Modeling the Hydraulic Effects of Instream Habitat Restoration

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Abstract

The two-dimensional (2D) hydrodynamic model, River2D, was used to model the instream hydraulic conditions of a 150m reach on the main stem of Pennypack Creek, Philadelphia, PA, USA. To predict how instream habitat restoration structures would affect instream flow variability and weighted usable area (WUA) for invertebrates, design specifications for a j-hook rock vane and a double-wing flow deflector were modeled into the bed topography of the study site. Simulations for each modeling scenario (plain-bed, j-hook modified, wing-deflector modified) spanned a range of discharges from low flow (0.07 cms) to bankfull (2.05 cms). Hydraulic parameters and (WUA) for three functional feeding groups (FFG) were compared between each of the three modeling scenarios. Results indicate that the model was capable of resolving meso-scale variation in flow patterns caused by the different deflectors and results of 2-way ANOVA show significant differences in (WUA) between both (FFG) and modeling scenario. The (2D) modeling approach applied to this stream reach has the potential for use as a management tool whereas, reach-scale hydraulic and ecological changes caused by disturbance ("hydrograph flashiness") or manipulations in channel bed topography can be evaluated under steady-state conditions or using stage-discharge relationships. For reaches on gauged streams this could play a significant role in making predictions of hydraulic conditions and their effects given alterations in flow regime from anthropogenic influences and watershed management practices. If such an approach was scaled-up to encompass an entire watershed and coupled with sediment transport models such as HEC-RAS, it would allow for more thorough evaluation and monitoring while providing a framework for adaptive management.

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Introduction

Streams play a significant role in the dynamics of urban ecosystems as: habitat for a potentially diverse and productive array of biota, carriers of water and processors of water-borne materials, and as important social and cultural foci for the human inhabitants of their catchments (Walsh et al., 2005). Given their importance, streams in urban areas are gaining increased scientific attention as their position within the landscape makes these ecosystems particularly vulnerable to the impacts associated with landcover change and urbanization. The most obvious feature of landcover change within urban catchments is the large amount of impervious surfaces, such as roads, roofs, driveways, and parking areas. For a typical urban residential area, these surfaces cover about 40% of the land area, half of which is roads and driveways, while imperviousness can be 80% or more in commercial or industrial areas (Paul and Meyer 2001).

Increasing the impervious cover within a catchment results in changes in a stream's hydrologic regime, as most of the rain from a storm event is converted immediately to surface runoff instead of infiltrating into the ground. This rapid and efficient delivery of water from the catchment to the stream also has devastating impacts on stream morphology (Chin 2006), function, and both habitat and water quality (Paul and Meyer 2001). There is also a tremendous amount of sediment delivered to stream channels through infrastructure conduits.(Booth 1991); (Paul and Meyer 2001);(Chin 2006), which can also lead to degraded water quality as inputs of suspended solids and sediment bind highly toxic heavy metals and hydrocarbons, nutrients and bacteria washed from the impervious urban catchment (Arnold and Gibbons 1996). These impacts could become magnified as demands on water resources and undeveloped land are expected to increase dramatically due to both climate change and projected urban populations (Paul and Meyer, 2001).

The persistent hydraulic disturbances that occur in urbanized catchments continually shift ecosystems in these environments toward instability. A disturbance occurs when potentially damaging forces are applied to habitat space occupied by a population, community, or ecosystem. The magnitude of the forces may be such that organisms may be killed or displaced, consumable resources (e.g., living space and food) may be depleted, and habitat structure may be de-graded or destroyed (Lake 2000). Urban streams are often characterized by stream channels that: have steep banks; are disconnected from floodplain interaction; have homogenous depth, substrate and velocity conditions (Chin 2006); have "flashy" hydrographs such that floods occur very soon after the onset of precipitation events and can recede very rapidly (Booth, 1997), and an absence of refugia during times of high discharge (Paul and Meyer, 2001).

During a disturbance, macroinvertebrates and fish actively move or are passively carried into the refugia. In a structurally heterogeneous channel, there may be an assortment of substrate classes (i.e. boulder, cobble) which provide refuge between interstitial spaces, or pieces of coarse woody debris that may also offer protection from disturbance. As within-habitat refugia, which is a habitat patch having regions in which the effects of a disturbance is reduced, becomes diminished; it can be certain that changes will occur to the instream habitat template and have impacts on community dynamics in the stream. In flooding streams, large volumes of rapidly moving water exert high shear forces that suspend sediments, move and redistribute bottom materials (from sand to boulders), scour and abrade the streambed, remove plants (from microscopic algae to macrophytes), move detritus, snags and debris dams, and kill, maim, and displace biota (Lake 200). These conditions, which are amplified in urban systems, can have significant deleterious effects on stream invertebrate communities and ecosystems. (Lake 2000). Numerous studies in urban watersheds over the past few decades have provided evidence of decreased species richness and density, especially for EPT taxa (Ephemeroptera, Plecoptera and Trichoptera), most of which are especially sensitive to pollution. As EPT taxa richness and abundance decrease, densities of pollution-tolerant taxa such as oligochaetes, chironomids, and physid (left-handed) snails increase dramatically and these species replace the diverse array of taxa present before disturbance.(Booth et. al 1993). These kinds of adverse impacts have been observed even when as little as 10% of the catchment is covered with impervious surfaces such as roads, roofs and parking lots (Paul and Meyer, 2001).

Due to the negative scientific attention urban streams now receive; efforts to rehabilitate or restore urban streams have increased dramatically. In the last few decades, restoration of degraded streams in urban or urbanizing catchments has become a major concern for local, state and federal government agencies. Many urban stream restoration projects focus on re-establishing channel morphologies that are in equilibrium with landscape processes, either through bank stabilization or through longitudinal regarding of the stream channel (Paul and Meyer 2001). There is, however, great potential for restoration regiments that focus on the rehabilitation of ecological structure and function in urban streams. To achieve such goals, it will be necessary to set ecologically rigorous goals and objectives based upon sound science.

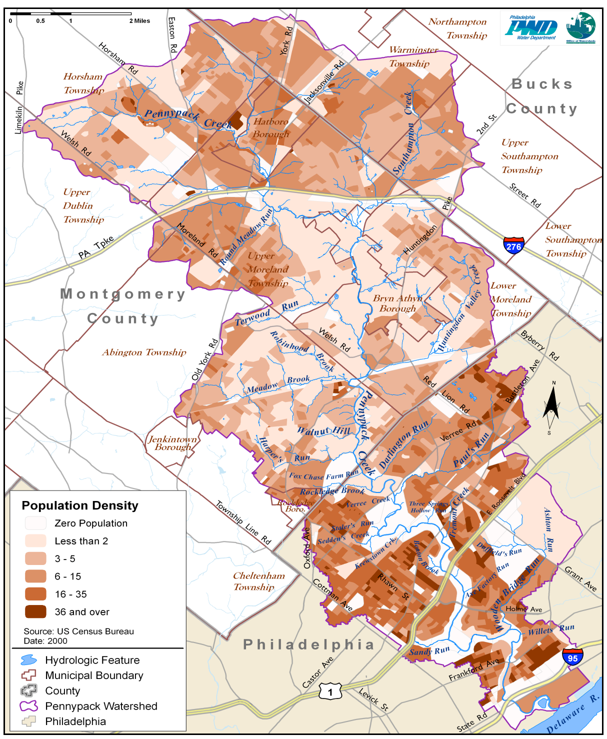
Millions are spent annually to restore and manage stream ecosystems toward more naturally functioning and structured systems, but little is known about the effectiveness of most approaches (Moerke et al., 2004). This is due to the fact that monitoring of restoration activities after they are completed has been rare or has produced inconclusive or unintended ecological responses. Many projects may set the objectives of enhancing or stimulating the recovery of instream ecological conditions such as habitat quality, but seldom record ecological data before or after restoration. Many project budgets include funds for siting, designing and constructing restoration applications but do not allocate funds for monitoring. Given the upfront cost of the design and installation of river restoration applications and the long-term costs of maintenance and monitoring, it is vital to have a thorough understanding of the tradeoffs associated with different restoration approaches.

Specifically, the goal of this study was to rate the effectiveness of instream habitat restoration applications prior to their construction and installation. The effectiveness of most restoration applications is usually judged based on permanence of the structure or the amount of streambank it protects. Rarely is the effectiveness of restoration applications assessed by ecologically important metrics such as the amount of new habitat it creates. Such a predictive capability could figure greatly into the previously stated conceptual processes. A 150m reach on a third-order, urban stream in Philadelphia, PA was modeled under three different scenarios. The hydraulic and ecological model outputs from the observed streambed topography were compared between scenarios where the bed topography was modified to simulate two different restoration applications. The two structures, a double wing deflector and j-hook rock vane, are flow deflectors meant to increase pool and riffle habitat in streams and can have perform the secondary function of bank protection . To predict how such a structure would affect both flow within the channel and habitat quality for invertebrates, the two-dimensional (2D) hydrodynamic model,River2D (Stefler and Blackburn ,University of Alberta, Canada), was used to model instream hydraulic conditions and weighted usable area (WUA) for functional feeding group classes under the three scenarios.

Often, ecologically relevant goals are established for restoration projects without taking the necessary steps to ensure that ecological function will be able to gain a foothold within restored stream reaches. In streams, biota and food and habitat resources are viewed as being distributed within streams as patches. Patches of biota and resources are linked with other patches longitudinally (e.g., upstream-downstream), laterally (e.g., channel-floodplain, channel-riparian zone), and vertically (hyporheic zone-channel bed). Patches can change in position, quality (i.e. availability of resources) dimension with time and thus constitute parts of an ever-changing mosaic (Lake 2000). The obvious implication is that small, isolated patches of enhanced streams in urban matrices are unlikely to be recolonized by sensitive aquatic invertebrates unless corridors of naturalized waterway sections and riparian vegetation link stream reaches through the urban landscape. Greater emphasis should thus be placed on enhancing areas within selected catchments to ensure a continuous corridor of improved instream habitat and riparian zones (Suren and McMurtie, 2003). If improved biodiversity is a goal for stream enhancement projects, then it is especially important to prioritize the enhancement and linkage of waterways in the urban area with those areas known to support desirable species.

The Philadelphia Water Department's Office of Watersheds (PWD-OOW) is a very progressive, specialized unit within the Philadelphia Water Department's Office of Planning and Engineering. They are charged with the planning and implementation of storm water management, combined sewer overflow mitigation, source-water protection and restoration activities within the 5 watersheds that drain into the Schuylkill (Wissahickon) and Delaware Rivers (Darcy-Cobbs, Tookany-Tacony-Frankford, Pennypack, and Poquessing). One of the initials goals of the initiative was to protect, enhance, and restore the beneficial uses of the Greater Philadelphia waterways and their riparian areas. As such, PWD-OOW has created comprehensive management plans and strategies for these watersheds based on extensive physical, chemical and biological assessments. These plans present logical and affordable pathways to restoring and protecting the beneficial and [state] designated uses of the local waterways and their catchments.

As an intern with PWD-OOW, one of my responsibilities was to conduct an infrastructure assessment of the Pennypack Creek Watershed. Given the extent of the basin I was only able to survey the Philadelphia portion and about 30% of the remaining watershed in Montgomery County, PA; however, from the reaches I surveyed it was evident that the much of the Montgomery County portion of the watershed was in an ecological condition much better than the net ecological condition of the Philadelphia portion. This could be due to differences in the intensity of landuse between suburban Montgomery County and urban Philadelphia. In this assessment, I used (GIS) to catalogue the presence, distribution, condition of infrastructure elements such as bridges, dams, manholes, culverts, stormwater outfalls, and channelized portions of the stream bed. As expected, the size and frequency of infrastructure units increased dramatically along the suburban-urban transect due to increased population densities and demands on water resources. Given the need for infrastructure elements in urbanized basins, their role in stream degradation can not be ignored as they have adverse effects on flow patterns, discharge and the transport of non-point source pollution. As such, data from this assessment was ultimately used to aide in prioritizing restoration and planning activities within the watershed.



Current wisdom beckons researchers to "use the catchment to save the stream" (Walsh, 2005) whereas, at the catchment scale, restoration should focus on reducing or slowing the direct conveyance of water to infrastructure elements to increase ground water infiltration and reduce stormwater runoff. This follows the reasoning that the scale of degradation at the catchment scale greatly exceeds the potential for piece-wise, reach-scale restoration to restore a more natural equilibrium with landscape processes. Given the importance of this concept; reach-scale restoration should not be ignored, but rather there is the possibility that reach-scale restoration in combination with better catchment-scale land-use practices can work to revitalize urban streams. Conceptually, improved catchment practices can work to restore channel morphology equilibrium via the reduction of stormwater impacts (i.e increased sediment load, frequent hydraulic disturbance) while reach-scale practices can work to restore ecological integrity to urban streams if done in locations that extend or reconnect patch networks.

The fact that future reach-scale restoration projects are being planned for the urbanized downstream reaches of Pennypack Creek offers an opportunity to explore some of the different ideas currently being formulated in restoration ecology. The suburban-urban gradient observed on the Pennypack may offer geographic opportunities for ecological rehabilitation in the inner-city reaches. Upstream mainstem and tributary reaches that have better ecologic conditions than some of the downstream reaches, may offer a potential source-pool of colonizers given the feasibility and potential for better land-use and management practices in the watershed. Selective reach-scale restoration along this suburban-urban gradient could extend upstream "patches" of resources (i.e potential colonizers) closer to the city. The patchiness of resources in streams relates to island biogeography concepts (MacArthur and Wilson 1967) such that recolonization should be faster in near islands (i.e. urban habitat patches in close proximity to upstream source-pools) compared to far islands. Similarly, as reach-scale restoration creates or increases instream habitat, these "large islands" should also allow for faster recolonization from upstream source-pools of macroinvertebrates. While there are significant physical (i.e. dams, culverts), chemical (poor water quality) and ecological (mobility and recruitment success) barriers to (re)colonization within the watershed, many stream macroinvertebrates have highly mobile, winged lifehistory stages (i.e. emergent adults). As the increased efforts of stream managers to mitigate habitat degradation and stormwater-related impairment begin to take effect, the potential for successful recolonization of sensitive species (i.e. EPT taxa) into the mid-order and downstream reaches could increase as a function of time.

River2D Hydrodynamic Model

Depth-averaged modeling is based on the basic physical principles of conservation of mass and momentum and on a set of constitutive laws which relate the driving and resisting forces to fluid properties and motions (Stefler and Blackburn, 2002). River2D is a two dimensional depth averaged finite element hydrodynamic model that has been customized for fish habitat evaluation studies. The River2D model suite actually consists of four programs: R2D_Bed , R2D_Ice, R2D_Mesh and River2D. All three pre-processor programs have graphical user interfaces that are supported by any 32 bit version of

Windows. R2D_Bed, R2D_Ice, and R2D_Mesh are graphical file editors. R2D_Bed was designed for editing bed topography data while R2D_Ice is intended for developing ice topographies to be used in the modeling of ice-covered domains. The R2D_Mesh program is used for the development of computational meshes that will ultimately be input for River2D (Stefler and Blackburn, 2002).These programs are typically used in succession. The normal modeling process would involve creating a preliminary bed topography file (text) from the raw field data, then editing and refining it using R2D_Bed. The resulting bed topography file is used in R2D_Mesh to develop a computational discretization, which draws in nodal parameters from the bed topography file, as input to River2D. River2D is then used to solve for the water depths and velocities throughout the discretization. Finally, River2D is used to visualize and interpret the results and perform PHABSIM type habitat analyses. An iterative approach at various stages, including modification of the bed topography, is usual (University of Alberta, 2002).

