also used to develop and evaluate three spatial hydraulic metrics designed to distinguish between locations having uniform and non-uniform flow conditions. The first two metrics describe local variations in energy/velocity gradients, while the third metric provides a measure of the flow complexity occurring within an arbitrary area. The metrics based on principles of fluid mechanics (kinetic energy, vorticity, and circulation) can be computed in the field or with 2-D hydraulic model results. These three metrics, used in conjunction with detailed 2-D hydraulic model results, provide engineers, biologist, and water resource managers a set of tools with which to evaluate the importance of flow complexity within rivers. A conceptual model describing how such a tool can be used to help design channels being restored, better evaluate stream habitat, and evaluate how hydrologic changes in a watershed impact hydraulic conditions and concomitant habitat conditions is provided.

Dedication

I would like to dedicate this to my wife, Tricia, and my family who have so lovingly supported me throughout this very long endeavor.

Acknowledgements

Throughout my education at Virginia Tech and the preparation of this dissertation, I have had the fortune of meeting and interacting with many people who have aided me both technically and inspirationally.

First, I would like to thank my wife, Tricia, for her emotional support as well as her editorial inputs.

Second, I would like to thank my major advisor, Dr. Panos Diplas, for his enthusiasm and technical expertise.

Third, I would like to express my gratitude for the input that the rest of my dissertation committee (Dr. G.V. Loganathan, Dr. Donald Orth, Dr. Joseph Schetz, and Dr. David Kibler) has provided.

Finally, I would like to acknowledge some of my fellow graduate students and friends who have made my education a deeper and more enjoyable experience. The names of these people include Matt Moore, Bill Shelton, Craig Moore, Matt Chan, Ed Pert, Yi Shen, Bill Ross, and Kelly Ross.

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Chapter 1: Introduction

OVERVIEW

A channel's topographic features interact with a river's discharge to create highly complex flow patterns. These flow patterns occur at the macro-, meso-, and micro-scale levels of a stream and are dependent on the watershed's hydrologic conditions. These complex hydraulic conditions and the hydrologic conditions driving them ultimately determine a channel's morphological stability. Moreover, growing evidence also suggests that these spatial flow patterns play a vital role in determining the types, and quality of habitat available within a stream. It is also evident that a great number of urbanized and otherwise altered streams have relatively uniform flow patterns and degraded stream habitat, while more natural channels have more complex flows and better habitat.

The purpose of this thesis is to investigate a means of using two-dimensional hydraulic models to better reproduce and quantify the flow complexity within river reaches. It is anticipated that the results of such a study will provide a valuable tool for better linking the hydraulic characteristics of river to the spatial and temporal hydrologic attributes of a watershed as well as to the ecological attributes of a stream. Such a connection ultimately would allow one to better investigate how hydrologic parameters drive the hydraulic and morphologic conditions of a river and how the consequent hydraulic conditions influence stream ecology. A conceptual model for using detailed two-dimensional hydraulic models to help make links between a watershed's hydrologic characteristics and a stream's ecological health is presented. However, a detailed case study making this link is not the main objective here. Likewise, a thorough investigation trying to determine the types, magnitudes, and relative importance or flow patterns that specific aquatic organisms utilize is not undertaken and left to future researchers. Instead, the main purpose of this dissertation is to provide a methodology for better reproducing flow complexity within streams and quantifying them in a way meaningful to engineers, ecologists, and water resource managers. Thus, engineers, ecologists, and water resource managers can have a general set of tools, which they can use to describe the spatial flow patterns of importance to their particular studies.

ORGANIZATION

This thesis is organized into four major chapters (Chapters 2-5). Each of these chapters is a self-contained manuscript that has either been accepted for publication or has already been published in peer-reviewed journals. Though these manuscripts are virtually identical to the published or soon-to-be published versions, substantial editing differences exist. Among other things, the locations and sizes of figures and tables have been changed to make the presentation here more uniform.

Chapter 2 presents a conceptual model on how two-dimensional (2-D) hydraulic models and spatial hydraulic metrics can be employed to investigate the importance of flow complexity in streams. Here the limitations of using traditional 1-D modeling techniques to model and quantify flow complexity are highlighted. Examples of the types of information that one can obtain with detailed 2-D hydraulic models and spatial metrics are then provided. A detailed discussion coupled with model results is then used to describe how detailed 2-D modeling and spatial hydraulic metrics can be used to link a channel's hydraulic characteristics to its hydrologic and ecological attributes. As the purpose of this chapter is to present a conceptual model of how 2-D hydraulic models and spatial hydraulic models can be used to address a variety of water resource management issues, a rigorous discussion of the methods and procedures used to develop the spatial hydraulic metrics and implement the model scenarios is not provided. Instead, these issues are discussed fully in Chapters 3-5.

Chapter 3 focuses on implementing two-dimensional hydraulic modeling studies in a fashion that adequately captures spatial flow patterns of ecological importance. Here the general methodology that was used for collecting the bathymetry data, designing the finite element meshes, and assigning the boundary conditions for the modeling simulations described throughout this dissertation (including Chapter 2) is presented. The results of a detailed study determining the role and importance that topographic features such as exposed boulders have on creating important spatial flow patterns is presented. Specifically, a reach of the North Fork of the Feather River, in California, is modeled with and without topographic data on exposed boulders found within the reach. The impact that the presence of the boulders has on the flow field is then quantified.

The focus of Chapter 4 turns from the modeling of spatial flow patterns to describing spatial flow patterns of ecological/biological importance. Traditional habitat metrics describing flow conditions (point measurements of depth and velocity) are not capable of describing spatially varying flows. Consequently from a hydraulic perspective, two locations within a stream having the same depth and velocity, regardless of the flow conditions surrounding them are deemed equally suitable or unsuitable. Means of identifying and differentiating between locations within a stream having similar depth and velocity values, but different flow patterns surrounding them are developed. Specifically, a spatial metric capable of quantifying local energy/velocity gradients is developed and evaluated as a means of quantifying the energy and velocity gradients, which some species of fish are known to utilize.

In Chapter 5, additional spatial metrics, that complement the energy/velocity gradient metric proposed in Chapter 4, are proposed. Specifically, vorticity is proposed and evaluated as spatial metric capable of quantifying important local flow patterns, much as the energy/velocity metric does. A comparison of the vorticity and spatial energy/velocity gradient metric is made to highlight how these metrics differ and complement each other. The circulation metric, unlike the vorticity and energy metrics, is designed to provide a means of quantifying the amount of 'flow complexity' within an arbitrary area of a stream. Both vorticity and the circulation metrics are evaluated through the use of the model simulations developed in Chapter II. Additionally, the circulation metric is computed at two locations within the Smith River, without the aid of model results. An extended discussion is then provided to show how the proposed spatial hydraulic metrics can be employed by engineers, biologists and water resource managers to quantify flow complexity at the micro-, meso-, and macro-scales found within rivers.

Finally, Chapter 6 summarizes the major finding of this dissertation. A brief discussion on future work is also provided.

Chapter 2. Assessing Changes in Watershed Flow Regimes with Spatially Explicit Hydraulic Models*

David W. Crowder[1] and Panayiotis Diplas[2]

*This chapter is a modified version of the published article: Crowder, D.W., and Diplas, P., 2002, Assessing Changes in Watershed Flow Regimes with Spatially Explicit Hydraulic Models, *Journal of American Water Resources Association*, 38 (2): 397-408, reproduced with permission of AWRA.

Keywords: Numerical Modeling, Urbanization, Stream Habitat, Interdisciplinary Approach, Hydraulic Modeling

ABSTRACT: Urbanization, farming, and other watershed activities can significantly alter storm hydrographs and sediment erosion rates within a watershed. These changes routinely cause severe economic and ecological problems manifested in the form of increased flooding, and significant changes in channel morphology. As the activities within a watershed influence the hydrologic, hydraulic, and ecological conditions within a river, interdisciplinary approaches to predict and assess the impacts that different land uses have on streams need to be developed. An important component of this process is ascertaining how hydrologic changes induced by specific watershed activities will affect hydraulic conditions and the accompanying flood levels, sediment transport rates, and habitat conditions within a stream. A conceptual model for using spatially explicit (two-dimensional) hydraulic models to help evaluate the impact that changes in flow regime might have on a river is presented. This framework proposes that reproducing and quantifying flow complexity allows one to compare the hydraulic conditions within urban, urbanizing, and non-urban streams in a more biologically and economically meaningful way.

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The justification, advantage, and need for such a method is argued through the results of one- and two-dimensional hydraulic model studies. The implementation of this methodology in watershed urbanization studies is described.

INTRODUCTION

Changes in land use and water allocation can alter storm hydrographs and base flows within a watershed. Urbanization often affects, erosion rates, flood frequency, flood duration, flood volume, and the peak flow associated with a specific storm event (e.g., Hollis, 1975 and MacRae, 1997). These changes in turn impact hydraulic conditions and sediment transport rates within the rivers of a watershed. The overall effect is often excessive scour or deposition. Bridge piers, water intake pipes, and other hydraulic structures are buried or undercut causing extensive economic loss. The alterations in hydraulic and sediment transport conditions can also lead to changes in stream morphology that degrade crucial stream habitat. Reducing base flows may decrease the amount of useable habitat within a river as well as make the stream's temperature more dependent on ambient temperature conditions.

A primary motivation of using hydraulic and geomorphic models in watershed studies is that they provide a physically based means of quantifying interactions between a river's hydrologic characteristics and its instream hydraulic behavior. The flow depth, velocity, and shear stress values computed by a hydraulic model can be coupled with sediment transport equations and bank erosion models to predict how a channel will evolve over time (ASCE, 1998). As the hydrologic, hydraulic and geomorphic conditions interact both spatially and temporally, such models have great potential for assessing both existing and future stream habitat conditions at a particular site.

Recently, substantial research has been devoted to the advancement and utilization of 2-D hydraulic and morphological models to help evaluate potential impacts of various water resource related projects and assess stream habitat. Hardy et al. (2000) developed a 2-D hydraulic and sediment transport model to analyze floodplain sedimentation at the river reach scale. Wiele et al. (1996) studied changes in channel bed elevation along segments of the Colorado River where sand bars of ecological importance were being eroded. Leclerc et al. (1995) used a 2-D hydraulic model to assess juvenile Atlantic salmon habitat on the Moise River, Quebec, Canada. Crowder and Diplas (2000a-b) used a 2-D hydraulic model to investigate the effects that meso-scale topographic features (e.g. exposed boulders) have on stream hydraulics and proposed a hydraulic metric that quantifies spatially varying flow patterns of biological importance. Often such hydraulic and morphologic studies are undertaken to supplement studies being performed by other disciplines. Some of the personnel studying potential impacts of a watershed development plan may include economists, chemists, biologists, geologists, engineers, and landscape architects. The combined results of the various studies are then used by decision makers to determine whether a specific plan should be adopted or which of a number of several alternatives should be implemented. A problem with assessing information collected by different disciplines, particularly when using 2-D hydraulic and morphologic models, is that the data collected by one discipline may not be directly or physically related to the data collected by another discipline. Some data are qualitative while other data are quantitative in nature or are collected and analyzed at different spatial scales. The net result is that the end product obtained through the use of 2-D hydraulic and morphological models has the potential of either being underutilized or having been obtained more efficiently with a one-dimensional (1-D) model.

A conceptual framework for implementing 2-D hydraulic models to help assess impacts that urbanization may have on a watershed is presented here. The first part of this paper uses the results of several researchers to briefly highlight some important issues regarding the implementation and use of 2-D hydraulic models. Such a discussion is important because the procedures used in setting up a 2-D modeling study affect how well one can compute weighted useable area, use spatial metrics to quantify stream habitat, evaluate the role channel topography and flow complexity have on stream habitat, and determine potential impacts that changes in flow regime might have on stream habitat. While this discussion is not exhaustive, it provides the non-specialist a context for justifying the need and advantages of reproducing and quantifying flow complexity with 2-D models. Because, few 2-D hydraulic model studies have attempted to evaluate the importance of stream complexity, steps that hydrologists, hydraulic modelers, and stream biologists can take to model stream complexity and fully utilize 2-D hydraulic model capabilities and output are outlined. These steps include selecting an appropriate model, determining model resolution, collecting appropriate bathymetry data, and use spatial metrics to analyze the spatially explicit output of 2-D hydraulic models.

The second part of this paper describes how higher resolution 2-D model simulations can be used to help evaluate the effects that urbanization can have on rivers within a watershed. Relatively few, if any, urbanizing watershed studies have specifically focused on quantifying flow complexity within a river and linking it to the river's ecological and economic attributes. Therefore, a general example describing the implementation of such a study methodology seems appropriate, particularly as this methodology also has potential benefits for routine stream habitat studies, minimum instream flow analyses, stream restoration projects, and channel stability studies.

IMPLEMENTING 2-D HYDRAULIC MODELS IN URBANIZATION STUDIES

Improving Spatial Resolution

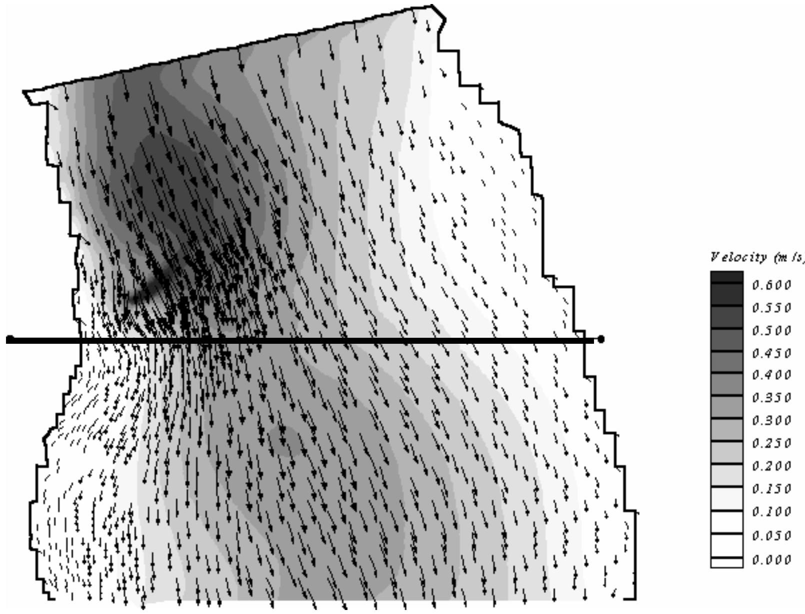
A commonly used tool to evaluate the quantity and quality of habitat within a river reach is PHABSIM (Milhous et. al., 1989). PHABSIM uses a 1-D hydraulic model to predict depth and velocity throughout a river reach. This information combined with data regarding the types of substrate, and cover found within the river is then compared to habitat suitability criteria to estimate the quality and quantity of habitat within the modeled section. PHABSIM divides a river reach into a series of elongated rectangular cells, each having uniform depth and velocity values (Bovee, 1978). The uniform flow conditions within each cell, combined with the assumption that the flow is always in the downstream direction, prevents the accurate modeling of spatial flow patterns that can occur in streams having complex channel topography. Two-dimensional numerical models, in contrast, can discretize a river into a series of much smaller areas called elements. Each element contains a number of points or nodes at which a river's depth and depth-averaged velocities in the lateral and downstream directions are computed. Moreover, depth and velocity values within an element are interpolated from the nodes belonging to that element in a manner that produces a continuous and spatially varying flow field throughout the study site. Two-dimensional hydraulic models are thus more suitable for modeling complicated flow patterns in river reaches having complex topography.

One example of the ability of a 2-D model to better predict velocity within a stream having complex channel topography was provided by Ghanem et al. (1996). Specifically, Ghanem et al. (1996) compared 1-D and 2-D hydraulic model velocity outputs with measured velocity values along cross sections upstream and downstream of a submerged island within a reach on the Waterton River, Alberta, Canada. Along the upstream cross-section, both the 1-D and 2-D hydraulic models appeared to predict velocity values equally well. However, at the downstream cross-section, where flow patterns can be influenced by the presence of the submerged island, the 2-D model performed significantly better than the 1-D model. At this cross-section, the 2-D model correctly predicted high velocity values in the left portion of the channel and lower velocity values in the right portion of the channel. In contrast, the 1-D model predicted low velocity values in the left portion of the channel and high velocity values in the right portion of the channel. Hence, the 2-D velocity values had significantly less error than the 1-D values and correctly predicted the spatial trends in the velocity field across the transect. The more accurate representation of the spatial flow pattern obtained with the 2-D model is important because accurately modeling spatial distributions of depth and velocity values within a river might lead to better means of identifying available habitat.

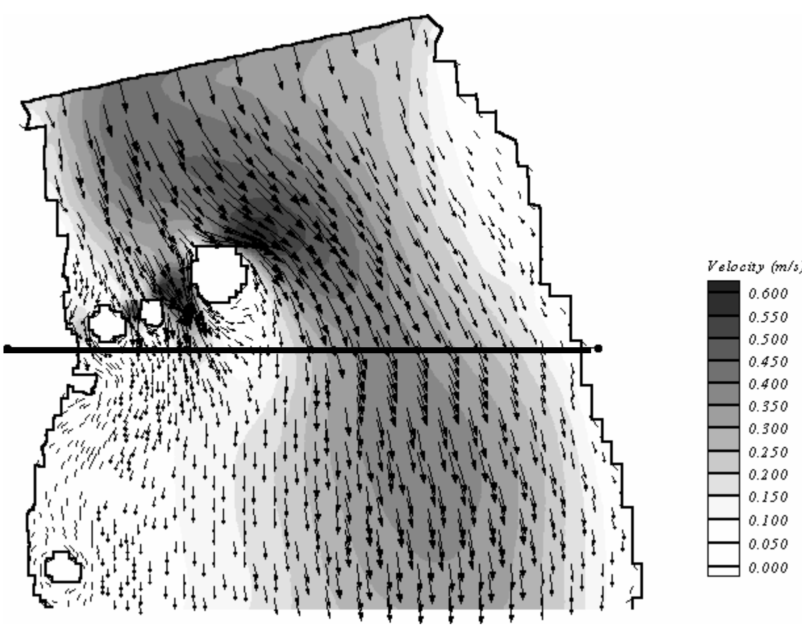
A second situation for which implementing a 2-D model rather than a 1-D model might be advantageous is demonstrated through the results of Shirvell (1989), who examined the ability of PHABSIM to predict the amount of useable habitat for Chinook salmon in the Nechako River. The conclusions of this study indicated that PHABSIM overestimated the amount of useable spawning habitat by 210 to 600 percent depending on the cell sizes and other inputs employed in PHABSIM. A main reason for the overestimation of useable habitat was attributed to the assumption that habitat conditions, like depth and velocity values, are uniform within each cell. Shirvell also suggested that the ability to account for the changes in depth and velocity within a cell would improve useable habitat computations.

If a two-dimensional hydraulic simulation with elements much smaller than those of the cells used by Shirvell had been run to quantify the flow field in this study, more accurate useable spawning calculations would likely have been obtained. With both depth and velocity values varying continuously among the elements found between transects, the smaller elemental areas can be deemed suitable or unsuitable based on their local depth and velocity values and not the depth and velocity values computed at the nearest transect.

The ability of a 2-D hydraulic model to accurately describe the spatial variations in depth and velocity between transects and throughout a study site depends largely on how well the channel topography is described. Crowder and Diplas (2000a) demonstrated that the presence or absence of topographic data on exposed boulders and other features found within a stream can significantly impact the flow fields predicted by 2-D hydraulic models. Here, using the 2-D hydraulic model RMA-2V (King, 1990), SMS software, and bathymetry data used by Crowder and Diplas (2000a), a river reach is modeled with and without boulder geometry at a discharge of 2.13 m^3/s. The velocity fields generated by the 2.13 m^3/s discharge are shown in Figure 1. Specifically, Figure 1a shows the velocity field obtained when topographic data on the exposed boulders found within the study site are not incorporated into the 2-D hydraulic model. Figure 1b depicts the velocity field generated when the boulders' geometry is incorporated into the model. In the absence of boulder geometry, the model produces a uniform velocity field with slow velocities occurring only near the banks. With bathymetry data on the boulders incorporated into the model, complex flow patterns are generated. The presence of four closely spaced boulders at the head of the reach shifts the main flow from the left bank to the right bank and creates a velocity shelter downstream of their positions.



a)



b)

Figure 1. Velocity fields at 2.13 m^3/s. a) without boulders b) with boulders. Velocity vectors are scaled to velocity magnitude; the line depicts the location of the cross section discussed in Figures 1-2.

The differences in model resolution/detail shown in Figures 1a and 1b demonstrate the importance of collecting appropriate bathymetry data according to the needs of a particular study. Model resolution significantly improves when more comprehensive topographic data is incorporated into the model. If the flow patterns generated by meso-scale topographic features (e.g exposed boulders) produce biologically important flow patterns, then such topography must be incorporated into the stream bathymetry data. However, determining the extent to which a channel's bathymetry should be described is quite subjective and often relies on professional judgment and the needs of a study. If long reaches are being modeled or flow is fairly uniform, then a 1-D model or a 2-D model using bathymetry data describing only major channel features might provide sufficient resolution and be the most efficient modeling approach. If a study needs to reproduce and quantify the flow patterns generated by meso-scale topographic features, then a 2-D model and thorough bathymetry data may be required. Other applications needing very high resolution may require 3-D models. Once the various disciplines involved in a project decide the type of hydraulic information needed in a study, an appropriate model can be chosen and bathymetry data can be collected in a fashion that produces the desired model resolution.

Quantifying Spatially Varying Flows

Habitat suitability criteria are often derived from measurements of depth, velocity, substrate, and cover values at the exact locations where fish (or other aquatic organisms of interest) were observed within a river. As these habitat parameters describe only the flow conditions at the exact location of an organism, the resulting habitat suitability criteria inherently assume that flow conditions surrounding a particular location do not influence habitat quality. A consequence of this assumption is that two different locations having similar depth, velocity, substrate, and cover values are deemed equally suitable or unsuitable regardless of the flow conditions surrounding these locations. If aquatic organisms prefer to surround themselves with specific spatially varying flow patterns, then spatial metrics, capable of quantifying the hydraulic conditions surrounding a particular location, can help identify biologically important flow patterns within a stream. According to Bovee (1996), one of the most promising attributes of 2-D hydraulic modeling is its ability to help develop such spatial habitat metrics. However, if spatial hydraulic metrics are to be successfully used in conjunction with 2-D hydraulic model output, stream biologists and hydraulic modelers need to work together to establish: 1) what spatial hydraulic metrics are of biological importance in a study; and 2) what level of resolution the stream's flow field needs to be modeled to assess the amounts and locations of areas within a stream having biological importance.

The identification of an appropriate spatial habitat metric is not straightforward. Maddock (1999) points out that physical habitat is not simply a quantifiable physical feature, but must be a quantifiable physical feature that has biological significance. If trout take up feeding positions downstream of boulders, are the boulders the physical features of biological importance, or are the spatially varying flow patterns created by the boulders the physical features that fish find desirable? If fish are responding to the flow features generated by the boulders, then spatial hydraulic metrics describing the velocity and energy gradients of these flow patterns are potential means of quantifying suitable habitat. The identification of biologically significant metrics is further complicated because aquatic organisms of different species and life stages require and use different hydraulic conditions within a stream. Therefore, a single spatial metric is unlikely to adequately quantify all of the important flow patterns within a stream. Instead, a number of different metrics may need to be developed and tested. Furthermore, even if a single metric can be used to quantify the habitats of organisms coming from different species and life stages, the metric values being used by the various species and life stages may vary substantially.

Crowder and Diplas (2000b) proposed and evaluated a spatial metric that quantifies the average rate of spatial change in a flow's kinetic energy between two points as a means of identifying energy gradients that brown and brook trout might use as feeding locations. The proposed metric is written as follows:

$$\frac{2V_{ave}\dfrac{V_2 - V_1}{\Delta s}}{V_{\min}^2}$$

where V_1 and V_2 are the velocity values found at two points (points 1 and 2) separated by a distance Δs, V_{ave} is the average of the velocity values found at points 1 and 2 and V_{min} is the smaller value of V_1 and V_2. As the direction s is arbitrary, lateral, longitudinal, and vertical energy gradients can be described. The ability to describe different energy gradients is useful because different species may use different types of velocity/energy gradients to feed. Moreover, the sign of this metric provides information on how the kinetic energy is changing throughout a flow field. If the metric has a positive value, the flow's kinetic energy is increasing as one moves from point 1 to point 2. Likewise, a negative metric value indicates that kinetic energy is decreasing from point 1 to point 2. In some cases, the direction the energy is changing may not be important and the absolute value of the metric may be more suitable.

Estimates of the spatial metric values that surrounded trout feeding positions or other biologically important areas can be computed from velocity and velocity gradient data obtained in the field. Crowder and Diplas (2000b) used velocity and velocity gradient data collected by Fausch and White (1981) to estimate a range of spatial metric values that surrounded observed 20-30 cm brook trout. The resulting computations estimated that for the range of velocity values at which brook trout had taken up feeding positions (0.15 – 0.21 m/s) the corresponding range of spatial metric values surrounding the trout locations was 4.35 – 13.77 m^{-1}. Here, these ranges of velocity and spatial metric values are used to identify potential brook trout feeding locations along the cross section shown in Figures 1a and 1b for three different discharges (1.06, 2.13, and 4.24 m^3/s). The potential brook trout feeding locations are identified by plotting velocity and spatial metric values along the cross section for each modeling scenario. Locations along the transect where both the velocity and spatial metric values fall within the ranges presumed to be used by feeding trout represent potential brook trout feeding stations. Out of the six simulations, only one simulation produces flow conditions consistent with potential feeding locations. The simulation containing boulders and having a discharge of 4.24 m^3/s predicts two potential trout feeding stations. These locations along with the velocity and spatial metric values obtained along the cross section are shown in Figure 2a. For comparison purposes, the velocity and spatial metric values obtained in the absence of boulder geometry and a discharge of 4.24 m^3/s are displayed in Figure 2b.

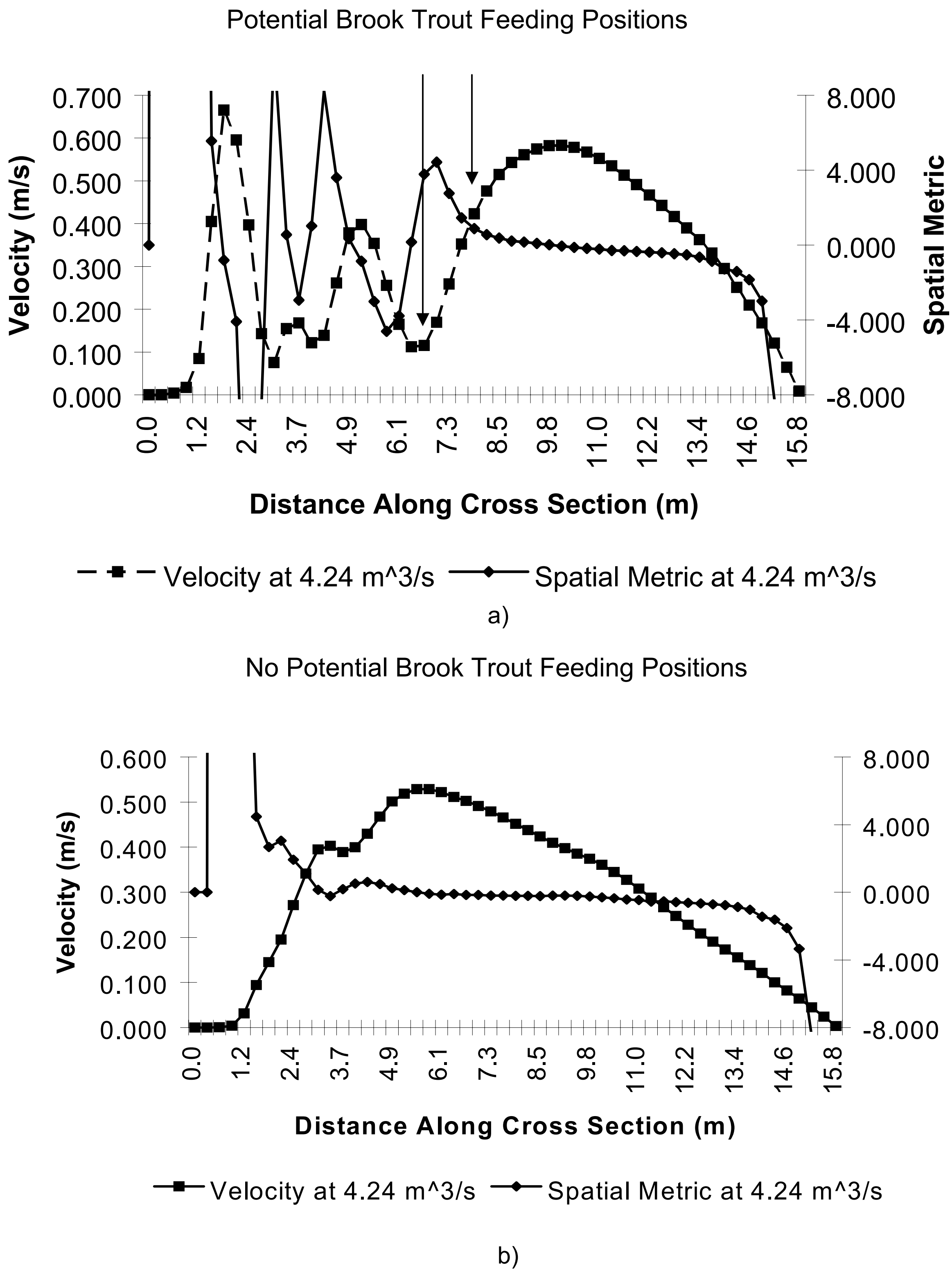


Figure 2. Potential brook trout feeding positions identified by the velocity and spatial metric values found along the cross section: a) with boulders; b) without boulders.

Extending the type of analysis just discussed throughout a modeled area can provide information on whether or not changing a channel's discharge will impact aquatic organisms that use or require certain spatially varying flow patterns. While the spatial metric described above provides a means of identifying specific locations within a stream of biological importance, future spatial metrics may be developed to characterize a pool's or even a stream reach's overall flow complexity. Such metrics would allow the overall flow complexity of two different river reaches to be directly compared. Moreover, such metrics could be used to help quantify specific stream features as potential habitats (i.e. pools, runs, and riffles) that are normally only identified qualitatively.

Assessing Impacts of Changes in Hydrologic Regime

Using information from land development plans and computer programs, hydrologists can model how a new land use pattern will affect the duration, frequency, stage, and sediment inputs associated with a particular storm event. This information can be used to determine what locations, if any, are susceptible to flooding under the new development plan and how often it is likely to be flooded. Economically, such information is quite valuable. However, ecologically, this information may reveal little about how the new hydrology and sediment inputs will affect the stream. Specific changes in local hydraulic and sediment transport rates, that play an important role in stream ecology, accompanying the new hydrologic regime remain unknown. Nonetheless, one can use the hydrographs and sedimentographs representative of the new hydrologic regime as input into 2-D models to predict the hydraulic and morphologic conditions that will be induced by the proposed land development plan. The resulting detailed depth, velocity, and sediment transport rates may be more directly comparable to the data collected and needed by stream biologists to evaluate the impacts that a new hydrologic regime will have on the existing habitat.

Clausen and Biggs (1997) investigated the role that 34 hydrologic variables play in determining the periphyton and invertebrate populations in 83 New Zealand streams. They suggested that the single variable that best described the variance in benthic communities was (FRE_3), where FRE_3 represents the number of times per year a stream experiences a discharge greater than three times the stream's median flow. Specifically, they found that both periphyton biomass and periphyton species and richness decreased with increasing FRE_3, while invertebrate density increased. The hydrological variable FRE_3, however, does not directly describe the depth, velocity, shear stress, and sediment transport rate values induced by a discharge three times that of the median flow rate ($3Q_{50}$). If the depths, velocities and shear stresses induced during flows greater than $3Q_{50}$ and not just the number of times this discharge is exceeded is responsible for affecting benthic community populations, then a 2-D model hydraulic model provides a means of quantifying these values. Moreover, a comparison of the hydraulic conditions generated by flows greater than $3Q_{50}$ in channels having different morphologic characteristics may provide insights into the role that channel morphology and discharge play in determining benthic populations.

2-D HYDRAULIC MODELING COMPONENT OF AN URBANIZING WATERSHED STUDY

Overview

The following paragraphs describe the role that 2-D hydraulic modeling plays in an interdisciplinary study that focuses on developing an integrated approach for assessing the economic, and biological impacts that urbanization has on a watershed. The various disciplines involved in this study are biological science, computer science, economics, GIS, hydrology, hydraulics, and water policy/law. The interactions among, and the types of information collected by, the various disciplines are not fully described here. Instead, the primary steps taken by the group to meet the project's goal and a more detailed discussion of the project's hydraulic modeling component are provided.

The first task in the overall project was deciding on a case study watershed. The watershed chosen is the Upper Roanoke River Watershed (URRW). The URRW is located in Southwest Virginia's Appalachian Mountains and has an area of approximately 1326 km^2. The watershed has urban, agricultural, and forested lands. After selecting the URRW as a case study site, several land development patterns that could potentially be adopted in the URRW were identified. These land development patterns were selected based on the input of the different disciplines involved in the study and various stakeholders. Having selected different land development patterns that might occur within the URRW, GIS layers were built to reflect how the land use characteristics (e.g., percent impervious land) within the watershed would change under each selected land development scenario. These new land use values were used as input into hydrologic simulations to determine how specific land use patterns would change existing hydrologic conditions. Output derived from these hydrologic simulations, in the form of stream hydrographs, can be used as input into the 2-D hydraulic model simulations. The results from the hydraulic simulations will then be exported to biology personnel where the hydrologic and hydraulic data will be combined with biological data collected throughout the watershed. Using the combined data, an assessment will be made regarding the biological impacts that the various land developments are likely to induce. Similarly, hydrologic and hydraulic data will be provided to economics personnel to facilitate the evaluation of the economic impacts various land development scenarios might have. A generalized schematic of the major interactions between the hydraulic modeling component of the project and the other disciplines involved in the study is depicted in Figure 3.