Using hydraulic outputs from the hydrodynamic component of the model, River2D uses the PHABSIM methodology to quantify the physical habitat available within the stream according to a species-specific habitat suitability index (HSI) which contains information on the biological preference for the variables depth, velocity and substrate. The habitat-suitability index (HSI) is used to weight the wetted area of the river to describe the quantity of habitat available for a specific organisms under specific conditions (i.e. flow) (Pioter 2007) The metric weighted usable area (WUA), which is the cumulative area within the channel that is physically suitable for the species of interest, is then computed based on the values of depth and velocity predicted from the model and the (HSI) criterion. In order to make predictions about a wider range of macroinvertebrates, (WUA) was compared between functional feeding groups (FFG) instead of individual species. (FFG)'s represent a way to group macroinvertebrates based on the physiological structures or behavioral mechanisms used to acquire food. Examples include: shredders, which process detrital material and coarse particulate organic matter (CPOM); scrapers, which remove algae and periphyton from the surface of streambed substrate; and also collectors, which acquire food through filtering the water column (collector-filterers/collector-netspinners) or feeding on deposits of fine or coarse particulate organic matter (collector-gatherers) (Vonshell, 2002).

(2D) hydrodynamic modeling has been gaining favor with stream biologists and hydrologists because of its superior ability to resolve spatial variations in flow when compared to (1D) models. (1D) models analyze a river reach by dividing it into discrete sub-sections called cells, with each cell having uniform values of depth and velocity (Bovee 1978 in (Crowder and Diplas, 2000). The uniform flow conditions within each cell, combined with the assumption that flow is always in the downstream direction, prevents the accurate modeling of spatial flow patterns that can occur in streams having a complex channel topography. This methodology does not allow for the explicit analysis of variation in flow conditions at the meso-scale (e.g. flow in pools, riffles etc) or micro-scale (e.g. flow around rocks in a riffle) which is the scale of most importance to macroinvertebrate life history stages.

Two-dimensional numerical models, however, discretize reaches into much smaller sub-units 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. 2D hydraulic models are thus more suitable for modeling the complicated flow patterns in river reaches having complex topography (Crowder and Diplas 2002).

The most critical feature of (2D) models in regards to habitat studies, is their potential to accurately and explicitly quantify spatial variations and combinations of flow patterns important to stream flora and fauna (Crowder and Diplas, 2000). Movement of macroinvertebrates in directly related to near-bed microtopography and hydraulic conditions, both are which are structured by substrate particle size and distribution. As such, boulders and clusters of rocks create low shear stress zones that play an important role in determining the diversity of periphyton and invertebrates after stormflows (Biggs et al., 1997); therefore, the local flow patterns introduced by boulders and other meso-scale obstructions are critical features in enhancing habitat for flora and fauna within streams (Crowder and Diplas, 2000). By using a meso-scale resolution (~1m) to model the effects of instream restoration structures, it should be possible to capture variations in flow that are of importance to structuring the habitat template of macroinvertebrates.
In most 2-D modeling endeavors, meso-scale topographic features, such as boulders, root wads and other instream obstructions are not incorporated into the model as significant contributors to instream flow conditions. Such an approach to 2-D modeling allows for accurate predictions of large-scale trends in average depth and velocity values; however, this approach does not provide any information about the flow patterns in the vicinity of these obstructions. In numerical simulations based on a natural river channel containing several boulders, (Crowder and Diplas, 2000) found that explicitly modeling local obstructions and boulders can significantly impact predicted flow parameters. The study found that the presence of these obstructions create velocity gradients, velocity shelters, transverse flows and other ecologically important flow features that are not produced when their geometry is not incorporated into hydraulic models.

At the meso-scale (pool, riffle, run etc.), there is evidence that small variations in hydraulic conditions and flow patterns could cause variation in habitat suitability for macroinvertebrates. (Brooks et al., 2005) showed that there are distinct areas with different hydraulic conditions within riffles and that these distinct regions influence community dynamics. In the study there was significant variation between biological metrics measured within the different hydraulic microhabitats described in riffles at their study sites. The metrics, roughness Reynolds number, Froude number, velocity and shear velocity, were significantly related to macroinvertebrate abundance, taxonomic richness and community composition. Depth was also related to macroinvertebrate abundance, but explained little of the spatial variation. Also, for each hydraulic variable, the relationship with benthic fauna was negative (i.e. lowest hydraulic values corresponded to highest macroinvertebrate abundance and taxonomic richness).

Study Site

The Pennypack Creek Watershed covers 56 square miles over twelve municipalities and includes a population of more than 300,000 people (2000 Census). Over the past 70 years, the watershed has undergone considerable development and urbanization. Of the 5 major watersheds, it was one of the last to be developed. This has led to a number of problems, including increased incidence of flooding and ecological degradation. The key issues identified in this watershed are unplanned land development, poor stormwater management, impaired water quality, and outdated floodplain maps (Meenar, 2006). The site selected for this study is located on the main-stem (river mile 9.7) of the Pennypack, about 150m downstream of the Montgomery County-Philadelphia border at Pine Rd. The site represents an important transition zone as upstream of the site, Pennypack Creek drains is a less-densely populated suburban area and a large expanse of protected natural reserve (Lorimer Park); however, the downstream reaches drain progressively more urbanized and densely populated regions in Northeast Philadelphia. Due to the landuse dynamics of the Greater Philadelphia region, there are significant impairments in some of the upstream and headwater sudsheds of the Pennypack. Many of these impairments are stormwater-related such that water quality parameters such as dissolved oxygen (DO), stream temperature, conductivity, and pH may limit the suitability of certain sites for aquatic life uses. The River2D habitat module only incorporates the physical characteristics of a stream section, thus sites with poor or impaired water quality may still offer optimal physical habitat conditions (i.e. substrate particle size distribution, riffle velocity, riffle-pool ratios etc.) capable of sustaining aquatic fauna.

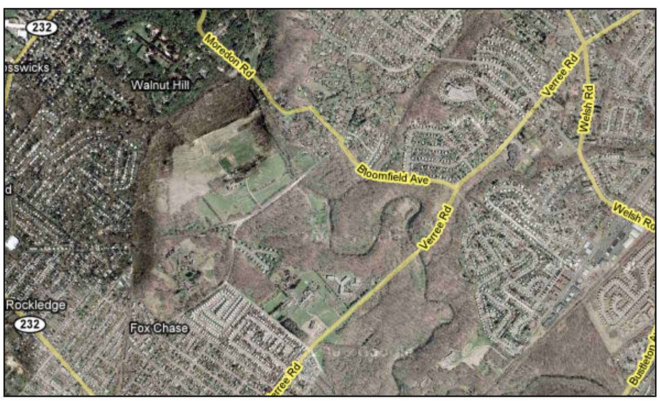


Figure 1.1 Montgomery County-Philadelphia transition zone at Verree Rd.

The site exhibits some signs of urbanization such as widening and bank erosion, both of which could be the result of increased flow velocity and hydrograph "flashiness" due to upstream infrastructure such as a bridge and stormwater outfalls at Pine Rd. There is also evidence of large scale sediment deposition as a large portion of the downstream right bank (DSR) is abutted by a channel bar. This depositional feature ultimately reduces the area of the low-flow channel available to fish and invertebrates. There are substantial differences in discharge and related hydraulic variables between the base-flow and bank-full channels. This factor could have important implications for habitat availability as the large range of discharges between base and bankfull flows are associated with large-scale fluctuations in the values of hydraulic variables important to invertebrates. Table 1.1 illustrates the large magnitude of change in the values of hydraulic variables as discharge (Q) increases. Of importance to note are the discrepancies in width to depth ratio (W:D) and channel cross-sectional area. (W:D) defined by (width of bankfull channel/ mean depth of bankfull cross-section) describes the channel geomorphology (Rosgen and Silvey, 1998) of a reach given the dimensions of a representative cross-section. At lower discharges, the channel is much wider than it is deep, therefore at lower discharges there is less habitat available to macroinvertebrates due to the extremely shallow channel conditions.

stage(m)	Q (m^3/s)	velocity(m/s)	X-area (m^2)	Wettted Perimeter	Rh	W:D ratio	Ent. Ratio
0.472	0.064	0.024	2.595626	28.529	0.091	312.3	1.6
0.563	0.203	0.039	5.217264	28.956	0.180	159.7	1.6
0.685	0.477	0.054	8.675931	29.535	0.296	98.5	1.6
0.853	0.993	0.072	13.757561	30.327	0.453	65.9	1.5
0.960	1.396	0.081	16.999771	30.937	0.549	55.4	1.5
1.112	2.064	0.095	21.734884	31.790	0.683	45.6	1.5

Table 1.1 range of hydraulic variables from low-flow to bankfull discharges

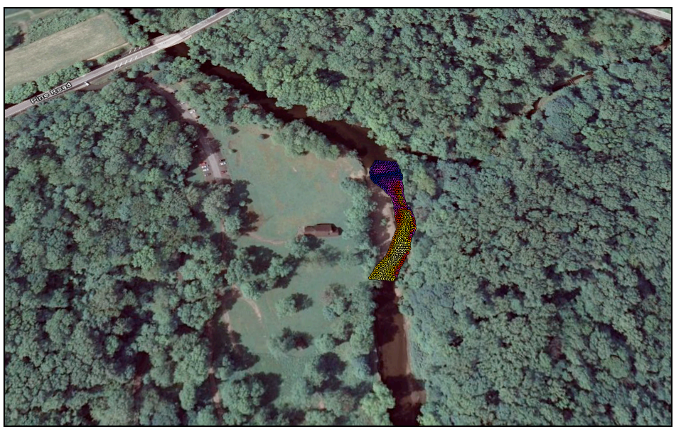


Figure 1.2 Low-flow channel nodes exported to Google Earth in KML format

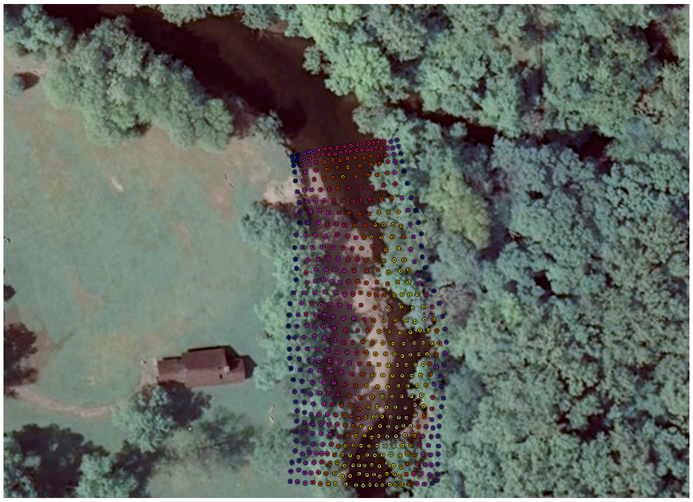


Figure 1.3 Bankfull discharge nodes displayed in Google Earth using KML format

Methods

As input data, 2D hydrodynamic models require channel bed topography, roughness and transverse eddy viscosity distributions, boundary conditions, and initial flow conditions. In addition, some kind of discrete mesh or grid must be designed to capture flow variations. Bed roughness, in the form of a roughness height or Manning's n value, is a less critical input parameter. Compared to traditional one-dimensional models, where many two-dimensional effects are abstracted into the resistance factor, the two-dimensional resistance term accounts only for the direct bed shear. Observations of bed substrate and particle size distributions are usually sufficient to establish reasonable initial roughness estimates. Calibration to observed water surface elevations gives the final values (Blackburn & Steffler 2002).

One of the first and most crucial steps involved in 2D finite element modeling is the representation of the stream channel topography in the first model preprocessor River2D_Bed, which is a graphical bed topography file editor. The normal modeling process involves creating a preliminary bed topography file (text) from the raw field data in the form of x,y,z coordinates, then editing and refining it using R2D_Bed. The x and y coordinates were taken as eastings and northings respectively and the z coordinates were recorded as water surface elevations. The bathymetry data (x,y,z coordinates) for bed topography construction were taken on two days in August 2007 using a TOPCOM® model Digital Total Station. A total station is a digital surveying and mapping tool that calculates the georeferenced position, in terms of three dimensional Cartesian coordinates, of a point of interest by shooting a laser beam to a reflector held at either land or water surface elevation. Based on the x,y,z coordinates of the reference or control point, the Total Station calculates the x,y,z coordinates of the point of interest based on the angle at which the laser beam returns to the Total Station. Each data point or node in the bed topography file has a unique code along with four parameters: x,y,z coordinates and roughness height(Ks), which is a parameter that accounts for friction between flow and bed materials/substrate.

On August 14, 2007, data points were taken at both the right and left edges of flow at low flow conditions and within the stream channel, both at about 1.0m resolution. With respect to the downstream direction of flow, edges of flow were coded as either (REW) or (LEW), for right edge of water and left edge of water respectively and points taken in stream channel were coded (SB) for streambed. Most of the (REW) points were defined by a large point bar that extended from 15m downstream of the inflow boundary to 10m upstream of the outflow boundary. The (LEW) points were defined by the interface between the wetted channel and the left bank, as there was no large-scale depositional features on the left side of the channel. The total length of the stream channel as defined by parallel (REW) and (LEW) points at inflow and outflow sections was approximately 145m.

At (SB) points, non-zero values of depth and velocity as well dominant substrate classes were taken simultaneously with bathymetry data by attaching a velocimeter to the Total Station reflector. Values of depth and velocity are the eventual output from the hydrodynamic component of River2D; however, measured values of depth and velocity provided the opportunity to calibrate the model to observed flow conditions. Depth was measured at 0.1 ft resolution and water column velocity was taken 0.6 depth. These measurements were recorded using a tablet PC-specific version of ArcGIS, which allowed the point measurements of depth, velocity and substrate to be linked with nodal coordinates in an attribute table. As with the rest of the raw field data, velocity and depth were initially measured in English units and were subsequently converted to SI units as the hydrodynamic component of River2D expects all parameters in SI units.

On August 22, 2007, a second set of bathymetry data was collected at different points of interest within the wetted channel and on the adjacent stream banks. Data collected on this day was vital to modeling the stream channel at discharges other than the low flow, calibration discharge. The data allowed for model domain boundaries to be extended outside of the base-flow wetted channel based on channel bed topography, for modeling higher discharges. These points represented estimated bankfull elevations on both banks, right and left banks and floodplains, delineation of a large point bar extending from the right bank, and also cross sections at different locations within the reach. Estimates of bankfull elevations were made at approximately 10m increments on each bank using a variety of qualitative indicators. The estimation of bankfull elevation is not an exact science; thus, indicators such as: changes in the grain size of depositional bank sediment; large changes in bank gradient; bank scour patterns; and rooted, emergent vegetation are used to delineated the approximate bankfull channel (Rosgen and Silvey, 1996). All of these indicators were used at different frequencies depending on which gave the most accurate/trustworthy estimate of bankfull elevation at respective locations within the reach.

Cross sections were taken at the first riffle downstream of the inflow boundary and also at a riffle in the middle of the reach. Each cross section extended from the right bank floodplain to the left bank floodplain and thus encompassed approximate bankfull elevations and the wetted base-flow channel. Cross sectional data was important for this project in that it allowed for model calibration and calculation of hydraulic parameters such as: hydraulic radius, cross sectional channel area, width to depth and entrenchment ratios, discharge and average depth as seen in Table 1.1.
Once all nodal data was recorded for the site, nodes were output as text files and sent to a spreadsheet in Excel. The Total Station output only contained the point-specific codes and x, y, z coordinates, thus values of (Ks) had to be entered for each line of data. In general, roughness height can set to the default value of 0.1 as roughness height can be modified throughout the entire computational domain or on a nodal or regional basis in River2D bed. Once each node was given a default (Ks) value, the text file was saved with a ".bed" extension and sent to the R2D_Bed processor. Once imported, the ".bed" file nodes were triangulated resembling the TIN (triangulated irregular network) common to GIS-based interfaces. The triangulated bed was then displayed in a color contour format at 0.25m elevation intervals. In places where triangulated elements formed "wedges", which are unrealistic shapes or triangulated elements much larger than adjacent elements, nodes were interpolated linearly using breakline segments. Breakline segments allow new nodes to be added between nodes that represent features following longitudinal elevation gradients such as the tops or toes of banks and water edges. In situations where large triangulated elements were adjacent to smaller elements, nodes were added such that in all directions, no element was greater than a factor of 1.5 the size of adjacent elements. Large size discrepancies between elements could be detrimental to accurate flow solutions in that they may not capture the variation in elevation that drives the hydrodynamic component of R2D. The 0.25m topographic resolution was recommended as being the ideal resolution for the bed topography by R2D developers, thus editing of the ".bed file" continued until no more wedges existed within the domain.

The next step was to assign values of bed roughness to all nodes. In R2D_Bed, roughness heights can be set at individual nodes, for the entire domain or for particular, polygonal regions. Values of (Ks) are calculated from values of Manning's "n" (n) and the hydraulic radius (Rh) of the channel by a roughness height conversion command within R2D_Bed interface using the formula $K_s = (12Rh) / e^m$ where m= ((R^0.167)/(2.5n(g^-.5)) and (g) equals acceleration due to gravity. The actual values of Manning's "n" were determined from the dominant substrate classes (eg. sand, gravel, cobble, boulder) observed at each reference node (non-interpolated) within the reach. These classes correspond to a range of grain diameters (sand-boulders) derived from previous pebbles counts throughout Pennypack Creek conducted by the Philadelphia Water Department Office of Watersheds. The "substrate class" method was used as opposed to D50's derived from pebble counts because roughness estimates are not as vital to flow solutions as other parameters such as elevation. Furthermore, there was not much large-scale variation in substrate throughout the reach. Besides a few patches of sand, gravel and boulders near the inflow end of the reach, approximately 85-90% of the wetted base-flow channel substrate was comprised of medium to coarse-grained cobble. The large point bar was also composed almost exclusively of coarse-grained cobble except for a small downstream portion composed of 80% coarse sand and 20% cobble.

Following the addition of roughness parameters, three separate computational boundaries were added to the bed topography based on corresponding discharges and saved as separate ".bed files." The calculations of discharge and other hydraulic parameters relevant to estimating boundary conditions were made using a Microsoft Excel-based model created by Dan Mecklenburg and distributed by the Ohio Department of Natural Resources. The model allows for hydraulic parameters to be calculated at cross sections based on values of measured slope, and prescribed water surface elevation and channel roughness parameters (n). A range of discharges was calculated by the model through increasing the water-surface elevation at the inflow cross section incrementally from low-flow to bankfull elevation. Gauge data was not used for estimation of discharge ranges as the closest USGS stream gauge, which is located approximately 100m upstream, had been offline since 1980 (although it became operational as of September 2007). Furthermore, the gauge had only been operational from 1965-1980, a period of record too short to draw accurate estimations of discharge variability; however, the model estimation of bankfull discharge (2.09 m^3/s) closely matched that of historic gauge data records which give a mean avg. annual peak discharge of 1.95 m^3/s.

The first computational boundary was the base-flow boundary which encompassed the inflow and outflow portions of the wetted channel in the y-direction and the edges of water in the x-direction which is the direction of flow.

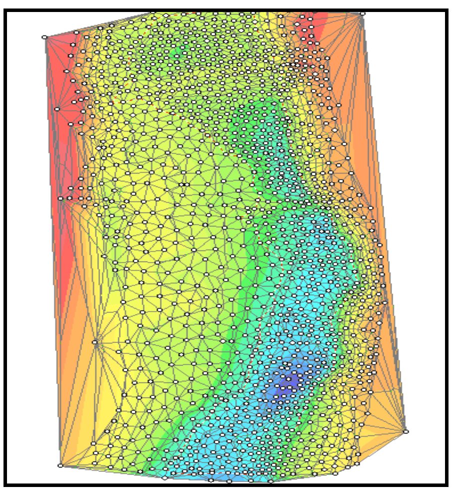


Figure 1.4 Low-flow bed topography file shown with computational boundary (red dashed line)

The bankfull-flow boundary was draw using estimations of the cross-sectional channel area and right and left bank elevations derived from the Mecklenberg Model. The model only provided the bank elevations at cross sections so the rest of the computational boundary was interpolated by raising the low-flow boundary up along the banks based on the modeled change in elevation. This assumption of boundary position was based on the trend exhibited by the calibration flow boundary nodes. The right and left edge of water nodes were distributed rather uniformly between respective adjacent 0.25m contours without large variation in elevation. The flow boundary for the bankfull bed topography file was drawn by connecting surveyed bankfull nodes longitudinally. These nodes were also closely positioned within adjacent lines of topography.

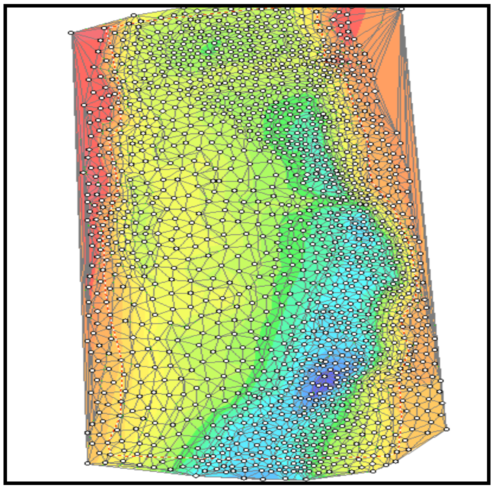


Figure 1.5 Bankfull-flow bed topography file shown with computational boundary (red dashed line)

Once computational boundaries were established for each of the bed topography files, the j-hook rock vane and double wing-deflector were modeled into the bed topography. The representations of the structures were modeled into the bed topography by manually increasing the elevation of specific stream bed and bank nodes according to the design specifications given by in (Shueler and Brown, 2004). A similar process was used by (Lacey 2004) when modeling the hydraulic effects of instream large woody debris and rock groyne habitat structures; however in that study extracted bathymetry data from existing structures. Design specifications required that the modeled structures: grade from the bankfull elevation of the streambank down to the stream channel invert; extend into the stream about one-third (rock vane) to one-half (wing deflectors) the bankfull width; be located downstream of the point where the stream flow encounters the stream bank at acute angles; and for the j-hook rock vane, the "vane arm" portion of the structure should be oriented upstream at an angle of 20-30˚ from the stream bank measured upstream from the tangent line where the vane intercepts the bank (Scheuler and Brown 2004). Once node elevations were adjusted for the specified nodes, nodal roughness height parameters were adjusted to that of large boulders. This value was not the same for all bed topography files as each file represented the channel at different values of (Rh).

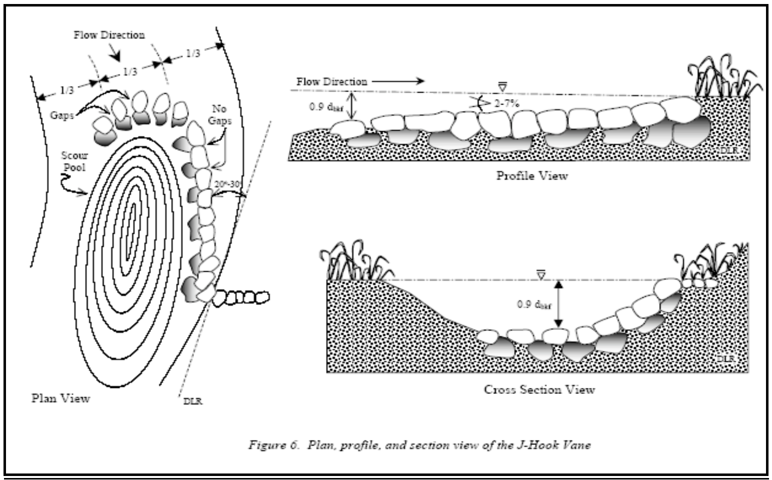


Figure 6. Plan, profile, and section view of the J-Hook Vane

Figure 1.6 J-Hook rock vane design specifications (adapted from Rosgen 2001)

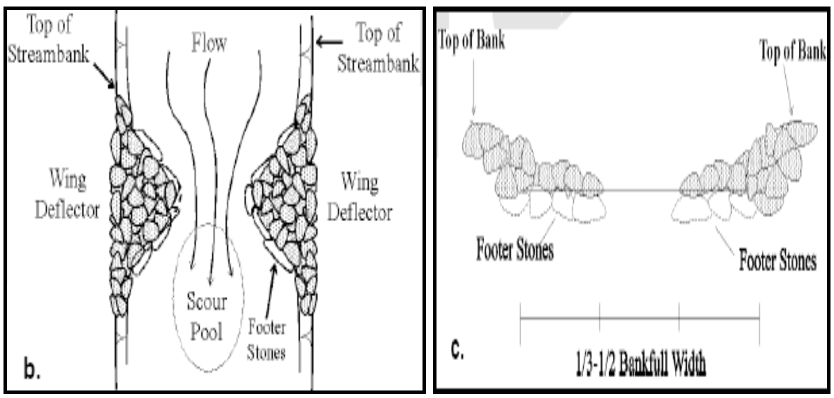


Figure 1.7 Plan b.) and cross-sectional c.) view of double-wing deflectors (adapted from Scheler&Brown)

The final steps needed to prepare bed topography files for the mesh editor involved extending the model domain upstream and downstream of inflow and outflow boundaries respectively. This was done to ensure that the constructed meshes created in the next program would fall within the defined topography. Without this step, it was observed that portion of constructed meshes near inflow and outflow boundaries would extend slightly outside of the prescribed boundaries. In these situations, the mesh would not have topographic data to reference causing the model to crash. Similarly, the domain was extended beyond the computational boundary for the bankfull bed topography file in instances where the computational boundary was very close to the edge of the model domain. These modifications had no effect on flow calculations, they merely allowed for improved mesh quality.

Creation of computational meshes for each of the finished bed topography files involved the same process. Each bed topography file was first imported into the R2D_Mesh application and boundary nodes were generated at 15m spacing around the computational boundary and triangulated. Next the inflow and outflow mesh boundaries were parameterized. In R2D-Mesh, inflow boundaries are determined by setting the inflow discharge (Q_{in}) along the boundary nodes that comprise the inflow portion of the computational boundary. A similar process is used for the outflow boundary, except that outflow elevation is used instead of discharge. The program allows parameters for both types of boundary to be set at all nodes simultaneously using the, "set inflow/outflow by area command". To ensure that the mesh compute an adequate number of flow solutions at the inflow and outflow boundaries, existing boundary segment were bisected such that both boundaries comprised at least 15-20 boundary nodes.

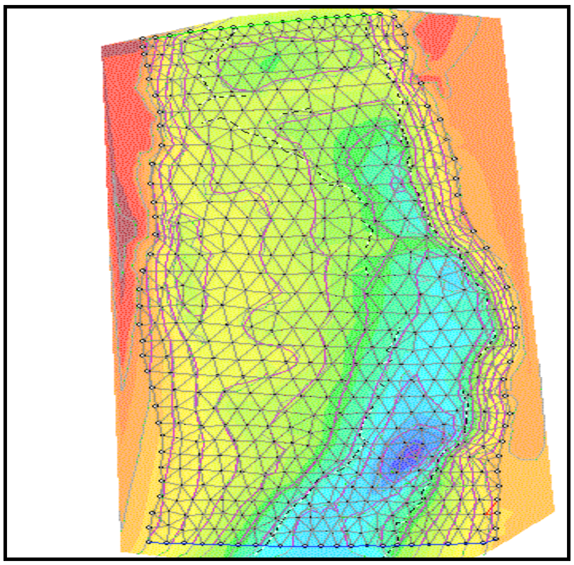


Figure 1.8 Computational mesh for bankfull bed topography file

Using the "uniform fill" command, mesh nodes were added to the entire mesh at 2.5m spacing and triangulated. This node spacing was determined empirically, based on the degree to which different resolution computational meshes could capture flow field variations within the channel. In general, finer meshes with node spacing between (2.5-3.5m) performed better than coarser meshes in capturing flow variations, as determined by comparison of velocity vectors. The positioning and size of mesh elements were then modified such that all elements were close to uniform in size. Special attention was given to mesh nodes near lateral boundaries as the non-linear planform of natural channels often causes elements to form irregular shapes in areas where the channel boundary begins to meander or is curvilinear. In instances where irregular triangle formed near boundaries, either additional nodes were added or boundary segments were bisected to allow for smaller, more regular elements.

Additional modifications to meshes were based on several quality control parameters that govern the computational success of created meshes. To ensure that mesh elements capture variations in bed elevation, an elevation difference threshold parameter can be set. This parameter specifies the maximum allowable elevation difference between bed topography nodes and mesh elements; whereas, any elements that are above the prescribed threshold are highlighted. This threshold ultimately depends on the scale of the project. Considering the size of the reach, it was necessary to capture as much small-scale variation as possible, thus a 0.1m threshold was used for each mesh. Elements displaying elevation differences greater than the threshold were fixed by decreasing the size of both the highlighted element and adjacent elements such that none of them would be positioned between two areas of the channel that had rapidly changing elevations. There were however, some instances where mesh nodes were added or deleted to remove highlighted elements. Another parameter, the Quality Index (QI), measures the size uniformity of each mesh element such that the (QI) increases as irregularly-shaped (obtuse, hyper-acute) triangles are modified to a more equilateral shape. A perfectly straight channel would have a completely uniform mesh and a (QI) of 1.0. Given that natural channels are not straight, values these high are not possible and (QI) values between 0.35-0.5 are considered acceptable. Meshes created from each of the bed topography files had (QI) values between 0.48-0.52.

Computational meshes were ready to for input into the hydrodynamic component of the model once all quality control parameters reached satisfactory values. At this point, mesh files were saved as a ".cdg file" which is the file format used by River2D.Upon saving, it was necessary to input an inflow water surface elevation, which was determined by the elevation along the inflow boundary that was halfway between the elevations of the inflow boundary nodes at the right and left banks. Once imported in the River2D, steady-state flow solutions were easily computed using appropriate model commands. Each flow solution took an average of 1000 times steps before reaching steady state.

The hydrodynamic flow solution output from the observed low-flow bed topography file was used to calibrate the model. Predicted water surface elevations (WSE) at the inflow cross section were compared to observed (WSE) from the total station surveys. Initial comparison showed a close relationship between observed and predicted (WSE). Adjustments to the initial roughness parameters did not significantly reduce the model error, which had a max error of 0.11m and mean error of 0.04m.

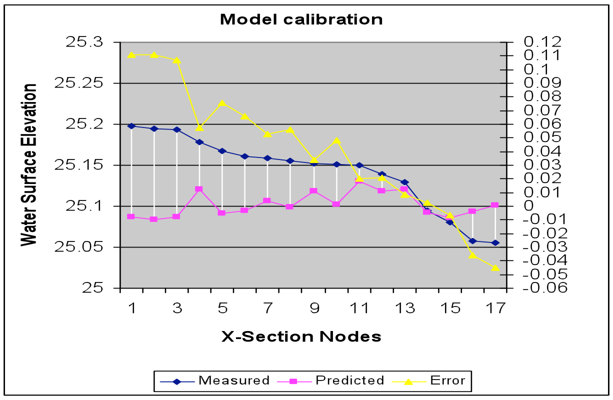


Figure 1.9 Results of model calibration

After flow solutions were computed, it was then possible to begin the habitat modeling process. The inputs necessary to run the habitat availability component of the model are a species-specific preference file and a channel index file. Channel index files were created in Microsoft excel. Channel index files, which end in a ".chi" extension, resemble bed topography files except that the roughness height parameter in replaced by a channel index value which was a function of roughness height.

Baseline estimation of functional feeding group (FFG) preference files were derived from habitat suitability criterion developed by (Gore and Judy, 1981) and (Jowett and Richardson, 1990) and reflect the combined velocity, depth and substrate suitability values of a number of species within each FFG. The combined estimates of habitat suitability criterion from these two sources were further modified using the USGS publication, (Vieira et al., 2006) which provides a comprehensive profile of relevant species-specific traits. Literature-based information, in conjunction with professional experience, is recommended as the foundation of the habitat suitability indices model as species-specific information for macroinvertebrates is not available (Piotter 2007). Traditionally, habitat suitability studies are targeted on fish species of economic importance to fisheries management such as salmon and trout species; consequently, very few references regarding stream invertebrate habitat suitability exist. Where suitability curves are available in the literature, the acceptable attribute range is considered to be equal to the range listed for all values above 50 per cent suitability. For example, if a species is reported to use velocities between 0.5 and 4.0 m/s but had suitability indices above 50 per cent only for a range of 1.0–2.5 m/s, then the latter range would be used to compute (HIS) (Piotter 2007). In this study, literature was used more as a guide because the systems studies in the literature had higher discharges and different environmental conditions; however these sources were very helpful when determining optimal levels of substrate suitability.