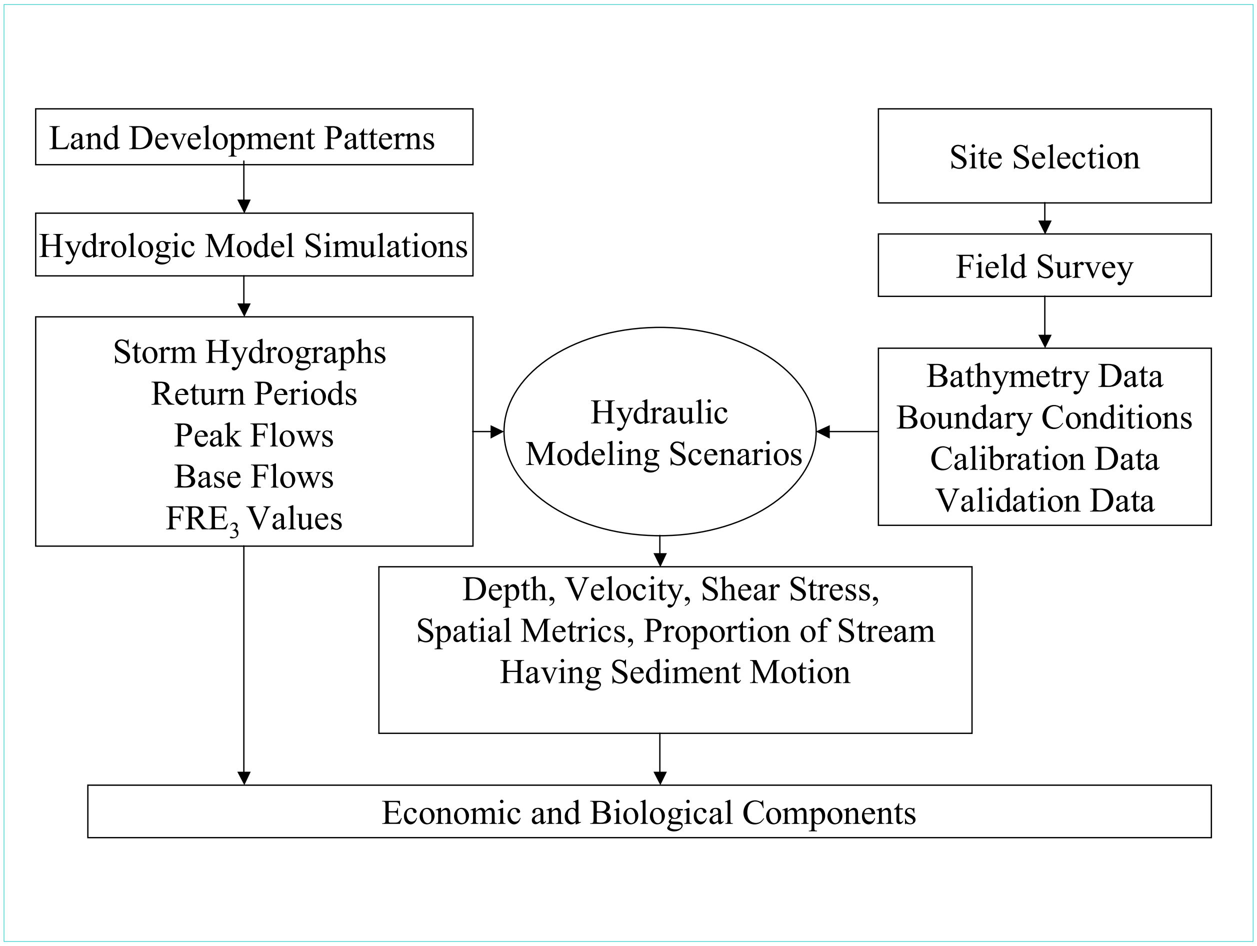


Figure 3. Schematic of the 2-D hydraulic modeling component of an urbanizing watershed study

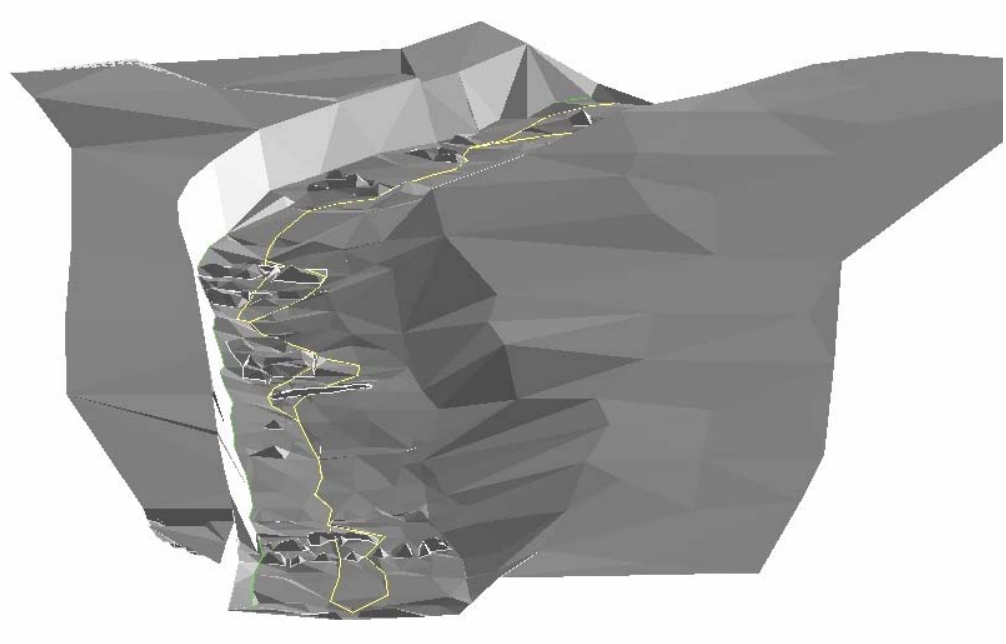
The Hydraulic Modeling Component

Based on the input from stream biologists studying the URRW, two study sites having lengths of about 64 meters (8-10 channel widths) were selected for 2-D hydraulic analysis. The first site is located on Mudlick Creek in Salem, Virginia. The stream is located in an urbanized sub-basin draining an area of approximately 25 km^2. Both commercial and residential development can be found adjacent to the stream. The modeled reach is partially channelized by a wooden retaining wall that has rip-rap at its base. Mudlick's fish habitat was ranked the third worst out of 13 sub-basins of similar size in the URRW and the 6th worst habitat of 43 sites studied in the URRW (Stancil, 2000). The second reach to be modeled is located on Lick Fork.

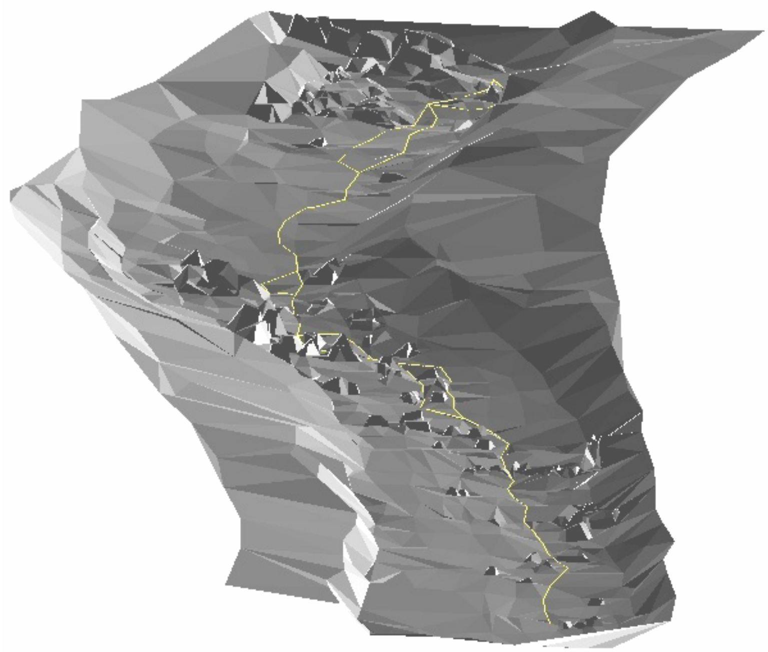
The stream is located within a largely forested sub-basin draining an approximate area of 31 km^2. Although there is a road running adjacent to the reach to be modeled, the site appears relatively unimpacted by human development. This site has the third best habitat out of 13 sub-basins of similar size and the 15th best habitat out of 43 sites studied (Stancil, 2000).

A field survey of each of these two sites was conducted to collect the data necessary to run, calibrate, and validate the 2-D hydraulic model RMA-2V at each study site. This data included channel bathymetry, water discharge, water surface elevation, and depth and velocity values taken throughout the study sites. Bathymetry data was collected in the form of XYZ coordinates using a Leica TC-605 total station. Extensive effort was spent describing the bathymetry in sufficient detail to reproduce the meso-scale flow patterns found within the sites. The channels' thalweg, top of banks and bottom of banks were surveyed as breaklines (lines whose elevations should not be interpolated across). XYZ coordinates were measured at random locations throughout the study sites. The location of these random shots formed a grid that had a spacing of approximately one step apart going across the channel and two steps apart in the upstream and downstream directions.

Topographic features such as exposed boulders and bedrock outcrops that were judged to significantly influence local flow patterns were also surveyed. In order to approximate the dimensions of these features, XYZ coordinates were surveyed along the bases and tops of boulders and bedrock outcrops. The total number of XYZ coordinates surveyed was 2881. However, as the topography at the Lick Fork site was substantially more complex, 1971 of the survey points were collected at that site. The resulting channel topographies for the Mudlick and Lick Fork sites are shown in Figures 4a and 4b, respectively. A visual comparison of the two topographies shows how the numerous boulders and bedrock outcrops found at Lick Fork create a more complex channel geometry than that found at the Mudlick site. The absence of a retaining wall at the Lick Fork site also allows the stream banks to undulate in a more natural and complex way.



a)



b)

Figure 4. a) Topographic map of the 62-meter long Mudlick site; b) Topographic map of the 66-meter long Lick Fork site (both exhibit a maximum relief of about 4.0 meters and a line indicating the location of the Channels' Thalweg).

At each study site, depth, velocity, and water surface elevations were measured along several cross sections. For the Mudlick site, velocity and depth data was collected along eight cross sections at a discharge of 0.104 m^3/s. For the Lick Fork site, data was measured at 11 cross sections when the discharge was 0.0934 m^3/s. Neither site had equally spaced cross sections. Instead, the cross sections were placed such that they passed through the different types of flow features visually identified within each of the streams (e.g. pools, riffles, and runs). Collecting depth and velocity data along cross sections placed in this manner provides a means of evaluating how well the model predicts flow conditions within various flow patterns.

2-D Hydraulic Modeling Simulations

With the detailed topography collected on the Mudlick and Lick Fork sites, several types of simulations can be performed to help better understand how channel morphology and watershed hydrology interact together to influence stream habitat and channel stability. Specifically, model simulations can predict the depth, velocity, shear stresses, and spatial metric values within each reach and for a variety of discharges. Comparisons of the existing flow conditions between the Mudlick and Lick Fork sites can then be made to ascertain how the urban and forested streams currently differ. Likewise, using hydrologic data representative of various hypothetical land development patterns as input into the 2-D model, predictions of the hydraulic conditions that would exist under different future land development patterns can be made. Such information can then be used as a basis for assessing how a specific land use pattern would at least initially impact existing stream conditions and the stream’s susceptibility to morphological changes.

An important aspect of performing model simulations is determining what flow events should be simulated. Modeling flow events that have biological significance may be particularly important. Two ecologically important discharges might include a stream’s average base flow rate, and a relatively high flow rate such as the stream’s bankfull discharge or a flow rate three times that of the channel’s median flow rate ($3Q_{50}$) (Clausen and Biggs, 1997). The bankfull and FRE_3 flow rates, represent relatively high flow rates, which have the potential of stressing stream biota over a rather short, but crucial, period of time. In contrast, modeling an average base flow rate provides a measure of the flow conditions one might typically expect to find within the stream.

To demonstrate the influence that discharge has on determining the type of flow features found in a stream, the upstream half of the Mudlick site was modeled at discharges of 0.104 m^3/s and 20.5 m^3/s. These two discharges approximate base flow and bankfull conditions. The velocity field generated by each of these discharges is shown in Figure 5. At base flow conditions (Figure 5a) the stream has velocity values ranging from about 0.0 to 1.1 m/s and meso-scale channel complexity plays a significant role in creating the flow patterns found within the stream. Boulders and bedrock outcrops create constrictions where velocity values are much higher than at locations elsewhere in the stream. Likewise, in certain locations, meso-scale channel complexity causes the main flow to divide or shift from one bank to the other. In contrast, the flow patterns found in the stream at bankfull conditions are more uniform. The boulders and bedrock outcrops, being submerged, no longer create significant local flow patterns. Instead, the relatively straight, steep banks, commonly found in urbanized streams, force the flow to be relatively uniform and much faster (0.0 to 2.6 m/s).

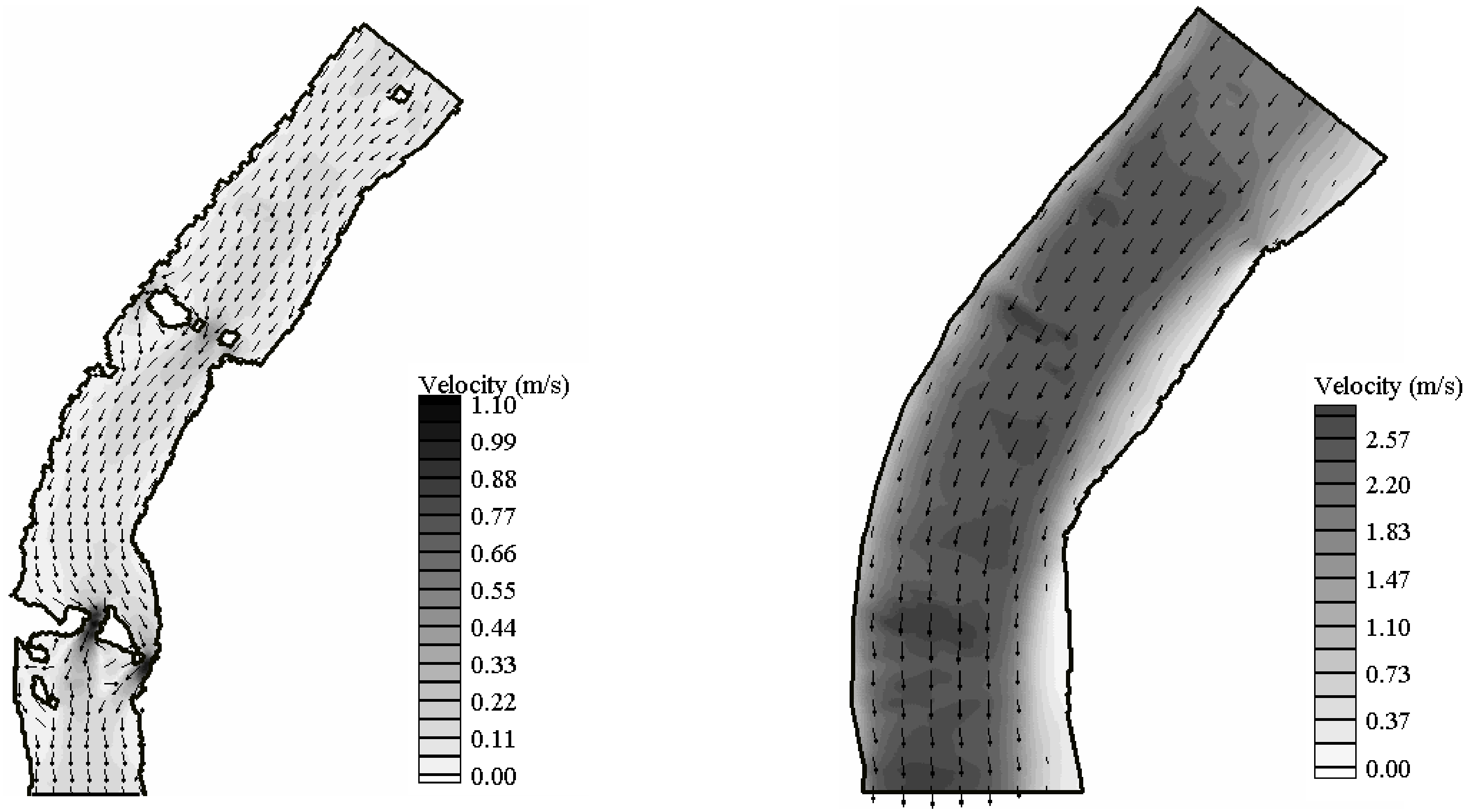


Figure 5. a) Velocity field at base flow conditions throughout the upper half of the Mudlick site (white formations within the stream are exposed boulders and bedrock outcrops); b) Velocity field at bankfull conditions at the same site.

Discharge and channel complexity might also play an important role in determining the amounts and locations within a stream that have biologically important flow patterns. This relationship is shown by shading the regions within the Mudlick site where the spatial metric proposed by Crowder and Diplas (2000b) has values ranging from 4.349 and 13.774 m^{-1} (Figure 6). These shaded regions, represent locations having energy gradients equal to those that surrounded the feeding brook trout that Fausch and White (1981) observed. At base flow conditions (Figure 6a), the presence of the exposed boulders and bedrock outcrops create a number of locations that represent potential trout habitat. Comparisons of Figures 5a and 6a reveal that the shaded regions to a large extent correspond to locations that have significant flow complexity. This complexity is manifested in the form of velocity gradients and changes in flow direction occurring around the exposed boulders and bedrock outcrops. At bankfull conditions (Figure 6b), few locations within the stream have spatial metric values between 4.349 and 13.774. The regions that do have such spatial metric values are restricted to the west (right) bank, where the flow is not particularly complex, but has relatively high velocity gradients that produce the spatial metric values of interest.

To limit the scope of this paper, comparisons of the model results obtained at the Mudlick and Lick Fork sites are not provided. However, many useful comparisons can be made using simulation results obtained from both sites at a variety of discharges. The detailed output provided by the 2-D model enables one to select from a variety of metrics to perform these comparisons. For example, to evaluate the physical consequences that higher flows ($> 3Q_{50}$) have on a stream's biology and morphology a boundary shear stress (the force per unit area exerted by flowing water on the streambed) analysis may be appropriate. Shear stresses can be used to estimate the proportion of a channel's bed that is subject to sediment motion during a storm event. This proportion, in turn, can provide a surrogate measure of the channel's stability and the amount of refuge available for a stream's biota during different storm events. In contrast, the computation of the amount of area within a stream having specific depth and velocity values may be useful in evaluating the impacts of low flow events. Knowing the depth and velocity distributions within a river can help determine if a river will have enough deep holes to sustain aquatic organisms during periods of low flow. As differences in the spatial variability within streams might be correlated with habitat quality and channel stability, one may also wish

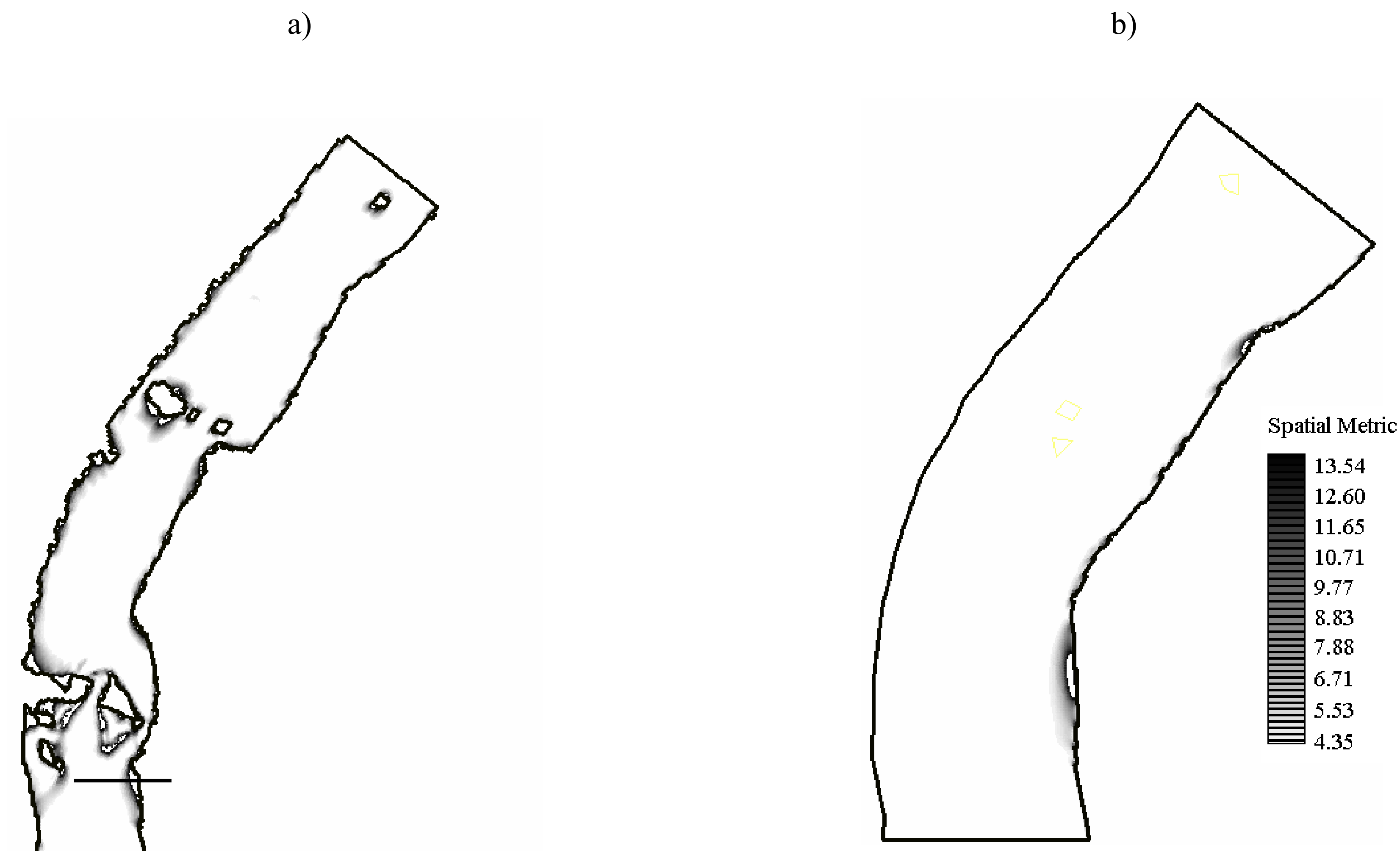


Figure 6. Areas (shaded) Having Spatial Metric Values That Surrounded the Feeding Brook Trout (20 – 30 cm) Observed by Fausch and White (1981). a) Baseflow Conditions b) Bankfull Conditions.

to use spatial metrics to compare model results, as was done for the Mudlick site's base and bankfull conditions. Regardless of the type of comparisons one wishes to make, the various disciplines involved in a study need to determine what information is important and how the 2-D model output can be best utilized to meet the study's objectives.

CONCLUSIONS

Several applications for which one may wish to implement a detailed 2-D hydraulic models study have been identified. These applications include modeling spatially varying flows in channels having complex topography, developing and using spatial metrics to better quantify stream habitat, and examining the role that channel morphology and hydrologic regime have on stream hydraulics. However, for such analyses to be meaningful, biologists, hydrologists, and hydraulic modelers must work closely to identify study needs and how the 2-D model study should be implemented. Hydraulic modelers must be aware of the resolution needed by stream biologists in a particular study and collect the necessary data to provide this detail. Input from stream biologists is also needed to help evaluate how 2-D model output and spatial hydraulic metrics can be best used to help assess stream habitat.

A conceptual model, based on experience from a watershed urbanization study, is proposed as one means of applying 2-D hydraulic models to help evaluate the impacts that urbanization may have on stream habitat. The procedure evaluates how channel topography, discharge, and watershed land use interact and affect a stream's aquatic habitat and stability. Detailed channel geometry is collected on a stream reach to be modeled. Hydrologic data representative of existing and future land development scenarios is then used as input into a 2-D hydraulic model to predict how flow conditions within the study site(s) change under different land use patterns at key discharges. Detailed comparisons of the model results are then performed using appropriate metrics.

Examples from an urbanizing watershed study describe the major steps taken in implementing the conceptual model on a stream within the Upper Roanoke River Watershed. Two-Dimensional hydraulic model results pertaining to an urban stream suggest that at base flow conditions channel complexity in the form of exposed boulders and bedrock outcrops plays a significant role in creating localized flow patterns of potential biological importance. However, at bankfull conditions, these meso-scale topographic features do not play a significant role in generating localized flow patterns. Instead, the steep well-defined banks of the urbanized channel create relatively uniform flow conditions.

In the results presented here, the direct effects of changing imperviousness, overland runoff, and evapotranspiration within the study watersheds have not been evaluated. However, as outlined in Figure 3, it may be possible to link hydrologic and hydraulic model simulations to predict how specific watershed development scenarios will influence the spatial and temporal characteristics of a stream's flow during specific storm events or seasonal changes in precipitation. A key component of such a study will be determining an appropriate means of linking the hydrologic and hydraulic models based on study needs. Just as a project's goals dictate whether a 1-D or 2-D hydraulic model is needed to evaluate a stream's hydraulic properties, a project's goals may require either a 1-D or 2-D hydrologic model to predict the hydrologic characteristics of the watershed.

While there are several advantages of applying 2-D hydraulic models to answer watershed management problems, implementing 2-D hydraulic model studies can be difficult and steps need to be taken to improve the usefulness of this technology. Bovee (1996) and Hardy (1998) suggest these steps include: developing software that simplifies 2-D modeling, finding means to quickly obtain detailed bathymetry data, and the development and validation of spatial metrics of biological significance. Further research also remains to be done on ascertaining the accuracy and resolution at which 2-D hydraulic models can reproduce flows in complex channels under different conditions. Finally, appropriate means of integrating Hydrologic and Hydraulic model simulations need to be developed.

ACKNOWLEDGEMENTS

The support provided by EPA Grant R82-5760, NSF Grant CTS-9257335, Pacific Gas and Electric, the Virginia Department of Game and Inland Fisheries, and a competitive grant (PL 98-242 and PL 104-134) from the U.S. Geological Survey, Department of the Interior, through the Virginia Water Resources Research Center at Virginia Tech is gratefully acknowledged. The field and technical support provided by Craig Moore, Paul Bartholomew, Matt Chan, Scott Chapel, Eugene Bosley, Brendan Lockard, Yi Shen, Sean Brooks, and Jaber Almedeij is also appreciated.

REFERENCES

ASCE Task Committee. 1998. River width adjustment II: modeling. Journal of Hydraulic Engineering 124(9): 903-917.

Bovee, K. D. 1996. Perspectives on two-dimensional river habitat models: the PHABSIM Experience. In Proc. Ecohydraulics 2000 Proceedings of the Second International Symposium on Habitat Hydraulics, eds. M. Leclerc, H. Capra, S. Valentin, A. Boudreault and Y. Cote, B149-B162. Quebec, INRS-Eau & FQSA, IAHR/AIRH.

Bovee, K. D. 1978. The incremental method of assessing habitat potential for coolwater species with management implications. American. Fisheries. Society Special. Publication No. 11, ed. Kendall R.L., 340-346, Washington, D.C.

Clauesn, B. and B. J. F. Biggs. 1997. Relationships between benthic biota and hydrological indices in New Zealand streams. Freshwater Biology. 38: 327-342.

Crowder, D. W., and P. Diplas. 2000a. Using two-dimensional hydrodynamic models at scales of ecological importance, Journal of Hydrology 230(3-4): 172-191.

Crowder, D. W., and P. Diplas. 2000b. Evaluating spatially explicit metrics of stream energy gradients using hydrodynamic model simulations. Canadian Journal of Fisheries and Aquatic Sciences. 57(7): 1497-1507.

Fausch, K. D., and R.J.White. 1981. Competition between brook trout (*Salvelinus fontinalis*) and brown trout (*Salmo trutta*) for position in a Michigan stream. Canadian Journal of Fisheries and Aquatic Sciences. 38:1220-1227.

Ghanem, A., P. Steffler and F. Hicks. 1996. Two-dimensional hydraulic simulation of physical habitat conditions in flowing streams. Regulated Rivers: Research and Management 12: 185-200.

Hardy, R. J., P. D. Bates and M. G. Anderson. 2000. Modeling suspended sediment deposition on a fluvial floodplain using a two-dimensional dynamic finite element model. Journal of Hydrology 229: 202-218.

Hardy, T. B. 1998. The future of habitat modeling and instream flow assessment techniques. Regulated Rivers: Research and Management 14: 405-420.

Hollis, G. E. 1975. The effect of urbanization on floods of different recurrence interval. Water Resources Research 11(3): 431-435.

King, I. P. 1990. Program documentation RMA-2V. Two dimensional finite element model for flow in estuaries and streams, Version 4.3. Resource Management Associates, Lafayette, CA.

Leclerc, M., A. Boudreault, J. A. Bechara and G. Corfa. 1995. Two-dimensional hydrodynamic modeling: a neglected tool in the instream flow incremental methodology. Transactions of the American Fisheries Society124(5): 645-662.

MacRae, C. R. 1997. Experience from morphological research on Canadian streams: Is control of the two-year frequency runoff event the best basis for stream channel protection? In Proc. Effects of Watershed Development and Management on Aquatic Ecosystems, ed. L. A. Roesner, 144-162. Snowbird, Utah, Proceedings of an Engineering Foundation Conference.

Maddock, I. 1999. The importance of physical habitat assessment for evaluating river health. Freshwater Biology 41: 373-391.

Milhous, R. T., M. A. Updike, and D. M. Schneider. 1989. Physical habitat simulation system (PHABSIM) reference manual, version II. Instream Flow Information Paper No. 26, U.S. Fish and Wildlife Service Biol. Rep. 89 (16*)*.

Shirvell, C. S. 1989. Ability of PHABSIM to predict chinook salmon spawning habitat. Regulated Rivers: Research and Management. 3: 277-289.

Stancil, V. F. 2000. Effects of watershed and habitat conditions on stream fishes in the upper Roanoke River watershed, Virginia. M.S. thesis. Virginia Polytechnic Institute and State University, Blacksburg.

Wiele, S. M., J. B. Graf and J. D. Smith. 1996. Sand deposition in the Colorado River in the Grand Canyon from flooding of the Little Colorado River. Water Resources Research 32(12): 3579-3596.

Chapter 3. 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, rootwads 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.

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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.

Keywords: Numerical Analysis, Bathymetry, Rivers and Streams, Aquatic Environment, Fish Habitat, Spatial Variations, Boulders

INTRODUCTION

Flow through natural channels is typically quite complex. The flow interacts with sediment and the topographic features of the channel bed to create complex flow patterns that vary both spatially and temporally (e.g., Mosselman, 1998; Wiele et. al., 1996; and Diplas, 1994). This dynamic interaction between flow, sediment, and topographic features consequently plays 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., Rosgen, 1996; Waters; 1995 and Diplas, 1994). 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 1-D flow routing subroutines, such as those used in PHABSIM (e.g. Milhous et. al., 1989). However, these one-dimensional 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 flow patterns, stream biology researchers are beginning to evaluate the usefulness of two-dimensional (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 two-dimensional 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, root-wads, 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 2-D hydraulic models can provide requires that the meshes used in hydraulic models 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 two-dimensional 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 ten 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.

DESCRIPTION OF THE TWO-DIMENSIONAL HYDRAULIC MODEL

RMA-2V, originally developed by Ian 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 two-dimensional 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 (1) and two equations for the conservation of momentum in the horizontal directions (2) and (3). These equations can be written as follows:

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

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

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

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 is water depth; ε_{xx}, ε_{xy}, ε_{yx}, and ε_{yy} are eddy viscosity coefficients; C is the Chezy coefficient; g is gravity; ρ is fluid density; z_0 is 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 equations 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.

STUDY METHODOLOGY

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.

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 two-dimensional 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.

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 m^3/s 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 m3/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).

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.

Modal 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, ten 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 ten 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 Figure 1.

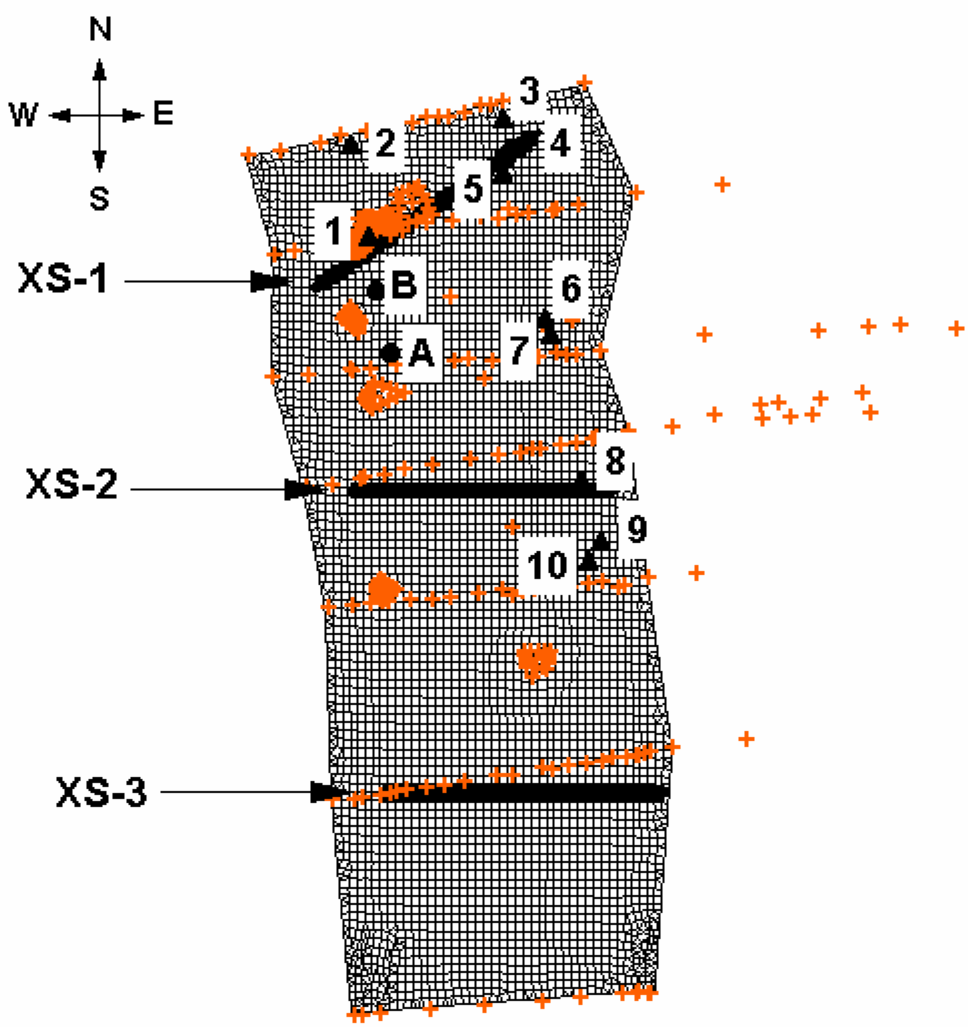


Figure 1. Top view of the modeled site. The second coarsest finite element mesh is shown here. The plus signs are the locations of the surveyed XYZ coordinates. The clusters of XYZ coordinates represent the locations of boulders. The triangles represent positions were juvenile trout were found in the 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-2 is 40 m downstream of XS-1.

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 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.

Mesh	Number of Elements	Number of Nodes	Average Element Size Near Boulders (m2)	Average Element Size Away from Boulders (m2)
1	1182	3595	1.252	1.270
2	4776	14237	0.175	0.327
3	16927	50598	0.076	0.082
4	19321	57462	0.025	0.082

Table 1. Meshes Used to Model the Site With and Without Obstructions Being Present

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. Figures 1 and 2 show the second coarsest and most refined meshes, meshes 2 and 4, respectively.

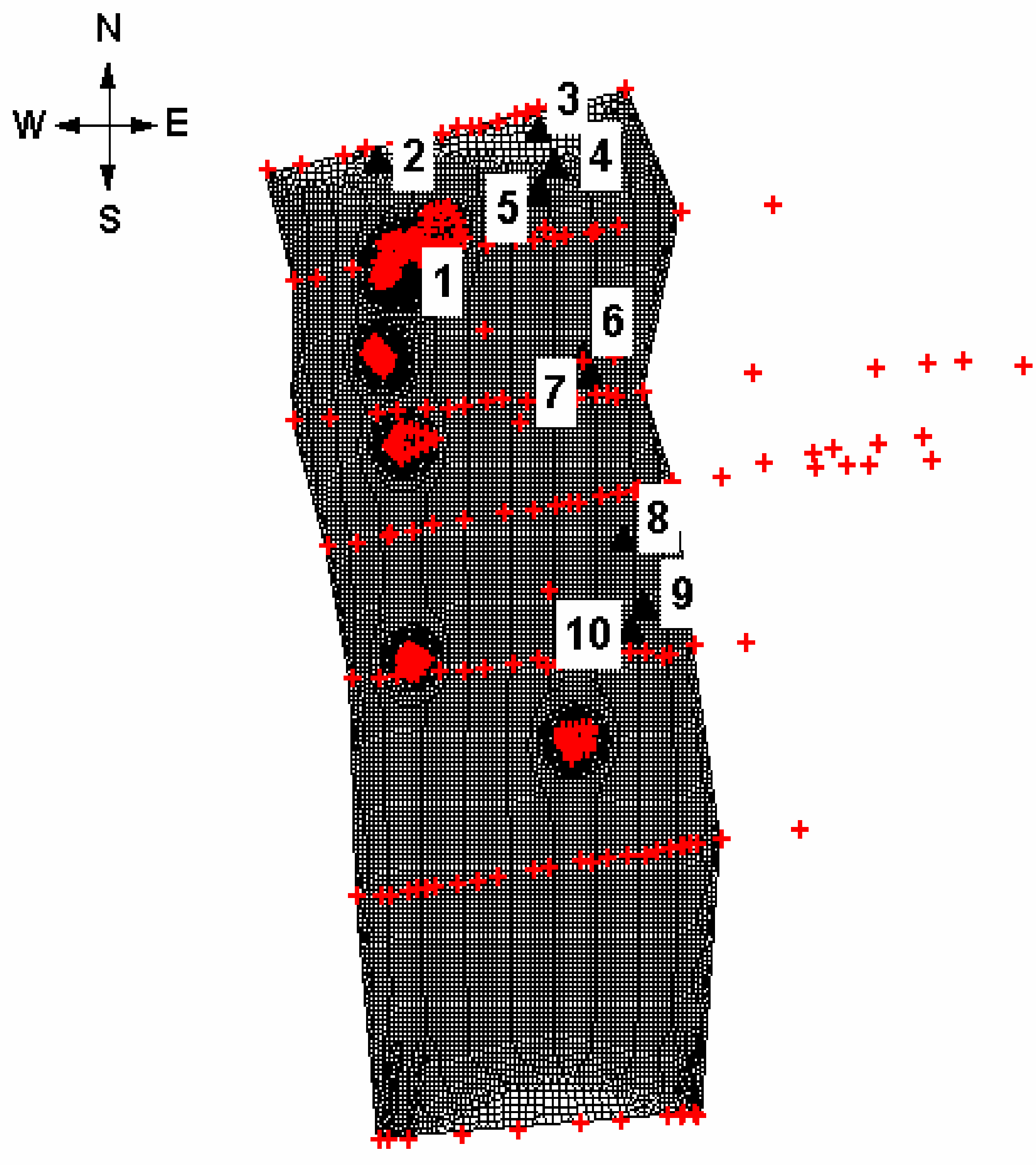


Figure 2. Most refined finite element mesh. The plus signs are the locations of the surveyed XYZ coordinates. The triangles represent positions were juvenile trout were found in the pool.