Actual ranges of depth, velocity and were empirically based in that they were extracted from model outputs of depth and velocity within the channel. Histograms were used to discriminate the hydraulic conditions within riffle, pool and run habitat units. From these mean conditions, FFG-specific ranges of depth and velocity were set such that they would be associated with environmental and hydraulic conditions relevant to each FFG. For example, the CNET functional feeding group would not be expected to be closely associated with the mean environmental and hydraulic conditions found in pools (i.e high depth and low velocity) as they need higher flows usually associated with riffles to maintain a constant flow of particulate organic matter through their filtering mechanisms (i.e constructed retreats or physiological filters). Similarly, the CG functional feeding group would not be very closely associated with the conditions found in riffles as the higher velocities in riffle habitats do not allow for the accumulation of coarse particulate organic matter and detritus.

Preference factor	Velocity	Depth	Channel Index
0	0.01	0.015	1
.85	0.018	0.26	4
1.0	0.245	0.145	3
0	0.85	0.9	6

Table 2.1 Collector-Gatherer Habitat Suitability Criteria

Preference factor	Velocity	Depth	Channel Index
0	0.015	0.083	1
.85	0.439	0.38	3
1.0	0.139	0.214	4
0	1.25	0.65	6

Table 2.2 Collector-Netspinner Habitat Suitability Criteria

Preference factor	Velocity	Depth	Channel Index
0	0.01	0.01	1
.85	0.32	0.163	3
1.0	0.16	0.44	2
0	0.79	1.2	5

Table 2.3 Shredder Habitat Suitability Criteria

Results

Comparison of velocity vectors between natural and modified flow conditions yielded evidence as to the effectiveness of the model at capturing small-scale variation in flow. . The modeled rock vane and double-wing deflectors deflected flows toward the center of the channel at all flows, with the greatest magnitude of deflection occurring at lower flows (.07-.9 m^3/s). Compared to the j-hook rock vane, the wing deflector did not perform as well in terms of increasing WUA. In general, outputs from the modified channel simulations contained more eddies and larger ranges of water column velocity values within the channel. In the model outputs, eddies are depicted by "swirled" velocity vectors. These eddies created by the rock vane are considered optimal habitat for fish as they provide velocity shelters in which fish can conserve energy and even forage during high flows. They serve a similar function, as velocity shelters for macroinvertebrates. The increase in the number of eddies could explain the variation between inflow (Q_{in}) and outflow discharges (Q_{out}) in the modified simulations. In Tables II.1 and II.2, comparison of (Q_{in}) to (Q_{out}) shows that in modified simulations water is "lost" to the model domain; whereas, at steady-state conditions the total volume of water that enters through the inflow does not exit the channel through the outflow boundary. This "loss" of volume could be accounted for by loss of momentum as volumes of water are held within eddy currents as opposed to moving toward the outflow boundary directly.

Given the large range of discharges that this channel conveys on an annual basis and the effects of upstream infrastructure such as the stormwater outfalls and the bridge at Pine Rd, bank stability is a major concern at this site and along the Pennypack Creek in general. During data collection and subsequent site visits, the downstream left bank showed evidence of medium to severe bank erosion, especially downstream of riffles. At higher flows, velocity vectors indicate that in modified simulations, high velocity flows are deflected away from the left bank and towards the margins of the large point bar on the downstream right side of the stream. The model does account for the effects of velocity on substrate in the form of scour; however, by comparing the threshold velocity for different substrates within the channel to modeled velocities, estimates of the severity and occurrence of scour and erosion can be computed at different regions in the domain.

Evidence of scour would have significance in that it would increase the total area of the low flow channel and contribute to flow heterogeneity with the channel. This concept may be contradictory to some principles of fluvial geomorphology in that the presence of a large channel bar indicates that the channel may be trying to repair itself or is in the process of reaching a new equilibrium state via aggradation; whereas, deposition along the channel bar is working to reduce the total width of the channel downstream of the channel bar's origin. This could suggest that if left alone, the channel could repair itself given time and a relatively stable sediment loading regime. If so, implications suggest that an artificial structure added to the channel may work to disrupt the neo-equilibrium conditions at the site and cause further alterations downstream.

Results from the habitat simulations were analyzed using Minitab 15 statistical software. The two metrics analyzed were weighted usable area (WUA) and habitability (H), which is a dimensionless ratio (WUA/total $\text{area}_{\text{wetted-channel}}$l) that represents the proportion of the total area of the active channel that is suitable for use. For each functional feeding group, comparisons were made between mean (WUA) under both the plain bed and modified bed scenarios over a range of discharges. To test for differences in (WUA) under each scenario and between FFG, a 2-way ANOVA was performed.

Plainbed Channel Hydraulics

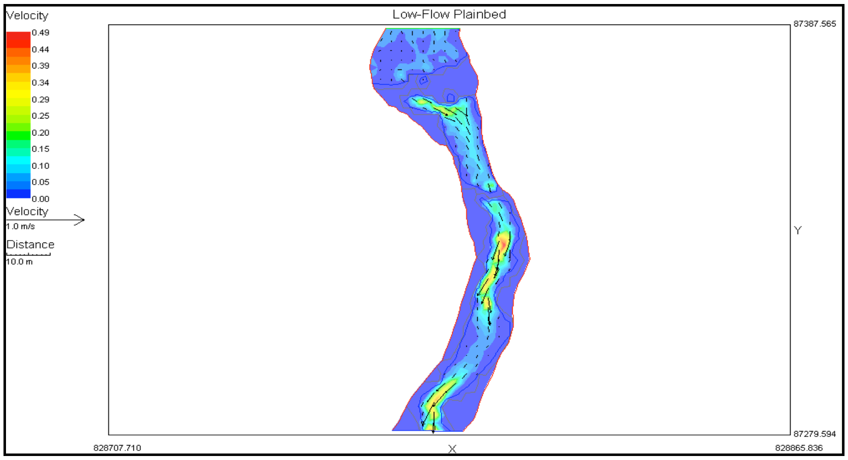


Figure 2.1 Velocity magnitude distribution at low-flow discharge

Figure 2.1 depicts the velocity distribution within the plainbed channel at low flow (0.07 m/s). The highest velocity magnitudes are within the thalweg, immediately downstream of riffle units. Regions that do not have velocity vectors have a minimum depth less than 0.02m and as such are not "wet" and therefore elements are not used in velocity, depth and WUA calculations. Similar patterns were observed during field sampling as some regions near streambanks and in riffles were extremely shallow during low flow and as such had values of near zero for velocity and depth.

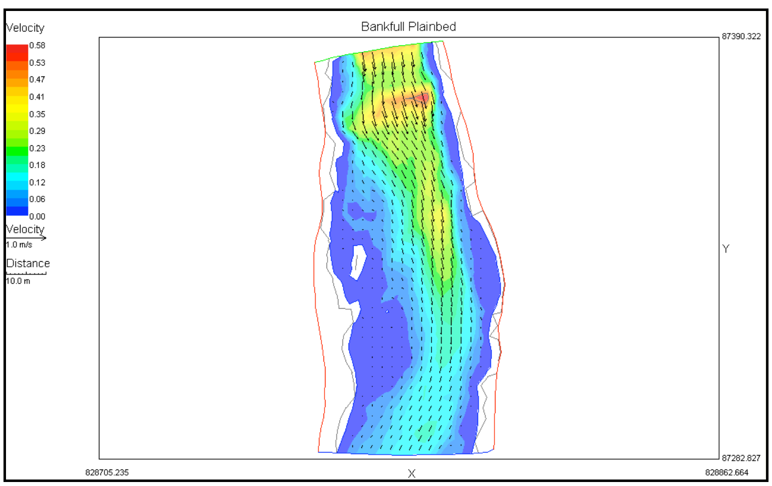


Figure 2.2 Velocity magnitude distribution at bankfull flow

Figure 2.2 depicts the velocity distributions within the bankful channel. The highest velocity magnitude occurs immediately downstream of the upstream most riffle. Regions near the channel margins have minimal or zero velocity values as in the low flow simulation.

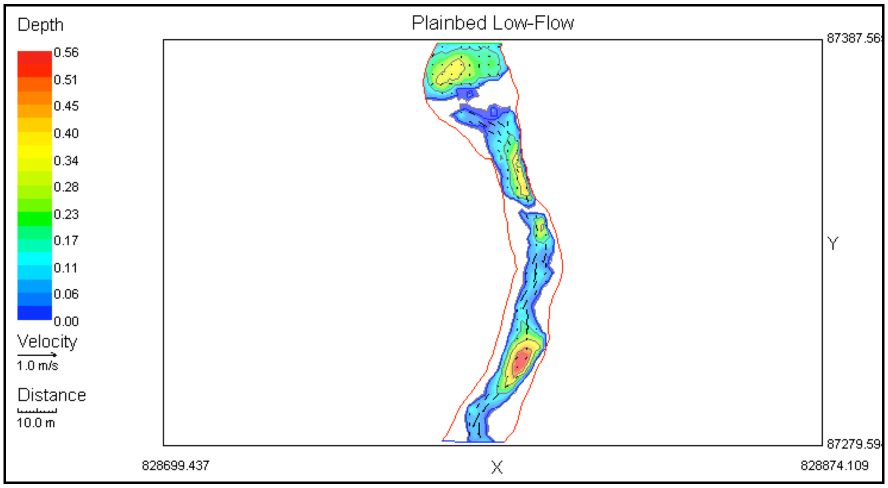


Figure 2.3 Depth distribution at low-flow discharge

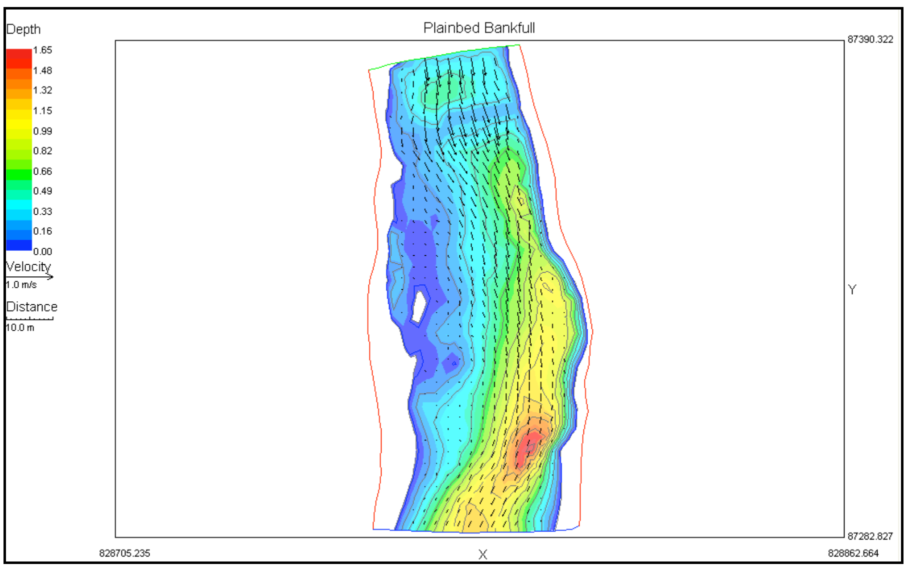


Figure 2.4 Plainbed depth distribution at bankfull discharge

Figures 2.3 and 2.4 depict depth distributions at low and bankfull discharges. The increase in discharge creates a significantly different channel hydraulic unit distribution when comparing the bankfull channel to the low flow channel. At low flow, the two “non-wetted” areas are riffle units. Under bankfull conditions, the second riffle, which is much smaller than the upstream most riffle, is completely submerged and has little effect on flow pattern as seen in the lack of variation or deflection in velocity vectors as flow passes over the riffle. Furthermore, the extent of both the upstream and downstream pool units is much greater in comparison to low flow channel.

Plainbed Habitat Analysis

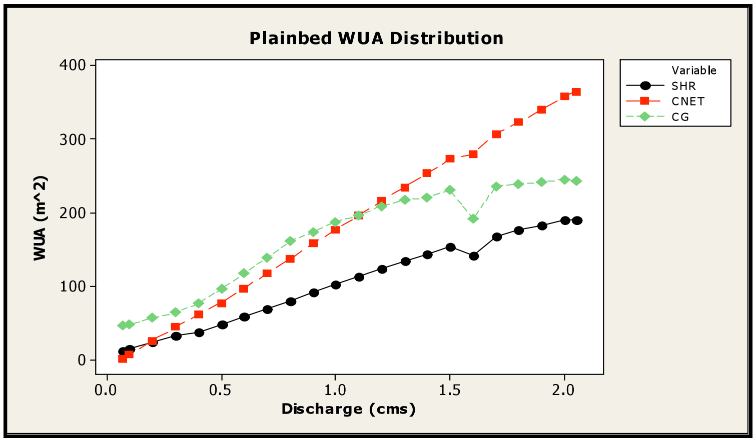


Figure 2.5 WUA vs. Discharge for all FFG

Figure 2.5 depicts the WUA distributions for the three FFG under plainbed simulations. For CNET, WUA increases almost linearly with increasing discharge, as this FFG has the most positive relationship with velocity. WUA for SHR also increases linearly with discharge, however WUA does not reach the magnitude of CNET as velocity suitability for shredders occurs between a lower range of velocity magnitudes. WUA for CG does not appear to have the same linear increase as in the other 2 FFG, rather WUA appears to increase rapidly at low flow discharges, then level off as discharge approaches median and bankfull discharges.

WUA distributions appear to be limited by the distribution of velocity magnitude and depth throughout the channel, more so than substrate. Substrate is relatively homogenous throughout the channel, with most of the channel bed being composed of coarse to medium grain cobble. There are a few isolated patches of boulders, fine cobble-coarse gravel combinations and coarse sand throughout the channel. Depth is not homogenous throughout the channel; in fact, there is more variation in depth compared to velocity, especially at low flow discharge; however at low discharge a large portion of the channel has values of depth that approach zero. Similarly, the range of velocity magnitude is limited by low discharges. The combination of low discharge effects on both depth and velocity make a limited portion of the channel available as suitable habitat space.

Collector-Gatherer WUA Distributions

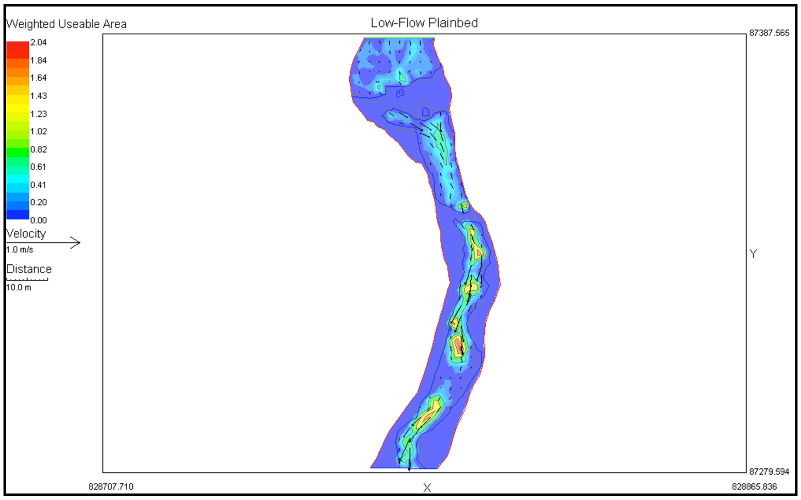


Figure 2.6 Collector-Gatherer WUA at low-flow discharge

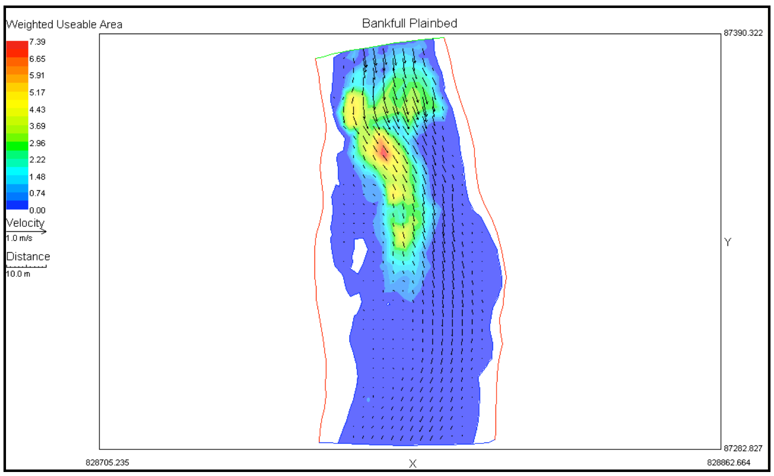


Figure 2.7 Collector-Gatherer WUA at bankfull discharge

Figures 2.6 and 2.7 show the distributions of WUA at low flow (0.07 m^3/s) and bankfull flow (2.09 m^3/s) respectively. At low flow, almost all WUA is distributed within shallow run and pool habitat; however, at bankfull flow, WUA is distributed within the large, upstream pool, the upstream-most portion of the channel bar of the channel and a small portion of the DSR bank. Farther downstream depths and velocity are not as suitable at bankfull discharge, as the large pool reaches depths approach 1.65m.

Collector-Netspinner WUA

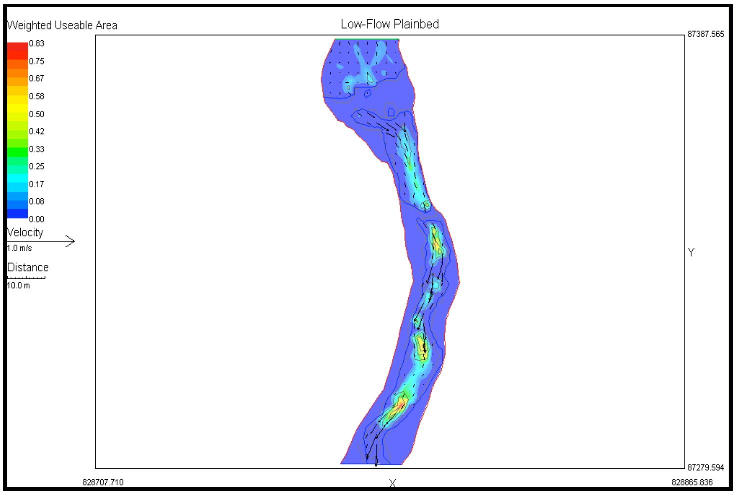


Figure 2.8Collector-Netspinner WUA at low flow discharge

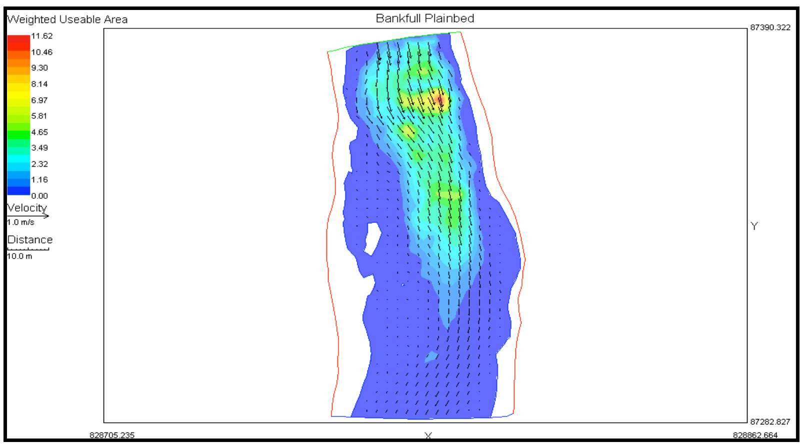


Figure 2.8 Collector-netspinner WUA at bankfull flow

Figures 2.8 and 2.9 depict WUA distributions for CNET under the minimum and maximum flow conditions. At the low flow discharge, WUA spatial distributions are somewhat similar to that of CG, however, CNET does not attain as high of a maximum WUA as does CG. This can be attributed to the fact that at low flow discharges, velocity magnitudes don't reach the level of suitability required by CNET throughout most of the channel. This is supported in part by the WUA distribution in the bankfull simulation. Under bankfull conditions, CNET are able to take advantage of the higher velocity magnitudes, which are distributed more frequently throughout the channel. As such, WUA for CNET under bankfull discharges is concentrated in middle of the channel on either side of the thalweg, where velocities are highest. The highest concentration of WUA occurs at the first riffle on the DSL side of the channel. On the DSR side of the riffle, there are a considerable patches of both boulder and cobble-gravel, neither of which has a high substrate suitability for CNET. Farther downstream, there is a considerable patch of suitable habitat at the second riffle, however, suitable habitat for CNET doesn't extend far beyond the second riffle, as depths begin to increase downstream in the run and pool habitats.

Shredder WUA Distributions

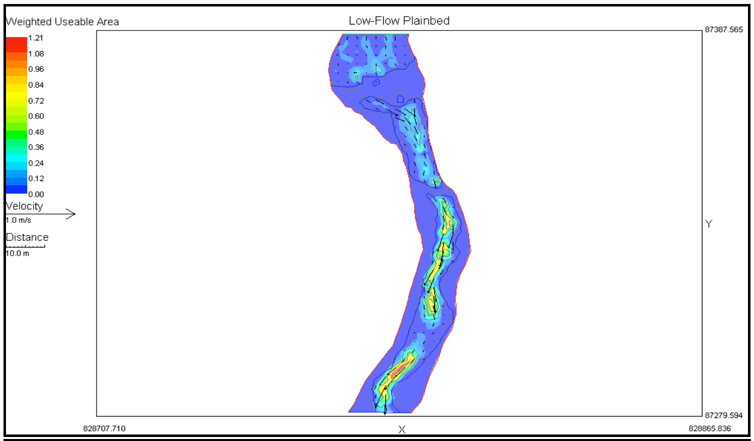


Figure 2.10 Shredder WUA at low flow discharge

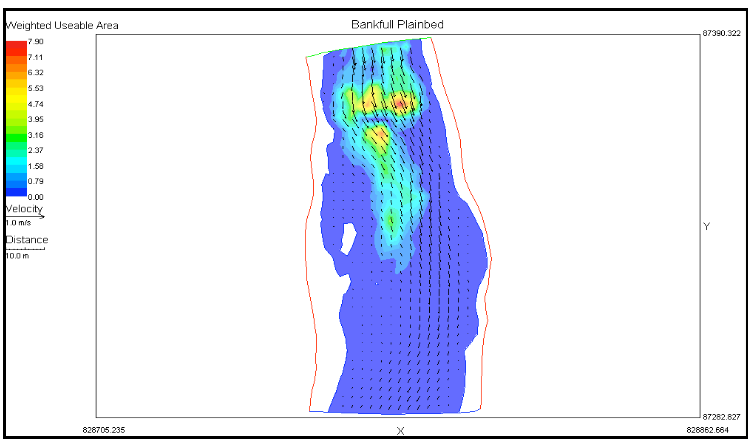


Figure 2.11 Shredder WUA at bankfull discharge

The WUA distribution for SHR at low flow show that this FFG is able to utilize much more of the channel compared to the other FFG classes. The optimal suitability criterion for SHR is such that the most suitable areas in the channel are those with low to median values of depth (0.163-0.44m), low velocity (0.16-0.32 m/s) and semi-stable substrate. As such, at lower discharges SHR is able to take advantage of the downstream pool and run habitat units. At bankfull discharge, the most suitable habitat is distributed within the upstream riffle and on the upstream portion of the channel bar. The higher depths and stable, cobble substrate downstream make for less suitable habitat. As habitat suitability criterions are based on the presence (i.e. abundance and density) of macroinvertebrates, there could be an effect of resource availability at higher flows. Higher depths and velocities may affect mobility and/or restrict access to food and shelter resources as lifehistory adaptations for most shredders are suited to conditions under which CPOM is most likely to settle out of the water column.

Double-Wing Deflector Channel Hydraulics

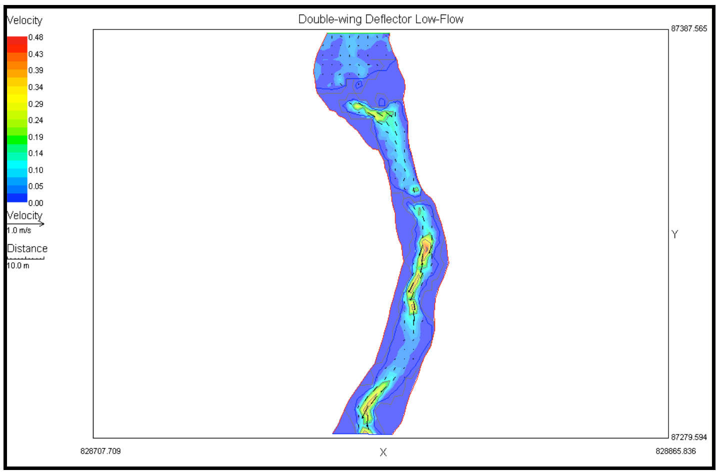


Figure 2.12 Double-wing deflector velocity magnitude distribution at low-flow discharge

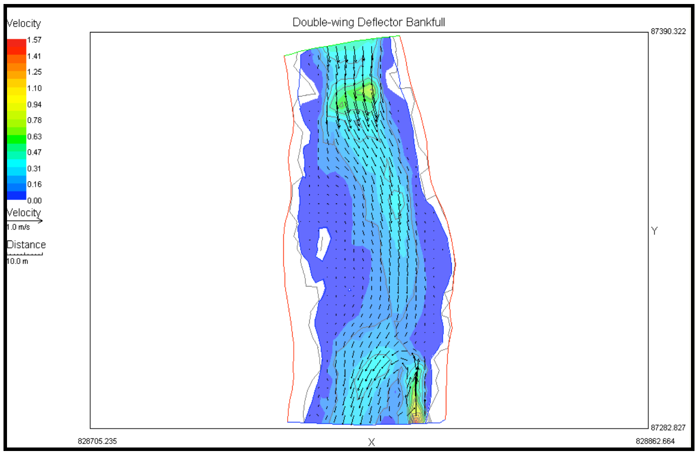


Figure 2.13 Double-wing deflector velocity magnitude distribution at bankfull discharge

In figures 2.12 and 2.13, both velocity magnitude distribution and velocity vectors display significant variation compared to the plainbed simulations. As intended by design, the deflectors do concentrate flow towards the center of the channel. For the low-flow discharge, the most significant derivation from plainbed conditions in the velocity magnitude at the inflow boundary. There are slightly higher velocities near the center of the channel when compared to the plainbed simulation. Throughout the remainder of the channel, both velocity magnitude and velocity vectors are for the most part similar.
The modification to the bed topography has a more significant effect at bankfull discharge. There are higher velocity magnitudes at the upstream riffle, throughout the center of the channel and along the margins of the point bar. Either because of the alteration to flow pattern or a combination of this effect in addition to a boundary effect, a large eddy is formed at the outflow boundary. This effect was not seen in any of the other simulations. Observation of the cumulative discharge plot (appendix) shows that the alteration in flow pattern causes cumulative discharge to be greatest in the region contained by the eddy, whereas for both the plainbed and j-hook rock vane simulations, cumulative discharge increased along a gradient from DSR to DSL.

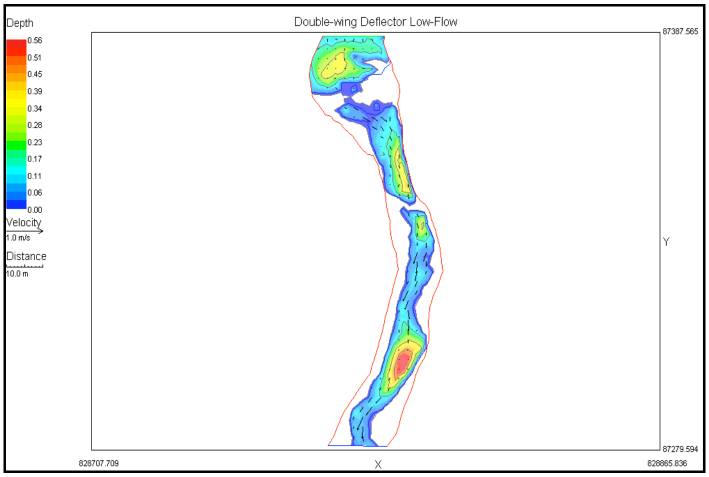


Figure 2.14 Double-wing Deflector Depth Distribution at low-flow discharge

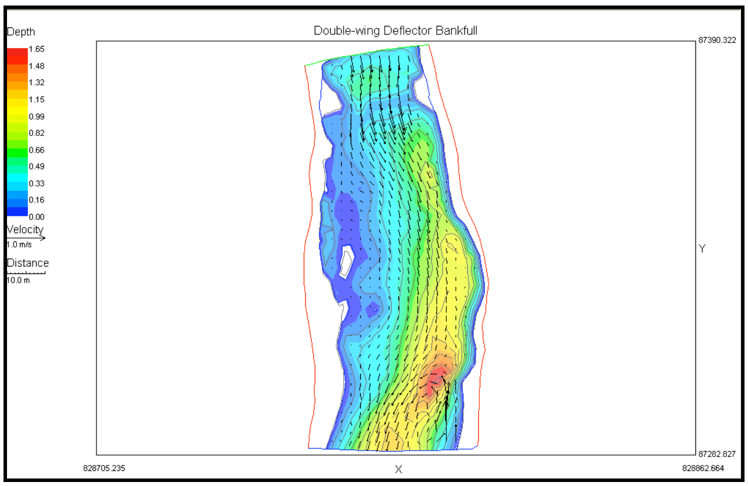


Figure 2.15 Double-wing Deflector depth distribution at bankfull discharge

The depth distributions for the two deflector simulations are similar to that of the plainbed simulations. The only difference occurs at the upstream riffle, whereas the elements that contain the wing-deflectors are non-wetted. In the low-flow simulation, this effect is seen in a slightly larger proportion of elements and in the bankfull simulation, all elements contained within the structures are non-wetted.

Habitat Analysis

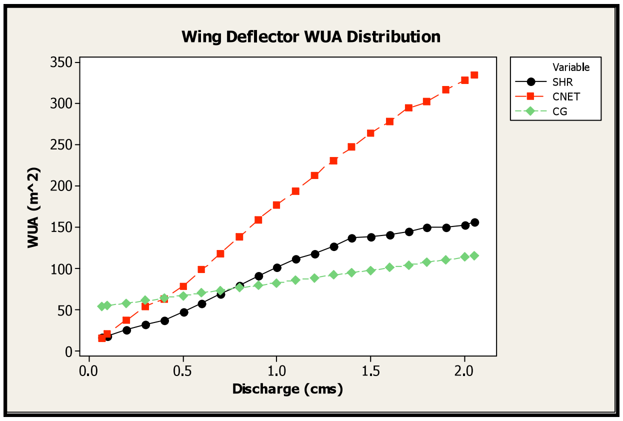


Figure 2.16 Double-wing deflector WUA vs. Discharge

As in the plainbed simulations, CNET has a positive linear relationship with discharge; however, WUA does not reach the same maximum value when compared to the plainbed treatment (363.85 m^2). WUA for SHR follows a similar trend as in the plainbed treatment, yet doesn't reach the maximum observed in the plainbed bed treatment (189.66 m^2). As in the plainbed treatment, WUA increases linearly with discharge until 1.4 m^3/s where increases in WUA begin to level off with increasing discharge. Interestingly, SHR habitat surpasses that of CG, which was not the case in the plainbed treatment. At low discharges WUA for CG is much higher (53.84 m^2) than that of both CNET (15.85 m^2) and SHR (16.58 m^2), however with increasing discharge, WUA increases very little and reaches a maximum of (115.06 m^2) compared to (155.8 m^2) for SHR and (355.23 m^2) for CNET.