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.

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 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.

Mesh	Obstruction Base Dimensions (m)	Obstruction Height (m)	Elements in Mesh	Nodes in Mesh	Average Element Size Near Boulders (m2)	Average Element Size Away from Boulders (m2)
5	0.914 x 0.914	0.51	17447	52194	0.031	0.082
6	1.83 x 1.83	1.02	17449	52202	0.030	0.082
7	2.74 x 2.74	1.53	17479	52280	0.030	0.082
8	2.26 x 2.11	1.99	16828	50362	0.034	0.082

Table 2. Meshes Used to Model Single Obstruction Scenarios

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 m x 0.914 m x 0.51 m obstruction; meshes 6 and 7 contain obstructions with dimensions of 1.83 m x 1.83 m x 1.02 m and 2.74 m x 2.74 m x 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 figures 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 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.

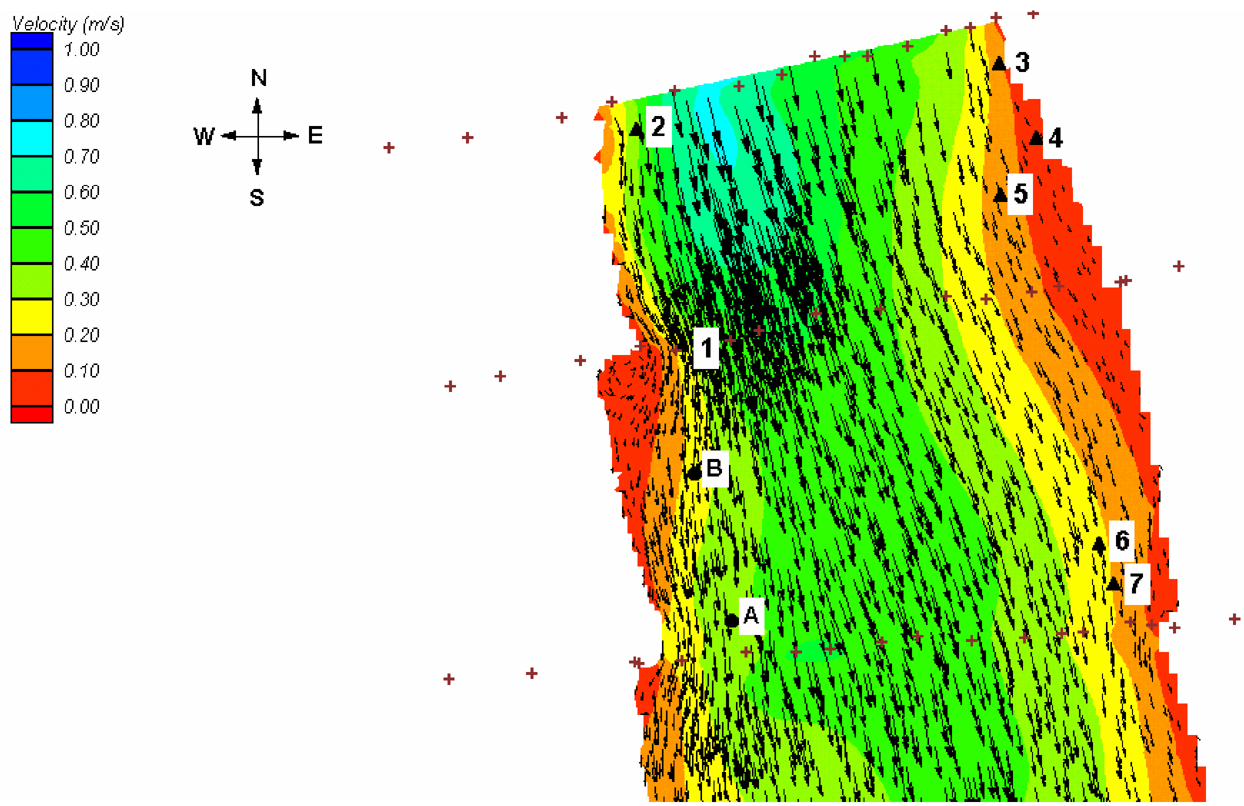


Figure 3. Model velocity output for the pool when boulders are not present. Arrows represent the direction of flow and are scaled to velocity magnitude. Color contours give the magnitude of the velocities within the pool. Triangles represent locations within the pool where young trout were located and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

RESULTS

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 Figures 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.

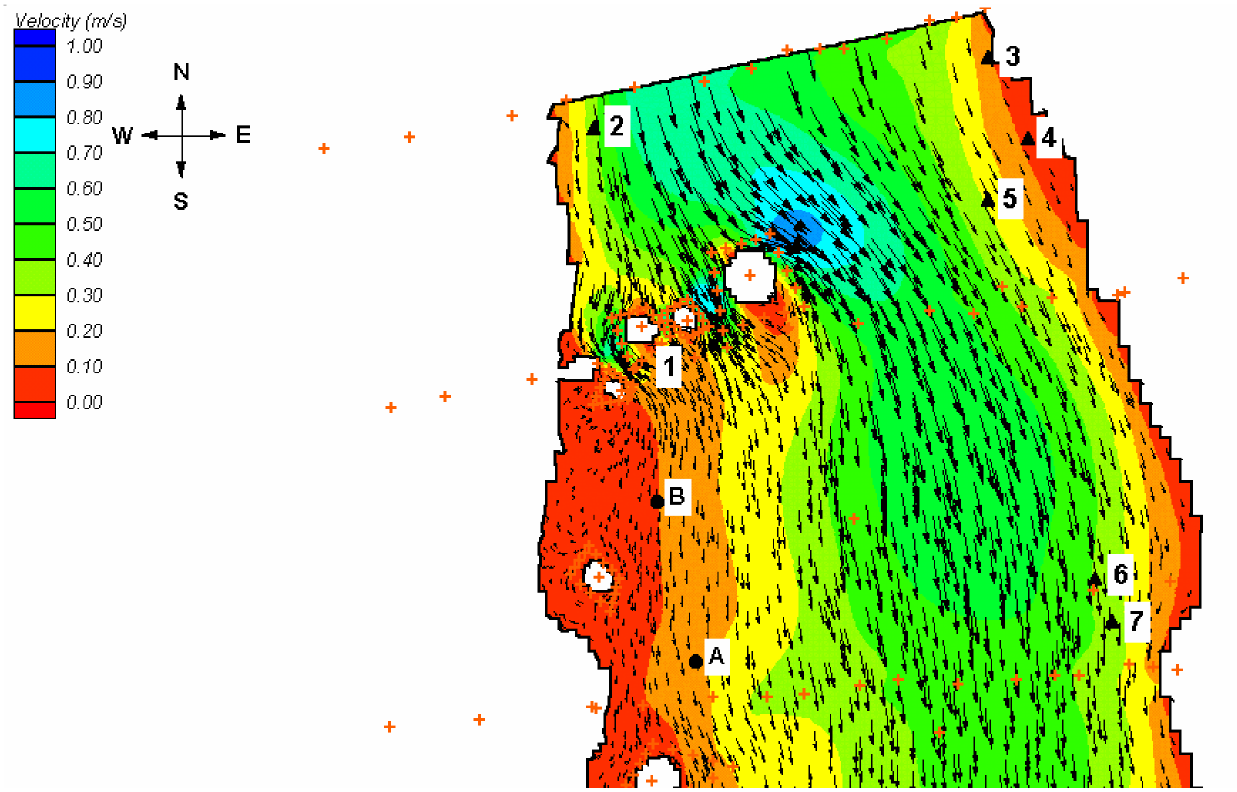


Figure 4. Model velocity output for the pool when boulders are incorporated into the model's bathymetry. The six boulders shown here appear as white shapes completely surrounded by the flow. Mesh #4 is the underlying mesh.

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. Figure 5 depicts the change in velocity magnitude that occurs within the upper 20 meters 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 0.10m/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, Figure 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.

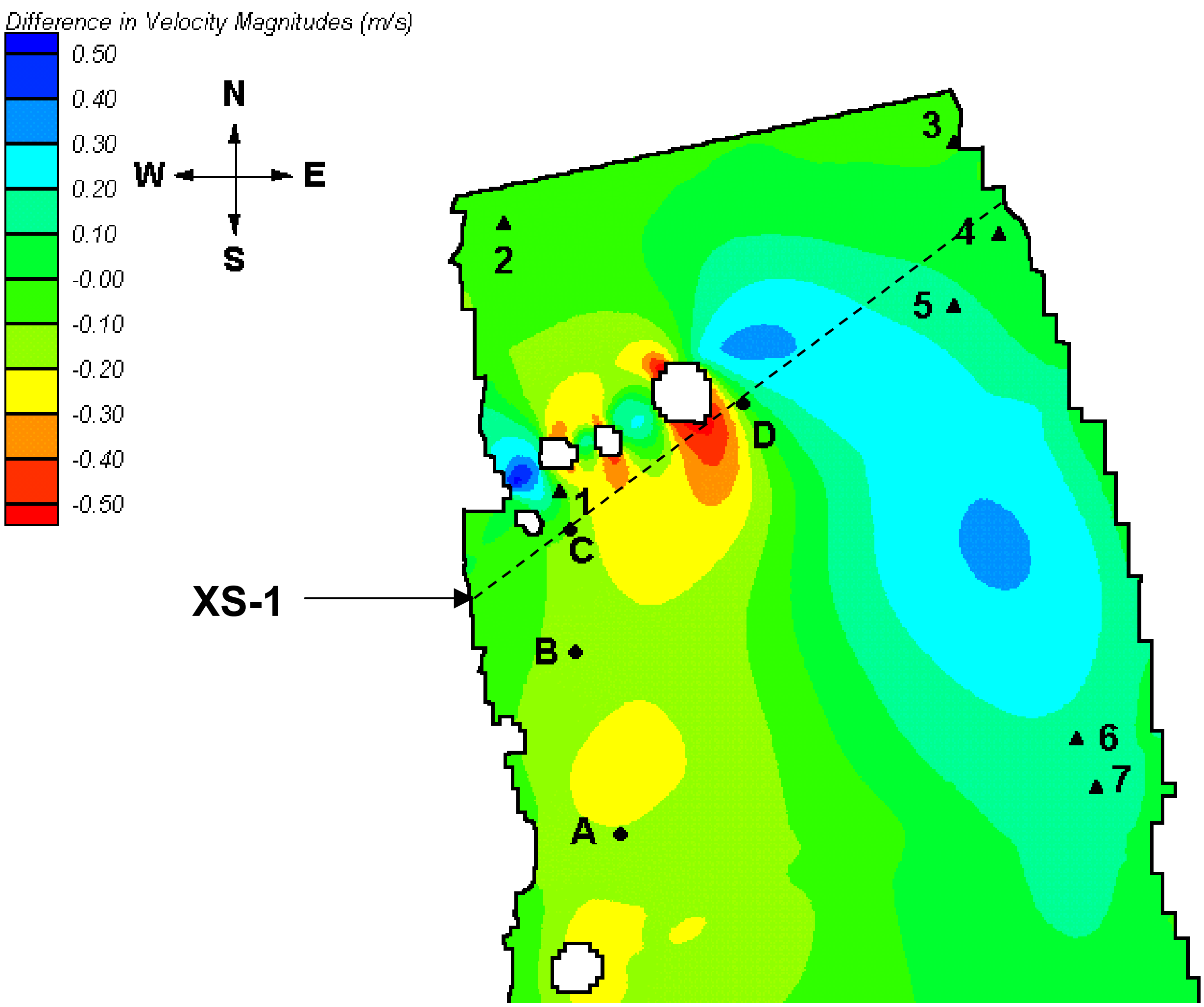


Figure 5. Contour plot showing the differences in velocity magnitudes predicted by modeling the site with and without obstructions in the bathymetry data. Positive values show the areas that the presence of the boulders increase predicted velocity values. Negative values show the areas that experience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

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 Figure 5) for the two scenarios were compared in Figure 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 $0.184s^{-1}$ and

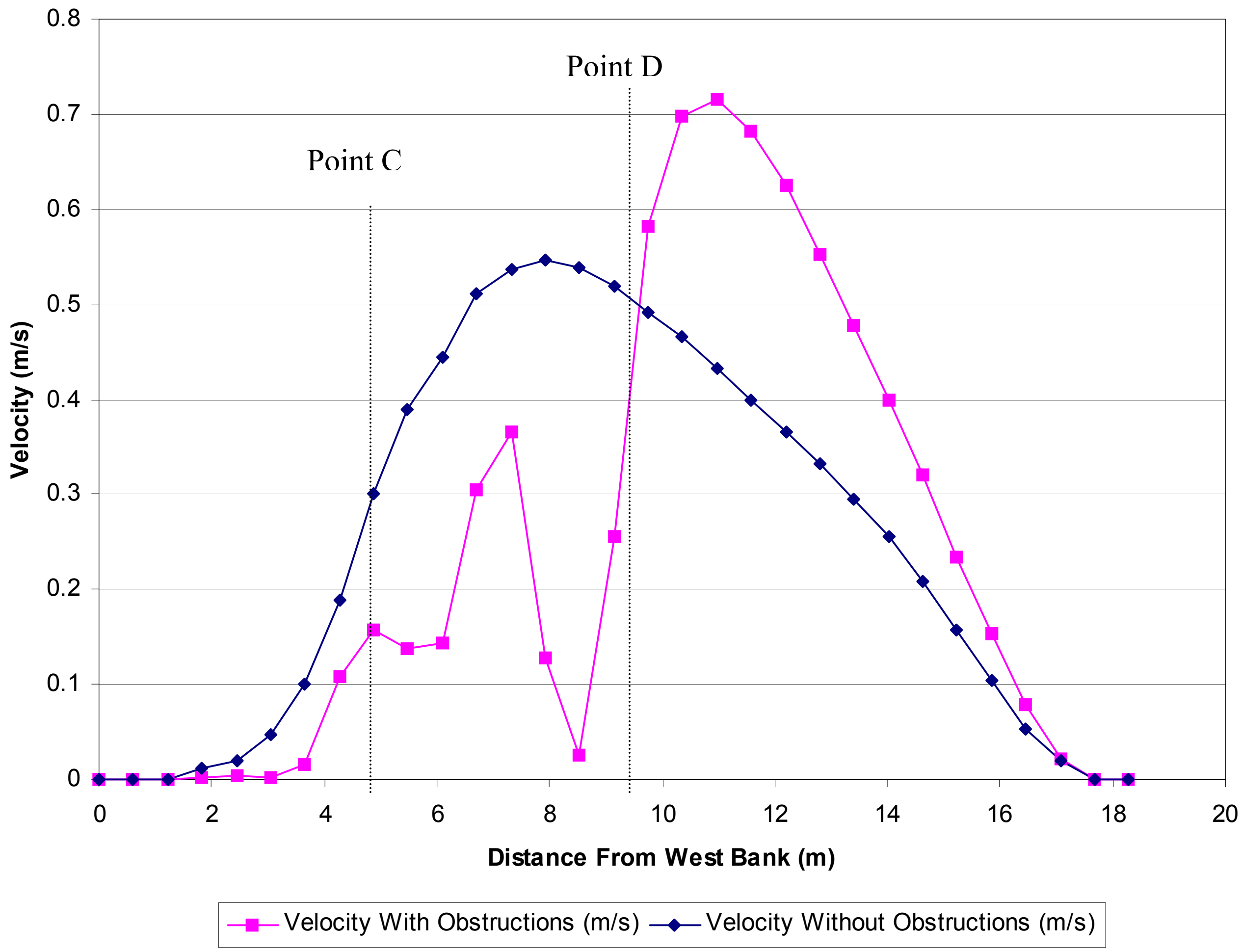


Figure 6. Velocity profiles along XS-1 (shown in Figure 5). The dashed lines represent the locations where points C and D cross the profiles. Point C refers to the location having the maximum velocity gradient when boulder geometry is not incorporated into the model. Point D is the location having the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

$0.537s^{-1}$, 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 to 6.0 m along

XS-1) is a potential location where periphyton and invertebrates might 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 Figures 3 - 5. On average the ten 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, 6 and 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.

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

Table 3. Comparison of Flow Parameters at Locations within the Modeled Reach

Model Conditions	Maximum Depth	Maximum Velocity	Average Depth	Average Velocity	Average Water Surface Elevation
Without Obstructions	1.50 m	0.71m/s	0.78 m	0.28 m/s	721.140 m
With Obstructions	1.49 m	0.86 m/s	0.77 m	0.27 m/s	721.137 m

Table 4. Model Average Nodal Results Using Most Refined Mesh

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 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 Figure 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 m 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. Figure 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 is the more pronounced these effects become. The fourth obstruction, located farther 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 Figure 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.

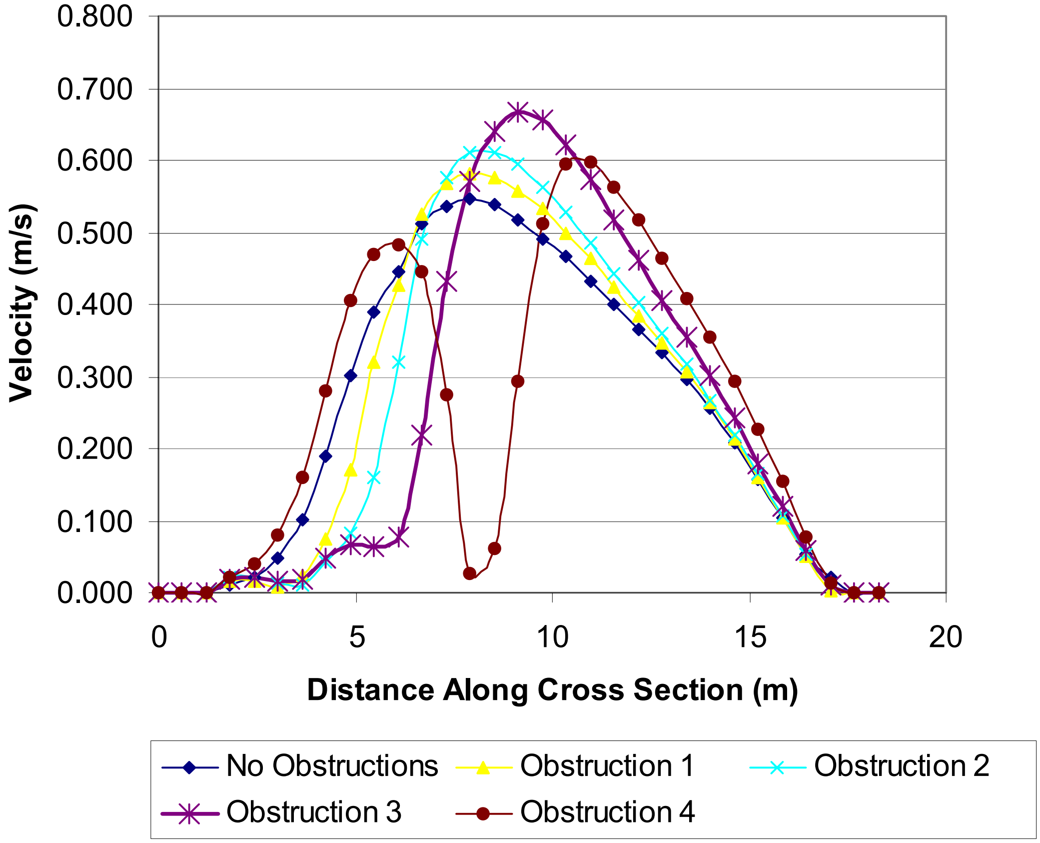


Figure 7. Velocity profiles along XS-1 that were generated by the meshes having a single obstruction incorporated into their bathymetry data. Obstructions 1-3 correspond to meshes 5-7 in Table 2, which have square obstructions of increasing size at the same location. Obstruction 4 corresponds to mesh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

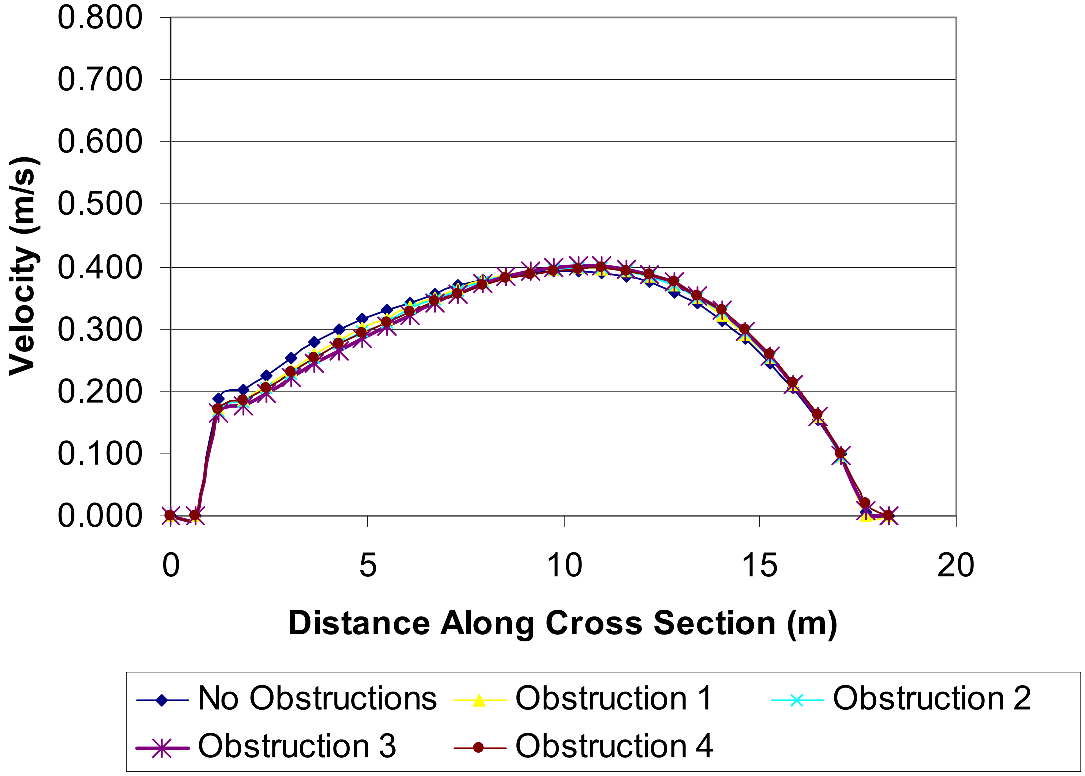
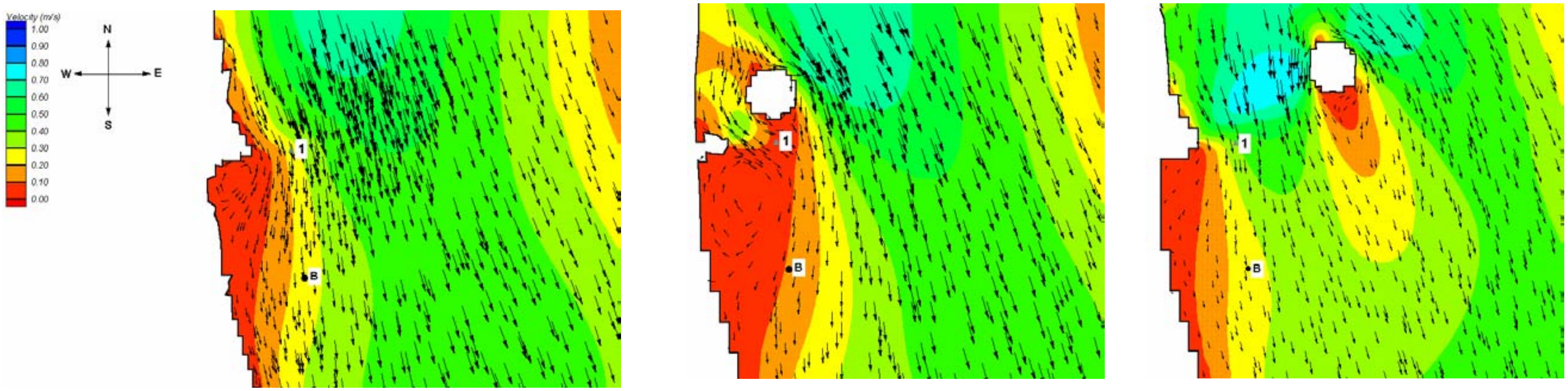


Figure 8. Velocity profiles along XS-2 that were generated by the meshes having a single obstruction incorporated into their bathymetry data. Obstructions 1-3 correspond to the meshes 5-7 in Table 2, which have square obstructions of increasing size at the same location. Obstruction 4 corresponds to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

A single obstruction need not influence a large portion of the river to significantly impact a river's habitat conditions. Figure 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 Figures 7, 8, and 9 indicate that a single obstruction appreciably impacts downstream flow conditions only to a distance of about 6 to 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). Figures 9a and 9b demonstrate that by adding just a single obstruction (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, Figure 9c would probably be a far better indicator of actual habitat conditions than Figure 9a.

Sensitivity Analysis

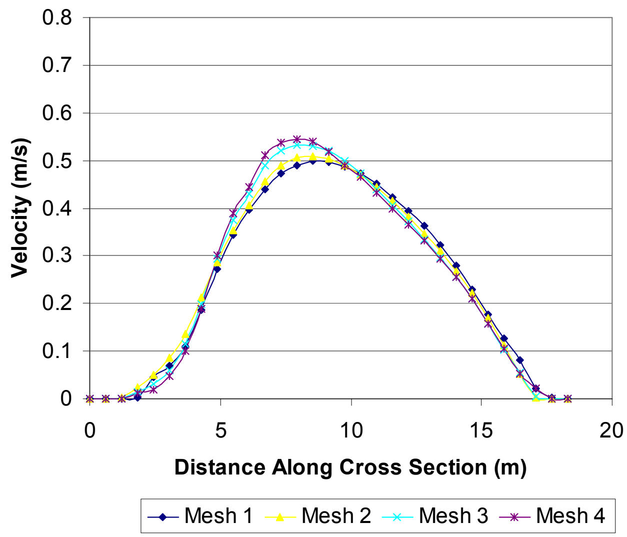
While coarse mesh elements reduce computer time and allow the modeling of larger river segments, they may also prevent the model from accurately quantifying important local flow features that influence stream habitat. Consequently, when modeling meso-scale flow patterns one must not only assure that 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.



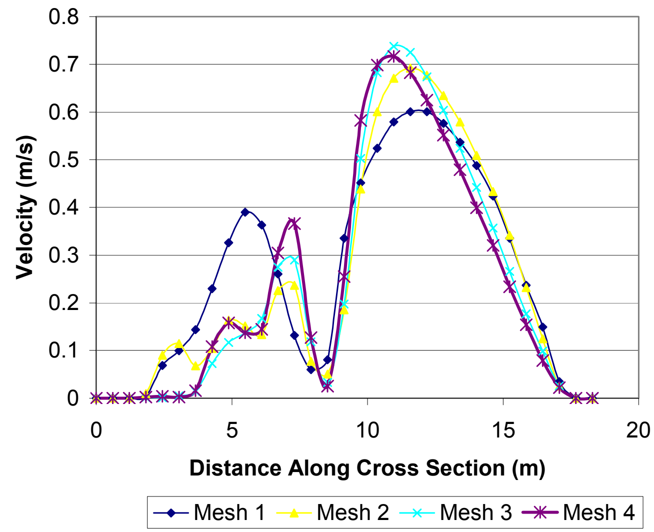
a) b) c)

Figure 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 Figure 9a. Figure 9b reflects the influence of a 1.83 x 1.83 m obstruction placed near the bank. Figure 9c depicts the flow conditions produced by a single 2.26 x 2.11 m boulder placed further out in the stream.

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 Figure 1). Figures 10a and 10b graph 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 (Figure 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 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.



a)



b)

Figure 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 (10a). Velocity profiles generated with meshes containing information on the presence of boulders are shown in (10b). Distance is measured from the left (west) bank.

Figure 11a and 11b demonstrate 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 to 8 times the effective width.

While figures 10-11 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 large errors and instabilities finite element meshes are required to increase or decrease element sizes slowly throughout a mesh. Consequently,

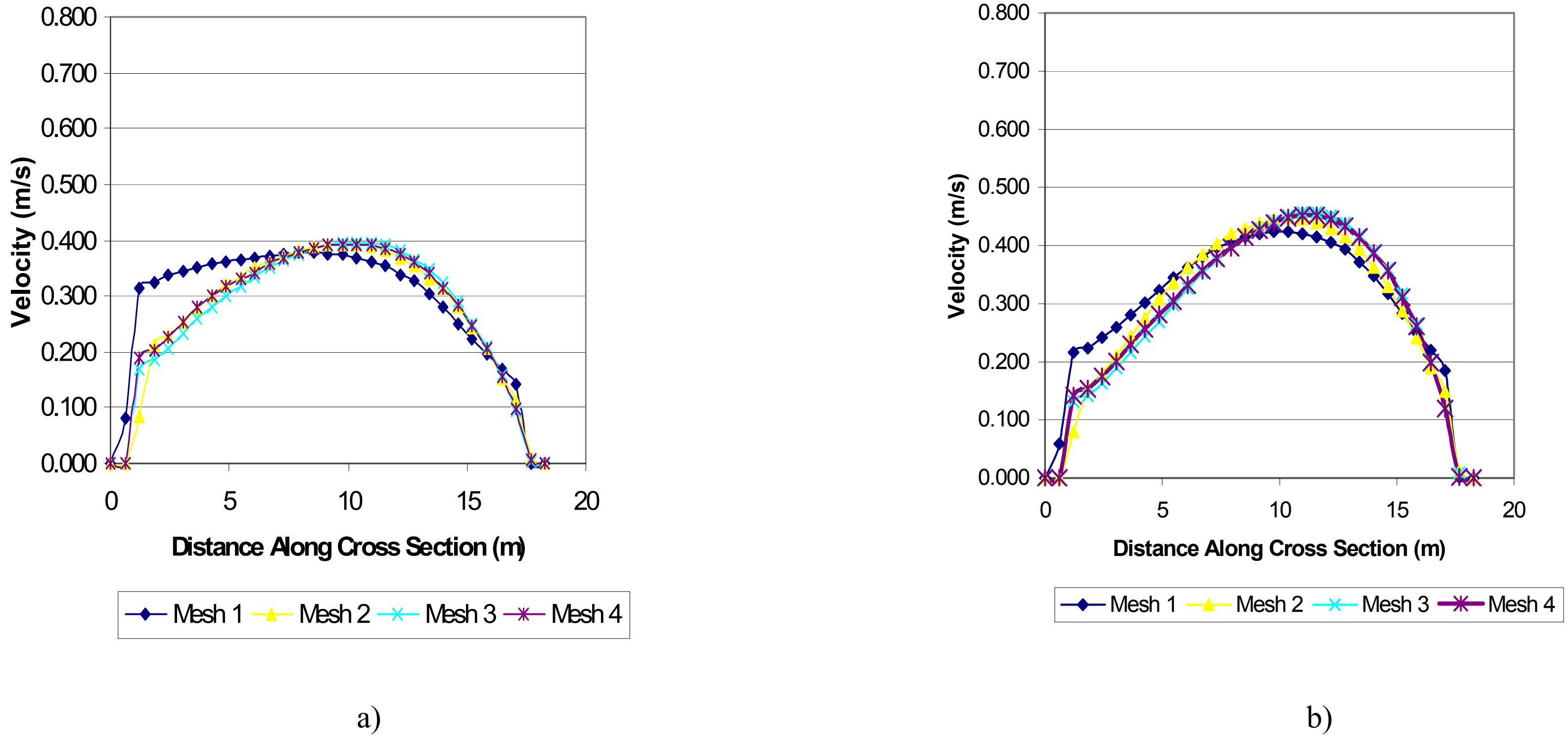


Figure 11. The effect of mesh refinement on velocity profiles at XS-2. Meshes 1-4 refer to the meshes described in Table 1. Profiles generated with meshes not containing data on boulder geometry are shown in (11a). Velocity profiles generated with meshes containing information on the presence of boulders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

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.

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	- 152	102 (site 1) 402 (site 2)	1114 (site 1) 800 (site 2)	2382 (site 1) 1700 (site 2)	- 76.0
Ghanem et. al. [1996]	14.6	50	245	1516	853	8.08
Present Study	4.24	15	61	1182-19321	3595-57462	1.27-0.082

Table 5. Comparison of Mesh Sizes Used in Various 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 seconds for mesh 1. This number increased to approximately 560 seconds 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 seconds to 50 minutes.

Figures 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.

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 two-dimensional 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 m x 20 m. 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.

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 to 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 $(0.20d)^2$ 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 to 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 two-dimensional 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.

ACKNOWLEDGEMENTS

We gratefully acknowledge the support provided by Pacific Gas and Electric, the NSF Grant CTS-9257335 and the EPA Grant R82-5760. Support for this project was also provided by a competitive grant (PL 98-242 and PL 104-134 from the U.S. Geological Survey, Department of the Interior, through the Virginia Water resources Research Center at Virginia Tech. We further appreciate the technical support and field data provided by Edmund Pert, Donald Orth, Steve Railsback, and Craig Roghair.

REFERENCES

Allan, D. J., 1995. Stream Ecology Structure and Function of Running Waters, 1st ed., Chapman & Hall, London, 388 pp.

Biggs, J. F., M. J. Duncan, S. N. Francoeur, and W. D. Meyer, 1997. Physical characterisation of microform bed cluster refugia in 12 headwater streams, New Zealand. New Zealand J. of Marine and Freshwater Res., 13, 413-422.

Bovee, K. D., Perspectives on two-dimensional river habitat models: the PHABSIM Experience, 1996. In: M. Leclerc, H. Capra, S. Valentin, A. Boudreault, and Y. Côté (Editors), Ecohydraulics 2000 Proceedings of 2nd International Symposium on Habitat Hydraulics B. INRS-Eau & FQSA, IAHR/AIRH, pp. B149-B162.

Bovee, K. D., 1978. The incremental method of habitat potential for coolwater species with management implications. American Fisheries Society Special Publication 11., 340-346.

Connor, A. H., 1991. The use of hydraulic principles for the design of fish habitat structures. M.S. Thesis, University of Idaho.

Crowder, D.W., and P. Diplas, Evaluating spatially explicit metrics of stream energy gradients using hydrodynamic model simulations. Submitted for publication in the Canadian Journal of Fisheries and Aquatic Sciences.

Diplas, P., 1994. Modeling of fine and coarse sediment interaction over alternate bars. J. of Hydrology., 159, 335-351.

Ghanem, A., P. Steffler, F. Hicks, and C. Katopodis, 1996. Two-dimensional hydraulic simulation of physical habitat conditions in flowing streams. Regulated Rivers Research & Management., 12 185-200 (1996).

Hayes, J. W. and I. G. Jowett, 1994. Microhabitat models of large drift-feeding brown trout in three New Zealand rivers. North American J. of Fisheries Management., 14, 710-725.

King, I. P., 1990. Program documentation RMA-2V. Two dimensional finite element model for flow in estuaries and streams, Version 4.3, Resource Management Associates, Lafayette, California.

Leclerc, M., A. Boudreault, J. A. Bechara, and G. Corfa, Two-dimensional hydrodynamic modeling: a neglected tool in the instream flow incremental methodology, 1995. Transactions of the American Fisheries Society., 124, No.5, 645-662.

Milhous, R. T., M. A. Updike, and D. M. Schneider, 1989. Physical habitat simulation system (PHABSIM) reference manual, version II. Instream Flow Information Paper No. 26, U.S. Fish and Wildlife Service Biol. Rep. 89 (16).

Mosselman, E., 1998. Morphological modeling of rivers with erodible banks. Hydrological Processes., 12, 1357-1370.

Rosgen, D., and Silvey, H., L., (ills), 1996. Applied River Morphology. Wildland Hydrology, Pagosa Springs, CO, USA.

Tarbet, K., and T. B. Hardy, 1996. Evaluation of one-dimensional and two-dimensional hydraulic modeling in a natural river and implications in instream flow assessment methods. In: M. Leclerc, H. Capra, S. Valentin, A. Boudreault, and Y. Côté (Editors), Ecoydraulics 2000 Proceedings of 2nd International Symposium on Habitat Hydraulics B. INRS-Eau & FQSA, IAHR/AIRH, pp. B395-B406.