Collector-Gatherer WUA Distribution

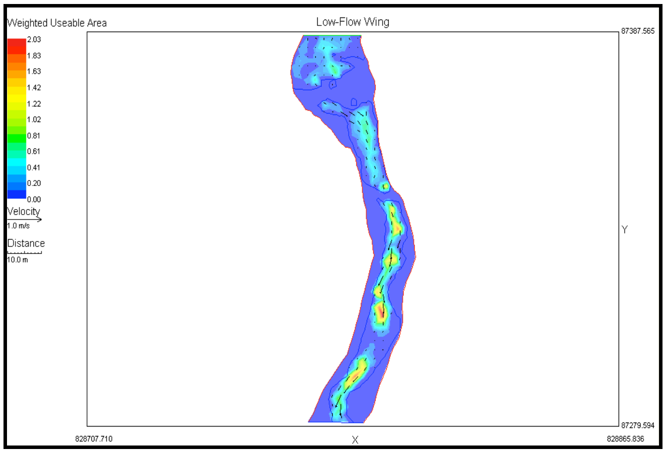


Figure 2.17 Collector-Gatherer WUA distribution at low-flow discharge

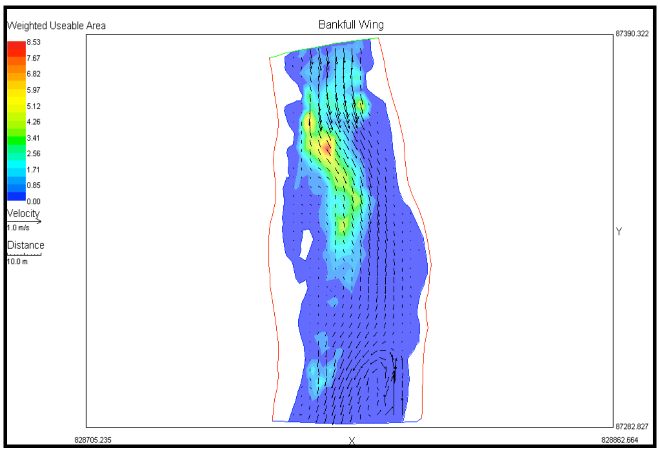


Figure 2.18 Collector-Gatherer WUA distribution at bankfull discharge

Under the low-flow discharge, CG is able exploit much of the channel with the exception of the two riffles, which do not meet depth suitability requirements. At low-flow, most of the habitat units meet the low to median velocity requirements in the 0.85-1.0 preference range (0.02-0.245m/s) and the 0.85-1.0 preference range for depth (0.145-0.26m). Although habitat suitability is a composite of depth, velocity and substrate criterion, the high level of suitability within the low-flow channel is weighed heavily upon CG velocity suitability. The required velocity range occurs more frequently than that of depth in the low-flow channel, especially in the downstream portion of the reach. At bankfull discharge, WUA is distributed within the pointbar and the DRL side of the upstream riffle. These regions are adjacent to the channel thalweg and thus are not exposed to the higher discharges in the center of the channel. There are also patches of less suitable habitat in the pool upstream of the deflectors and along the DSR bank near the outflow boundary.

<u>Collector-Netspinner WUA Distribution</u>

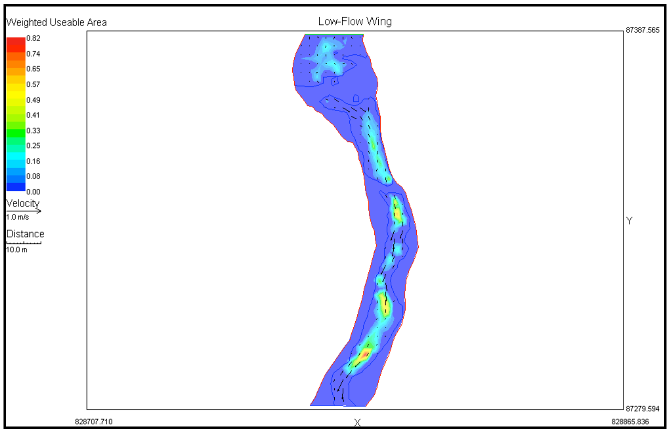


Figure 2.19 Collector-Netspinner WUA distribution at low-flow discharge

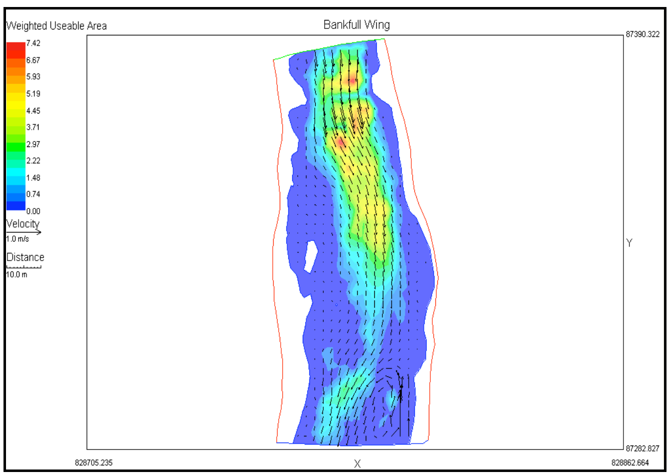


Figure 2.20 Collector-Netspinner WUA distribution at bankfull discharge

At low-flow, the WUA distribution for CNET is similar to the distribution seen in the plainbed treatment. There are slight increases in WUA in the pool upstream of the deflectors and also in the magnitude of WUA within the channel when compared to the plainbed treatment. At bankfull discharge WUA follows much the same distribution pattern as in the plainbed treatment; however, because flow is deflected towards mid-channel, the spatial extent of suitable habitat for CNET is increased farther downstream. There is a small patch of relatively suitable habitat near the DSR bank, although the magnitude of WUA is much lower throughout the channel.

Shredder WUA Distribution

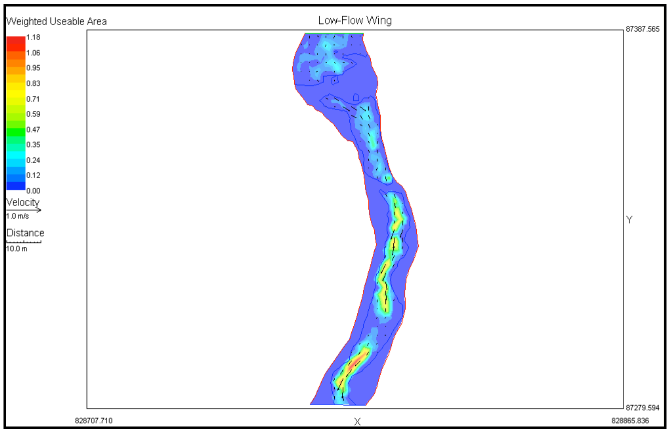


Figure 2.21 Shredder WUA distribution at low-flow discharge

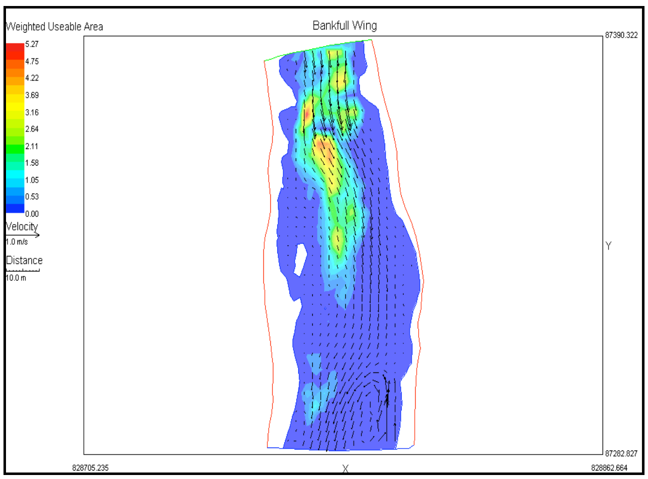


Figure 2.22 Shredder WUA distribution at bankfull discharge

The distribution of WUA follows much the same patterns as the plainbed treatment at both discharges except for small deviations. At the low-flow discharge, the only difference is in the upstream pool where suitable habitat reaches a slightly higher spatial extent compared to the plainbed treatment. There is also a difference in the magnitude of WUA; whereas the wing-deflector has slightly higher WUA (16.58 m²) than the plainbed treatment (10.96 m²). The relative WUA distribution is also similar to the plainbed distribution at bankfull discharge; however there is less suitable habitat in the upstream riffle and slightly more in the upstream pool and near the DSR bank. There is also a small patch of suitable habitat near the DSR bank close to the outflow boundary. The wing-deflector did not outperform the plainbed treatment as in the low-flow simulation. WUA at bankfull discharge was (155.8 m²) for the wing-deflector treatment and (189.66 m²) for the plainbed treatment.

J-Hook Rock Vane Channel Hydraulics

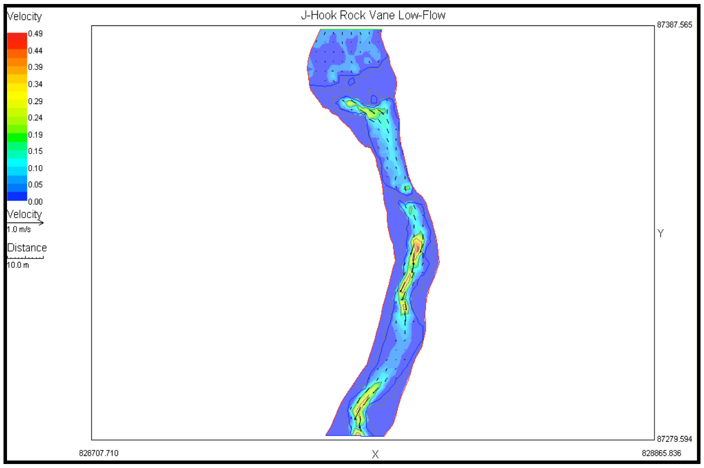


Figure 2.23 Velocity magnitude distribution at low-flow discharge

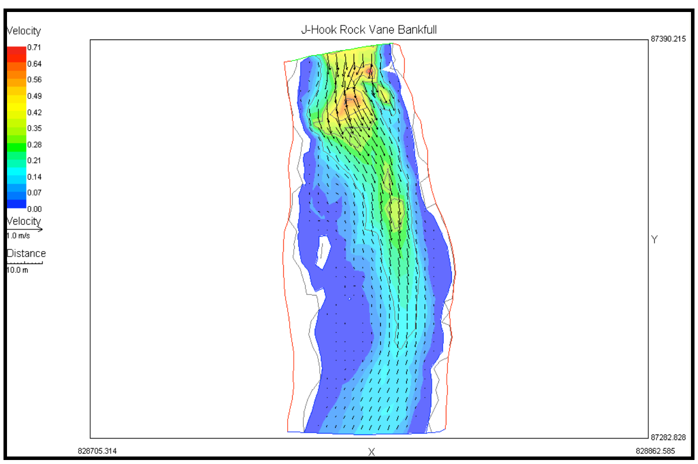


Figure 2.24 Velocity distribution at bankfull discharge

The J-Hook Rock Vane structure has a significant effect on velocity magnitude in both the low-flow and bankfull channel. At the low-flow discharge, the structure decreased the velocity magnitude downstream of the first riffle and altered the velocity vector farther downstream. The influence of the structure increases with increasing discharge as the riffle section downstream of the structure increases in depth. At the bankfull discharge the structure increases the velocity magnitude both in the DSR side of the riffle and father downstream. As intended by the functional goals inherent in the structure, velocity magnitude and cumulative discharge is decreased near the stream margins. As in the low-flow simulation, velocity vector pattern is also altered.

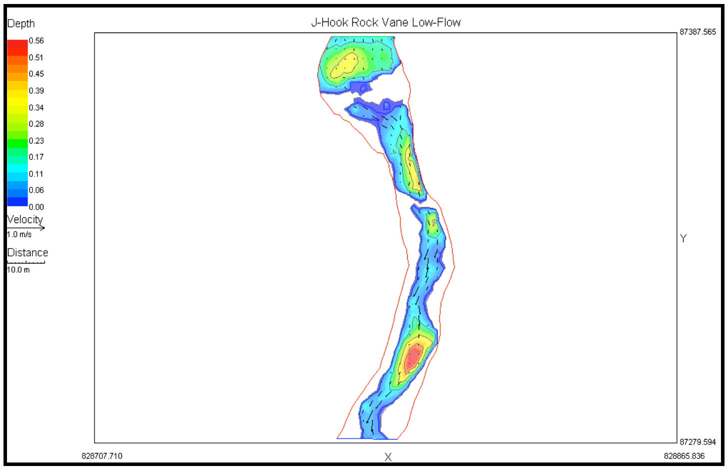


Figure 2.25 Depth distribution at low-flow discharge

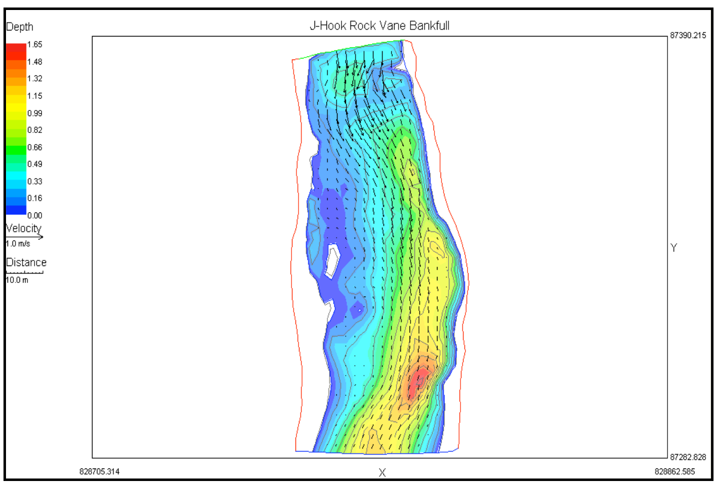


Figure 2.26 Depth distribution at bankfull discharge

Depth distributions were similar in both J-Hook Rock Vane simulations when compared to the plainbed treatments. At the low-flow discharge, depth distributions between the plainbed and rock vane treatments were indistinguishable. At the bankfull discharge, there were very similar with the exception of a shallow pool formed downstream of of the vane-arm portion of the structure.

J-Hook Rock Vane Habitat Analysis

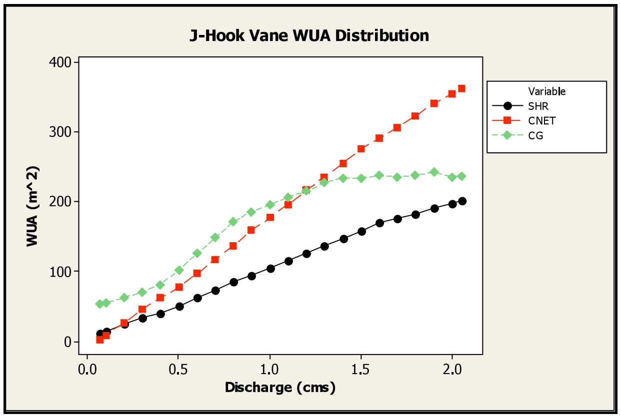


Figure 2.27 J-Hook Rock Vane WUA vs. Discharge

As in the other treatments, CNET has the highest magnitude of WUA compared to the other FFG and WUA increases linearly with increasing discharge. At lower discharges, the j-hook rock vane treatment (2.71 m^2) outperforms the plainbed treatment (1.43 m^2) by a minimal margin. At higher discharges, the rock vane treatment outperforms the plainbed treatment or does equally as well in terms of WUA. WUA for SHR increases at a linear rate with discharge similar to the trend exhibited by CNET. This trend was not evident in the other treatments suggesting that the vane structure would be capable of increasing habitat availability for this FFG. WUA at both low-flow (11.44 m^2) and bankfull (201.12 m^2) discharges was higher in this treatment compared to the plainbed treatment in which values of WUA for SHR were (10.96 m^2) and (189.66 m^2) respectively. For CG, WUA increased logistically until (1.4-1.5 m^3), then increased slightly only to decrease again at bankfull discharge. WUA for GC was higher at the low-flow discharge (53.46 m^2) for this treatment compared to (45.64 m^2) for the plainbed treatment. At bankfull discharge the plainbed treatment (242.76 m^2) outperformed the j-hook rock vane treatment (236.89 m^2), however mean WUA was higher for the rock vane treatment.

<u>Collector-Gatherer WUA Distribution</u>

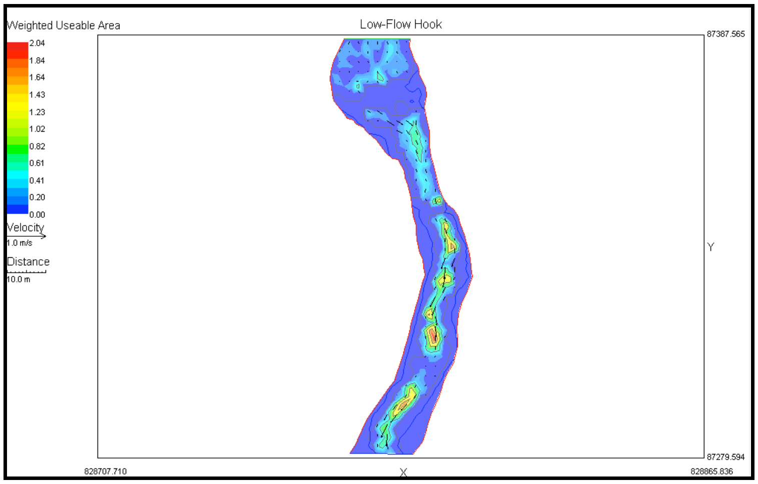


Figure 2.28 Collector-Gatherer WUA distribution at low-flow discharge

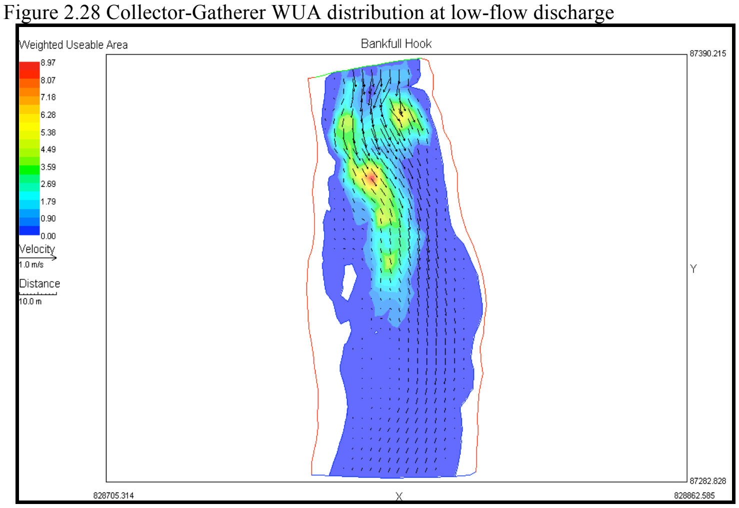


Figure 2.29 Collector-Gatherer WUA distribution at bankfull discharge

At the low-flow discharge, there were no significant changes in WUA distribution between the rock vane and plainbed treatments, although WUA reaches a slightly higher magnitude in the rock vane treatment. At the bankfull discharge, WUA is reduced dramatically in the high turbulence area created in the thalweg immediately downstream of the first riffle. This has an effect of increasing the magnitude of WUA within the large patch of suitable habitat that extends across the first riffle and along the margin of point bar.

Collector-Netspinner WUA Distribution

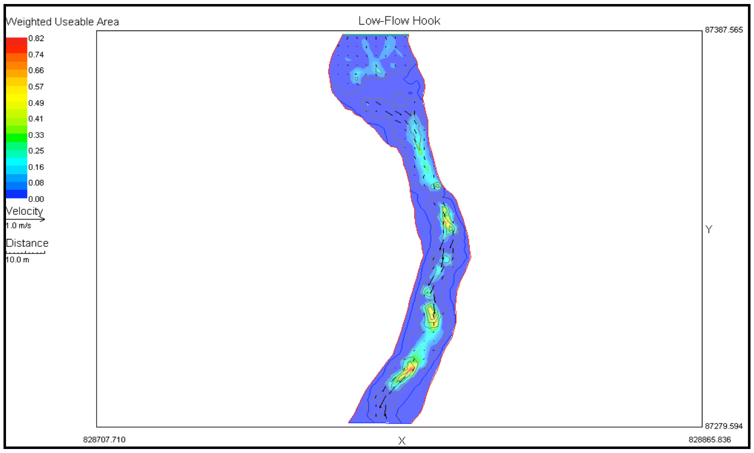


Figure 2.30 Collector-Netspinner WUA distribution at low-flow discharge

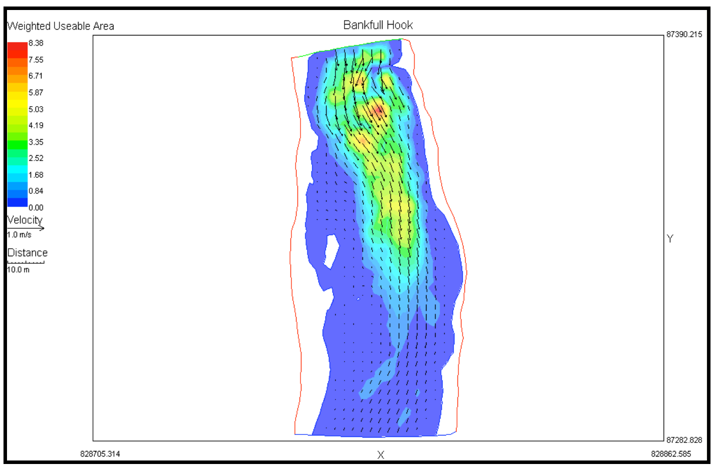


Figure 2.31 Collector-Netspinner WUA Distribution at bankfull discharge

At the low-flow discharge, there is no distinguishable shift in the distribution of WUA between the plainbed and rock vane treatments, although total WUA is slightly higher for the rock vane treatmnent. At the bankfull discharge, the rock vane treatment extends the contiguous patch of suitable habitat farther downstream, extending beyond the second riffle and into the downstream portion of the point bar. This treatment also causes a shift toward mid-channel of the highly suitable patch of habitat in the first riffle. It also creates two small patches of habitat, one immediately downstream of the vane arm in the first pool and another immediately downstream of the first riffle along the margin of the point bar. Near the DSL bank, in the small pool created by the rock vane, another patch of suitable habitat not seen in the plainbed treatment was created.

Shredder WUA Distribution

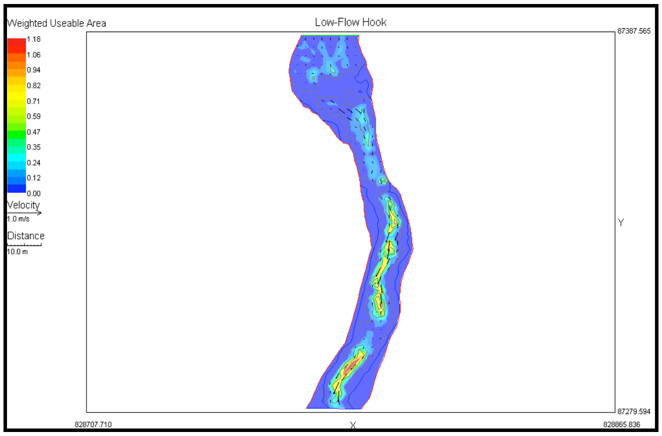


Figure 2.32 Shredder WUA distribution at the low-flow discharge

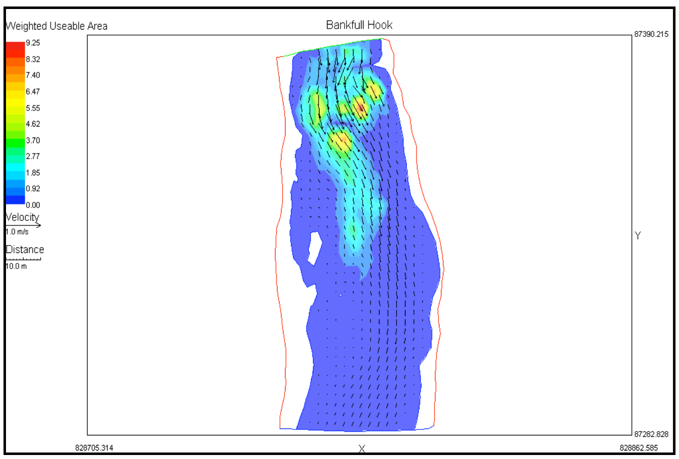


Figure 2.33 Shredder WUA distribution at bankfull discharge

As observed with the other low-flow simulations in the rock vane treatment, there was no distinguishable variation in the WUA distribution for SHR compared to the plainbed treatment; however the rock vane treatment slightly increased total WUA by a (0.48 m²) At bankfull discharge, there was no change in the spatial extent of suitable habitat but there was an increase in total WUA between the rock vane treatment (201.12 m²) and the plainbed treatment (189.66 m²). This was due in part to a new patch created on the DSL side of the riffle, close to the location of the rock-vane created pool. There were also suitable habitat patches lost in the rock-vane treatment. There was one small, relatively suitable patch lost in the downstream segment of the point bar and another large patch of suitable habitat along the mid-line of the first riffle in the high turbulence area created by the structure.

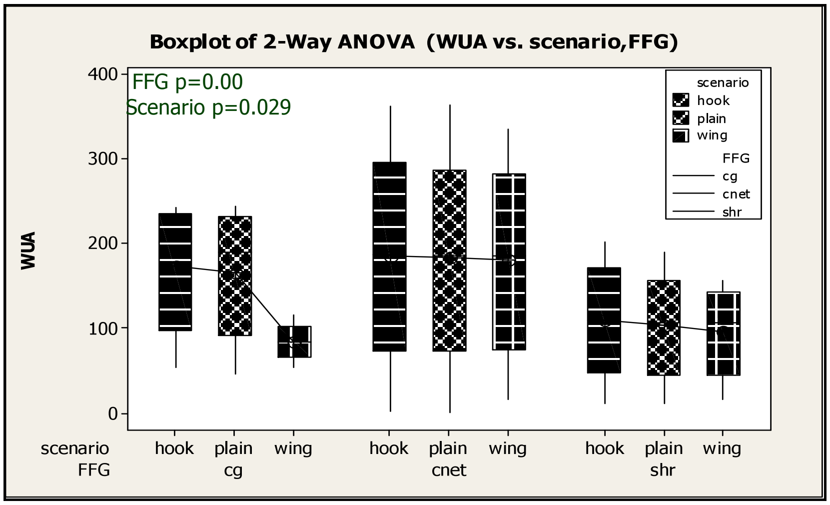


Figure 2.34 2-WAY ANOVA of WUA vs. treatment (scenario) and FFG

Figure 2.28 depicts the results of 2-WAY ANOVA comparing WUA between the three levels of treatment and FFG. Results of the 2-WAY ANOVA indicate that the differences in WUA between FFG and treatment (scenario) were statistically significant with p-values of (0.00) and (0.029) respectively. The J-Hook Rock Vane treatment outperformed each of the other treatments in terms of WUA for each FFG and was the only restoration application to exhibit a net gain in suitable habitat. The wing-deflector treatment actually reduced WUA in the channel for each FFG. One possible explanation could be that the large extent of channel taken up by the structure may limit the potential for such a structure to increase total WUA in the channel. These results seem to follow the restoration application guidelines set in (Rosgen 1998); whereas for type C3 streams, the J-hook Rock Vane was rated as excellent and the double-wing deflector was rated as good. These results are interesting because these assessments were not based upon ecological metrics, but rather the effectiveness of the structure at maintaining or stabilizing channel morphology.

The CNET functional feeding group was the least sensitive to treatment effects as mean WUA and respective variances for each treatment were similar; however the wing-deflector treatment does create habitat for CNET as total WUA at the low-flow discharge is higher than observed for the plainbed treatment. This could be an interaction effect between low-discharge and the concentration of flow through the upstream riffle; whereas low-discharge limits the potential magnitude of turbulence in the riffle, thus creating an ideal habitat template for this FFG. Evidence for this explanation is exhibited in the fact that increases in WUA do not increase significantly with increasing discharge, as this would increase turbulence and associated shear forces on the stream bed. The wing-deflector treatment had the strongest effect on the CG functional feeding group, as WUA decreases dramatically in this treatment compared to both the other treatments and FFG's. This effect can be attributed to the high turbulence and shear forces concentrated in the center of the channel, which are not conditions suitable to the CG functional feeding group.

Discussion

Streams are not equilibrium systems but non-equilibrium and stochastic systems. An argument can be made that disturbances (floods, droughts, pollutants, sedimentation etc.), both seasonal and stochastic, structure communities and that their frequency, duration and magnitude will affect the nature of responses from ecosystems and individual species (Lake 2000. The nature of these responses may differ between similar ecosystems in different regions or with different physical and environmental conditions. The responses of the biological community may likewise exhibit differential responses to the same disturbance. In a benthic community this may translate to differential responses to disturbances between functional feeding groups such as scrapers and filterers as they may be associated with different stream units, flow conditions and substrate types. In terms of the differential response of similar ecosystems to a similar disturbance manifests itself when comparing the responses of urban and forested catchment after storm events. This effect has been studied in pair-watershed studies of similar catchments with different land-uses (i.e. the Hubbard Brook studies of Boreman and Likens).

It is also important to note that instream habitat and stream channel restoration practices can not be the sole solution to stream urbanization or degradation of ecological conditions. (Walsh et al. 2005) states that the dominant catchment-scale impacts on biotic communities of degraded urban ecosystems are usually associated with urban storm water runoff, thus attempts at restoration by instream or riparian habitat enhancement are, therefore likely to fail because they do not match the scale of the restoration to that of the constraining impact. That does not leave reach-scale restoration obsolete nor unnecessary, instead it signifies the magnitude of effort and cooperation that will be needed to make lasting impacts upon the once pristine waterways that are now by-products of human population growth and subsequent urban sprawl. (Crowder and Diplas 2002) suggests that in order for habitat and hydraulic analyses to be meaningful in a restoration or management sense, than biologists, hydrologists, and hydraulic modelers must work closely to identify study needs and how 2D modeling studies should be implemented. As such, 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 2D model output and spatial hydraulic metrics can be best used to help assess stream habitat. Caution must also be taken as to not assume that restoring habitat will restore diversity, as recolonization may depend heavily on: patch connectivity (Lake 2000), species-specific migration capacities and behaviors (Downes et.al 2005), potential larval supply, habitat selection and post-settlement events (i.e. environmetal conditions and resource availability in new habitat patch) (Sharpe and Downes 2006)

Analysis of model outputs from the River2D hydrodynamic model yield promising conclusions as to the utility of modeling the effects instream habitat restoration structures. It was shown that the meso-scale alterations in flow and velocity due to the placement [simulated] of a j-hook rock vane were effectively captured by the model. Furthermore, these alterations were captured at a scale that could be ecologically important to macroinvertebrates inhabiting the reach. The implications surrounding the results of this study are that this methodology could have a significant role in evaluating the effects of reach-scale instream habitat restoration; however, caution should be taken in using such a method to make decisions over very large spatial scales. To make such conclusions over larger scales, it would be necessary to model a large number of reaches that are representative of the prevalent stream conditions throughout the watershed, while maintaining an appropriate bathymetry resolution. Furthermore, the data collection process could be very tedious and over a large spatial scale, would involve a large time investment.