US Army Corps of Engineers – Waterways Experiment Station Hydraulic Laboratory, 1996. Users Guide to RMA2 Version 4.3.

Waddle T., P. Steffler, A. Ghanem, C. Katopodis, and A. Locke, 1996. Comparison of one and two-dimensional hydrodynamic models for a small habitat stream. As presented at Ecoydraulics 2000 Proceedings of 2nd International Symposium on Habitat Hydraulics.

Waters, T. F., 1995. Sediment in Streams: Sources, Biological Effects and Control, American Fisheries Society Monograph 7. Bethesda, MD.

Wiele, S. M., J. B. Graf and J. D. Smith, 1996. Sand Deposition in the Colorado River in the Grand Canyon from Flooding of the Little Colordo River. Water Resources Research, 32, No.12 3579-3596.

Chapter 4. Evaluating Spatially Explicit Metrics of Stream Energy Gradients Using Hydrodynamic Model Simulations*

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*This chapter is a modified version of the published article: Crowder, D.W, and P. Diplas, 2000, "Evaluating Spatially Explicit Metrics of Stream Energy Gradients Using Hydrodynamic Model Simulations, *Canadian Journal of Fisheries and Aquatic Sciences*, 57 (7), 1497-1507, reproduced with permission of NRC Research Press.

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Abstract: Localized energy gradients and velocity shelters created by boulders, bars and channel banks are often essential components of aquatic habitat. Two-dimensional hydraulic models have the potential to predict the amounts and locations of such spatially varying flow patterns. However, little effort has been devoted to reproducing these flow features and developing spatial habitat metrics to describe and differentiate between various types of flow patterns. Two-dimensional numerical simulations, based on actual channel geometry, are used here to model a variety of flow patterns encountered in natural streams. The simulation results are used to develop spatial habitat metrics that quantify local velocity gradients and changes in kinetic energy. The proposed metrics are evaluated at various points within the different flow patterns of interest. The metrics produce large values for flow patterns exhibiting considerable spatial variation and small values in areas experiencing uniform flow conditions. Comparisons to other researchers' field data suggest that the metric values produced in the modeled flows are consistent with values found near fish resting and feeding locations. The habitat metrics, measures of the flow's rate of spatial change in kinetic energy, can also be incorporated into bioenergetic models to facilitate the computation of fish energy expenditure rates.

INTRODUCTION

Focal point velocity (assumed to be equal to the depth-averaged velocity unless noted otherwise) and depth, along with other parameters, measured at observed fish locations are routinely used to derive habitat suitability criteria. If a location within a stream has parameters that fall within the ranges in which fish were observed to inhabit, the location is deemed suitable habitat. Focal point data by itself contains no information on flow direction or on any nearby spatial variations such as eddies, velocity gradients and transverse flows surrounding the fish. A critical implicit assumption in many habitat studies is that habitat conditions found at fish's location determine habitat suitability and that flow conditions surrounding the fish are irrelevant.

The assumption that only focal point values influence habitat suitability is consistent with the use of one-dimensional (1-D) hydraulic models to predict depth and velocity in habitat studies. One-dimensional hydraulic models, such as that used in PHABSIM (physical habitat simulation system), often analyze a river by breaking it into elongated discrete cells, each assumed to have a uniform depth and velocity (Bovee 1978; Milhous et al., 1989). One-dimensional models also assume that the flow in an individual cell does not interact with adjacent cells and that the flow is always in the downstream direction. Consequently, the uniform flow conditions predicted in each cell can easily be compared to focal point depth and velocity values. As the assumptions in one-dimensional models preclude the modeling of two-dimensional features such as eddies, velocity gradients, and transverse flows, additional data describing the flows surrounding a fish's location is of little value.

Some researchers have indicated that spatially varying flow patterns are important to a stream's ecological health. Topographic features (channel shape, boulders, bars, and irregularities along stream banks) create velocity gradients, velocity shelters, wakes, and other meso-scale flow patterns that are important or preferred features of fish, periphyton, and invertebrate habitat (e.g. Hayes and Jowett 1994; Lancaster and Hildrew 1993; Rempel et al., 1999). Disturbed flows (e.g. wakes) downstream of boulders and other objects are used by trout as feeding stations and influence the abundance and diversity of flora and fauna in a stream after a spate (Biggs et al. 1997: Hayes and Jowett 1994). The absence of these topographic features often provide poor stream habitat, as evidenced by the many urban and channelized streams that have simple channel shapes and few spatially varying flow patterns.

The accurate quantification and prediction of amounts and locations of the spatially varying habitats created by meso-scale topographic features is not straightforward. If the traditional approach of collecting habitat data at observed fish locations to determine habitat suitability criteria and then using a hydrodynamic model to help quantify the quality and quantity of stream habitat is to be used, two conditions need to be met. First, the habitat data collected should be capable of quantifying any important spatial variations surrounding the aquatic organisms being studied. Second, the hydrodynamic model chosen to predict the flow field must be able to reproduce these spatial variations.

Several studies have been performed to ascertain the benefits of using two-dimensional (2-D) hydraulic models to predict depth and velocity values in stream habitat studies (e.g. Leclerc et al. 1995; Tarbet and Hardy 1996; Ghanem et al. 1996). Unlike 1-D models, 2-D models predict flow velocity in both the downstream and lateral directions. Two-dimensional models also represent the flow as a continuous field instead of independent cells. Hence, 2-D models are capable of modeling flow features such as velocity gradients and transverse flows. To date, most 2-D model studies have focused on modeling longer reaches of river at rather low resolution. In these lower resolution studies, bathymetry data on meso-scale topographic features (large boulders, root-wads, etc,) are typically not incorporated into the model's bathymetry data, but are viewed as channel roughness. Without bathymetry data on these features, velocity gradients, velocity shelters, transverse flows, and other spatially varying flow features created by these objects cannot be modeled. Moreover, most 2-D model studies have adopted habitat suitability criteria based on focal point data and not spatial habitat metrics that can better quantify and describe the spatially explicit output provided by detailed 2-D models.

The 2-D simulations used here to evaluate the proposed habitat metrics were specifically designed to model a short reach at high resolution. Extensive efforts were taken in collecting bathymetry data on meso-scale topographic features and developing a finite element mesh capable of modeling the velocity gradients and complex flow patterns created by the meso-scale topography (Crowder and Diplas 2000). The influence that meso-scale topography has on predicted model output, the computational effort needed to reproduce local velocity gradients, and model accuracy, which are topics of their own, are extensively discussed in Crowder and Diplas (2000). Here only enough information regarding the influence that topographic features have on local flow patterns is given to provide a context of the gradients and degree of influence that the meso-scale topographic features have on flow patterns within the modeled stream reach.

A concerted effort is made here toward developing a general and meaningful way of using and interpreting the spatially explicit output provided by 2-D models to better describe and quantify stream habitat. Simple spatial habitat metrics that incorporate local velocity gradients are developed to distinguish between two areas that have similar velocity values but surrounded by different flow patterns. The parameters are indicative of spatial changes in the flow's kinetic energy and directly relate to fish energy expenditure rates and the proximity to flows that provide velocity shelters or potential high drift rates. Ranges of metric values found at observed fish resting and feeding locations are computed from other researchers' data. The parameter values computed at fish locations are compared to the metric values obtained in the model simulations.

METHOD OF ANALYSIS

Two-dimensional model development and comparisons

The flow through a 61 m long pool of the North Fork of the Feather River near Belden, California, USA was modeled using the 2-D finite element computer program RMA-2V (King 1990). The modeled river is a mountainous trout stream that has an average width of 15 m and a maximum depth of approximately 1.5 m. Regulated by an upstream reservoir, the summer time discharge is approximately 4.25 $m^3 \cdot s^{-1}$. Four large boulders are located near the head of the pool. These boulders create a significant velocity shelter and complex localized flow patterns immediately downstream of their position. The presence of these boulders shifts the main current from the west bank of the river to the east bank. Figure 1 illustrates the upper 25 meters of the pool. It includes the boulders and the 2-D flow patterns created by them.

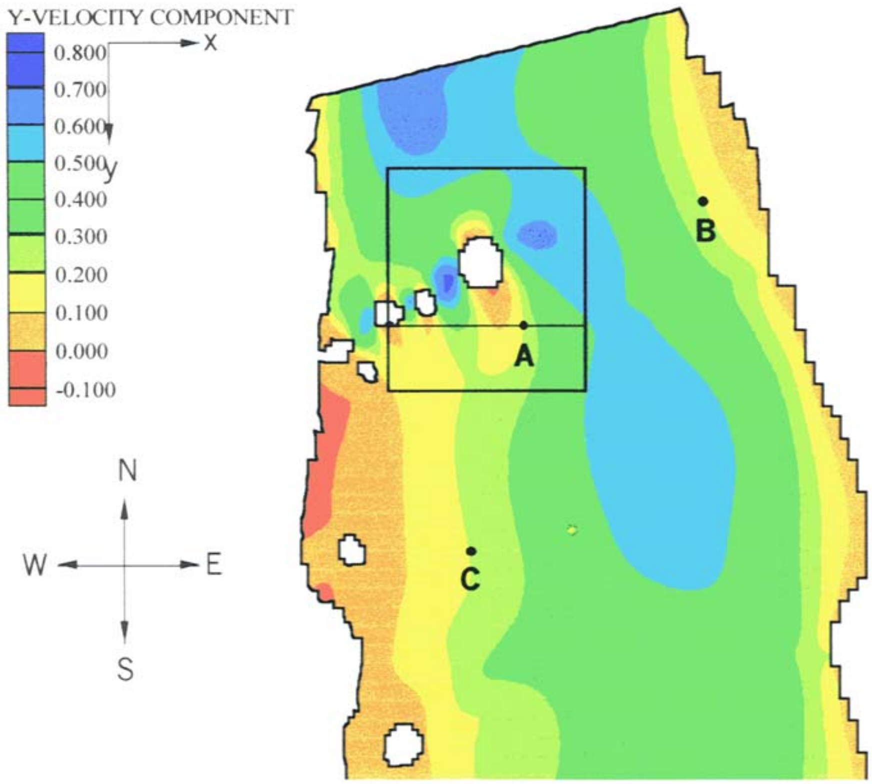


Figure. 1. Y-velocity components for the upper 25 m of the study site when all boulders are incorporated into the model. The white spots represent the dry portions of the boulders. Color contours provide the magnitude of the y-velocity component. The square represents a 6-m x 6-m area in which local velocity and kinetic energy per unit mass values where analyzed. The line passing through point A represents the cross section along which velocity, velocity gradient, $v_{ave} \times |(v_2 - v_1)/\Delta s|$ and $2v_{ave} \times |(v_2 - v_1)/\Delta s| / v_{\min}^2$ are plotted in Figure 4. Points A-C are locations that have the same velocity, but are surrounded by different velocity gradients. Channel width is 15 m.

The study site was modeled three different ways. In each case, the model simulations assumed steady flow. Model output consisted of depth and depth-averaged velocity in the x and y directions at each node point within the finite element mesh. The first simulation modeled the river without bathymetry information on the four exposed boulders at the head of the pool and four more boulders located elsewhere in the pool. The second simulation incorporated bathymetry data on these boulders. The eight boulders had basal areas ranging from 0.56 to 4.10 m^2 and heights from 1.0 to 2.0 m. The third simulation modeled the study site incorporating bathymetry data only on the single largest boulder (one of the four boulders at the head of the pool). Each simulation, based on different bathymetry models, created flow patterns of different complexities.

The flow patterns generated by these numerical simulations are used to represent different spatially varying flows that one might find in natural streams. Computing the values of the proposed spatial habitat metrics at points within these flow patterns, allows one to determine if the metric reasonably quantifies and distinguishes between certain flow patterns found in natural rivers. Specifically, these metrics are computed for each simulation along a cross section located immediately downstream of the four boulders at the head of the pool (Figure 1). In each model simulation, the cross section runs through an area that has a distinctly different flow pattern. A comparison of the spatial habitat metric values along the cross section is made to determine if the obtained values are capable of distinguishing between flow regions that have fairly uniform velocity profiles from regions that have non-uniform velocity profiles. The ability of the proposed metrics to differentiate between areas having identical focal velocity (0.20 $m \cdot s^{-1}$), but having different flow features surrounding them, is tested. Specifically, the spatial metric values at three points (points A, B, and C in Figure 1) having the same velocity, but located in different flow patterns are compared. While the velocity value of 0.20 $m \cdot s^{-1}$ was chosen arbitrarily, this velocity closely corresponds to the velocity values at brook trout feeding locations observed by Fausch and White (1981). Therefore, points A-C can be viewed as three possible brook trout feeding locations with potentially different metric values. Point A is located in the immediate vicinity of a large boulder that creates significant velocity gradients. Point B is located along the east bank near the transverse flow created by the boulders. Point C is located in the velocity refuge immediately downstream of the four boulders at the head of the pool.

Choice of spatial habitat metrics

A fundamental component of a spatially varying flow pattern is the velocity gradient. Velocity gradients are present near banks, boulders, and other obstructions. Therefore, the velocity gradient is a potentially useful measure for quantifying and distinguishing between flows having similar depth and velocity values, but surrounded by different spatially varying flow patterns. Two parameters that incorporate local velocity gradients were evaluated as potential habitat metrics. These parameters follow:

$$\frac{\partial}{\partial s}\frac{V^2}{2} = V\frac{\partial V}{\partial s} \cong V_{ave}\frac{V_2 - V_1}{\Delta s} \qquad \text{and} \qquad \frac{\frac{\partial}{\partial s}\frac{V^2}{2}}{\frac{V^2}{2}} \cong \frac{\frac{1}{2}\left(\frac{V_2^2 - V_1^2}{\Delta s}\right)}{\frac{V_{\min}^2}{2}} = \frac{2V_{ave}\frac{V_2 - V_1}{\Delta s}}{V_{\min}^2}$$

where V is the magnitude of the depth-averaged velocity, V_1 and V_2 are velocity magnitudes measured a distance Δs apart, V_{ave} is the average of V_1 and V_2, $V_{\min}$ is the minimum value of V_1 and V_2 and s indicates the direction of the line between points 1 and 2. The first parameter represents the spatial change in a flow's kinetic energy per unit mass and unit length ($\mathrm{J \cdot kg^{-1} \cdot m^{-1}}$). The second parameter divides this spatial change by the kinetic energy of the flow at the point having the lower velocity magnitude. Scaling the spatial change in kinetic energy by the kinetic energy at the point with the smaller velocity provides a measure of how much more energy an organism must expend if it moves from the lower velocity to the higher velocity.

The primary reason for choosing the first parameter is that kinetic energy per unit mass ($V^2/2$) multiplied by a drag coefficient and a frontal area provides the drag force acting on a specific object or organism (Munson et al., 1990). Using the drag force, one can estimate the power expended by a particular organism moving from one location to another. Hence, the parameter has the potential to be employed in individual-based instream flow models (e.g. Rader and Poff 1999) that incorporate an organism's location and energy expenditures into habitat suitability criteria.

Since flow conditions at both the location of the fish as well as within the surrounding area seem to influence habitat conditions, the second metric might be of more general usefulness. Furthermore, because the difference in energy is scaled by the energy value at the point having the slower velocity, this metric might unify flow conditions at different stream locations, such as banks and boulders, which are frequented by different species or by the same species but at different life stages.

The parameters $V \times \partial V / \partial s$ and $2 \times \partial V / \partial s \div V$ apply only at a point in the flow field and may not be accurately computed if Δs is large. If Δs is large, then the use of equations $V_{ave} \times (V_2 - V_1) / \Delta s$ and $2 V_{ave} \times (V_2 - V_1) / \Delta s / V_{\min}^2$ can be used to accurately calculate the average energy gradient and the average rate that the kinetic energy changes between points 1 and 2 relative to the kinetic energy at the point with the smaller velocity. As the Δs distances used in this paper are relatively large, the latter two expressions are used to compute the spatial habitat parameter values. Selection of an appropriate Δs is discussed later. The potential usefulness of evaluating velocity gradients in different directions or using the x- (lateral) or y- (downstream) velocity components (u and v) instead of the velocity magnitude ($V = \sqrt{u^2 + v^2}$) in the two proposed parameters is also discussed later. Here, the parameters $v_{ave} \times \left|(v_2 - v_1) / \Delta s\right|$ and $2v_{ave} \times \left|(v_2 - v_1) / \Delta s\right| / v_{\min}^2$ are initially used to evaluate flow conditions in the model simulations. However, the parameters $V_{ave} \times \left|(V_2 - V_1) / \Delta s\right|$ and $2 V_{ave} \times \left|(V_2 - V_1) / \Delta s\right| / V_{\min}^2$ were computed for the three model scenarios and are used for comparing the habitat parameter values obtained from the model with those evaluated in the field studies**.** The absolute value signs were added to make the gradient term values independent of direction. For all model results, the distance between V_1 and V_2/v_1 and v_2 velocity measurements was 0.305 m, moving always along the x-axis (Figure. 1). When these metrics are calculated along cross sections, V_1 and v_1 are always taken to be left (west) of V_2 and v_2. The metric values are also always plotted midway between the locations of V_1 and V_2 or v_1 and v_2. Hence, the metric values quantify the variations in the flow conditions occurring between the two velocity measurements in an averaged sense.

Spatial habitat metric values at fish locations

Hayes and Jowett (1994) and Fausch and White (1981) provided data that can be used to estimate the minimum and maximum possible values of $2V_{ave} \times \left|(V_2 - V_1)/\Delta s\right| / V_{\min}^2$ that existed at the fish locations observed in their studies. Specifically, both studies provided a range of focal point velocity values (V_{min}), “velocity shears” and “velocity differences” that existed at fish locations. This information does not allow one to compute the exact parameter values found at each individual fish location. Only, the minimum and maximum metric values that could have existed at the observed fish locations can be computed. The range of parameter values calculated here may therefore be substantially wider than those at which the fish were actually observed.

While Hayes and Jowett provide several data sets, only the optimal lateral velocity gradient data (using depth-averaged velocities) and the optimal vertical velocity gradient data (using point velocities) are analyzed here. These two data sets were collected at the locations of drift-feeding brown trout (*Salmo trutta*). The trout were 45-65 cm in length. Four data sets collected by Fausch and White were selected for analysis. These sets pertain to the allopatry resting and allopatry feeding locations of brook trout (*Salvelinus fontinalis*). Two of the data sets are for 15-20 cm trout locations; the other two are for 20-30 cm trout locations. The focal point velocities, velocity gradients, and Δs values used for each data set are shown in Table 1. The individual data sets will be referred to as data sets 1 – 6.

Data set	Study and conditions	Range of focal point velocities $(m \cdot s^{-1})$	Range of velocity differences (V_2-V_1) $(m \cdot s^{-1})$	Range of velocity gradients (s^{-1})	Δs used between velocity measurements (m)
1	Hayes and Jowett (1994): Lateral Optimal	0.38 – 0.48	NA	0.02 – 0.06	0.5 or 1.0
2	Hayes and Jowett (1994): Vertical Optimal	0.19 – 0.28	NA	0.50 – 0.65	0.198 - 0.274
3	Fausch and White (1981): Resting 20-30 cm	0.095 – 0.169	0.348 -0.384	NA	0.60
4	Fausch and White (1981): Feeding 20-30 cm	0.156 – 0.210	0.217 – 0.393	NA	0.60
5	Fausch and White (1981): Resting 15-20 cm	0.109 - 0.145	0.158 – 0.194	NA	0.60
6	Fausch and White (1981): Feeding 15-20 cm	0.232 – 0.262	0.184 – 0.234	NA	0.60

Table 1. Summary of the fish location data sets

RESULTS

Spatial flow patterns generated by the three modeling scenarios

In terms of depth, the flow fields of the first two simulations were very similar, regardless of whether or not bathymetry data on the boulders were incorporated into the model. The only significant differences in depth occurred immediately upstream of the four boulders at the head of the pool. There, depths increased on average by about 0.06 m, or by 10%. The second simulation (with all boulders) had a significantly different velocity field throughout the upper 25 m of the pool, particularly in the immediate vicinity of the boulders. Near the boulders, complex flow patterns existed that were absent in the first simulation. The differences in the velocity fields are illustrated by mapping the amount that the kinetic energy per unit mass ($\nu^2/2$) changes between the two simulations (Figure. 2). A change in kinetic energy of 0.100 $J{\cdot}kg^{-1}$ corresponds to a change equal to 2.74 times the kinetic energy of water flowing at 0.27 $m{\cdot}s^{-1}$ (the study site's average velocity), or 27% of the kinetic energy of water flowing at 0.86 $m{\cdot}s^{-1}$ (the study site's maximum velocity).

The velocity fields generated within the 6 x 6 meter box (Figure 1) for each modeling scenario are plotted (Figure. 3). Specifically, the y-velocity component (ν) within a 6 m x 6 m square surrounding the location of the largest boulder is plotted for each scenario. Without boulders (Figure 3a), the local flow pattern was fairly uniform except in one location where the presence of a small ridge on the channel bottom increased velocity values. The flow pattern around the single largest obstruction (Figure 3b) was more complex. Steep velocity gradients adjacent to the boulder and a downstream wake were created. With all the boulders present, (Figure 3c) the surface plot became even more complex. It contained several velocity peaks and valleys, which provide several velocity magnitudes and velocity gradients which aquatic organisms can choose to inhabit.

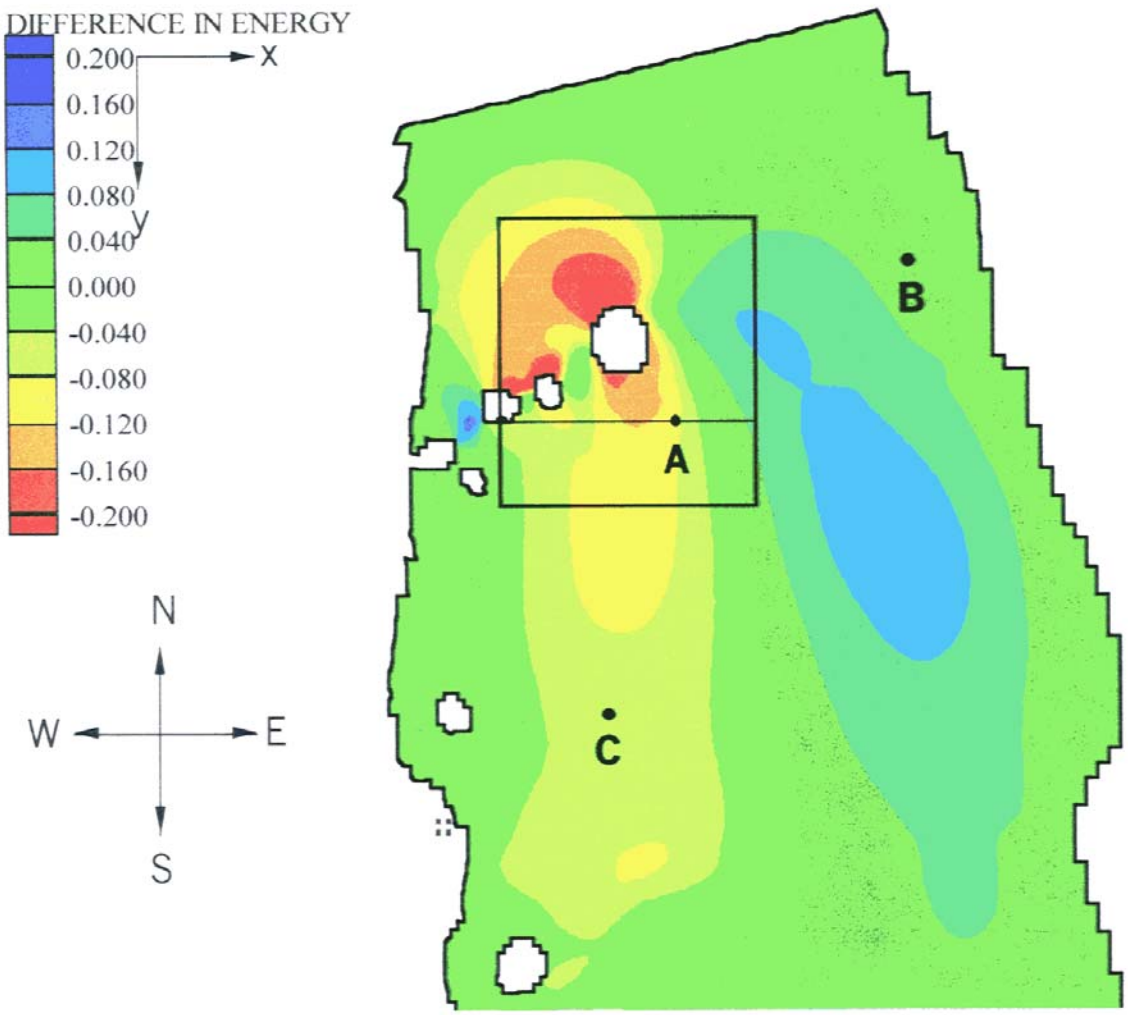


Figure 2. Change in kinetic energy per unit mass ($v^2/2$) induced by the presence of all the exposed boulders. Color contours provide the magnitude of change in the kinetic energy per unit mass ($J \cdot kg^{-1}$). The area shown is the upper 25 meters of the pool.

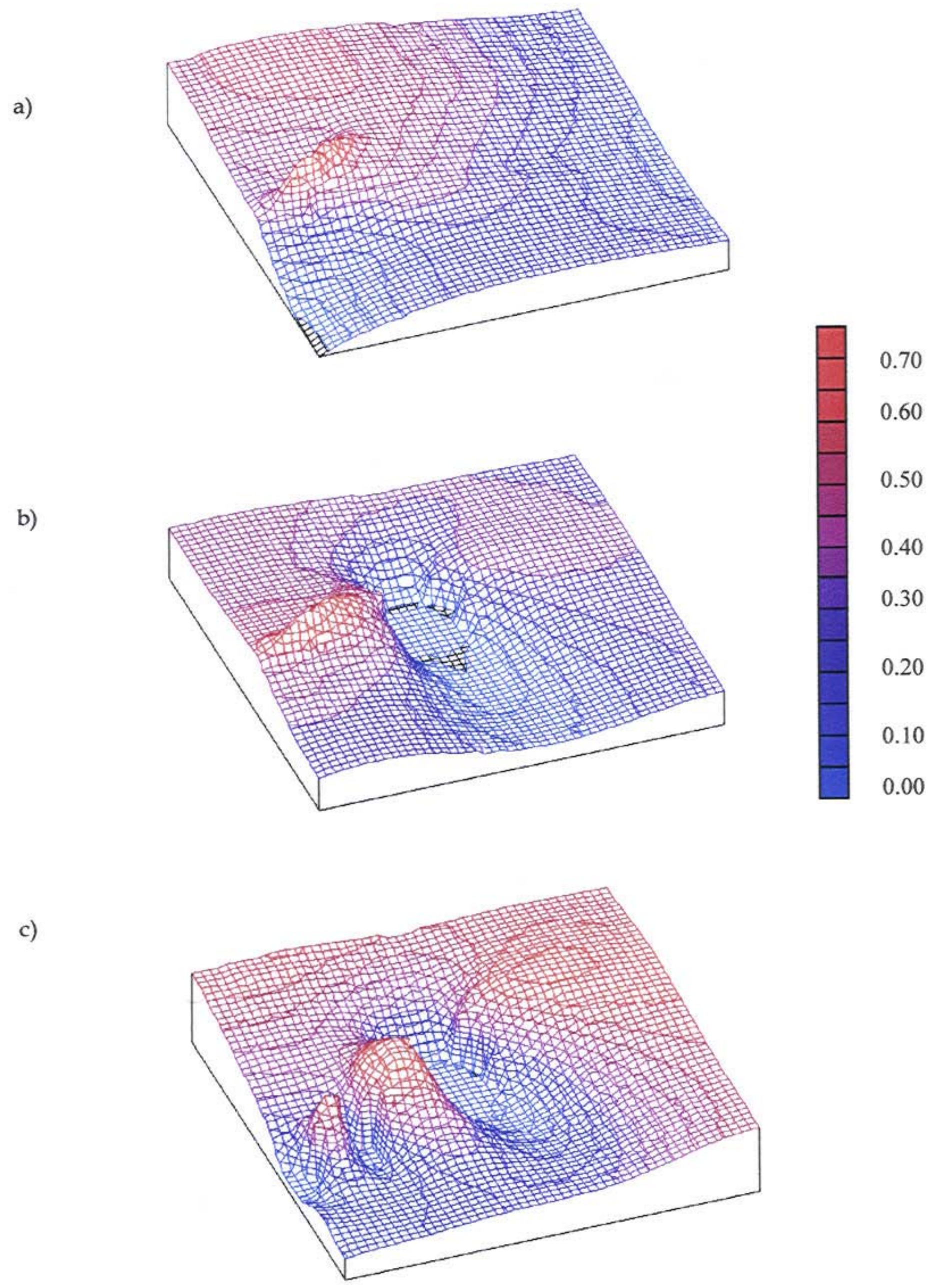


Figure 3. Surface plots of the y-velocity component found within the 6 m x 6 m square shown in Figure 2. The surface plot obtained without boulders is shown in Figure 3a while the surface plots obtained for the single largest boulder and all of the boulders are in Figure 3b and Figure 3c, respectively. Color contours represent velocity in $m \cdot s^{-1}$. The flat locations having zero velocity in Figures 3a and 3b indicate the locations of boulders.

Spatial habitat metric results

The three different model simulations produced distinctly different velocities and velocity gradients along the cross section taken just below the four boulders at the head of the pool (Figure 1). Figure 4a graphs the lateral y-velocity profile for each model simulation. The velocity gradients corresponding to each of the velocity profiles are illustrated in Figure 4b. Without incorporating the boulders into the model, the velocity profile was relatively flat and had velocity gradients with absolute magnitudes of up to 0.122 s^{-1}. Model results obtained by incorporating only the single largest boulder into the channel geometry produced a sinuous velocity profile typical of a wake. Low velocity values existed immediately behind the boulder and high velocity values existed elsewhere. Associated with this velocity profile were velocity gradients having absolute magnitudes of up to 0.582 s^{-1}. With all of the boulders included, the velocity profile became even more sinuous and local velocity gradients had absolute magnitudes of up to 0.692 s^{-1}, which is 5.67 times those predicted in their absence.

The range of velocity and velocity gradient magnitudes associated with the three simulations produced a wide range of spatial change in kinetic energy ($v_{ave} \times |(v_2 - v_1)/\Delta s|$) values. Figure 4c plots $v_{ave} \times |(v_2 - v_1)/\Delta s|$ along the cross section for each model scenario. Without including boulder geometry into the model, the spatial change in kinetic energy was generally lower than that predicted when either the single boulder or all of the boulders were incorporated into the model. The maximum spatial change in kinetic energy per unit length in the absence of boulders was 0.051 $J \cdot kg^{-1} \cdot m^{-1}$ and represented only 0.31 and 0.47 times the maximum spatial change in kinetic energy computed for the single boulder and multiple boulders scenarios, respectively. The maximum change in kinetic energy per unit length in the profiles for the single obstruction was 0.165 $J \cdot kg^{-1} \cdot m^{-1}$ and occurred at a location in the boulder's wake, which had a velocity of approximately 0.29 $m \cdot s^{-1}$. An organism at that location has access to flow within 0.30 m that has 2.18 times more kinetic energy passing through its location, or 1.48 times its focal point velocity. With all of the obstructions present, the maximum change in kinetic energy was 0.11 $J \cdot kg^{-1} \cdot m^{-1}$ and occurred at a location having a velocity of 0.39 $m \cdot s^{-1}$. A spot 0.30-m away would have 1.43 times more kinetic energy than the original location.

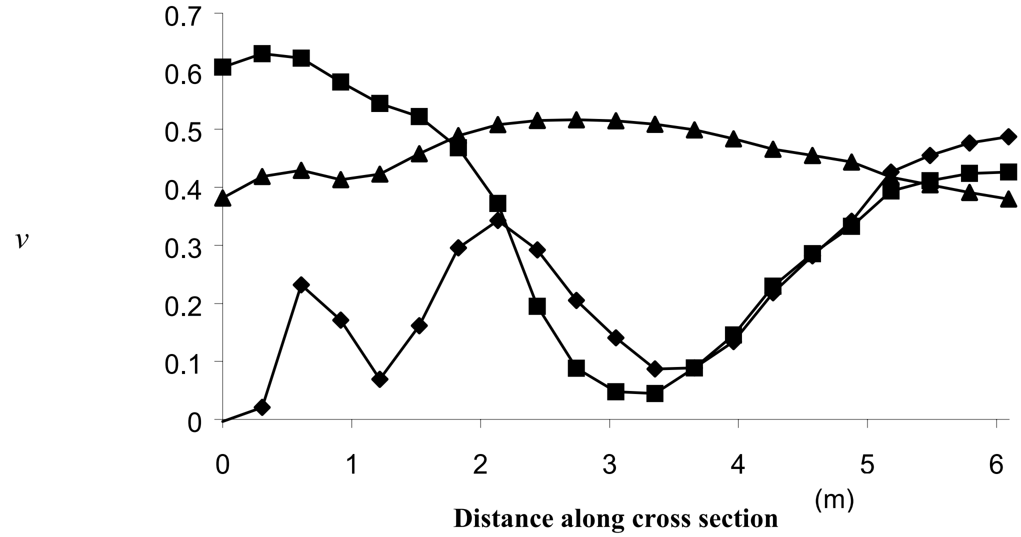


Figure 4a. Graph of velocity along the cross section shown in Figure 1 for each model simulation. Distance is measured from the west end of the line passing through point A (Figure 1). For all plots in Figure 4, diamonds indicate values obtained from the simulation containing all the boulders. The squares and triangles represent values obtained from the simulations containing the single boulder and no boulders, respectively. Velocity gradient, $v_{ave} \times |(v_2 - v_1)/\Delta s|$, and $2v_{ave} \times |(v_2 - v_1)/\Delta s|/v_{\min}^2$ are plotted midway between v_1 and v_2.

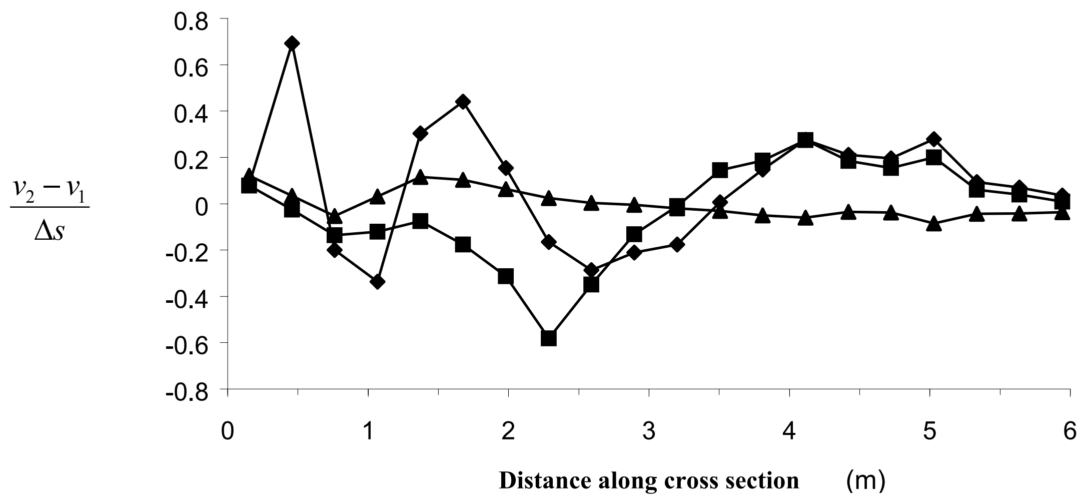


Figure 4b. Graph of velocity gradient along the cross section shown in Figure 1 for each model simulation.