In terms of the applicability to macroinvertebrate habitat suitability, the model performed well at extracting respective usable areas from the reach. Undoubtedly, in any (2D) modeling project, the species-specific habitat suitability criterion plays a significant role in the ultimate predictions of instream habitability. It thus seems pertinent for future studies to develop regionally-specific estimates of habitat suitability criterion for macroinvertebrate species of interest. (Doledec et al., 2007) suggests that extending invertebrate preference models to multiple taxa and sites and relating them to available hydraulic models would make it possible to predict the potential impact of flow regime and its modifications on the whole invertebrate community.

Innumerable studies have been conducted on the optimal reach and catchment-scale conditions suitable for maintaining diverse macroinvertebrate communities; however, the lack data collection pertaining to the hydraulic conditions at actual sampling sites hinders this data from being used to estimate suitability curves. The development of species-specific macroinvertebrate habitat suitability curves has been attempted by a number of studies, most notably (Gore and Judy, 1981; Jowett and Richardson, 1990), however, the argument has been made that the criterion used for fish studies should not be used for macroinvertebrate habitat studies as these metrics tend to be averaged over the entire water column (Doledec et al., 2007). In particular, the velocity metric draws considerable distain as in most studies, velocity is measured as mean water-column velocity. The criticism for this metric comes in the fact that the hydraulic variables most pertinent to benthic macroinvertebrates are those that describe near-bed hydraulic forces as these are the forces that act upon macroinvetebrates within their respective microhabitats. A study by (Merigoux and Doledec, 2004) found that the distribution of almost 70% of the taxa collected (151 taxa representing 580 samples) for their study was related to the hydraulic parameters bed shear stress and Froude Number. Near-bed hydraulic conditions that are of critical importance to invertebrates are either calculated from a combination of kinematic viscosity, mean velocity, depth and substratum roughness or measured directly as shear velocity, shear stress or substrate particle size variability and are good predictors of benthic macroinvertebrate distribution (Merigoux and Doledec, 2004).

Bed shear stress is an appealing candidate variable for describing the hydraulic microhabitat of benthic invertebrates. Under simplifying assumptions, it determines the velocity profile close to the bed and can also be used to estimate sediment bedload movement (Doledec et al., 2007); however it can be difficult to measure in the field, thus estimates based on average water-column velocity are often used. In defense of the depth-averaged methodologies based on water-column variables used in 2D modeling applications, (Brooks et. al 2005) used such a method to determine how hydraulic parameters influenced the spatial distribution, diversity and community composition for taxa in riffles . They measured velocity (column), depth and substrate roughness variability at 56 macroinvertebrate sampling locations and complex hydraulic variables such as roughness Reynolds's number, shear velocity, and Froude number were calculated from combinations of the directly measured variables. Roughness Reynolds number explained more of the spatial variation in invertebrate abundance, number of taxa and community composition than the other hydraulic variable; however, out of the directly measured variables, velocity had the greatest explanatory power, which was marginally less than roughness Reynolds number and shear velocity.

The true intellectual merit of this research lies not in the results from the study, but in the attempt to utilize the model in an application that could supplement existing methods used in the evaluation and monitoring of restoration goals and objectives. This approach was taken in hopes that such a method could be applied to multiple reaches within watersheds and serve as an interactive tool for stream managers. Model results indicate statistically significant increases in (WUA); however the relative significance of increases in (WUA) depends on specified project goals that are weighed by factors such as costs, spatial scale, and magnitude of environmental degradation.

The ability to accurately model the ecologic, geomorphologic and hydraulic conditions at the reach, sub-watershed and watershed scales can provide opportunities for government and private entities to set cost-effective yet effectual goals for proposed stream restoration. As described in previous sections, there may be potential in using selective reach-scale restoration to improve instream habitat and ecological integrity. The use of 2D models to evaluate the effectiveness of a given restoration application could have tremendous benefits to stream managers, as valuable time and financial resources may be conserved. New developments and applications of 2D hydrodynamic modeling have been producing interesting results that could play a significant role in making predictions of hydraulic conditions given alterations in flow regime from anthropogenic influences and watershed management practices. (Lacey et al., 2004) used the River2D model to investigate the effects of instream large woody debris and rock groyne habitat structures. Taking bathymetry data before and after bankfull flow events, they were able to estimate both scour and pool formation within the modeled reach. Such applications of 2D modeling shed light onto the feasibility of using 2D modeling to predict processes other than velocity, depth and (WUA) distributions. The use of such modeling techniques could yield even more powerful predictions if coupled with a model capable of modeling sediment mass transport such as the 1-dimensional HEC-RAS model used by the US Army Corp of Engineers. (Duan2004) concluded that a depth-averaged two-dimensional model, if parameterized with appropriate dispersion terms, could reasonably simulate instream flow fields and sediment transport in meandering channels. 3D models are more accurate and can capture transport and dispersion processes in sharp meander bends, whose geometry and associated physical properties make modeling difficult; however they are require extensive computational capacity. Although the 2D model is not as accurate, it's use in applications for policy, management, planning and preliminary design purposes could be preferred as it is computationally most cost-effective than the 3D model (Duan2004). If scaled up to include entire watersheds or sub-basins, aside from the considerable upfront cost and time investments, it seems entirely feasible that managers could use such tools to make large-scale forward predictions about the effects of current management practices and strategies.

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Appendix Section I: Riffle Cross-sections

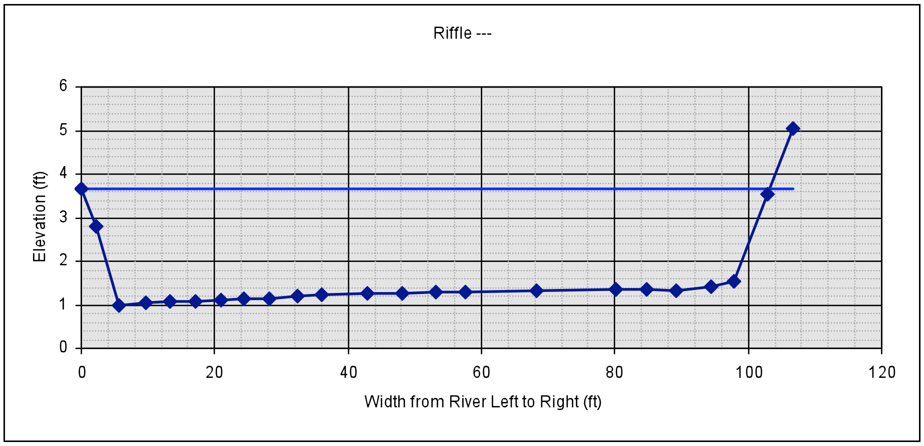

Figure Ia. Inflow cross-section at approximate bankfull water surface elevation

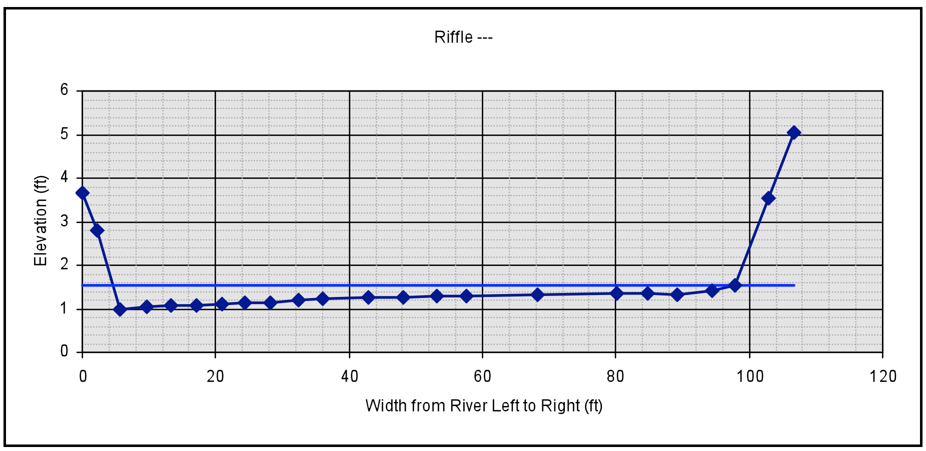

Figure Ib. Inflow cross-section at low-flow water surface elevation

Appendix Section II: Tables

Discharge Classes	Rh Classes	0.033	0.034	0.036	0.037	0.039	0.042
0.07	0.091135	0.0815	0.08796	0.10118	0.10791	0.12151	0.14216
0.1-0.2	0.1506728	0.1074	0.11668	0.13587	0.14571	0.1658	0.19665
0.25-0.35	0.2243328	0.1317	0.14395	0.16938	0.18253	0.20954	0.25146
0.4-0.55	0.2968752	0.1509	0.16561	0.1964	0.2124	0.24544	0.29712
.6-0.75	0.3685032	0.1668	0.18369	0.2192	0.23774	0.27619	0.33669
0.8-0.95	0.4253484	0.1779	0.19632	0.23527	0.25567	0.2981	0.36516
1.0-1.15	0.4811268	0.1877	0.20755	0.24966	0.27178	0.3179	0.39104
1.2-1.35	0.5224272	0.1943	0.21524	0.25958	0.28291	0.33163	0.4091
1.4-1.55	0.563118	0.2005	0.22237	0.26881	0.29329	0.34448	0.42609
1.6-1.75	0.61722	0.2082	0.23124	0.28036	0.3063	0.36065	0.44755
1.8-1.9	0.644	0.2118	0.23541	0.28581	0.31245	0.36832	0.45777
1.95-2.05	0.6737096	0.2156	0.23987	0.29164	0.31903	0.37655	0.46877

Table II.a Roughness height categories derived from Manning's n

Discharge (Q)	FFG	plainbed¹ (WUAavg)	modified_bed² (WUAavg)	plainbed¹ (Havg)	modified_bed² (Havg)	(WUAavg)² - (WUAavg)¹	(Havg)²- (Havg)¹
low	c-g	118.6441	155.2903	0.0744	0.1005	*36.6462	*0.0261
high	c-g	231.3228	222.1998	0.0538	0.0522	*-9.1229	*-0.0016
low	c-net	103.4363	116.8281	0.0649	0.0756	*13.3918	*0.0107
high	c-net	306.7243	299.9003	0.0714	0.0522	*-6.8239	*-0.0192
low	shr	71.0222	108.1012	0.0445	0.0700	*37.079	*0.0254
high	shr	167.3190	165.4495	0.0389	0.0385	1.8695	-0.0004

Table 1I.b Comparison of habitat suitability between flows, restoration treatment and (FFG)
WUA=Weighted Useable Area **H**= (WUA)/(Total Channel Area) (*)=p<0.05

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Appendix Section III: Bed topography files

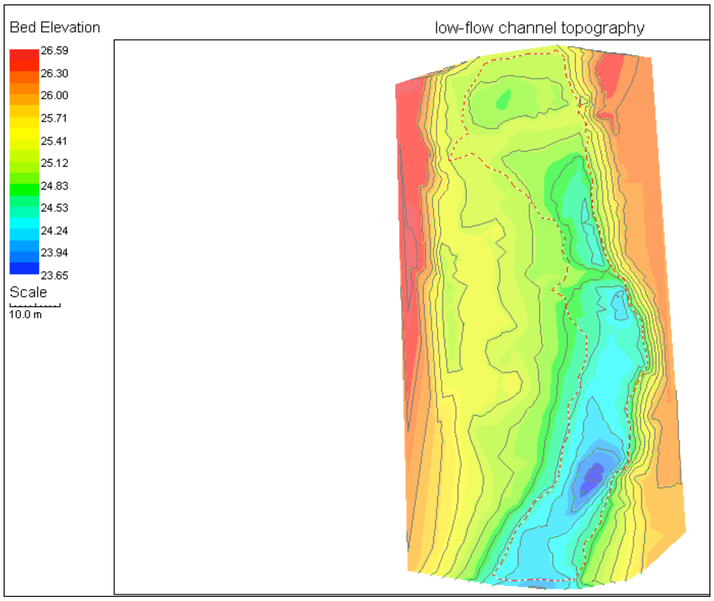

Figure III.1 Untriangulated channel topography with low-flow boundary in red

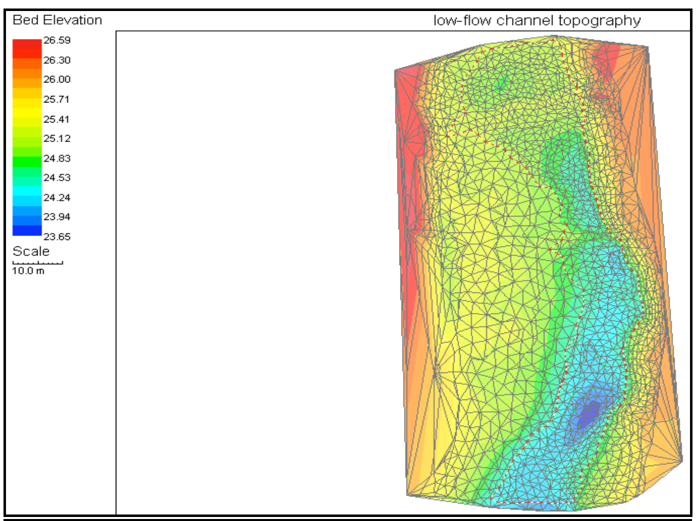

Figure III.2 triangulated bed topography file with low-flow boundary in red

Appendix Section III: Bed topography files

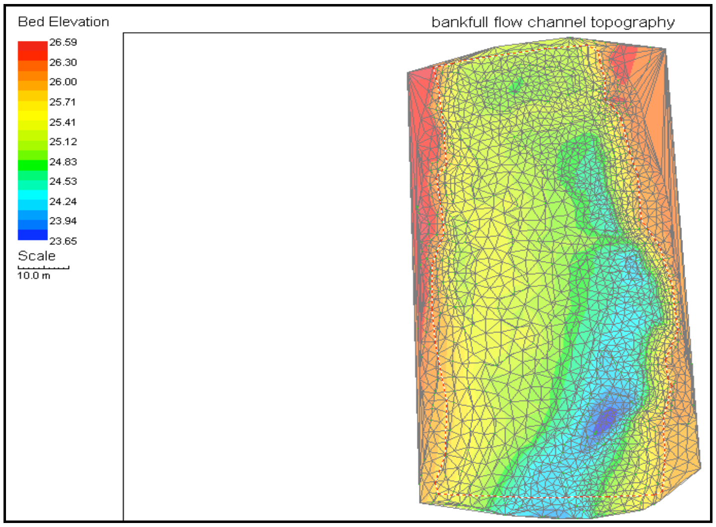

Figure III.3 triangulated bed topography file bankfull-flow boundary in

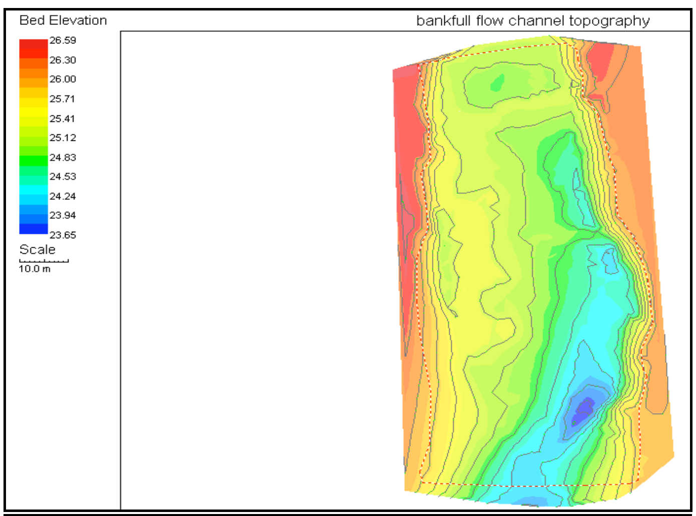

Figure III.4 untriangulated bankfull bed topography with computational boundary in red