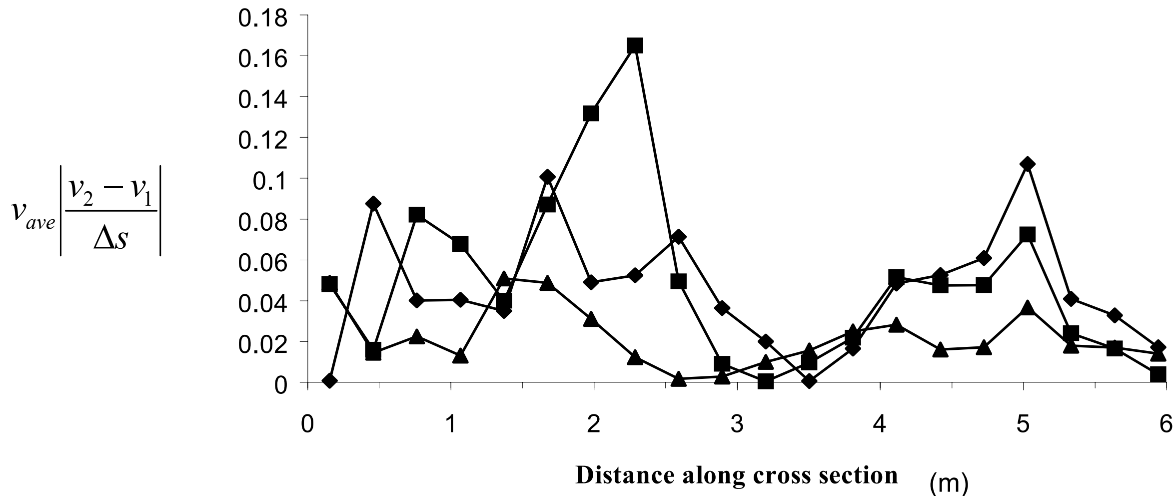


Figure 4c. Graph of $v_{ave} \times \left|(v_2 - v_1)/\Delta s\right|$ along the cross section shown in Figure 1 for each model simulation.

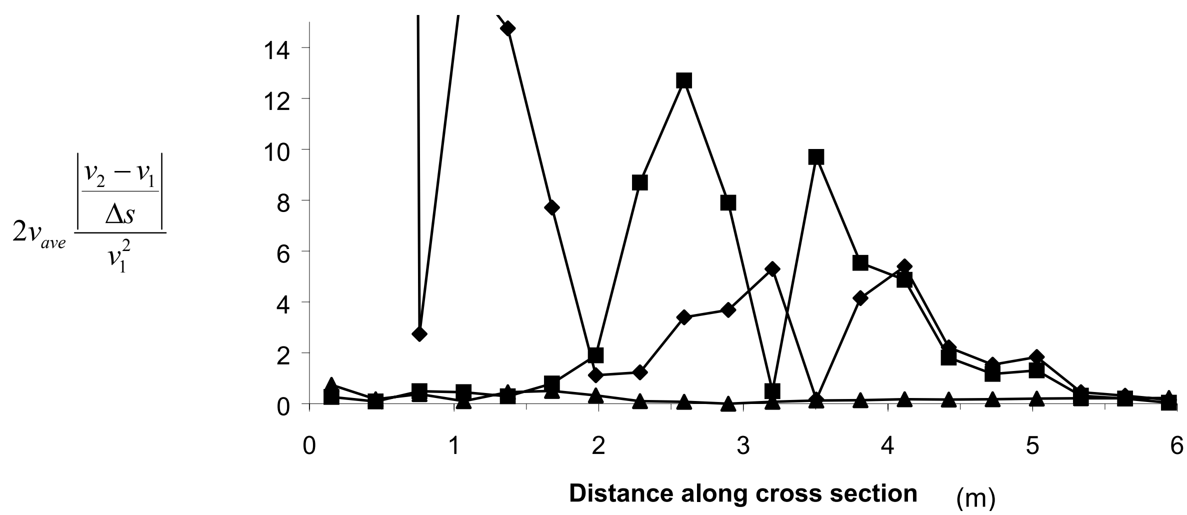


Figure 4d. Graph of $2v_{ave} \times \left|(v_2 - v_1)/\Delta s\right| / v_{\min}^2$ along the cross section shown in Figure 1 for each model simulation.

Since identical values of $v_{ave} \times |(v_2 - v_1)/\Delta s|$ can be obtained with different combinations of velocity and velocity gradient [e.g. small v and large $|(v_2 - v_1)/\Delta s|$ or large v and small $|(v_2 - v_1)/\Delta s|$], it was difficult to visually determine from Figure 4c which velocity profile exhibits the most spatial variability. A plot of $2v_{ave} \times |(v_2 - v_1)/\Delta s| / v_{\min}^2$, however, clearly identified the locations along the three velocity profiles where significant spatial variations are present (Figure. 4d). The values of this metric along the profile generated without obstructions were small (ranging from 0.01 to 0.67 m^{-1}) everywhere along the profile. Such results are consistent with what one expects of relatively uniform flow conditions. The values of the parameter ranged from 0.04 to 9.69 m^{-1} along the profile for the single boulder simulation. The larger of these values occurred in the wake region behind the boulder. This is expected. These locations correspond to areas having relatively low velocities and high velocity gradients. The parameter values obtained for the profile generated with all the boulders incorporated into the model ranged from 0.15 to 393.59 m^{-1}. As with the profile obtained with the single boulder, the larger values were typically found in the wake regions created by the boulders. The largest values (393.59 and 97.00 m^{-1}) were located immediately next to a boulder. These large values can be expected extremely close to banks or boulders and are triggered by the very small $V_{\min}$ values at these locations. A comparison of the three profiles shown in Figure 4d quickly reveals that the velocity profiles obtained with the single boulder and all of the boulders have significantly more spatial variability than the profile obtained without boulders.

The spatial parameters $v_{ave} \times |(v_2 - v_1)/\Delta s|$ produced values that differed by a factor of four between points A- C. Because the velocity is the same at these three points, the values of $2v_{ave} \times |(v_2 - v_1)/\Delta s| / v_{\min}^2$ will differ by the same factor as the first parameter values. The velocity, velocity gradient, and habitat metric values at points A-C are summarized (Table 2). The highest parameter values occurred at point A, which is surrounded by the steep velocity gradients and complex flow patterns generated by boulders (Figure 1). The lowest parameter values were found at location C, which is in the middle of a velocity shelter where flow conditions are not changing quickly. Point B, near the east bank where velocity values are changing fairly quickly, created intermediate parameter values. Such results are expected.

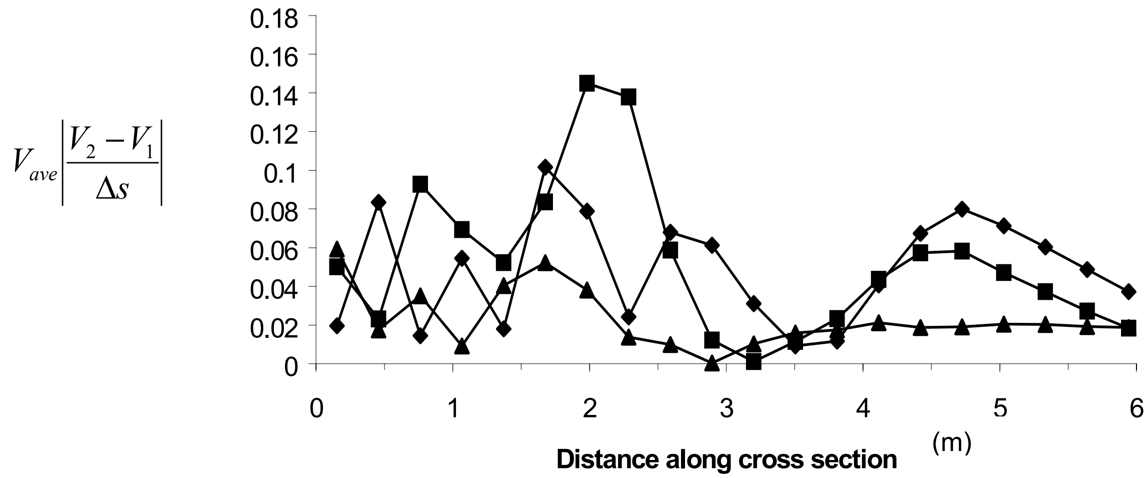
Point	v (m·s^{-1})	$\left\lvert\frac{v_2-v_1}{\Delta s}\right\rvert$ (s^{-1})	$v_{ave}\times\left\lvert\frac{v_2-v_1}{\Delta s}\right\rvert$ (J·kg^{-1}·m^{-1})	$2v_{AVE}\times\frac{\left\lvert\frac{v_2-v_1}{\Delta s}\right\rvert}{v_1^2}$	Representative flow condition
A	0.200	0.249	0.050	2.487	Boulder's wake
B	0.199	0.106	0.021	1.065	Unprotected bank
C	0.200	0.052	0.010	0.520	Velocity shelter

Table 2. Habitat metrics at points A-C when all boulders are modeled

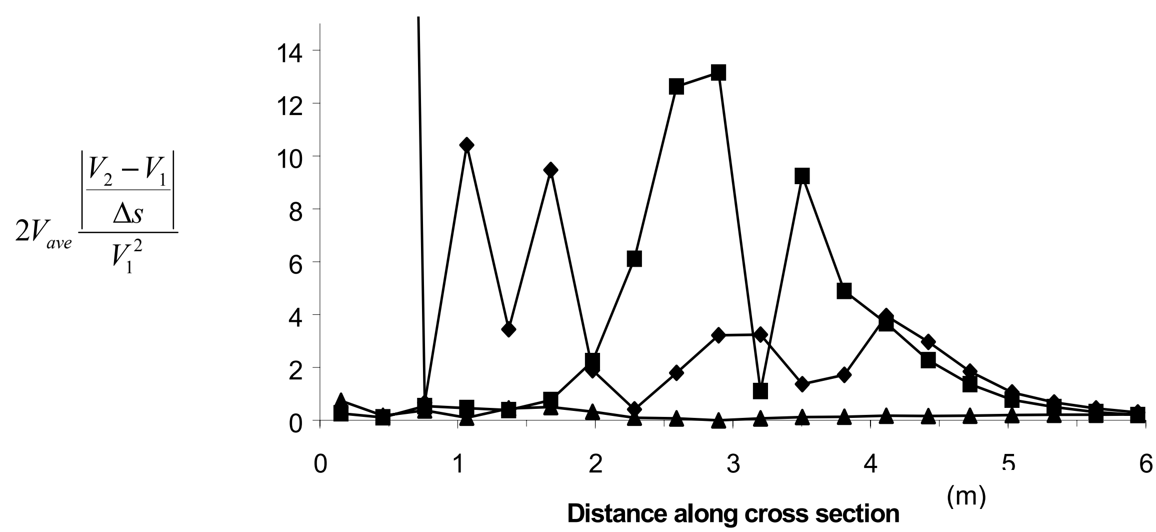
Since the parameter values range by a factor of four, the metrics appear to provide a useful means of distinguishing between various flow conditions within the study site. The velocity at points A-C falls within the range of focal velocities observed for the fish in field data set 4. Therefore, points A-C represent potential feeding locations of 20 – 30 cm brook trout. As shown later, point C has the metric value closest to those which the trout in data set 4 were surrounded.

The velocity magnitude, V, is often of primary importance in stream management issues. Consequently, the parameters $V_{ave}\times\lvert(V_2-V_1)/\Delta s\rvert$ and $2V_{ave}\times\lvert(V_2-V_1)/\Delta s\rvert/V_{\min}^2$ were plotted along the cross section below the boulders for each simulation (Figure. 5). The profiles generated using $V_{ave}\times\lvert(V_2-V_1)/\Delta s\rvert$ and $2V_{ave}\times\lvert(V_2-V_1)/\Delta s\rvert/V_{\min}^2$ are similar to those obtained with $v_{ave}\times\lvert(v_2-v_1)/\Delta s\rvert$ and $2v_{ave}\times\lvert(v_2-v_1)/\Delta s\rvert/v_{\min}^2$ (Figure 4 and Figure 5), except for some differences that exist in certain locations. These differences occur in locations where v is significantly less than V. A comparison of the y-velocity components to velocity magnitudes along the cross sections revealed that on average the y-velocity component constitutes over 96% of the velocity magnitude for the simulations with the single boulder and no boulders. With all the boulders present, the y-velocity component represented, on average, 84% of the velocity magnitude. These high percentages suggest that, in this case, v can be used to approximate V and will produce similar habitat parameters along most of the cross-section.

The absolute values in the spatial metrics plotted in Figure 5 render the energy gradients independent of direction. This independence is useful when analyzing the magnitudes of the energy gradients found within a study reach. One may wish to remove the absolute value signs as this provides a more descriptive representation of how the flow's energy is changing throughout a river. The metrics $V_{ave} \times (V_2 - V_1) / \Delta s$ and $2V_{ave} \times (V_2 - V_1) / \Delta s / V_{\min}^2$ are plotted for each model scenario in Figure 6a and Figure 6b, respectively. The plots of $V_{ave} \times (V_2 - V_1) / \Delta s$ for all three simulations are sinuous and do not clearly reveal which simulations had significant variations in their flow patterns. However, the plots of $2V_{ave} \times (V_2 - V_1) / \Delta s / V_{\min}^2$ clearly distinguish the spatially varying flows patterns found in the single and multiple boulders simulations from the uniform flows found in the no boulders simulation. With no boulders present, $2V_{ave} \times (V_2 - V_1) / \Delta s / V_{\min}^2$ plots almost as a straight line with values approaching zero. In contrast, the profiles for the single and multiple boulder simulations are quite sinuous. As the metric values were calculated from left to right (V_1 always being left/west of V_2), a positive value of $2V_{ave} \times (V_2 - V_1) / \Delta s / V_{\min}^2$ indicates that the flow's energy is increasing from west to east at that point. A negative value of $2V_{ave} \times (V_2 - V_1) / \Delta s / V_{\min}^2$ indicates that the flow's energy is decreasing from west to east at that point in the river. The magnitude of the parameter represents the relative rate at which the energy is changing. Had the values been calculated from right (east) to left (west) all the metric values would have the same magnitude, but would be opposite in sign. The values would also be indicative of how the flow's kinetic energy is changing from east to west.

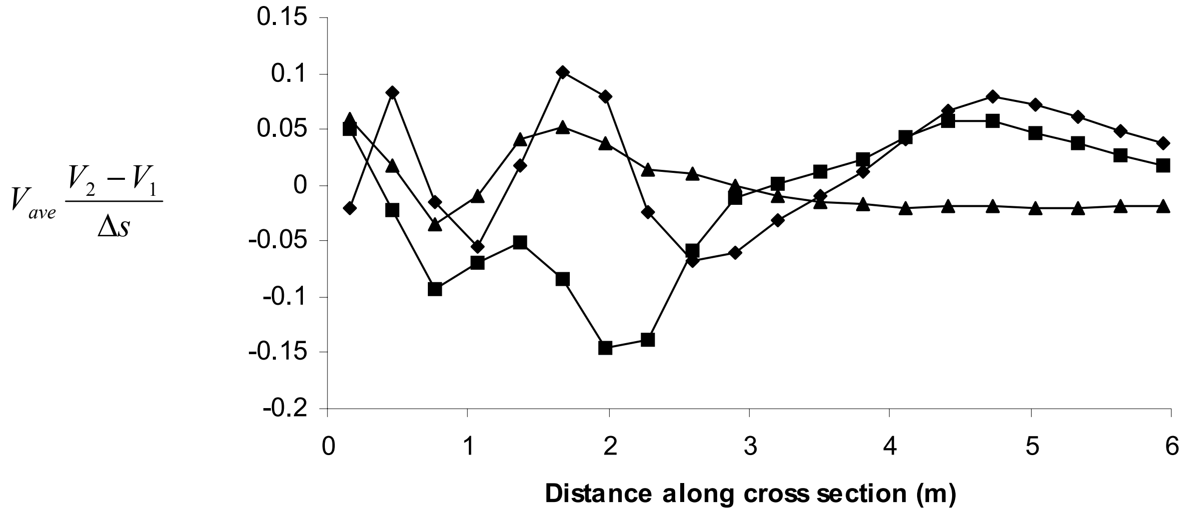


a)

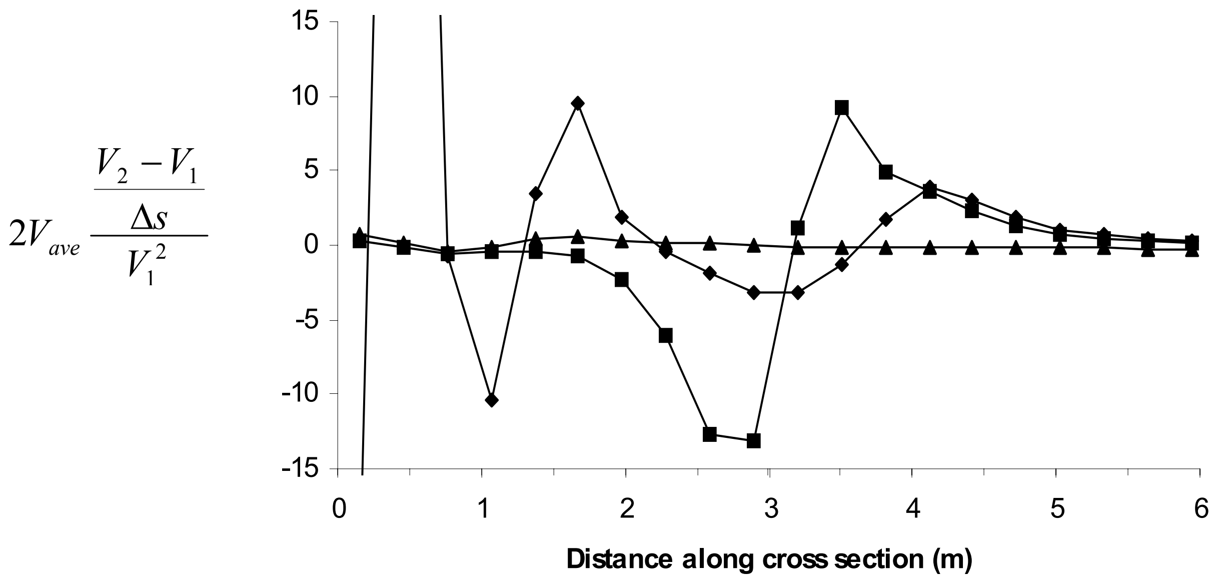


b)

Figure 5. Graphs of $V_{ave} \times \left|(V_2 - V_1)/\Delta s\right|$ (Figure 5a) and $2V_{ave} \times \left|(V_2 - V_1)/\Delta s\right|/V_{\min}^2$ (Figure 5b) along the cross section shown in Figure 1 for each model simulation. Distance is measured from the west end of the line passing through point A (see Figure 1). The diamonds indicate values obtained from the simulation containing all the boulders. The squares and triangles represent values obtained from the simulations containing the single boulder and no boulders, respectively. The metric values $V_{ave} \times \left|(V_2 - V_1)/\Delta s\right|$ and $2V_{ave} \times \left|(V_2 - V_1)/\Delta s\right|/V_{\min}^2$ are plotted midway between V_1 and V_2.



a)



b)

Figure 6. Graphs of $V_{ave} \times (V_2 - V_1)/\Delta s$ (Figure 5a) and $2V_{ave} \times (V_2 - V_1)/\Delta s / V_{\min}^2$ (Figure 5b) along the cross section shown in Figure 1 for each model simulation. Distance is measured from the west end of the line passing through point A (see Figure 1). The diamonds indicate values obtained from the simulation containing all the boulders. The squares and triangles represent values obtained from the simulations containing the single boulder and no boulders, respectively. The metric values $V_{ave} \times \left|(V_2 - V_1)/\Delta s\right|$ and $2V_{ave} \times \left|(V_2 - V_1)/\Delta s\right| / V_{\min}^2$ are plotted midway between V_1 and V_2.

Spatial habitat metric values at observed fish locations

The minimum possible value of $2V_{ave} \times \left|(V_2 - V_1)/\Delta s\right| / V_{\min}^2$ for each fish habitat data set would occur if the mildest velocity gradient surrounded the fish location having the fastest focal point velocity. The maximum possible value would occur if the steepest velocity gradient existed at the location having the slowest focal point velocity. The minimum and maximum possible parameter values at the Δs values used to collect data sets 1-6 are tabulated (Table 3). Values at $\Delta s = 0.305$ m were estimated for comparison with the results obtained along the cross section in each model simulation.

The largest parameter values, ranging from 10.456 – 27.316 m^{-1}, were obtained from data set 3. These values are typically much larger than those found in the three model simulations. Only one point in the all boulders simulation had a parameter value higher than the values found in data set 3. That point had a value of 97.350 and occurred in the all boulders simulation. Excluding the 97.350 value and a value of 22.850 (found in very slow water near a boulder), the parameter values range from 0.304 to 10.416 m^{-1} along the cross section shown in Figure 1. For the simulations containing the single boulder and no boulder cases the corresponding ranges are 0.116 – 13.155 m^{-1} and 0.002 – 0.738 m^{-1}. Only two values (12.624 and 13.155) fall within range of 10.456 – 27.316 m^{-1}. This suggests that the energy gradients along the cross-section are routinely smaller than those used by the trout observed in data set 3. The lowest metric values were obtained from data set 1. The parameter values range from 0.084 – 0.328 m^{-1} and coincide most closely with the values found in the model simulation containing no boulders. The ranges of parameter values found in data sets 2, 4, 5, and 6 are similar to each other. Combined, the data sets have parameter values ranging from 2.759 – 13.774 m^{-1}. These values overlap with the ones predicted by the model for the single and multiple boulder simulations (0.116 – 13.155 m^{-1}). The likeness of these two ranges suggests that the flow patterns in the single and multiple boulder simulations may provide suitable habitat for the fish studied in data sets 2, 4, 5, and 6.

Data Set	Study Conditions	V_1	V_2	Δs	V_{ave}	$\left\lvert \frac{V_2 - V_1}{\Delta s} \right\rvert$	$2V_{ave} \times \frac{\left\lvert \frac{V_2 - V_1}{\Delta s} \right\rvert}{V_1^2}$	Extrema
1	Hayes and Jowett (1994): Lateral	0.380	0.440	1.000	0.410	0.060	0.341	Maximum
		0.480	0.500	1.000	0.490	0.020	0.085	Minimum
		0.380	0.410	0.500	0.395	0.060	0.328	Maximum
		0.480	0.490	0.500	0.485	0.020	0.084	Minimum
2	Hayes and Jowett (1994): Vertical	0.190	0.368	0.274	0.279	0.650	10.049	Maximum
		0.280	0.417	0.274	0.349	0.500	4.445	Minimum
		0.190	0.319	0.198	0.254	0.650	9.159	Maximum
		0.280	0.379	0.198	0.330	0.500	4.203	Minimum
3	Fausch and White (1981): Resting 20 – 30 cm	0.095	0.479	0.600	0.287	0.640	40.705	Maximum
		0.169	0.517	0.600	0.343	0.580	13.931	Minimum
		0.095	0.290	0.305	0.193	0.640	27.316	Maximum
		0.169	0.346	0.305	0.257	0.580	10.456	Minimum
4	Fausch and White (1981): Feeding 20 – 30 cm	0.156	0.549	0.600	0.353	0.655	18.975	Maximum
		0.210	0.427	0.600	0.319	0.362	5.224	Minimum
		0.156	0.356	0.305	0.256	0.655	13.774	Maximum
		0.210	0.320	0.305	0.265	0.362	4.349	Minimum
5	Fausch and White (1981): Resting 15 – 20 cm	0.109	0.303	0.600	0.206	0.323	11.212	Maximum
		0.145	0.303	0.600	0.224	0.263	5.611	Minimum
		0.109	0.208	0.305	0.158	0.323	8.617	Maximum
		0.145	0.225	0.305	0.185	0.263	4.638	Minimum
6	Fausch and White (1981): Feeding 15 – 20 cm	0.232	0.466	0.600	0.349	0.390	5.058	Maximum
		0.262	0.446	0.600	0.354	0.307	3.163	Minimum
		0.232	0.351	0.305	0.291	0.390	4.224	Maximum
		0.262	0.356	0.305	0.309	0.307	2.759	Minimum
7	Present Study: No Boulders	0.400	0.444	0.305	0.422	0.140	0.738	Maximum
		0.524	0.524	0.305	0.524	0.001	0.002	Minimum
8	Present Study: Single Boulder	0.050	0.097	0.305	0.074	0.156	13.155	Maximum
		0.643	0.632	0.305	0.637	0.036	0.112	Minimum
9	Present Study: All Boulders	0.041	0.229	0.305	0.135	0.616	97.350	Maximum
		0.495	0.517	0.305	0.506	0.073	0.304	Minimum

Table 3. Metric values generated for the numerical simulations and fish location data

DISCUSSION

Two-dimensional hydraulic models provide stream managers with spatially explicit information about flow patterns within a study reach, including flow direction, velocity gradients, velocity shelters, and transverse flows. If such 2-D features provide essential, or even preferred, habitat conditions, then the accurate quantification of the number and type of these features may lead to improved instream flow analyses and stream restoration techniques.

Despite recent progress in using 2-D models in habitat suitability studies, substantial research remains to be performed to determine the accuracy at which one can predict the complex flow patterns natural streams exhibit. Differences between implementing 1-D and 2-D models make it difficult to compare the labor costs and model accuracy associated with 1-D and 2-D models. Both the labor required and the accuracy of particular model depend on the individual site being studied. Some researchers (e.g. Ghanem et al., 1996) suggest, but have not conclusively shown, that the collection of field data for a 2-D hydraulic models may be less intensive than that needed to run and calibrate PHABSIM. One reason for this belief is that the more intensive bathymetry data required by 2-D models can be collected faster than the velocity data needed to run PHABSIM simulations.

The type of spatial variability that is important to quantify may depend on both the species and life-stage of the organism being studied. The spatial habitat metrics $2V_{ave} \times (V_2 - V_1)/\Delta s / V_{\min}^2$ and $2v_{ave} \times (v_2 - v_1)/\Delta s / v_{\min}^2$ were found to be capable of describing and differentiating between various flow conditions within the study site. In this case, the direction of the line between velocities 1 and 2 was in the x-direction. Therefore, the parameter describes lateral velocity and energy gradients. Such a parameter has the potential to identify the habitat of drift feeding fish, which often use the lateral velocity/energy gradients generated by boulders as feeding stations. However, longitudinal velocity/energy gradients may be a more useful means of quantifying other habitats. Foraging fish may find longitudinal velocity gradients, such as those located between the tail of a pool and the head of a riffle, to be an important habitat feature. Likewise, the evaluation of potential salmon spawning grounds may benefit from an analysis of local longitudinal velocity gradients, as it may be indicative of the flow's capacity to prevent siltation from destroying the redd. In other cases fish may be using vertical velocity/energy gradients to feed. Fortunately, the parameter $2V_{ave} \times (V_2 - V_1) / \Delta s / V_{\min}^2$ is general in nature and the line between the two velocity measurements can be in the x, y-, z- (or any other desirable) direction. If the x- or y- velocity components are important characteristics then the substitution of these velocities into the parameter may also lead to an appropriate means of quantifying stream habitat.

All of the variations of the parameter described above reflect spatial changes in energy and the percent increase/decrease in energy expenditure levels an organism will encounter by moving in a specific direction of the flow. Consequently, the amount of energy a fish or other organism must expend to move to a nearby location, as well as the amount of kinetic energy nearby flow has available for bringing in food, can be calculated. These spatial changes in energy are also indicative of the degree to which flow patterns are changing around a location. The faster the flow is changing spatially, the higher these values will be. Such information combined with focal point velocity and depth information may lead to better suitability criteria. For example, adding velocity/energy gradient values into habitat suitability criteria would allow one to distinguish between a fairly uniform flow and a highly spatial flow pattern having similar focal depth and velocity values. Each of these different habitats can then be weighted appropriately.

The values of $2V_{ave} \times \left|(V_2 - V_1) / \Delta s\right| / V_{\min}^2$ for the single boulder and multiple boulder simulations are similar to the magnitudes found at fish locations observed by Hayes and Jowett (1994) and Fausch and White (1981) (data sets 2, 4, 5 and 6). These comparisons, however, are based on the maximum and minimum possible values and not on the actual parameters observed at each individual fish location. The direction and distance between the velocity measurements also varied between and within the studies making a complete comparison difficult. Input from stream biologists is needed to determine if particular velocity/energy gradients (vertical, lateral, or longitudinal) best describes a specific habitat. Field data needs to be collected to determine what parameter values can be expected to be found surrounding a particular species and age/size-group. The distances between the velocity measurements necessary to calculate these parameter values need to be established. A distance that is too short or too long will not describe the velocity/energy gradient of importance and under- or overestimate local gradients. One possible approach is to space the velocity measurements a distance *l* apart, where *l* is a distance related to the length of the fish or the diameter of the boulder generating the flow pattern. Spacing related to the fish length or boulder diameter allows one to multiply *l* by $2V_{ave} \times (V_2 - V_1) / \Delta s / V_{min}^2$ and obtain a dimensionless parameter. Dimensionless parameters have the potential to unify stream habitat suitability criteria when comparing data corresponding to different species, ages, and size-classes. Moreover, a distance related to the fish length seems appropriate, as it can be related to the distance which a fish may be expected to travel to obtain food and the area it may defend.

The additional data needed to incorporate the proposed spatial habitat metric into a study depends on which velocity gradients are important and how the velocity gradients are measured. If an approach similar to that used by Hayes and Jowett (1994) and Fausch and White (1981) is followed, velocity should be measured at the focal point and at a point in the direction of the gradient of interest. If longitudinal or lateral velocity gradients are important, then depth-averaged velocity measurements provide a means of directly relating the resulting habitat data to 2-D model output. For vertical velocity gradients, point velocities must be measured and a vertical velocity profile assumed in the 2-D model output, if 2-D model output is to be used to help quantify useable habitat. Depending on the habits of a particular organism, this information may be needed at different locations the fish or organism routinely uses (e.g. resting and feeding locations).

In conclusion, flow patterns such as velocity gradients, recirculation zones, and transverse flows, typically generated by the presence of meso-scale topography, play an important role in stream ecology. Point measurements (focal depth, velocity, substrate and cover) are inadequate to characterize and differentiate between these types of spatially varying flow features. Consequently, metrics that are capable of capturing the spatial flow characteristics need to be developed. Spatial metrics combined with focal point depth, velocity, substrate, and cover values will more fully describe local flow conditions and therefore might lead to better habitat suitability criteria. This emphasizes the need for including boulders and other obstructions when simulating stream flows with the use of 2-D numerical models. Spatially explicit output provided by such models can be employed to better assess the quantity and quality of habitat within a stream.

The parameters $V_{ave} \times (V_2 - V_1)/\Delta s$ and $2V_{ave} \times (V_2 - V_1)/\Delta s / V_{\min}^2$ were tested as potential spatial habitat metrics that can be used with field data and 2-D models. Both parameters quantify velocity gradients and changes in kinetic energy that are associated with spatially varying flows. The parameter $2V_{ave} \times (V_2 - V_1)/\Delta s / V_{\min}^2$, however, better quantified and distinguished between locations having high spatial variation and those having more uniform flow conditions. Locations near the bank and exposed boulders, which had high spatial velocity variability, a feature known to be characteristic of natural streams having good habitat, produced the highest absolute values of $2V_{ave} \times (V_2 - V_1)/\Delta s / V_{\min}^2$. Locations within stream segments without boulders, typically exhibited low spatial velocity variability and resulted in significantly lower absolute values of $2V_{ave} \times (V_2 - V_1)/\Delta s / V_{\min}^2$.

The spatial habitat metric $2V_{ave} \times (V_2 - V_1)/\Delta s / V_{\min}^2$ is indicative of the average rate of change in kinetic energy between two points scaled by the kinetic energy at the point having the smaller velocity. The parameter can be adapted to quantify vertical, lateral, or longitudinal velocity gradients, depending on which gradient best describes a specific habitat. As the parameter is directly related to a flow's kinetic energy it can facilitate the computation of fish energy expenditure rates and locate potential feeding and resting stations.

The parameter $2V_{ave} \times \left|(V_2 - V_1)/\Delta s\right| / V_{\min}^2$, while capable of quantifying spatial changes in kinetic energy, is only one choice of a spatial habitat metric. Other spatial habitat metrics characterizing different spatially varying flow properties may be devised and chosen to develop habitat suitability criteria. Identifying the most appropriate parameters for a given circumstance needs further research. However, the ability to accurately quantify spatially varying flow features important to aquatic flora and fauna can facilitate instream flow decisions and provide much needed information for stream restoration projects. The results presented here can be used as a guide to future research efforts toward attaining that objective.

ACKNOWLEDGEMENTS

We gratefully acknowledge the support provided by Pacific Gas and Electric, The National Science Foundation, and The United States Environmental Protection Agency. Several insightful comments, provided by Lane Watson and two anonymous reviewers, helped improve the overall presentation and expand the scope of this work.

REFERENCES

Biggs, J. F., Duncan, M. J., Francoeur, S. N., and Meyer, W. D. 1997. Physical characterisation of microform bed cluster refugia in 12 headwater streams, NZ J Mar Freshwater Res. **13**: 413-422.

Bovee, K. D. 1978. The Incremental method of habitat potential for coolwater species with management implications, Am Fish Soc Spec Publ 11. 340-346.

Crowder, D. W., and Diplas, P. 2000. Using two-dimensional hydrodynamic models at scales of ecological importance, accepted for publication J of Hydrol. **230**(1-2).

Fausch, K. D., and White, R. J. 1981. Competition between brook trout (salvelinus fontinalis) and brown trout (salmo trutta) for position in a Michigan stream, Can J Fish Aquat Sci. **38** (10): 1220-1227.

Ghanem, A., Steffler, P., Hicks, F., and Katopodis, C. 1996. Two-dimensional hydraulic simulation of physical habitat conditions in flowing streams, Reg Rivers Res and Manage **12**: 185-200.

Hayes J. W., and Jowett, I. G. 1994. Microhabitat models of large drift-feeding brown trout in three New Zealand rivers, N Am J Fish Manage. **14**: 710-725.

King, I. P. 1990. Program documentation RMA-2V, Two dimensional finite element model for flow in estuaries and streams, Version 4.3, Resource Management Associates, Lafayette, California.

Lancaster, J., and Hildrew, A. G. 1993. Flow refugia and the microdistriubtion of lotic macroinvertebrates, J N Am Benth Soc. **12** (4): 385-393.

Leclerc, M., Boudreault, A., Bechara, J. A., and Corfa, G. 1995. Two-dimensional hydrodynamic modeling: a neglected tool in the instream flow incremental methodology, Trans Am Fish Soc. **124**, No.5: 645-662.

Milhous, R. T., Updike, M. A., and Schneider, D. M. 1989. Physical habitat simulation system (PHABSIM) reference manual, version II, Instream Flow Information Paper No. 26, USFWS Biol. Rep. 89 (16).

Munson, B. R., Young, D. F., and Okiishi, T.H. 1990. Fundamentals of fluid mechanics, 2nd ed., John Wiley and Sons, Inc., New York.

Rader, R. B., and Poff N. L. 1999. Development of an individual-based trout instream flow model, *Stream Notes*, Stream Systems Technology Center, USDA Forest Service, Rocky Mountain Research Center, Jan.

Rempel, L. L., Richardson, J. S., and Healey, M. C. 1999. Flow refugia for benthic macroinvertebrates during flooding of a large river, J N Am Benth Soc. **18** (1): 34-48.

Tarbet, K., and Hardy, T. B. 1996. Evaluation of one-dimensional and two-dimensional hydraulic modeling in a natural river and implications in instream flow assessment methods, Ecoydraulics 2000 Proc 2nd Intl Symp Habitat Hydraulics **B** (eds. Leclerc, M., Capra, H., Valentin, S., Boudreault, A. and Côté, Y.) B395-B406 (INRS-Eau and FQSA, IAHR/AIRH).

Chapter 5. Vorticity and Circulation: Spatial Metrics for Evaluating Flow Complexity in Stream Habitats

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* This chapter is a modified version of the published article: Crowder, D.W., and P. Diplas, 2002, Vorticity and Circulation: Spatial Metrics for Evaluating Flow Complexity in Stream Habitats, *Canadian Journal of Fisheries and Aquatic Sciences*, 59: 633-645, reproduced with permission of NRC Research Press.

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Abstract: Channel topography, formed by boulders, submerged bars, and meanders, creates complex flow patterns. These flow patterns exist over a variety of spatial scales and provide habitat for many aquatic organisms. Spatial flow features cannot be adequately characterized with qualitative descriptions or hydraulic metrics such as depth and velocity. Two-dimensional hydraulic model simulations, based on detailed channel geometry, are used to develop and test vorticity (a point metric) and a circulation-based metric (an area metric) as means of quantifying spatial flows occurring within micro- meso- and macro-habitat features. The proposed spatial metrics are computed throughout distinctly different regions of a study site. The vorticity metric produces small absolute values in uniform flows and large absolute values in complex flows. Circulation metric values varied by a factor of 11.7 within distinctly different regions of the modeled study site and suggest that the metric provides a means of quantifying flow complexity within a study reach or within individual meso-scale habitats such as pools, eddies, riffles and transverse flows. The circulation metric is used to quantify flow complexity around three brown trout redds to provide an example of how the proposed metric might be employed in habitat studies.

INTRODUCTION

Flow within natural rivers is typically highly complex. The presence of boulders, submerged bars, meanders, and other topographic features create eddies, transverse flows, vortices, velocity gradients, and other spatial flow patterns. Observers of stream flow phenomena know that even rivers that appear to be tranquil have complex flow patterns created by topographic features within the streambed (e.g., Whiting and Dietrich 1991). Such flow complexity provides micro-, meso-, and marco-scale habitat features from which aquatic organisms can choose to inhabit.

Growing evidence suggests that different aquatic organisms use and surround themselves with flow patterns that are not readily quantifiable or differentiable using standard habitat metrics (e.g. point depth, velocity, and substrate data). Fausch and White (1981) and Hayes and Jowett (1994) suggest that velocity gradients are important features of brown trout (Salmo trutta) and brook trout (Salvelinus fontinalis) feeding stations. Shields et. al (1995) reported the placement of spur dykes, which create vortices, in degraded warm-water streams can substantially increase fish biomass. Freeman and Grossman (1993) suggest that, during the summer, rosyside dace (Clinostomus funduloides) dispersion may be dependent on the availability of depositional zones found near swift adjacent water.

How channel topography and discharge interact to create and provide the different types and amounts of habitat used by various aquatic organisms is poorly understood. A major obstacle to understanding this interaction is the inability to quantify and differentiate between flow features within a river. Routinely, point depth, velocity, and substrate values are employed to quantify the hydraulic habitat within streams. However, these measurements are point metrics and quantify only what is occurring at a single point within the river. Hence, one cannot use point measurements to accurately quantify the hydraulic habitats of aquatic organisms that prefer, or use, spatial flow features surrounding a particular point or within an extended area.

The inability to quantify such spatially varying features forces one to adopt qualitative descriptions of flow features (e.g., pools, riffles, runs, and eddies). A significant drawback to this qualitative approach is that the characteristics and functions of pools, eddies, and runs differ from stream to stream, depending on discharge, channel roughness, slope, and channel morphology. Moreover, many of these features occur over a variety of spatial scales, making comparisons between similar features even more difficult. The development of spatial metrics that quantify flow complexity and differentiate between specific flow features might lead to better means of assessing stream habitat, restoring degraded streams, and predicting how specific land activities might impact a stream's ecology.

Recently, researchers have begun looking at the usefulness of employing two-dimensional (2-D) hydraulic models to evaluate the hydraulic conditions in stream habitat studies (e.g., Ghanem et al. 1996; Leclerc et al. 1995). Two-dimensional hydraulic models, unlike commonly used 1-D hydraulic models, are capable of reproducing transverse flows, eddies, velocity gradients, and other complex flow patterns found within streams. Hence, 2-D hydraulic models provide a spatially explicit representation of a river reach that stream biologists can analyze with traditional habitat metrics and/or spatial hydraulic metrics to identify important features such as velocity gradients, eddies, and vortices. Unfortunately, there is a paucity of research focusing on modeling and quantifying the spatial flow patterns of biological importance that are created by topographic features (exposed boulders, submerged bars, etc.). Crowder and Diplas (2000a,b) used a 2-D hydraulic model to reproduce flow patterns induced by exposed boulders and proposed a spatial hydraulic metric to quantify biologically important velocity/kinetic energy gradients, such as those used by brown and brook trout. The metric proposed by Crowder and Diplas (2000b) computes the spatial rate at which a flow's kinetic energy is changing relative to the kinetic energy at that point. The metric can be used to distinguish between two points having similar depth and velocity values, but surrounded by different velocity/kinetic energy gradients. Mathematically, the metric is expressed as follows:

(1)
$$\frac{\frac{\partial}{\partial x}\frac{V^2}{2}}{\frac{V^2}{2}}$$

where V is the magnitude of the depth-averaged velocity at a point and x represents the direction in which the spatial change in kinetic energy ($V^2 \div 2$) is being evaluated. This metric provides an indication of how flow is changing spatially around a point and provides a useful means of quantifying micro-habitat features within a stream. The development of additional spatial hydraulic metrics designed to characterize different types of flow features, occurring within arbitrary areas, can complement the usefulness of this metric and allow stream biologists to more fully describe biologically important micro- meso, and macro-habitat features found within streams.

Here, the two-dimensional hydraulic model simulations and spatial energy metric used by Crowder and Diplas (2000a,b) are used to develop and evaluate two new spatial metrics capable of quantifying flow complexity within rivers. The first spatial metric, vorticity, measures the rate at which a tiny fluid element rotates around its axes. As vorticity describes flow conditions only at a point, comparisons between vorticity and the previously proposed spatial energy gradient metric are made to determine how these metrics complement each other in their ability to quantify and locate points of biological importance. A second metric, one that integrates the absolute vorticity values over a specified region, is then proposed and evaluated as a means of quantifying flow complexity within any arbitrary area, whether it be a meso-scale habitat or the entire stream reach. The resulting combination of spatial metrics, measuring different flow properties, can be used to better quantify spatial flow patterns existing at the micro-, meso- or macro-scale level.

METHODS

The development of vorticity and circulation as spatial hydraulic metrics

In fluid mechanics, it is well established that the motion of a small fluid element within a flow field can be described in terms of its translation, linear deformation, rotation, and angular deformation. For a full discussion on this topic and how vorticity and circulation relate to fluid motion, the reader should refer to a basic fluid mechanics book, for example, Batchelor (1967), Munson et. al. (1990), and others. Of particular importance here is the ‘vorticity’ vector, which describes the rotation rate of a small fluid element about its axes. For a three-dimensional flow field, vorticity can be expressed mathematically as follows:

(2)
$$\overline{\xi} = 2\overline{\omega} = \nabla \times \overline{V}$$

where $\overline{\xi}$ is the vorticity vector, $\overline{\omega}$ is the rotation vector and $\overline{V}$ is the fluid's velocity vector. The right hand of the expression is known as the curl of the velocity vector and is expressed below:

(3)
$$\nabla \times \overline{V} = \left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} \right) \hat{i} + \left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \right) \hat{j} + \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) \hat{k}$$

where u, v, and w are a flow's x-, y-, and z-velocity components and $\hat{i}$, $\hat{j}$, and $\hat{k}$ are unit vectors in the x-, y-, and z-directions (for this paper, x and y are the downstream and cross-stream directions, respectively, and z is the vertical direction).

For two-dimensional flow fields, which this paper models and analyzes, the z-velocity component in the above equation is ignored and the vorticity vector simplifies to the following expression:

(4)
$$\overline{\xi} = 2\overline{\omega} = \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) \hat{k}$$

and represents twice the rate at which a very small fluid element is rotating about its vertical axis. The vorticity vector is considered positive when the fluid is rotating in the counter clockwise direction. Vorticity at a point within a flow is zero under two conditions: 1) when both $\partial v \div \partial x$ and $\partial u \div \partial y$ are zero; and 2) when $\partial v \div \partial x$ = $\partial u \div \partial y$. In the first case, a fluid element, as it moves with the flow, may undergo pure translation and/or linear deformation (stretching), but does not rotate or undergo angular deformation (change in shape). In the second case, a fluid element may undergo translation, linear and/or angular deformation, but will not rotate or "spin" about its vertical axis as it moves. Flows falling within either of these two categories are referred to as potential flows. Perhaps, one of the most important potential flows is uniform flow. In natural streams, however, channel topography creates velocity gradients, transverse flows, eddies and other complex nonuniform flow patterns that are characterized by nonzero vorticity. Consequently, vorticity provides a physically meaningful basis for identifying these complex or spatially varying flows, and distinguishing them from uniform flow conditions within a stream.

Vorticity does not necessarily reflect whether the fluid surrounding that location has circular motion similar to that associated with tornadoes, whirlpools, or hurricanes. For example, in a free vortex (a form of potential flow), flow occurs in concentric circles around a central point and has velocity values that increase toward the center of the circle, but has zero vorticity at every point within the flow ($\partial v \div \partial x = \partial u \div \partial y$ everywhere). In a forced vortex, the fluid rotates like a solid body and therefore the velocity decreases linearly towards the center of the circle. In this case, vorticity is nonzero and, in fact, has the same value throughout the flow. It can also be shown that velocity gradients, created by channel banks, produce non-zero vorticity values even when the flow is largely in the downstream direction and lacks the circular motions associated with vortices.

Since vorticity is computed at a single point in the flow field, it cannot directly quantify the flow complexity within an arbitrary area or throughout a river reach. However, a commonly used mathematical term, circulation, is closely related to vorticity and sums the vorticity values of all the fluid elements within an arbitrary area S. The mathematical expression for circulation follows:

(5)
$$\Gamma = \oint_L \overline{V} \cdot d\overline{L} = \iint_S \overline{\xi} \cdot d\overline{A}$$

where Γ is the circulation, $d\overline{L}$ is the unit vector along the length of a closed path, L. The closed line, L, surrounds a surface area S, and $d\overline{A}$ represents the area of an infinitesimal element of the surface S. Circulation can be used to measure the strengths of vortices, such as those responsible for making scour holes behind spur-dykes. Depending on the vorticity values that are within the area of interest, circulation can be positive, negative, or zero. A positive circulation value suggests a vortex spinning in a counterclockwise direction.

If circulation is computed within a region containing areas of positive and negative vorticity, the areas of opposing sign will work to cancel each other out and may result in a positive, negative, or zero circulation value. Moreover, the resulting circulation value will not be reflective of the total flow complexity within the region. For example, computing circulation within a region that contains two distinct eddies circulating in opposite directions can result in a zero or near zero circulation value. Such a value is what one expects to find in uniform flow conditions and clearly does not reflect the flow complexity of the two eddies. However, a simple and effective means of quantifying the overall flow complexity within the region would be to compute the sum of the absolute values of vorticity throughout the area. Hence, the flow complexity found in each eddy would contribute to the resulting 'absolute circulation' value and be clearly distinguishable from uniform flow conditions. Moreover, by dividing the resulting circulation value by the total area being analyzed, a measure of the average stream complexity over the area of interest can be obtained. The mathematical expression for this variation on circulation follows:

(6)
$$\frac{\Gamma_{ABS}}{A_{TOT}} = \frac{\iint_S \left|\bar{\xi}\right| dA}{A_{TOT}} = \frac{\sum \left|\bar{\xi}\right| \Delta A}{A_{TOT}}$$

where Γ_{ABS} is the modified circulation parameter and A_{TOT} is the total wetted area over which Γ_{ABS} is being computed.

While vorticity and circulation are numerical means of quantifying the physical nature of vortices and other flow complexity, vorticity and circulation also appear to have biological significance. Bandyopoadhyay et al. (2000) found that vortices generated by the movement of a fish's fins play a part in determining a fish's maneuverability. Hanke et al. (2000) and Kiorboe and Visser (1999) suggest that piscivorous predators and copepods can detect the presence of prey through the vortex structures left behind by fish and other organisms as they swim. Way et al. (1995) found that grooved blocks used to line parts of the Mississippi River create small eddies that allow macroinvertebrates to build feeding structures that are sheltered from high velocity flows, but remain in contact with faster feeding flows. Such observations suggest that aquatic organisms use vortices and other complex flows in different manners and at different scales. The proposed vorticity and circulation metrics may be appropriate means of quantifying these habitats.

Testing vorticity as a spatial metric applied at a point

The ability of the vorticity and circulation metrics to quantify flow patterns of biological importance is evaluated through numerical simulations performed with the 2-D hydraulic model RMA2 (King 1990). RMA2 is a well-known two-dimensional finite element program that solves the shallow water equations for depth and depth averaged velocities (in the x and y direction) at every node within a finite element mesh. The two specific simulations employed here to evaluate the proposed metrics were previously used and described in detail by Crowder and Diplas (2000a-b). These simulations modeled a 61-meter reach of a regulated mountain stream (The North Fork of the Feather River in California) that has a summer discharge of 4.24 $m^3 \cdot s^{-1}$, an average width of 15 meters and a maximum depth of about 1.5 meters. The first simulation modeled the study site without incorporating topographic data on exposed boulders found within the study site. The resulting flow field for this simulation is largely uniform and similar to what one would expect to see in urban channels having rather simple geometry. The second simulation incorporated topographic data on exposed boulders found within the study site and generated highly complex flow patterns within the upper 21 meters of the study site. Together the simulations provide a means to evaluate the role that channel topography has on creating potentially important flow patterns and how such flows can be quantified.

To test the ability of vorticity to identify locations within a stream containing nonuniform flows, vorticity was plotted throughout the study site for both simulations (with and without boulders). By dividing a location's absolute vorticity value by the mean absolute vorticity value found within the entire study reach, regions having relative high and low vorticity values were then identified for each simulation. Comparisons of regions with relatively high and low vorticity values are found within the two simulations are then made to quantify the influence that channel complexity has on creating vorticity within a stream. Likewise, the spatial energy metric proposed by Crowder and Diplas (2000b) was computed throughout the study reach for both simulations. The absolute energy metric values found at each point within the study site are then divided by the mean absolute energy metric value obtained within the study reach. Plotting this ratio throughout the study site for both simulations allows one to identify areas within the stream having relatively high and low energy metric values and how channel topography influences stream energy gradients. Comparisons between the vorticity and energy metric ratios were then made to help determine the similarities and differences between the vorticity and energy metrics (Figures 1-3).

Testing circulation as a spatial metric applied over an area

To compute the proposed circulation metric value within an arbitrary area of the study site, a FORTRAN 90 program was developed. The program allows a user to define a rectangular area surrounding a specific location within the study reach where one wants to compute the circulation metric. The FORTRAN program, using data files generated from SMS (a commercially available pre- and post-processor for RMA-2V), computes the average nodal energy metric value, average nodal vorticity value, and average nodal velocity value for each wet element in the finite element mesh that lies completely within the rectangle area of interest. For each wet element, the program multiplies the absolute value of the element's average nodal vorticity value by the element's area. The resulting values for each wet element within the predefined area are then summed to provide the circulation value, as defined by the right hand term in equation (6). The program also computes the proportion of area within the defined rectangular region that has vorticity and energy metric values falling within user specified 'bins' or ranges of metric values. This information is used to plot and compare the vorticity and energy metric distributions found within the two different simulations and within distinct areas of the study site. For each simulation, circulation metric values are computed for the entire site, its upper 20 meters, and within three distinct regions of the site. The three distinct regions have areas of approximately 36 m^2 (Figures 1-2). The first region (A) surrounds an area in the middle portion of the site having uniform flow. The second region (B) is found within the upper portion of the site where a significant transverse flow exists and the third region (C) encompasses an area containing four exposed boulders that create highly complex flow patterns. The resulting circulation metric values are compared to determine if circulation metric values differed significantly between the two simulations and the three distinct areas of varying spatial complexity.

Computing the circulation metric with velocity data obtained in field studies

To ascertain the ability and usefulness of applying the circulation metric in field studies, the proposed circulation metric was computed for a 10.75 m^2 area and a 21.4 m^2 area within a reach of the Smith River, in Virginia (Figure 4). The first area (Area D), identified with the aid of fishery biologists, was within a portion of the river reach devoid of redds, but appeared to have substrate, depth, and velocity values similar to that of areas where numerous brown trout redds have been found. The second area (Area E) surrounded an area where fishery biologists studying the site previously found and recorded the locations of three brown trout redds. With no overhead vegetation observed at Area D or Area E, the two locations appeared to have quite similar habitat characteristics, except in terms of flow complexity. The flow in Area D was uniform and no visually identifiable vortices existed within it. In Area E, a large exposed boulder and a smaller submerged boulder created local flow constriction and two distinct regions in which one could see vortices rotating in opposite directions.

Using a compass and a Marsh Mcbirney velocity meter, velocity magnitude and direction were measured at 0.3 m intervals along each side of the perimeter encompassing Area D. These measurements, combined with the bearing of each side of Area D's perimeter, provided the information needed to use the line integral expression in equation (5) to compute circulation (Γ) within Area D. As no distinct positive and negative vorticity zones existed within Area D, the proposed circulation metric (Γ_{ABS}) value for Area D is equal to the absolute value of the circulation value.

The same approach was employed to calculate the circulation metric value for Area E. However, as Area E has a positive vorticity region and a negative vorticity region, circulation (Γ)

was computed for each of these regions separately. Areas LMNO and PLOQ represent the negative and positive vorticity regions respectively (Figure 4). The absolute circulation values for both regions were then summed to obtain the circulation metric (Γ_{ABS}) for entire Area E. To capture the spatial variations in velocity occurring along the perimeters of Areas LMNO and PLOQ, velocity magnitude and direction were measured at 0.15 meter intervals, except on line LO where measurements were taken every 0.3 meters. As the velocity varied slowly along line LO and the line integral contributions along this line ultimately cancel out, larger spacing along LO was justified. Comparisons of the circulation and circulation metric values obtained in Areas D and E and Areas LMNO and PLOQ are made.

RESULTS

Sensitivity of the energy and vorticity metrics to locating spatial flow patterns

The absolute energy metric value divided by the mean absolute energy metric value found within the reach ($|EnergyMetric| / |EnergyMetric|_{AVG}$) is plotted for each of the two model simulations (Figure 1). When boulders are present, the absolute mean energy metric value for the entire reach is 1.333 m^{-1}. Without boulders present this value becomes 0.947. However, for consistency purposes, energy metric ratios were computed based on the 1.333 value in both modeling scenarios. The resulting energy metric ratios ranged between 0 and 677 in the no boulder simulation and from 0 to 1168 in the simulation containing boulders. Energy metric ratios having very large magnitudes (> 15) are artifacts of having very low velocity values found in modest or large velocity/energy gradients. Hence, such values can be expected immediately next to channel banks and boulders. However, in both simulations, the total proportion of area having energy metric ratios greater than 1.5 (or with underlying absolute energy metric values greater than 2.00 m^{-1}) is only 6 - 7% of the reach's area.

Without incorporating exposed boulders into the model, the larger energy metric ratios are found only near the banks of the river. When boulders are incorporated into the model, the steep velocity/energy gradients produced in the vicinity of the boulders are reflected by the higher energy metric ratios found in the vicinity of the exposed boulders. The boulders also create a transverse flow in the upper portion of the study site. The main flow can be seen shifting from the West bank toward the East bank, as indicated by a comparison of the velocity vectors in the upper portion of the plots. However, the transverse flow, a form of flow complexity, does not contain significant velocity/energy gradients, as reflected by the low energy metric values found in this region (Area B).

The results of dividing absolute vorticity values by the mean absolute vorticity found within the study reach ($|Vorticity|/|Vorticity|_{AVG}$) for each model simulation are illustrated (Figure 2). As with the computation of the energy metric ratios, the mean absolute vorticity value obtained in the simulation containing boulders was used to compute all vorticity ratios. The mean absolute vorticity value for the simulation containing boulders is 0.0676 s^{-1} compared to the 0.0507 s^{-1} value obtained for the no boulder simulation. The resulting vorticity metric ratios ranged between 0 and 13.593 in the no boulder simulation and from 0 to 47.673 in the simulation containing boulders. Without boulders, 93% of the study reach has vorticity ratios less than 1.48 (or with underlying vorticity values between –0.1 s^{-1} and 0.1 s^{-1}). With boulders present, 88% of the study reach has vorticity ratios less than 1.48. Thus, only a small range of vorticity values occupies most of the area within the study site, despite the wide range of vorticity values actually present (–3.223 – 3.008 s^{-1}).

Without boulders, the vorticity metric ratios, like the energy metric ratios, tend to have values greater than 1.5 only near the banks. When boulders are incorporated into the model, relatively large vorticity ratios (> 1.5) are found near the banks and around the localized flow patterns created by the boulders. Hence, the vorticity metric, like the energy metric, reflects the presence of the velocity/energy gradients induced by channel banks and exposed boulders. Additionally, with the boulders present, a large portion of the area with Area B has vorticity metric ratios greater than 1.5, whereas without boulders a much smaller portion of Area B's area contains vorticity ratios greater than 1.5. These higher metric ratio values are a reflection of the vorticity generated by the transverse flow, which was induced by the presence of the boulders. This shift in the main flow from the west bank toward the east bank is also responsible for increasing velocity gradients and vorticity ratios along the upper 20 meters of the channel's east bank.

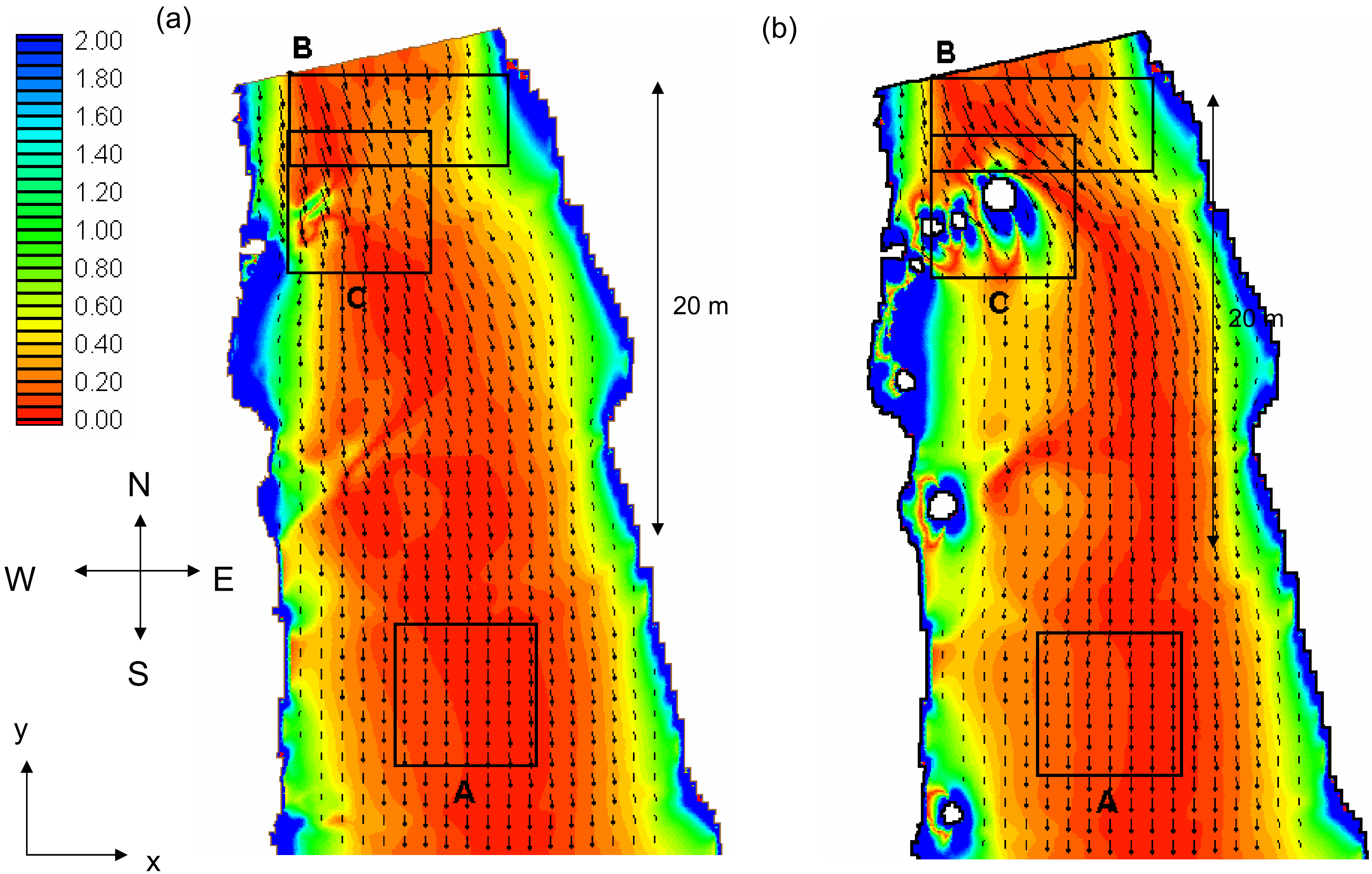

Figure 1. Plot of the absolute energy metric value at a point divided by the reach's mean absolute energy metric value ($|EnergyMetric| / |EnergyMetric|_{AVG}$): a) without boulders; b) with boulders. Contours represent the magnitude of the energy metric ratio. Arrows indicate direction of flow at a point and scaled to the velocity magnitude found at that point. White spots in Figure 1b represent exposed boulders within the stream. Areas A, B, and C represent locations where the circulation metric values were computed. Area A is in the middle portion of the 61-meter study reach where the flow is uniform. Area B has a transverse flow within it and Area C surrounds the location of the largest exposed boulder.

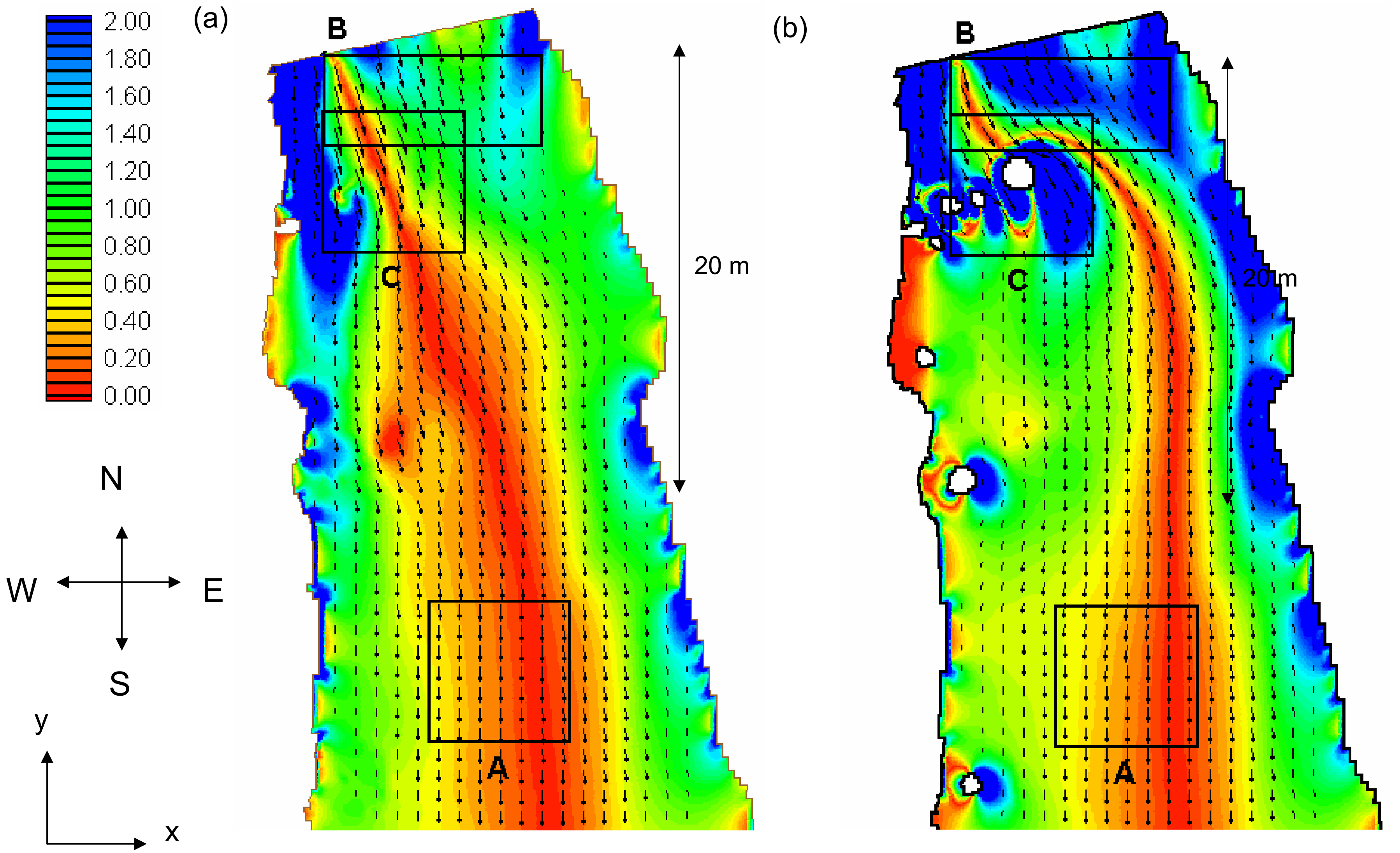

Figure 2. Plot of the absolute vorticity value found at a point divided by the reach's mean absolute vorticity value ($|Vorticity|/|Vorticity|_{AVG}$): a) without boulders; b) with boulders.

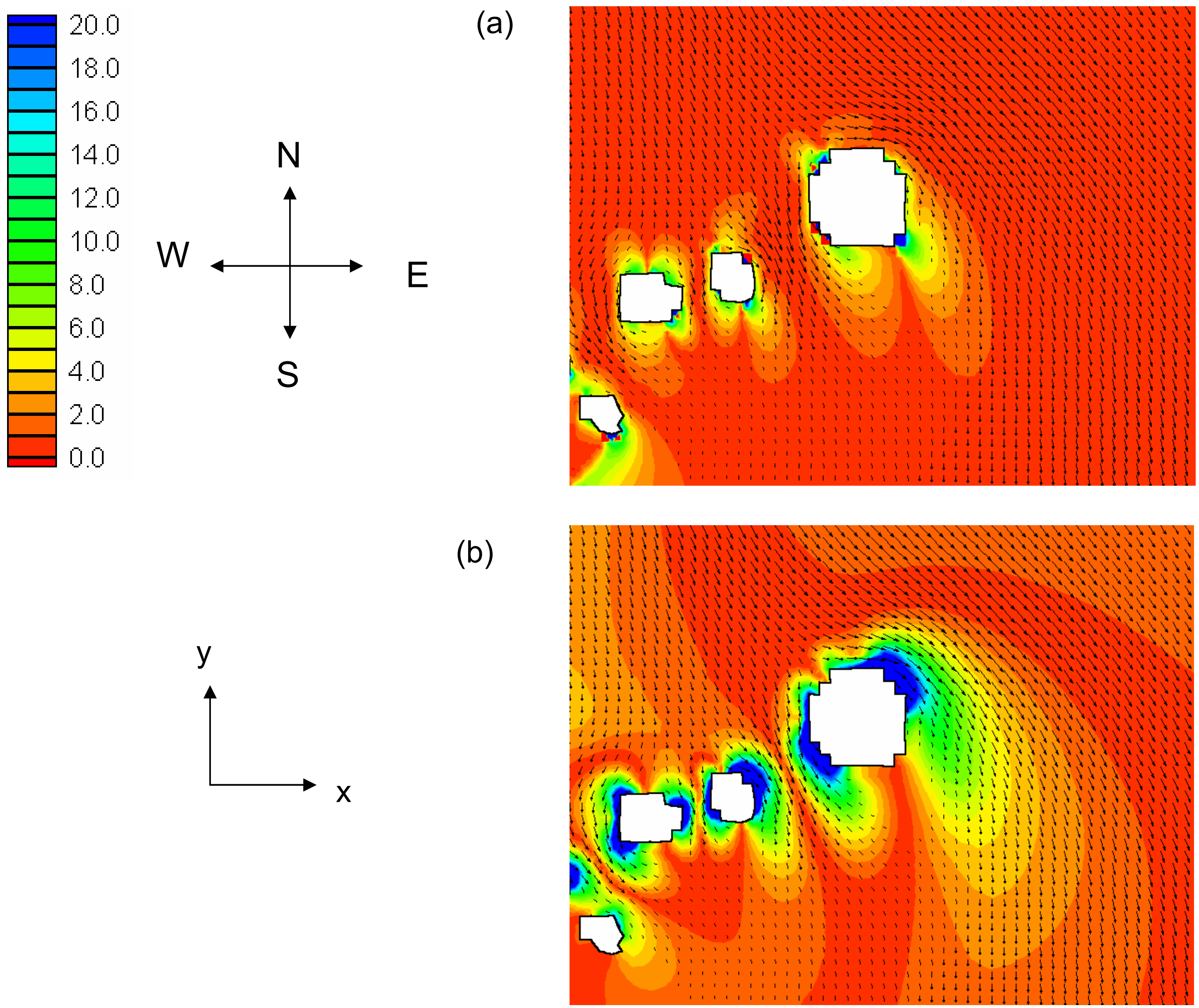

Figure 3. Comparison of the Energy metric ratios ($|EnergyMetric| / |EnergyMetric|_{AVG}$) and vorticity ratios ($|Vorticity| / |Vorticity|_{AVG}$) surrounding four exposed boulders found within the study site: a) energy metric ratios; b) vorticity ratios.

A direct comparison of the energy and vorticity ratios obtained throughout the study site when boulders are incorporated into the model simulations (Figures 1b and 2b) demonstrates that the proportion of the river reach having vorticity ratios exceeding 1.0 is substantially larger than the proportion of river having energy metric ratios exceeding 1.0. One reason for these larger ratios is that the transverse flow occurring within Area B appears to create relatively large vorticity values, but relatively low energy gradients. Hence, vorticity ratios highlight this region as having complex flow whereas the energy metric does not. The vorticity effects created by the presence of the boulders (Area C) also appear to permeate through a larger area surrounding the boulders than the energy gradient effects created by the boulder. Hence, the vorticity ratio highlights a larger portion of area surrounding the boulders as having complex flow than the energy ratio does. These results suggest that, in this case, vorticity is more sensitive to detecting flow complexity induced by channel topography than the energy metric. However, unlike vorticity, the energy metric provides information that can be linked to bioenergetic concepts and remains a useful spatial metric (Crowder and Diplas 2000b). For example, in the case of a free vortex, the flow is highly complex but has zero vorticity. Hence, vorticity cannot be used to describe its complexity. However, the high energy gradients within this flow can be quantified with the energy metric.

The differences between the energy and vorticity metrics are demonstrated further (Figure 3), by comparing the vorticity and energy metric ratios in the immediate vicinity of the boulders found in Area C. For both of these metrics, ratio values are very large (> 20) immediately next to the boulders. However, two important differences exist between them. First, the proportion of area having ratio values greater than 20 is much smaller for the energy metric, even though the maximum energy ratios near the boulders are higher than those of the highest vorticity ratio. Second, as one moves away from the boulders, the energy ratio values drop much quicker than the vorticity ratios. Hence, the area containing vorticity ratios between 1 and 20 is much larger than the area containing energy ratios between 1 and 20.

Circulation computations for the numerical simulations

For both simulations, the circulation metric, $\Gamma_{ABS} \div A_{TOT}$, was computed for the entire study reach, the upper 20 meters of the study reach, and within Areas A, B, and C (Figures 1 and 2). The circulation metric values calculated within each of these 5 areas for both simulations are summarized (Table 1). Circulation metric values measured in a field study (discussed later) are also summarized (Table 1). To provide a measure of how the circulation metric values in Table 1 differ among each of the various areas and simulations, the value of each area is divided by the circulation metric of every other area for which a circulation metric value was computed. The resulting circulation metric ratios, shown in Table 2, are used to make three comparisons. First, a paired comparison is made to determine how the absence or presence of boulders influences circulation values in each of the five identified areas in the model simulations. Second, for each model simulation, the circulation value obtained for the entire reach is compared with the circulation values obtained in the upper 20 meters of the reach and in Areas A, B, and C. This comparison reveals how the flow complexities within different portions of the modeled study site compare to the site's overall flow complexity. Third, the flow complexity within Areas A, B, and C are compared for each model simulation. This comparison reveals how flow complexity within three different locations of similar size differs and is analogous to comparing three different meso-scale habitat features in terms of their flow complexity.

Area Analyzed	Reach[a]	Reach[b]	20 meters[a]	20 meters[b]	Area A[a]	Area A[b]	Area B[a]	Area B[b]	Area C[a]	Area C[b]	Area D[c]	Area LMNO[c]	Area PLOQ[c]	Area E[c]
A_{TOT} (m^2)[d]	1034.237	1029.190	275.967	272.910	32.783	32.783	32.037	32.037	34.057	31.997	10.750	8.188	13.250	21.438
Γ $(m^2 \cdot s^{-1})$	-	-	-	-	-	-	-	-	-	-	-0.016	-0.377	1.666	-
Γ_{ABS} $(m^2 \cdot s^{-1})$	46.034	55.197	19.324	27.532	0.463	0.585	2.419	3.401	2.068	6.727	0.016	0.377	1.666	2.043
$\Gamma_{ABS} \div A_{TOT}$ (s^{-1})	0.045	0.054	0.070	0.101	0.014	0.018	0.075	0.106	0.061	0.210	0.001	0.046	0.123	0.095

[a] Results obtained from model simulations of the North Fork of the Feather River without boulders.

[b] Results obtained from model simulations of the North Fork of the Feather River with boulders.

[c] Results obtained from field measurements taken at locations in the Smith River.

[d] Total wetted area within a given analyzed area varies slightly between the model simulations due to wetting/drying and because elements do not always fall completely within the regions.

Table 1. Summary of circulation metric values.

Area Analyzed	Reach [a]	Reach [b]	20 meters[a]	20 meters[b]	Area A[a]	Area A[b]	Area B[a]	Area B[b]	Area C[a]	Area C[b]	Area D[c]	Area LMNO[c]	Area PLOQ[c]	Area E[c]
Reach[a]	1.000	1.200	1.556	2.244	0.311	0.400	1.667	2.356	1.356	4.667	0.022	1.022	2.733	2.111
Reach[b]	0.833	1.000	1.296	1.870	0.259	0.333	1.389	1.963	1.130	3.889	0.019	0.852	2.278	1.759
20 meters[a]	0.643	0.771	1.000	1.443	0.200	0.257	1.071	1.514	0.871	3.000	0.014	0.657	1.757	1.357
20 meters[b]	0.446	0.535	0.693	1.000	0.139	0.178	0.743	1.050	0.604	2.079	0.010	0.455	1.218	0.941
Area A[a]	3.214	3.857	5.000	7.214	1.000	1.286	5.357	7.571	4.357	15.00	0.071	3.286	8.786	6.786
Area A[b]	2.500	3.000	3.889	5.611	0.778	1.000	4.167	5.889	3.389	11.67	0.056	2.556	6.833	5.278
Area B[a]	0.600	0.720	0.933	1.347	0.187	0.240	1.000	1.413	0.813	2.800	0.013	0.613	1.640	1.267
Area B[b]	0.425	0.509	0.660	0.953	0.132	0.170	0.708	1.000	0.575	1.981	0.009	0.434	1.160	0.896
Area C[a]	0.738	0.885	1.148	1.656	0.230	0.295	1.230	1.738	1.000	3.443	0.016	0.754	2.016	1.557
Area C[b]	0.214	0.257	0.333	0.481	0.067	0.086	0.357	0.505	0.290	1.000	0.005	0.219	0.586	0.452
Area D[c]	45.00	54.00	70.00	101.00	14.00	18.00	75.00	106.0	61.00	210.0	1.000	46.00	123.0	95.00
Area LMNO[c]	0.978	1.174	1.522	2.196	0.304	0.391	1.630	2.304	1.326	4.565	0.022	1.000	2.674	2.065
Area PLOQ[c]	0.366	0.439	0.569	0.821	0.114	0.146	0.610	0.862	0.496	1.707	0.008	0.374	1.000	0.772
Area E[c]	0.474	0.568	0.737	1.063	0.147	0.189	0.789	1.116	0.642	2.211	0.011	0.484	1.295	1.000

[a] Results obtained from model simulations of the North Fork of the Feather River without boulders.

[b] Results obtained from model simulations of the North Fork of the Feather River with boulders.

[c] Results obtained from field measurements taken at locations in the Smith River.

Table 2. Matrix comparing the flow complexity of all the regions for which circulation metric values were computed.

A side-by-side comparison of the five areas analyzed in the model simulations (Table 1 and 2) shows that two scenarios (with and without boulders) generate different circulation metric values within each of the areas. The magnitude of the differences in circulation values, for a particular area, depends greatly on the total area and location over which the metric was computed. With boulders, the 61 meter long reach (1029.190 m^2) has a circulation metric value of 0.054 s^{-1} and is 1.200 times greater than the circulation metric calculated for the same area without boulders. Assuming that $\Gamma_{ABS} \div A_{TOT}$ is a measure of flow complexity, then one can state that the entire reach is 1.200 (column 2, row 1 of Table 2) times more complex when boulders are incorporated into the model. A 20% increase in complexity may not seem significant given the differences highlighted between the two model scenarios. However, a large portion of the study site has very similar flow patterns for both model scenarios. It is only within the upper 20 meters of the study site that the presence of the boulders clearly creates different flow patterns. Consequently, by computing the circulation metric at the reach-scale, the differences in vorticity values produced by the boulders in the upper 20 meters of the site are masked by the large area of the study site having similar vorticity values.

When the circulation metric is computed for the upper 20 meters of the site (272.910 m^2), one sees a more pronounced difference between model simulations. According to the circulation metric values, the flow within this region becomes 1.443 times more complex when boulders are present. Similarly, in the 31.997 m^2 area immediately surrounding the boulders (Area C) where the boulders have their strongest influence and the two simulations are the most different, the flow becomes 3.443 times more complex when boulders are incorporated into the model. These results show the relative influence that the boulders have on flow complexity at different scales and different locations within the study site. In this case, at the reach-scale, the boulders play a minor role in the channel's overall complexity. Had more exposed boulders been present throughout the site, the reach-scale results could have been significantly different. However, within Areas B and C, where the flows are most influenced by the presence of the boulders, one obtains significantly different circulation metric values that reflect the diversity of flow features created under the two different simulations.

The variation of circulation values within different parts of the study site compared to a simulation's reach-scale circulation value is also observed (Table 2). For both simulations, the circulation metric for Area A is about a third of the circulation value one obtains for the entire reach. The flow pattern found within Area A is quite uniform and has very little flow complexity compared to the average flow complexity found throughout the site. For the simulation without boulders, Areas B and C have circulation metric values 1.667 and 1.356 times that of the entire reach. For the simulation with boulders, Areas B and C have circulation metric values 1.963 and 3.889 times that of the entire reach, respectively. If the circulation metric value is considered as an indicator of flow complexity, then the most complex flow pattern occurs within Area B when the boulders are absent and in Area C when the boulders are present.

For a given simulation, the circulation metrics computed in Areas A, B and C vary significantly (Table 2). Without boulders, the flow in Areas B and C are 5.357 and 4.357 times as complex as the flow in Area A. With boulders, the flow in Areas B and C are 5.889 and 11.67 times more complex than the flow in Area A. In both scenarios, the uniform flow patterns found in Area A have small circulation values and are clearly distinguishable from the circulation values computed within Areas B and C. Hence, the circulation metric adequately differentiates between the uniform and non-uniform flows predicted in the two model scenarios. Without boulders, the circulation values for Areas B and C (0.075 s^{-1} and 0.061 s^{-1}, respectively) do not suggest that Areas B and C are substantially different in terms of their flow complexity. A visual analysis of the vorticity metric ratio plot (Figure 2a) confirms that finding. When the boulders are included in the model, the circulation metric values clearly distinguish between the highly complex flows surrounding the boulders and the moderately complex flows found in Area B. The sensitivity of the circulation metric in distinguishing between the visually observed flow patterns makes it a potentially useful tool for identifying between meso- or macro-scale habitat features of biological importance.

Circulation metrics computed from velocity data measured in the field

The circulation metric values computed within the two areas of the Smith River are significantly different. Consistent with the results of the previous numerical simulations, a large circulation metric value (0.095 s^{-1}) was computed in Area E (where significant flow complexity exists) and a small circulation metric (0.001 s^{-1}) was computed in Area D (where uniform flow existed). Moreover, the circulation values computed in Areas LMNO and PLOQ are consistent in sign with the clockwise and counterclockwise motion of the vortices observed within these regions. A summary of the circulation (Γ), absolute circulation (Γ_{ABS}), circulation metric ($\Gamma_{ABS} \div A_{TOT}$), and area ($A_{TOT}$) corresponding to Areas D and E, as well as the positive and negative vorticity regions (Areas LMNO and PLOQ), is provided (Table 1). A comparison of the results for Area D and Areas LMNO and PLOQ shows that the flow in Area D, which had no visually identifiable vortices, has the smallest absolute circulation (0.016 $m^2 \cdot s^{-1}$) and circulation per unit area (0.001 s^{-1}) values. Area LMNO, which had subtle but visually identifiable vortices, has absolute circulation and circulation per unit area values 23.5 and 46 times larger than those found in Area D. However, the absolute circulation and circulation per unit area values found in Area PLOQ, which had stronger and distinctly visible vortices, were 4.4 and 2.67 times larger than those found in Area LMNO. When the circulation metrics of the positive and negative vorticity regions are combined to represent the area surrounding the location of the three redds (Area E), the resulting circulation per unit area metric value is 95 times that found in Area D, where no redds were found. Hence, the proposed circulation metric clearly distinguished between the flow complexity surrounding the three redd locations and an area in which no redds were found.

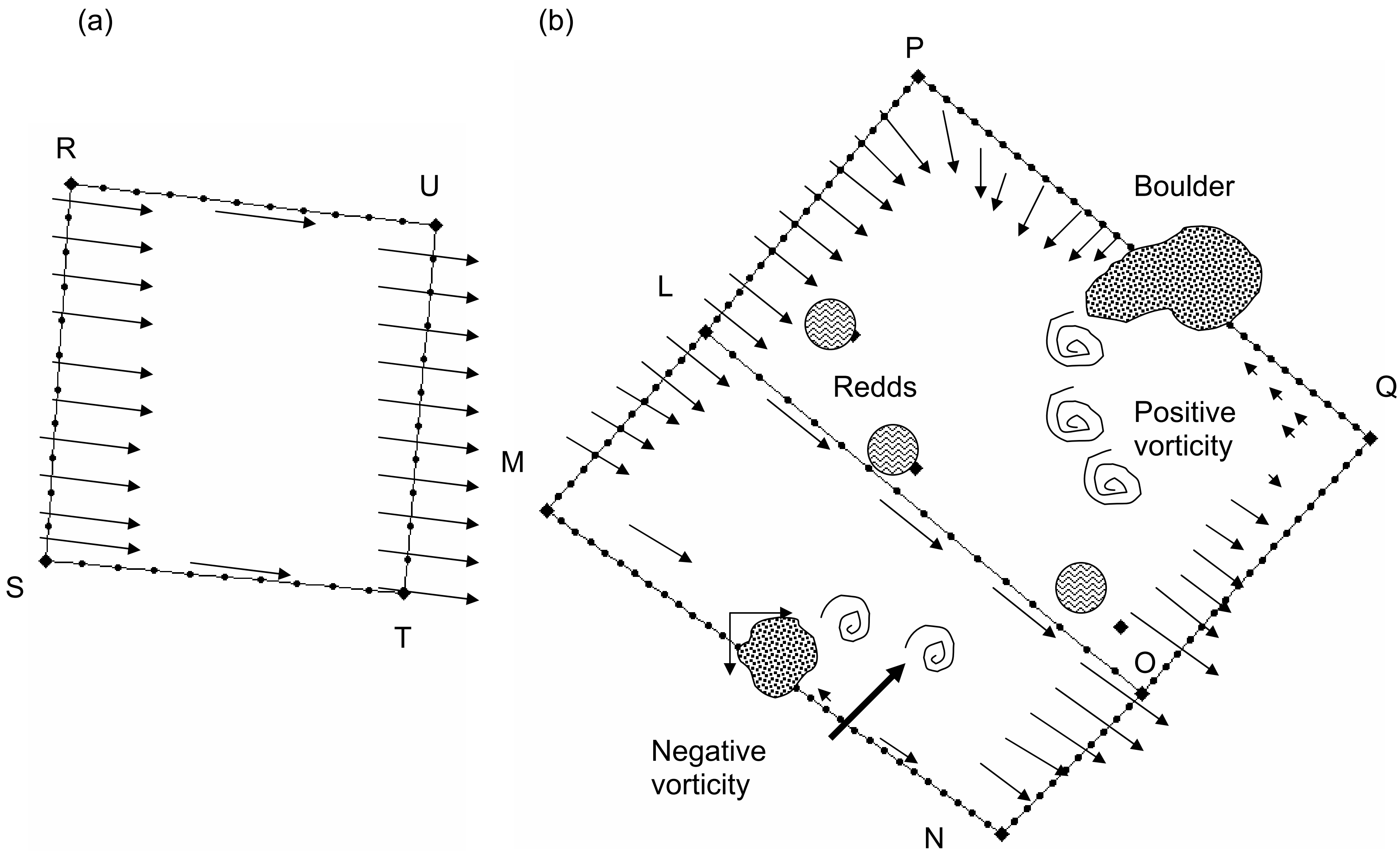

Figure 4. Schematic (not to scale) of the two areas the circulation metric was computed within the Smith River a) Area D without brown trout redds b) Area E with the three brown trout redds. Area LMNO contains negative vorticity values, while Area PLOQ contains positive vorticity values. The arrows indicate flow direction and magnitude along the lines which velocity was measured.

The locations of the three redds within Area E (Figure 4) are close to line LO which separates the positive and negative vorticity zones visually observed in the field. Along line LO, little, if any, vorticity could be seen and flow direction was largely parallel to the line LO. However, significant energy gradients and vorticity exist immediately adjacent to line LO. These flow conditions are analogous to the flow patterns found between the two most eastern boulders (Figure 3). Specifically, a line having near zero vorticity, and energy metric values passes between positive and negative vorticity zones. Hence, the hydraulic conditions surrounding the three brown trout redds can be described at two different scales using the proposed metrics. At the 'micro-habitat' scale, or at the exact locations of the redds, relatively small vorticity and energy gradient metric values are present. At the 'meso-habitat scale' (the 21.44 m^2 area surrounding the redds) the flow is highly complex and yields a high circulation per unit area value. In contrast, any location within Area D (containing no redds) will have low vorticity and energy metric values at the 'micro-habitat scale' and low circulation per unit area values at the 'meso-habitat scale' due to the uniform flow conditions found throughout this location. Consequently, if the flow complexity at the 'meso-habitat scale' (surrounding the redds) is biologically important, then Area E's circulation metric per unit area value used in conjunction with vorticity, energy gradient, and other habitat variables evaluated at the 'micro-habitat scale' is likely to best describe the overall flow conditions and differentiate between the flow conditions in Areas D and E.

While the proposed circulation metric provides a means of quantifying flow complexity at the 'meso-scale' or 'macro-scale' level, it is not known how large an area (or at what scale) the circulation metric should be computed over in order to best quantify biologically important flow patterns. In this example, a 21.44 m^2 area surrounding the locations of three redds was selected as an appropriate scale to test the metric and explore whether flow complexity might be an important component of brown trout spawning habitat. It is possible that only the flow patterns within about a meter of the redd's locations are biologically important and that the circulation metric should be computed at this scale and not the larger one used. However, an advantage of the circulation metric is that it can be computed at the scale stream biologists determine to be appropriate for quantifying specific flow patterns.

DISCUSSION

A better understanding of how channel topography and discharge interact to create spatially varying flows and suitable habitat features may lead to improved techniques of quantifying the types and amounts of habitat available within a stream. A stream's flow interacts with river's topographic features to create complex flow patterns that can occur over a range of spatial scales. Often, these features are described qualitatively and not quantitatively (eddies, pools, riffles, runs). Moreover, commonly used point metrics such as depth, velocity, and substrate values cannot be used to quantify the spatial characteristics within these features. Two-dimensional hydraulic models and spatial hydraulic metrics provide stream biologists the ability to analyze and quantify how channel topography interacts within the flow to create vorticity, velocity/energy gradients, and other spatial flow features of potential biological importance.

The energy, vorticity, and circulation metrics discussed here are all spatial hydraulic metrics that quantify physical attributes of flows and can be used to help locate and distinguish between flow features of biological importance. The energy and vorticity metrics describe how flow is changing around a point. Hence, two locations having the same depth and velocity values surrounded by different flow features can be distinguished from each other by comparing their local vorticity and/or energy metric values. A high vorticity or energy metric value would suggest a point is located within an area having significant spatial variation, or flow complexity, occurring around that point. Consequently, one can employ these metrics to help identify important micro-habitat features such as the velocity/energy gradients used by brown and brook trout to feed.

The circulation metric extends the concept behind the energy and vorticity metrics to an arbitrary area. Specifically, the circulation metric provides stream biologists a means of quantifying flow complexity within a given area. The higher the circulation metric value, the higher the flow complexity is within the area being analyzed. Note that a distribution of velocity values within a stream reach does not necessarily reflect the reach's flow complexity. Instead, flow complexity depends greatly on the spatial arrangement of the velocity values within a reach. For example, a river reach which gradually transitions from uniform high velocity values at its upstream section to uniform low velocity values at a downstream cross-section may, statistically, have the same depth and velocity distributions as a reach having complex topography that creates heterogeneous pockets of high and low velocity areas throughout the reach. While statistically similar, the latter stream would have far more flow complexity in terms of velocity gradients, eddies, etc. In the circulation metric, vorticity values dependent on the spatial arrangement of the velocity values are summed. Hence, the circulation metric reflects and accounts for the spatial arrangement of the velocity field within a river and provides stream biologists a means to quantify flow conditions within meso-scale habitat features (e.g. pools, riffles, runs). Moreover, one can conjecture on what types of physical processes (aeration, erosion, and deposition) might be associated with a circulation metric value. High circulation values are indicative of high vorticity, local aeration, and scour patterns. In fact, local aeration processes and depositional features were visually observed immediately adjacent to and downstream of the large exposed boulder near the three redd locations (Area E) in the Smith River. Specifically, one could see vortices entraining air and purging finer particles from the bed material immediately adjacent to the boulders, while finer materials were found deposited immediately downstream of the boulders. The circulation metric may also be useful in quantifying important differences between urban and non-urban streams and developing stream restoration techniques that create and maintain the flow characteristics found in natural streams.

The spatial hydraulic metrics proposed here can be incorporated into stream habitat studies in a number of ways. One means of using and calculating these metrics within an area is through the use of two-dimensional hydraulic model output. Two-dimensional models provide the depth, velocity, substrate, and cover data traditionally used in stream habitat assessments. Moreover, the spatially explicit output provided by 2-D models provides a means of directly computing the proposed spatial hydraulic metrics throughout a study site to help identify and distinguish between features within the river having biological importance. Plots, such as those generated in this study, can be generated to determine if specific ranges of energy gradients, vorticity values, or circulation values are characterizing biologically significant areas.

The energy, vorticity, and circulation metrics proposed here can also be computed in the field with standard velocity meters and a compass. One can collect the data needed to compute the energy and vorticity metrics at a particular point within the river by measuring the depth-averaged velocity at the midpoints of the four sides of a small imaginary square centered over the point where the vorticity or energy gradient is being calculated. Using the compass to measure the direction of the flow at each of the four points, one can decompose the velocity magnitudes at each point into the depth averaged x- and y- velocity components needed to compute vorticity (equation 4). Circulation (not the circulation metric) can be computed by measuring velocity magnitude and direction around the perimeter of an area. By observing the locations of positive and negative vorticity zones within an area of interest, one can compute and then sum the absolute circulation values for each region to obtain the proposed circulation metric value for the entire area of interest. This procedure was adopted to compute the flow complexity around two locations within the Smith River.

One cannot compute the proposed spatial hydraulic metrics with model output from one-dimensional hydraulic models, such as the one used in PHABSIM (Milhous et al. 1989). One-dimensional models represent a river reach as a series of rectangular areas each having uniform depth, and velocity (Bovee 1978). By assuming uniform flow within each cell, the energy metric, vorticity metric, and circulation values within a cell must be zero, as there is no spatial variation occurring within a cell. However, the inability to compute spatial hydraulic metrics from 1-D model output does not exempt the use of spatial hydraulic metrics in a habitat study employing a 1-D model. Spatial hydraulic metric values measured at key locations within the study site may provide valuable insights on a stream's characteristics and complement the depth, velocity, and substrate, values computed in 1-D models.

Input from stream biologists is needed to further develop and validate meaningful spatial metrics. Aquatic organisms of different species and life-stages are likely to require or respond to different types of vorticity, energy gradients, and flow complexities. Field studies need to be performed to determine what types and scales of spatial flow attributes different aquatic organisms are utilizing. If a specific spatial metric is determined to be biologically significant, one can then begin to incorporate it into habitat suitability criteria for that particular organism.

The two-dimensional hydraulic model results suggest that vorticity is a potentially useful metric for detecting spatial flows of biological importance. The highest vorticity values computed in the study site were found in the immediate vicinity of exposed boulders located in the river's main channel. Vorticity values were also relatively high along the channel banks and within an area containing a transverse flow. A comparison of the vorticity and energy metric values within the study site revealed that both vorticity and energy gradients are present in the spatial flow patterns generated by channel banks and exposed boulders. However, vorticity values appeared to be more sensitive to detecting spatial flow patterns. Specifically, the vorticity effects created by the presence of the boulders were detected further downstream than the energy gradients created by the boulders. Vorticity also reflected the location of a transverse flow whereas the energy metric did not. However, as each metric quantifies a different physical attribute of flow, both metrics provide useful means of differentiating between locations having similar depth and velocity values surrounded by different flow patterns. The best metric to use in a specific instance will depend on the type of flow pattern being analyzed and the physical attributes within that flow that aquatic organisms are utilizing. In some situations, both metrics might be necessary to describe the important attributes of a particular location within a river.

Circulation metric values computed over the entire reach, over the upper 20 meters of the study site, and within three distinct areas of the site were consistently higher when boulder geometry was incorporated into the model. The magnitude of the differences in circulation metric values for the two simulations depended on the location and total area over which the metric was computed. At the reach-scale, a difference of 20% was found. In the vicinity of the boulders, a difference of 350% was found. Circulation metric values computed within separate segments of the study site show that the metric can distinguish between the visually different flow patterns observed within the study reach. The circulation metric obtained around the locations of four exposed boulders is twice as large as the same metric computed within a region containing a transverse flow and twelve times larger than the metric value obtained within a region of the river having uniform flow.

By collecting velocity magnitude and direction data, circulation metric values were also computed (without the use of 2-d model output) for an area containing three brown trout redds and a location devoid of brown trout redds within the Smith River. The resulting circulation metric values varied by a factor of 95 and differentiated between the uniform flow conditions surrounding the area containing no redds from the complex flow patterns surrounding the three redds. However, given that the circulation metric was computed for the flow surrounding the locations of only three redds, no definitive statements can be made regarding whether or not flow complexity is actually an important factor in quantifying brown trout spawning habitat, especially as important non-hydraulic factors such as cover and predation were not addressed. Consequently, the circulation metric results for the redd comparison should be viewed solely as an example of how the proposed metric might be employed in future studies and a method of further exploring the metric's suitability to describe flow complexity.

The proposed spatial metrics provide stream biologists, engineers, and managers the ability to describe micro-, meso-, and macro-habitat scales features in a quantitative and physically meaningful way. This quantitative description allows one to compare how specific pools, or other habitat features, between or within streams, are hydraulically similar or different and how these differences might reflect a stream's aquatic health. The spatial hydraulic metrics proposed here are only a few of the many potential metrics that could be employed in evaluating stream conditions. Input from stream biologists is needed to help determine the best and most appropriate use of such metrics. The metrics provided here quantify well-established attributes of fluid motion and can be readily calculated in the field with standard velocity meters or from 2-D hydraulic model output.

ACKNOWLEDGEMENTS

The support provided by the United States Environmental Protection Agency, the National Science Foundation, and Pacific Gas and Electric is gratefully acknowledged. The field and technical support provided by Matt Chan, Doug Novinger, and Yi Shen is also appreciated.

REFERENCES

Bandyopadhyay, P.R., Castano, J.M., Nedderman, W.H., and Donnelly, M.J. 2000. Experimental simulation of fish-inspired unsteady vortex dynamics on a rigid cylinder. J. of Fluids Engr. –Trans. ASME. **122**: 219-238

Batchelor, G.K. 1967. An introduction to fluid dynamics. Cambridge University Prss, London, United Kingdom.

Bovee, K. D. 1978. The incremental Method of Habitat Potential for Coolwater Species with Management Implications. Am. Fish. Soc. Spec. Publ. 11: 340-346.

Crowder, D. W., and Diplas, P. 2000a. Using two-dimensional hydrodynamic models at scales of ecological importance. J. of Hydrol. **230**: 172-190.

Crowder, D. W., and Diplas, P. 2000b. Evaluating spatially explicit metrics of stream enery gradients using hydrodynamic model simulations. Can. J. Fish. Aquat. Sci. **57**: 1497-1507.

Fausch, K. D., and White, R. J. 1981. Competition between brook trout (salvelinus fontinalis) and brown trout (salmo trutta) for position in a Michigan stream. Can. J. Fish. Aquat. Sci. **38**: 1220-1227.

Freeman, M. C., and Grosssman, G. D. 1993. Effects of habitat availability on dispersion of a stream cyprinid. Environ. Bio. of Fishes **37**: 121-130.

Ghanem, A., Steffler, P., Hicks, F., and Katopodis, C. 1996. Two-dimensional hydraulic simulation of physical habitat conditions in flowing streams. Reg. Rivers Res. and Manage. **12**: 185-200.

Hanke W., Brucker, C., and Bleckmann, H. 2000. The ageing of the low-frequency water disturbances caused by swimming goldfish and its possible relevance to prey detection. J. Exp. Bio. **203**: 1193-1200.

Hayes J. W., and Jowett, I. G. 1994. Microhabitat models of large drift-feeding brown trout in three New Zealand rivers. N. Am. J. Fish. Manage. **14**: 710-725.

King, I. P. 1990. Program documentation RMA-2V, Two dimensional finite element model for flow in estuaries and streams, Version 4.3. Resource Management Associates, Lafayette, California.

Kiorboe T., and Visser, A.W. 1999. Predator and prey perception in copepods due to hydromechanical signals. Mar. Ecology-Progress Series **179**: 81-95.

Leclerc, M., Boudreault, A., Bechara, J. A., and Corfa, G. 1995. Two-dimensional hydrodynamic modeling: a neglected tool in the instream flow incremental methodology. Trans. Am. Fish. Soc. **124**: 645-662.

Milhous, R. T., Updike, M. A., and Schneider, D. M. 1989. Physical habitat simulation system (PHABSIM) reference manual, Version II. Instream Flow Information Paper No. 26, U.S. Fish Wild.l. Serv. Biol. Rep. 89 (16*)*.

Munson, B. R., Young, D. F., and Okiishi, T.H. 1990. Fundamentals of fluid mechanics, 2nd ed. John Wiley and Sons, Inc., New York.

Shields, F.D., Jr., Cooper, C. M., and Knight, S. S. 1995. Experiment in stream restoration. J. Hydr. Engrg., ASCE, **121**: 494-502.

Way, C.M., Burky, A.J., Bingham, C.R., Miller, A.C. 1995. Substrate roughness, velocity refuges, and macroinvertebrate abundance on artificial substrates in the lower Mississippi River. J. N. Am. Benth. Soc. **14**: 510-518.

Whiting, P. J., and Dietrich, W. E. 1991. Convective acccelerations and boundary shear stress over a channel bar. Water Resources Res. **27**: 783-796.

Chapter 6. Conclusions

SUMMARY OF MAJOR FINDINGS

A channel's topography and flow interact to create complex flow patterns occurring at the micro-, meso- and macro-scale levels. The importance of describing and quantifying the presence of velocity gradients, transverse flows, circulation zones, and other spatial flow patterns varies between disciplines and studies. Traditionally, most researchers have employed one-dimensional hydraulic models to describe flow conditions within rivers. However, such models are limited in the capacity to reproduce spatial flow patterns. Two-dimensional hydraulic models, capable of reproducing 2-D spatial flow patters, are beginning to be implemented on a more regular basis. However, the advantages and disadvantages of using a 1-D or 2-D model should be carefully analyzed in terms of a study's objectives. Moreover, if a 2-D hydraulic modeling study is implemented, efforts need to be taken to insure that appropriate bathymetry data and mesh refinement are used so that the needed model resolution is achieved. One should also consider how the spatially explicit output provided by 2-D hydraulic models can best be utilized to better describe and quantify flow complexity within rivers.

Model simulations show that the incorporation of meso-scale topographic features (e.g. exposed boulders) into a 2-D model's bathymetry data can have significant impact on the predicted flow field within a stream. Such features induce velocity gradients, transverse flows, and complex flow patterns not predicted in 1-D models or 2-D model simulations not incorporating topographic data describing meso-scale topographic features. Simulations also show that the development of sufficiently refined finite element meshes is also crucial in better describing the flow patterns generated within river's having complex flows.

Traditionally, point measurements of depth and velocity are used to describe hydraulic conditions in stream habitat studies. From a hydraulic perspective, this approach inherently assumes that two locations having the same depth and velocity are equally suitable or unsuitable, regardless of the flow conditions surrounding the two points. However, growing evidence suggests that certain aquatic organisms utilize or prefer certain spatial flow features. Three spatial hydraulic metrics have been developed and evaluated as potential means to quantify specific attributes of flow complexity within streams. The first metric describes localized velocity/energy gradients which trout and other aquatic organisms are known to utilize. Two-dimensional hydraulic model simulations show that it is capable of distinguishing between uniform and non-uniform flow conditions within a river, particularly those found near exposed boulders and channel banks. The metric being directly related to a flow's kinetic energy can be related to the drag forces exerted on a aquatic organism and that organism's energy expenditure rates.

The second spatial hydraulic metric proposed is vorticity. Vorticity is a well-established property of flow that prior researchers suggest may be an important component of the habitats of several aquatic organisms. Vorticity, like the spatial energy metric, describes local variations in flow. Model simulations indicated that vorticity, like the spatial energy metric, has relatively high values in the non-uniform flow conditions found near exposed boulders and streambanks. However, unlike the spatial energy metric, high vorticity values were found in a transverse flow region where significant vorticity existed but large velocity/energy gradients did not exist. Hence, the spatial energy metric and vorticity metrics complement each other, and when computed at the same location, provide a more complete description of the flow variation occurring at a point.

The third spatial metric proposed and evaluated here is a variation of circulation. The proposed circulation metric, unlike the spatial energy and vorticity metrics, represents a measure of the flow's complexity per unit area. As the circulation metric can be calculated over any size area, it can be used to characterize and differentiate between the flow conditions found in different river reaches or within different areas of a river. Hence, one can quantify the flow complexity associated with features such as pools, riffles, and runs, which are usually described in a rather subjective way in many studies. Model simulations and field measurements suggest that the proposed circulation metric is sensitive to being able to differentiate between different types of flow complexity at various scales found within streams.

All three of the proposed spatial metrics incorporate velocity gradients in an effort to describe flow complexity. However, each spatial metric is distinctly different and provides information well beyond a simple measure of velocity gradient imparts. For example, consider two different pairs/sets of point velocity measurements within a stream. The first pair has point velocities of 0.05 m/s and 0.15 m/s. The second pair has point velocities of 1.0 and 1.1 m/s. Moreover, assume that the distance between the velocity measurements in each set is 1.0 m. An average velocity gradient of 0.10 s^{-1} exists between the two velocity measurements in both data sets. Thus, if the velocity gradient is used to quantify flow complexity, the flow complexity between the points in each data set is the same. However, if the kinetic energy gradient metric is used to describe the flow complexity between the velocities in each data set, different metric values are obtained. The flow between the velocity points in the first data set has a kinetic energy gradient metric value of 8.0 m^{-1}, while the flow between the velocity points in the second data sets has a kinetic energy gradient metric value of 0.21 m^{-1}. The larger kinetic energy gradient metric associated with the first data set suggests that flow between the velocities in the first data set exhibits more spatial flow complexity than the flow found in the second data set. . Hence, it is possible for the rate at which the flow's kinetic energy is changing to remain the same for the two data sets given above, the relative rate at which the flow's kinetic energy is changing differs for each set.

The physical significance of the kinetic energy metric can be explained in terms of drag force, which is proportional to the flow's kinetic energy. Specifically, if a fish moves from the 0.05 m/s velocity location to the 0.15 m/s velocity location it will increase the drag force it must swim against by a factor of 800%, as reflected by the first data set's kinetic energy gradient metric. Similarly, a fish that moves from the location having a velocity of 1.0 m/s to the location having a velocity of 1.1 m/s will increase the drag force it must swim against by 21%. The kinetic energy gradient metric, therefore, reflects a physical component of the flow that velocity gradient by itself cannot quantify. Likewise, the vorticity and circulation metrics are calculated from velocity gradients, but represent different physical properties of the flow.

If the proposed spatial hydraulic metrics are used in conjunction with the output provided by a detailed 2-D hydraulic study, one can begin to study how flow complexity is important within streams in a variety of ways. For stream habitat studies, associations can be made between the locations of specific organisms and the types of flow features they are utilizing.

One can use 2-D hydraulic models to help determine how a stream should be restored and how fish rocks and other habitat creating features can best be implemented. Similarly, one can analyze the affects that changes in a watershed's hydrologic conditions (e.g. urbanization) will impact the hydraulic conditions within a stream for a specific storm event. The work presented here has not focused on performing a case study regarding any of these particular applications. However, the guidelines provided for performing collecting bathymetry data, developing appropriate finite element meshes, and the proposed spatial metrics provide engineers, aquatic biologists and water resource managers better tools to implement such studies.

DISCUSSION/FUTURE WORK

The model simulations performed in this dissertation have focused on developing means of using 2-D hydraulic models and spatial hydraulic metrics to better reproduce and quantify flow complexity within streams. The implementation of 2-D hydraulic model studies, however, is not straightforward and many issues have yet to be resolved. Three of the major issues include: defining and measuring flow patterns of biological importance, determining the best means of collecting bathymetry data, and developing better numerical algorithms to use in 2-D hydraulic modeling studies. A brief discussion on each of these issues follows.

The first major challenge in implementing spatial hydraulic metrics into habitat studies will be to identify the specific spatial flow patterns that specific aquatic organisms use and then quantify them in a manner that can be used in habitat suitability criteria. Different species and life stages may use different flow features. Consequently, different metrics (or different ranges of values of the same metric) might be better at describing specific habitat preferences. Aquatic biologists are probably the best equipped to determine such relationships. Such undertakings will likely involve collecting data beyond what is normally collected in the field. The best and most appropriate means of collecting such data will need to be determined. Biologists will also need to coordinate with hydraulic modelers to determine how models can best be used to help quantify the amounts and types of habitats within rivers. With an understanding of the type of modeling detail needed to reproduce the ecologically important flow patterns, hydraulic modelers can then focus on developing models and numerical procedures that meet these needs.

Currently, collecting bathymetry data for 2-D hydraulic models is an art that depends largely upon experience. It is up to the modeler to determine how detailed a bathymetric survey should be and how the data should be collected. Depending on the conditions at the study site, the number of spot elevations that could be collected in a day ranged from about 100 to 1000 (using a crew of two people and a Leica TC-605 total station). The main factors influencing data collection rates were the presence or absence of vegetation, and the ability (or inability) to set the total station in the middle of the stream where one has a clear field of vision. Regardless of site conditions, one also has to carefully consider the benefits of modeling longer river reaches with less detail versus modeling shorter reaches with more detail.

In this study, bathymetry surveys focused on describing the channel's bank, bed, and topographic features within the streambed that created spatial flow patterns that could be visually observed at low flow conditions. It was observed that taking spot elevation data over a grid (grid points being spaced about a step in the lateral direction and about two steps in the upstream and downstream directions) helped avoid interpolation problems associated with collecting data along equally or unequally spaced cross sections. Such a grid pattern can be surveyed fairly easily if the total station can be set up within the stream. Vegetation along the banks makes continuing the grid up the banks and into the flood plain problematic. However, surveying the toe of bank and top of bank and along with an elevation or two in the flood plain every two or three steps in the upstream and downstream directions allows one to create breaklines that can be used to describe the shape of the channel banks. Once the channel bed and banks have been surveyed, breaklines describing the thalweg, toe of bank, top of bank, and the tops and bottoms of obstructions found within the channel should be incorporated into the bathymetry data, as this information adds the topographic detail needed to reproduce spatial flow patterns. Identifying the topographic features creating the flow patterns of importance and how best to survey them is a highly subjective process. At a minimum, one should incorporate features that shift the flow from one bank to another bank. Exposed bars and topographic features that constrict the flow or help create pool/riffle sequences also need to be surveyed. As one cannot describe a channel's geometry in every detail, one may need to limit a survey to topographic features larger than a specific size or only features that protrude above the surface of the water during base flow conditions.

Measuring velocity data throughout the study site also becomes crucial in determining the ability of 2-D hydraulic models to reproduce spatial flow patterns. Measuring velocity values across cross sections (passing through spatial flow complexity) throughout the study site allows one to help calibrate and validate a 2-D model. Likewise, one may wish to measure velocity values over a grid within a specific area of the model reach to help calibrate or validate a model. A major study focusing on the calibration and validation of detailed 2-D hydraulic model studies has yet to be performed. As the number of detailed 2-D model results continues to increase, one can expect to obtain a better understanding of how accurately a model can reproduce flow features based on the underlying bathymetric survey. This understanding will, in turn, allow one to better determine which features in a river need to be surveyed and which features can be excluded. In the mean time, faster and more efficient means of collecting bathymetry data would improve one's ability to model flow complexity within streams.

If spatial hydraulic metrics are to be used in conjunction with 2-D hydraulic model results, one must be able to reproduce complex flow patterns reasonably well. Incorporating the topographic features responsible for creating the flow patterns into the model's bathymetry data is the first step in this process. The next step is developing an appropriate mesh capable of modeling the complex flow field. Experience has shown that the reproduction of topographic features responsible for flow patterns requires far more elements than previous researchers have used (up to 57462 nodes for a 20 meter long study reach). As a result, computation time, while not completely unreasonable, starts becoming a concern when using a standard desktop computer. This concern quickly arose, particularly during simulations for long reaches or unsteady simulations. Additionally, numerical models may have difficulty handling wetting and drying, as well as the modeling of localize flows that have Froude numbers near or exceeding one. Such problems are expected but significantly hinder the modeling of complex flow fields. Advances in numerical algorithms that more easily model these situations would facilitate the modeling of spatial flow patterns. Detailed investigations into how accurately 2-D models can reproduce complex flow patterns in a variety of situations are also needed.

Appendix A. FPREP Code

This code prepares data input files for use in the SPAT10 code.

```
      PROGRAM FPREP
********************************************************************************
*     VARIABLE ASSIGNMENTS
*     E8QN( ) AND E6TN( ) = NODE NUMBERS ON THE ELEMENT BEING ANALYZED
*     NX = NODAL X COORDINATE
*     NY = NODAL Y COORDINATE
*     ESTAT = ELEMENT STATUS (WET = 1; DRY = 0)
*     MAT = MATERIAL TYPE FOR THE ELEMENT
*     ETYPE = ELEMENT TYPE; TRIANGULAR OR QUADRALATERAL
*     NE = NUMBER OF ELEMENTS IN THE MESH
*     NN = NUMBER OF NODES IN THE MESH
*     ELEMENT NUMBER
*     COUNT = COUNTER FOR DO LOOPS
*     SCALAR1, SCALAR2, SCALAR3, THE THREE NODAL SCALAR VALUES BEING READ FROM
*  FILES 2, 3, AND 4
********************************************************************************
      IMPLICIT NONE
      INTEGER E8QN(8), E6TN(6), ESTAT, MAT, NE, NN, COUNT, ENUM, FLAG
      REAL NX, NY, SCALAR1, SCALAR2, SCALAR3
      CHARACTER*3 ETYPE
      CHARACTER*2 DUMMY1
      CHARACTER*75 FILE1, FILE2, FILE3, FILE4, FILE5, FILE6, FILE7
      CHARACTER*75 FILE8
      INTEGER DUMMY2
********************************************************************************
*     OPEN FILES AND READ INPUT CONTROL FILE WHICH ASSIGNS CONSTANTS AND CHANGES
*     DIMENSIONS AS NEEDED
********************************************************************************
*     OPEN FILES 1-8
*     1 ELEMENT TYPE AND RUN CONTROL FILE: PREVIOUSLY CREATED IN ACCESS OR EXCEL
*     2 SCALAR DATA FILE1: CREATED FROM SMS DATA EXPORT FEATURE
*     3 SCALAR DATA FILE2: CREATED FROM SMS DATA EXPORT FEATURE
*     4 SCALAR DATA FILE3: CREATED FROM SMS DATA EXPORT FEATURE
*     5 2DM DATA FILE: CREATED FROM SMS 2DM EXPORT FEATURE
*     6 FILE TO BE WRITTEN CONTAINING ELEMENT TYPE AND WET/DRY STATUS
*     7 FILE TO BE WRITTEN CONTAINING THE NODE NUMBERS ON EACH ELEMENT
```

```
*     8 FILE TO BE WRITTEN CONTAINING NODAL DATA SET VALUES (XCOORD, YCOORD,
*     SCALAR1, SCALAR2, SCALAR3)
*     TO CREATE THE INPUT FILES USE SMS TO SAVE A 2DMESH FILE AND 3 SCALAR DATA
*     FILES
*     THE 2DMESH FILE CONTAINS THE COORDINATES OF EVERY NODE.
*     IMPORT THE PORTION OF THE 2DMESH FILE CONTAINING ELEMENT TYPE INTO EXCEL
*     OR ACCESS TO CREATE FILE 1
      WRITE (*,*) "ENTER RUN CONTROL FILE (.CSV OR .TXT FILE)"
      WRITE (*,*) "USE SINGLE PARENTHESIS EXAMPLE: 'E:\FILENAME.CSV'"
      READ (*,*) FILE1
      OPEN (1, FILE = FILE1, STATUS ='OLD')
      READ (1,*) FILE2
      READ (1,*) FILE3
      READ (1,*) FILE4
      READ (1,*) FILE5
      READ (1,*) FILE6
      READ (1,*) FILE7
      READ (1,*) FILE8
      READ (1, *) NE
      READ (1, *) NN
      OPEN (2, FILE = FILE2, STATUS ='OLD')
      OPEN (3, FILE = FILE3, STATUS ='OLD')
      OPEN (4, FILE = FILE4, STATUS ='OLD')
      OPEN (5, FILE = FILE5, STATUS ='OLD')
      OPEN (6, FILE = FILE6, STATUS ='NEW')
      OPEN (7, FILE = FILE7, STATUS ='NEW')
      OPEN (8, FILE = FILE8, STATUS ='NEW')
      WRITE (*,*) "INPUT CONTROL FILE READ"
*     END OF INPUT CONTROL FILE
********************************************************************************
*     CREATE FILES 6 AND 7
*     BEGIN ADVANCING READ STATEMENTS TO BEGINNING OF ELEMENTAL DATA
      DO COUNT = 1, 7
        READ (2,*)
        READ (3,*)
        READ (4,*)
      WRITE (*,*) "ADVANCING FILES 2-4 ONE READ STATEMENT AT A TIME"
      END DO
      READ (5,*)
*     END ADVANCING READ STATEMENTS TO BEGINNING OF ELEMENTAL DATA
```

```
      WRITE (*,*) "CREATING FILES 6 AND 7"
      DO COUNT = 1, NE
*     BEGIN CREATING FILE 6
        READ (2,*) ESTAT
        READ (3,*) ESTAT
        READ (4,*) ESTAT
        READ (1,5) ETYPE
        WRITE (6,10) ETYPE, ESTAT
*       WRITE (*,*) "NE, ETYPE, ESTAT"
        WRITE (*,*) COUNT, ETYPE, ESTAT
*     END CREATING FILE 6
*     BEGIN CREATING FILE 7
        IF (ETYPE .EQ. "E6T") THEN
          READ (5,6) ETYPE, ENUM, E6TN, MAT
          WRITE (7,30) E6TN, MAT
*         WRITE (*,*) "N1, N2, N3, N4, N5, N6, MAT"
*         WRITE (*,*) E6TN, MAT
        END IF
        IF (ETYPE .EQ. "E8Q") THEN
          READ (5,7) ETYPE, ENUM, E8QN, MAT
          WRITE (7,30) E8QN, MAT
*         WRITE (*,*) "N1, N2, N3, N4, N5, N6, N7, N8, MAT"
*         WRITE (*,*) E8QN, MAT
        END IF
*     END CREATING FILE 7
*     END DO LOOP FOR CREATING FILES
      END DO
      WRITE (*,*) "FILES 6 AND 7 HAVE BEEN WRITTEN"
********************************************************************************
* BEGIN CREATING FILE 8
      WRITE (*,*) "CREATING FILE 8"
      DO COUNT = 1, NN
        READ (2,*) SCALAR1
        READ (3,*) SCALAR2
        READ (4,*) SCALAR3
*        WRITE (*,*) "SCALAR VALUES  ", SCALAR1, SCALAR2, SCALAR3
        READ (5,8) DUMMY1, DUMMY2, NX, NY
        WRITE (8,40) NX, NY, SCALAR1, SCALAR2, SCALAR3
        WRITE (*,*) "NODE = ", COUNT
*       WRITE (*,*) "NX, NY, SCALAR1, SCALAR2, SCALAR3"
```

```
*       WRITE (*,*) NX, NY, SCALAR1, SCALAR2, SCALAR3
*       PAUSE
      END DO
      WRITE (*,*) "FILE 8 HAS BEEN WRITTEN"
* END CREATING FILE 8
********************************************************************************
* FORMAT STATEMENTS
********************************************************************************
* READ FORMAT FOR FILE 1: ELEMENT TYPE
    5 FORMAT (BN, A3)
********************************************************************************
* READ FORMATS FOR FILE 5: ELEMENT TYPE
    6 FORMAT (BN, A3, 8I7)
    7 FORMAT (BN, A3, 10I7)
    8 FORMAT (BN, A2, I7, 2E16.8)
********************************************************************************
* OUTPUT FORMAT FOR FILE 6: ELEMENT TYPE AND WET/DRY STATUS
   10 FORMAT (BN, A3, I7)
********************************************************************************
* OUTPUT FORMAT FOR FILE 7: ELEMENT NODAL NUMBERS AND MATERIAL TYPE
   20 FORMAT (BN, 9I7)
   30 FORMAT (BN, 9I7)
********************************************************************************
* OUTPUT FORMAT FOR FILE 8: NODAL X- AND Y-COORDINATES AND NODAL SCALAR VALUES
   40 FORMAT (BZ, 5F15.6)
********************************************************************************
      CLOSE (1)
      CLOSE (2)
      CLOSE (3)
      CLOSE (4)
      CLOSE (5)
      CLOSE (6)
      CLOSE (7)
      CLOSE (8)
      PAUSE
      END
```

Appendix B. SPAT10 Code

This is the FORTRAN code used in Chapter 5.

```
      PROGRAM SWUA3
*************************************************************************************
*     VARIABLE ASSIGNMENTS
*     AREA1 = AREA OF FIRST TRIANGLE MAKING UP A QUADRALATERAL ELEMENT
*     AREA2 = AREA OF SECOND TRIANGLE MAKING UP A QUADRALATERAL ELEMENT
*     QAREA = TOTAL AREA OF A QUADRALATERAL ELEMENT
*     TAREA = AREA OF A TRIANGULAR ELEMENT
*     N( ) = NODE NUMBERS ON THE ELEMENT BEING ANALYZED
*     NX( ) = NODAL X COORDINATE
*     NY( ) = NODAL Y COORDINATE
*     ESTAT = ELEMENT STATUS (WET = 1; DRY = 0)
*     MAT = MATERIAL TYPE FOR THE ELEMENT
*     D( ) = DEPTH VALUES (AT EACH NODE ON AN ELEMENT)
*     ETYPE = ELEMENT TYPE; TRIANGULAR OR QUADRALATERAL
*     ENUM = ELEMENT NUMBER (BEING PROCESSED)
*     NE = NUMBER OF ELEMENTS IN THE MESH
*     NN = NUMBER OF NODES IN THE MESH
*     COUNT, AND COUNT2 = COUNTERS FOR DO LOOPS
*     WETAREA = TOTAL AREA OF THE ACTIVE ELEMENTS
*     METRIC = ARRAY OF METRIC VALUES READ FOR A SINGLE NODE (VELOCITY, DEPTH, VORTICITY)
*     NODEARRAY(NODE,METRIC) = ARRAY STORING ALL THE METRIC VALUES CONTAINED ON EACH NODE OF AN
*                 ELEMENT
*     METRICMIN(I) = MINIMUM VALUE FOR METRIC(I)
*     METRICMAX(I) = MAXIMUM VALUE FOR METRIC(I)
*     METRICINT(I) = INTERVAL BETWEEN BINS FOR METRIC(I)
*     METRICSUM(I) = SUM OF METRIC(I) VALUES ON AN ELEMENT
*     METRICAVG(I) = AVERAGE METRIC(I) VALUE FOR AN ELEMENT
*     METRICBIN(METRIC,BIN#) = REFERS TO THE AMOUNT OF WETTED AREA HAVING METRIC
*                    VALUES THAT FALL INTO A USER DEFINED BIN
*     METRICBINVAL(METRIC, BINVALUES) = AN ARRAY DEFINED BY THE USERS SPECIFIYING
*                    THE UPPER AND LOWER VALUES FOR A BIN
*     TUBBIN(I) = REFERS TO THE AMOUNT OF WETTED AREA HAVING METRIC
*                    VALUES THAT ARE LESS THAN THE USER DEFINED MINIUMUM BIN VALUES
*     SKYBIN(I) = REFERS TO THE AMOUNT OF WETTED AREA HAVING METRIC
```

```
*                    VALUES THAT ARE LESS THAN THE USER DEFINED MINIUMUM BIN VALUES
*      NUMMETRICS = NUMBER OF METRICS BEING ANALYZED AND PRESENT IN THE DATA FILES
*      NUMBINVALS = NUMBER OF BINS DEFINED BY THE USER
*      DEBUGNUM = NUMBER OF ELEMENTS YOU WANT TO DEBUG "CHECK OUTPUT FOR"
*      DEBUG(I) = ARRAY CONTAINING THE ELEMENT NUMBERS YOU WANT TO CHECK NOTE: THE
*                 ELEMENTS MUST BE WITHIN THE REGION BEING ANALYZED NOT OUTSIDE IT
*      VORTNUM =  NUMBER THAT CALLS UP VORTICITY VALUES WHEN THE ARRAY METRIC(VORTNUM)
*                 IS CALLED OR ACCESSED (USE ZERO IF NO VORTICITY METRIC IS PRESENT)
*      CIRCULATON = AMOUNT OF CIRCULATON WITHIN THE SPECIFIED REGION ANALYZED
*      METRICNAME = ARRAY STORING THE METRIC DESCRIPTORS
*      NUMWETNODES = NUMBER OF WET NODES BEING ANALYZED
*      NODESUMVALUES (I) = SUM OF METRIC(I) NODAL VALUES IN AREA BEING ANALYZED
*      NODALMETRICAVG (I) = AVERAGE METRIC VALUES ON THE WET NODES ANALYZED
*      D1, D2, AND D3 = DESCRIPTION OF THE SIMULATION RUN 75 CHARACTERS LONG
************************************************************************************
      IMPLICIT NONE
      INTEGER ENUM, N(8), ESTAT, MAT, NE, NN, COUNT, COUNT2
      REAL NX(8), NY(8)
      REAL TAREA, QAREA, AREA1, AREA2, WETAREA
      REAL METRIC [ALLOCATABLE](:)
      REAL NODEARRAY[ALLOCATABLE](:,:)
      REAL METRICMIN[ALLOCATABLE](:)
      REAL METRICMAX[ALLOCATABLE](:)
      REAL METRICINT[ALLOCATABLE](:)
      REAL METRICSUM[ALLOCATABLE](:)
      REAL METRICAVG[ALLOCATABLE](:)
      REAL METRICBIN[ALLOCATABLE](:,:)
      REAL METRICBINVAL[ALLOCATABLE](:,:)
      REAL TUBBIN[ALLOCATABLE](:)
      REAL SKYBIN[ALLOCATABLE](:)
      INTEGER DEBUG[ALLOCATABLE](:)
      CHARACTER*3 ETYPE
      CHARACTER*75 FILE1, FILE2, FILE3, FILE4, FILE6, D1, D2, D3
      REAL BXCOORD(2), BYCOORD(2), CIRCULATION
      INTEGER FLAG, FLAG2,NUMMETRICS, NUMBINVALS, DEBUGNUM, VORTNUM
      CHARACTER*75 METRICNAME[ALLOCATABLE](:)
************************************************************************************
*      OPEN FILES AND READ INPUT CONTROL FILE WHICH ASSIGNS CONSTANTS AND CHANGES DIMENSIONS AS NEEDED
*      BOUNDARY LAYOUT FOR THE AREA TO BE ANALYZED
*      THE BOUNDARIES ARE DESCRIBED BY BXCOORD( ) BYCOORD( )
```

```
*
*      BYCOORD(1)
*      ___________
*  B  |           | B
*  X  |           | X
*  C  |           | C
*  O  |           | O
*  O  |           | O
*  R  |           | R
*  D  |           | D
* (1) |___________|(2)
*      BYCOORD(2)
*
*

*************************************************************************************
*     OPEN FILES 1-4
*     1 CONTAINS ELEMENT STATUS ELEMENT TYPE AND WET/DRY STATUS
*     2 CONTAINS THE NODE NUMBERS ON EACH ELEMENT
*     3 CONTAINS NODAL DATA SET VALUES (XCOORD, YCOORD, V, VX,VY, D, ETC.)
*     4 METRIC SUMMARY OUTPUT FILE
*     6 THE RUN INPUT FILE CONTROLLING THIS PROGRAM
*     TO CREATE THE INPUT FILES USE SMS TO SAVE A 2DMESH FILE, SCALAR DATA FILES, AND
*     A SCATTERDATA FILE THAT CONTAINS THE COORDINATES OF EVERY NODE.
*     (COVERT THE MESH TO A SCATTERDATA SET AND SAVE)
*     THEN IMPORT THESE FILES INTO A NEW REPEAT NEW EXCEL FILE
*     CUT AND PASTE THE DATA INTO THE COLUMNS DICTATED BY THE HEADINGS SHOWN IN
*     THE FILE "COARSESTWOBSTEST3.XLS" AFTER THE DATA IS ARRANGED COPY THE DATA
*     WITHOUT THE HEADINGS ONTO THE CORRECT PAGES IN THE FILE "SWUATEMPLATE.XLS"
*     THEN SAVE EACH PAGE SEPARATELY AS THE FINAL INPUT FILES.
*     NOTE THE ELEMENTAL STATUS WET=1 DRY=0 IS CONTAINED IN THE SCALAR DATA FILES
*     GENERATED BY SMS
      WRITE (*,*) "ENTER RUN CONTROL FILE (.CSV FLE)"
      WRITE (*,*) "USE SINGLE PARENTHESIS EXAMPLE: 'E:\FILENAME.CSV'"
      READ (*,*) FILE6
      OPEN (6, FILE = FILE6, STATUS ='OLD')
      READ (6,*) FILE1
      READ (6,*) FILE2
      READ (6,*) FILE3
      READ (6,*) FILE4
```

```
      OPEN (1, FILE = FILE1, STATUS ='OLD')
      OPEN (2, FILE = FILE2, STATUS ='OLD')
      OPEN (3, FILE = FILE3
     + ,STATUS='OLD', ACCESS = 'DIRECT', FORM = 'FORMATTED', RECL = 75)
      OPEN (4, FILE = FILE4, STATUS='NEW')
      READ (6, *) NUMMETRICS
      READ (6, *) NUMBINVALS
      ALLOCATE (METRIC(NUMMETRICS))
      ALLOCATE (NODEARRAY(8,NUMMETRICS))
      ALLOCATE (METRICMIN(NUMMETRICS))
      ALLOCATE (METRICMAX(NUMMETRICS))
      ALLOCATE (METRICINT(NUMMETRICS))
      ALLOCATE (METRICSUM(NUMMETRICS))
      ALLOCATE (METRICAVG(NUMMETRICS))
      ALLOCATE (METRICBIN(NUMMETRICS,NUMBINVALS-1))
      ALLOCATE (METRICBINVAL(NUMMETRICS,NUMBINVALS))
      ALLOCATE (TUBBIN(NUMMETRICS))
      ALLOCATE (SKYBIN(NUMMETRICS))
      ALLOCATE (METRICNAME(NUMMETRICS))
      READ (6, *) NE
      READ (6, *) NN
      READ (6, *) VORTNUM
      READ (6, *) BXCOORD
      READ (6, *) BYCOORD
      READ (6, *) METRICNAME
      READ (6, *) METRICMIN
      READ (6, *) METRICMAX
      READ (6, *) DEBUGNUM
      ALLOCATE (DEBUG(DEBUGNUM))
      READ (6, *) DEBUG
      READ (6, *) D1
      READ (6, *) D2
      READ (6, *) D3
      WETAREA = 0
      CIRCULATION = 0
*      WRITE (*,*) "INPUT CONTROL FILE READ"
*      PAUSE
*     END OF INPUT CONTROL FILE
*************************************************************************************
*
```

```
*     ASSIGN BIN VALUES
      DO COUNT = 1, NUMMETRICS
          METRICBINVAL(COUNT,1) = METRICMIN(COUNT)
          METRICBINVAL(COUNT,NUMBINVALS) = METRICMAX(COUNT)
          METRICINT(COUNT) = (METRICMAX(COUNT) - METRICMIN(COUNT))/
     +    (NUMBINVALS-1)
      END DO

      DO COUNT = 1,NUMMETRICS
      DO COUNT2 = 2,NUMBINVALS
          METRICBINVAL(COUNT, COUNT2)=METRICMIN(COUNT)+(COUNT2-1)
     +    *METRICINT(COUNT)
*          WRITE (*,*) METRICBINVAL(COUNT,COUNT2)
      END DO
      END DO
*      WRITE (*,*) "BIN VALUES ASSIGNED"
*      PAUSE
************************************************************************************
*     READ NODAL INFORMATION INTO ARRAYS (DEPENDING ON ELEMENT TYPE)
*     DATA IS READ IN ONE ELEMENT AT A TIME
      DO ENUM = 1, NE
          DO COUNT = 1, 8
              DO COUNT2 = 1,NUMMETRICS
                  NODEARRAY(COUNT, COUNT2) = 0
              END DO
          END DO
      WRITE (*,*) ENUM, WETAREA
          READ (1, 10) ETYPE, ESTAT
*      WRITE (*,*) "ESTATUS AND TYPE READ"
*      PAUSE
*          IF (ESTAT .EQ. 1) THEN
           IF (ETYPE .EQ. "E6T") THEN
************************************************************************************
*     BEGIN COMPUTATIONS FOR TRIANGULAR ELEMENTS
*     BEGIN READING DATA FILE VALUES FOR TRIANGULAR ELEMENTS
              READ (2, 30) N(1),N(2),N(3),N(4),N(5),N(6),MAT
*      WRITE (*,*) "NODES ON ELEMENT READ"
*      PAUSE
              DO COUNT = 1, 6
                READ (3, 50, REC = N(COUNT)) NX(COUNT), NY(COUNT),
```

```
     +        METRIC
                  DO COUNT2 = 1, NUMMETRICS
                  NODEARRAY(COUNT,COUNT2) = METRIC(COUNT2)
                  END DO
              END DO
*      WRITE (*,*) "METRIC VALUES READ"
*      PAUSE
*     END READING DATA VALUES FOR TRIANGULAR ELEMENTS
*******************************************************************
*     DETERMINE IF ELEMENT IS WITHIN AREA TO BE ANALYZED
              FLAG = 0
              DO COUNT = 1, 6
              IF (NX(COUNT) .LT. BXCOORD(1) .OR. NX(COUNT) .GT.
     +        BXCOORD(2)) THEN
                FLAG = FLAG + 1
              END IF
              END DO
              DO COUNT = 1, 6
              IF (NY(COUNT) .GT. BYCOORD(1) .OR. NY(COUNT) .LT.
     +        BYCOORD(2)) THEN
                FLAG = FLAG + 1
              END IF
              END DO
*********************************************************************
              IF (FLAG .EQ. 0) THEN
              IF (ESTAT .EQ. 1) THEN
**********************************************************************
*     COMPUTE AREA OF TRIANGLE ELEMENT
              TAREA = (((NX(1)-NX(5))*(NY(3)-NY(5)))-((NX(3)-NX(5))*
     +        (NY(1)-NY(5))))/2
              WETAREA = WETAREA + TAREA
**********************************************************************
*     COMPUTE AVERAGE XVELOCITY, YVELOCITY AND VELOCITY MAGNITUDE ON TRIANGULAR ELEMENTS
          DO COUNT = 1, 6
              METRICSUM(COUNT)=0
          END DO
          DO COUNT = 1, NUMMETRICS
              DO COUNT2 = 1, 6
                  METRICSUM(COUNT) = METRICSUM(COUNT)+NODEARRAY(COUNT2,
     +            COUNT)
```

```
             END DO
         END DO
             DO COUNT = 1,NUMMETRICS
                 METRICAVG(COUNT) = METRICSUM(COUNT)/6
             END DO
*************************************************************************
*     ASSIGN VALUES IN CORRECT BINS
*         XVELOCITY BINS
      DO COUNT = 1,NUMMETRICS
         IF (METRICAVG(COUNT) .LE. METRICMIN(COUNT)) THEN
            TUBBIN(COUNT) = TUBBIN(COUNT) + TAREA
         END IF
         DO COUNT2 = 2,NUMBINVALS
            IF (METRICAVG(COUNT) .GT. METRICBINVAL(COUNT,COUNT2-1) .AND.
     +      METRICAVG(COUNT) .LE. METRICBINVAL(COUNT,COUNT2)) THEN
                   METRICBIN(COUNT,COUNT2-1) = METRICBIN
     +             (COUNT,COUNT2-1) + TAREA
            END IF
         END DO
         IF (METRICAVG(COUNT) .GT. METRICMAX(COUNT)) THEN
           SKYBIN(COUNT) = SKYBIN(COUNT) + TAREA
         END IF
      END DO
*************************************************************************************
*     COMPUTE CIRCULATION
      IF (VORTNUM .GT. 0) THEN
          CIRCULATION = CIRCULATION + ABS(METRICAVG(VORTNUM))*TAREA
      END IF
*************************************************************************************


*DEBUG CODE AND BIN SUMMARY OUTPUT
      FLAG2 = 0
      DO COUNT = 1, DEBUGNUM
          IF (ENUM .EQ. DEBUG(COUNT)) THEN
            FLAG2 = 1
          END IF
      END DO
      IF (FLAG2 .EQ. 1) THEN
```

```
      WRITE (*,*) "ELEMENT NUMBER = ", ENUM
      WRITE (*,*) "NODE NUMBERS", N
      WRITE (*,*) "NODAL XCOORDS", NX
      WRITE (*,*) "NODAL YCOORDS",NY
      WRITE (*,*) "NODAL ARRAY", NODEARRAY
      WRITE (*,*) "METRIC AVERAGES", METRICAVG
      WRITE (*,*) "ELEMENTAL AREA, TOTAL WETTED AREA", QAREA, WETAREA
      WRITE (*,*) "CIRCULATION",CIRCULATION
      PAUSE
       DO COUNT = 1, NUMMETRICS
      WRITE (*,*) "ELEMENTAL AREA, TOTAL WETTED AREA", TAREA, WETAREA
      WRITE (*,*) "METRIC AVERAGES", METRICAVG
         WRITE (*,*)
         WRITE (*,*) "BIN SUMMARY FOR ", METRICNAME(COUNT)
         WRITE (*,*) "MIN_VALUE_____", "MAX_VALUE_____", "AREA"
         WRITE (*,*) -99999, METRICBINVAL(COUNT,1),
     +   TUBBIN(COUNT)
         DO COUNT2 = 1, NUMBINVALS-1
           WRITE (*,*) METRICBINVAL(COUNT,COUNT2),
     +     METRICBINVAL(COUNT,COUNT2+1), METRICBIN(COUNT,COUNT2)
         END DO
         WRITE (*,*) METRICBINVAL(COUNT,NUMBINVALS), 99999,
     +   SKYBIN(COUNT)
       PAUSE
       END DO
      END IF
*****************************************************************************************
*             END IF STATEMENT FOR IF ELEMENT IS WET OR DRY
              END IF
*             END IF STATEMENT FOR IF ELEMENT IS IN BOUNDARY
              END IF
*     END COMPUTATION FOR TRIANGULAR ELEMENTS
*****************************************************************************************
*     BEGIN COMPUTATIONS FOR QUADRALATERAL ELEMENTS
            ELSE
              READ (2, 40) N(1),N(2),N(3),N(4),N(5),N(6),N(7),N(8),MAT
*      WRITE (*,*) "NODES ON ELEMENT READ"
*      PAUSE
               DO COUNT = 1, 8
                READ (3, 50, REC = N(COUNT)) NX(COUNT), NY(COUNT),
```

```
     +        METRIC
                  DO COUNT2 = 1, NUMMETRICS
                    NODEARRAY(COUNT,COUNT2) = METRIC(COUNT2)
                  END DO
              END DO
*      WRITE (*,*) "METRICS ON ELEMENT READ"
*      PAUSE
***********************************************************************************
*     DETERMINE IF ELEMENT IS WITHIN AREA TO BE ANALYZED
              FLAG = 0
              DO COUNT = 1, 8
              IF (NX(COUNT) .LT. BXCOORD(1) .OR. NX(COUNT) .GT.
     +        BXCOORD(2)) THEN
                FLAG = FLAG + 1
              END IF
              END DO
              DO COUNT = 1, 8
              IF (NY(COUNT) .GT. BYCOORD(1) .OR. NY(COUNT) .LT.
     +        BYCOORD(2)) THEN
                FLAG = FLAG + 1
              END IF
              END DO

              IF (FLAG .EQ. 0) THEN
              IF (ESTAT .EQ. 1) THEN
************************************************************************************
*     COMPUTE AREA OF QUADRALATERAL ELEMENTS
              AREA1 = (((NX(1)-NX(5))*(NY(3)-NY(5)))-((NX(3)-NX(5))*
     +        (NY(1)-NY(5))))/2
              AREA2 = (((NX(5)-NX(1))*(NY(7)-NY(1)))-((NX(7)-NX(1))*
     +        (NY(5)-NY(1))))/2
              QAREA = AREA1 + AREA2
              WETAREA = WETAREA + QAREA
*************************************************************************************
*     COMPUTE AVERAGE METRIC VALUES ON THE QUADRALATERAL ELEMENTS
          DO COUNT = 1, 8
              METRICSUM(COUNT)=0
          END DO
          DO COUNT = 1, NUMMETRICS
              DO COUNT2 = 1, 8
```

```
                  METRICSUM(COUNT) = METRICSUM(COUNT)+NODEARRAY(COUNT2,
     +            COUNT)
              END DO
          END DO
              DO COUNT = 1,NUMMETRICS
                  METRICAVG(COUNT) = METRICSUM(COUNT)/8
              END DO
************************************************************************************
*     ASSIGN VALUES IN CORRECT METRIC BINS
      DO COUNT = 1,NUMMETRICS
         IF (METRICAVG(COUNT) .LE. METRICMIN(COUNT)) THEN
            TUBBIN(COUNT) = TUBBIN(COUNT) + QAREA
         END IF
         DO COUNT2 = 2,NUMBINVALS
            IF (METRICAVG(COUNT) .GT. METRICBINVAL(COUNT,COUNT2-1) .AND.
     +      METRICAVG(COUNT) .LE. METRICBINVAL(COUNT,COUNT2)) THEN
                   METRICBIN(COUNT,COUNT2-1) = METRICBIN
     +             (COUNT,COUNT2-1) + QAREA
            END IF
         END DO
         IF (METRICAVG(COUNT) .GT. METRICMAX(COUNT)) THEN
           SKYBIN(COUNT) = SKYBIN(COUNT) + QAREA
         END IF
      END DO
******************************************************************************
*     COMPUTE CIRCULATION
      IF (VORTNUM .GT. 0) THEN
          CIRCULATION = CIRCULATION + ABS(METRICAVG(VORTNUM))*QAREA
      END IF
**********************************************************************************
*     DEBUGGING PROGRAM AND BIN SUMMARY
      FLAG2 = 0
      DO COUNT = 1, DEBUGNUM
          IF (ENUM .EQ. DEBUG(COUNT)) THEN
            FLAG2 = 1
          END IF
      END DO
      IF (FLAG2 .EQ. 1) THEN
      WRITE (*,*) "ELEMENT NUMBER = ", ENUM
      WRITE (*,*) "NODE NUMBERS", N
```

```
      WRITE (*,*) "NODAL XCOORDS", NX
      WRITE (*,*) "NODAL YCOORDS",NY
      WRITE (*,*) "NODAL ARRAY", NODEARRAY
      WRITE (*,*) "METRIC AVERAGES", METRICAVG
      WRITE (*,*) "ELEMENTAL AREA, TOTAL WETTED AREA", QAREA, WETAREA
      WRITE (*,*) "CIRCULATION", CIRCULATION
      PAUSE
       DO COUNT = 1, NUMMETRICS
         WRITE (*,*) "ELEMENTAL AREA, TOTAL WETTED AREA", QAREA, WETAREA
         WRITE (*,*) "METRIC AVERAGES", METRICAVG
         WRITE (*,*)
         WRITE (*,*) "BIN SUMMARY FOR ", METRICNAME(COUNT)
         WRITE (*,*) "MINVALUE_____", "MAXVALUE_____", "AREA"
         WRITE (*,*) -99999, METRICBINVAL(COUNT,1),
     +   TUBBIN(COUNT)
         DO COUNT2 = 1, NUMBINVALS-1
           WRITE (*,*) METRICBINVAL(COUNT,COUNT2),
     +     METRICBINVAL(COUNT,COUNT2+1), METRICBIN(COUNT,COUNT2)
         END DO
         WRITE (*,*) METRICBINVAL(COUNT,NUMBINVALS), 99999,
     +   SKYBIN(COUNT)
         PAUSE
       END DO
      END IF
*********************************************************************************
*             END IF STATEMENT FOR IF ELEMENT IS WET OR DRY
              END IF
*             END IF STATEMENT FOR IF ELEMENT IN BOUNDARY REGION
              END IF

*     END COMPUTATION FOR QUADRALATERAL ELEMENTS

            END IF
*          ELSE
*         READ (2,*)
*          END IF
*      WRITE (*, 20) ENUM, ETYPE, ESTAT
      END DO
*     WRITE OUTPUT
      WRITE (4,*) D1
```

```
      WRITE (4,*) D2
      WRITE (4,*) D3
      WRITE (4,*) "TOTAL_WET_AREA", WETAREA
      WRITE (4,*) "CIRCULATION", CIRCULATION
       DO COUNT = 1, NUMMETRICS
         WRITE (4,*)
         WRITE (4,*) "BIN_SUMMARY_FOR_", METRICNAME(COUNT)
         WRITE (4,*) "MIN_VALUE ", "MAX_VALUE ", "AREA ",
     +   "PROPORTION "
         WRITE (4,*) -99999, METRICBINVAL(COUNT,1),
     +   TUBBIN(COUNT), TUBBIN(COUNT)/WETAREA
         DO COUNT2 = 1, NUMBINVALS-1
           WRITE (4,*) METRICBINVAL(COUNT,COUNT2),
     +     METRICBINVAL(COUNT,COUNT2+1), METRICBIN(COUNT,COUNT2),
     +     METRICBIN(COUNT,COUNT2)/WETAREA
         END DO
         WRITE (4,*) METRICBINVAL(COUNT,NUMBINVALS), 99999,
     +   SKYBIN(COUNT), SKYBIN(COUNT)/WETAREA
         WRITE (4,*)
         WRITE (4,*)
       END DO
*     READ (1, 10) ETYPE, ENUM,
*     WRITE (*,10) ETYPE, ENUM,
*************************************************************************************
* FORMAT STATEMENTS FOR READING AND WRITING
*
   10 FORMAT (BN, A3, I7)
   20 FORMAT (I7, 4X, A3, I7)
   30 FORMAT (BN, 7I7)
   40 FORMAT (BN, 9I7)
   50 FORMAT (BZ, 5F15.6)
   60 FORMAT (BN, 3F15.6)
   70 FORMAT (BN, A30)
   80 FORMAT (BN, 5F15.6)
   90 FORMAT (BN, I7)
  100 FORMAT (BZ, 2F15.6)
      CLOSE (1)
      CLOSE (2)
      CLOSE (3)
      CLOSE (4)
```

```
CLOSE (5)
CLOSE (6)
PAUSE
END
```

Appendix C. Notation

NOTATION FROM CHAPTER 2

$V_{1,}V_2$	velocity values found at two points distance Δs apart
V_{ave}	average of the velocity values found at points
V_{min}	smaller value of V_1 and V_2

NOTATION FROM CHAPTER 3

d	average depth within the modeled area
g	gravity constant
h	water depth
t	time
u	depth averaged velocity in the x direction
v	depth averaged velocity in the y direction
x	cartesian coordinates in the horizontal plane
y	cartesian coordinates in the horizontal plane
z_0	channel bottom elevation
C	Chezy coefficient
F_x	sum of the forces acting in the x direction.
F_y	sum of the forces acting in the y direction.
ε	eddy viscosity coefficient
ρ	fluid density

NOTATION FROM CHAPTER 4

V	magnitude of the depth-averaged velocity
V_1, V_2	velocity magnitudes measured a distance Δs apart
V_{ave}	average of V_1 and V_2
V_{min}	minimum value of V_1 and V_2
s	direction of the line between points 1 and 2

NOTATION FROM CHAPTER 5

V	magnitude of the depth-averaged velocity at a point
X	direction in which the spatial change in kinetic energy ($V^2 \div 2$) is being evaluated
$\overline{\xi}$	vorticity vector
$\overline{\omega}$	rotation vector
$\overline{V}$	fluid's velocity vector
u, v, and w	flow's x-, y-, and z-velocity components
$\hat{i}$, $\hat{j}$, and $\hat{k}$	unit vectors in the x-, y-, and z-directions
Γ	circulation
$d\overline{L}$	unit vector along the length of a closed path L, which surrounds a surface area S
$d\overline{A}$	area of an infinitesimal element of the surface S
Γ_{ABS}	modified circulation parameter
A_{TOT}	total wetted area over which Γ_{ABS} is being computed

Vita

David W. Crowder was born in Alamosa, Colorado, where he graduated from Alamosa High School. He received his Bachelors, Masters and Doctoral degrees in Civil Engineering at Virginia Polytechnic Institute and State University.

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