Using Bathymetric LiDAR and a 2-D Hydraulic Model to Identify Aquatic River Habitat

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ABSTRACT

The Bureau of Reclamation (Reclamation) is currently studying various alternatives to improve salmonid habitat throughout the Yakima Basin in central Washington. In an effort to accomplish this goal, Reclamation is evaluating the effects of modifying flow releases throughout the year and increasing storage in the basin. A two-dimensional (2-D) hydraulic model has been used to identify various habitat types, including off channel habitat, spawning habitat, and pools, riffles, and glides for a wide range of flow rates. Spawning habitat was identified with Froude values between 0.3 and 0.6 using independently collected spawning data. Off-channel habitat is identified as side channels become active at various flow rates. Pool, riffle, and glide habitats are identified by assigning each habitat type a specific range of the Froude number. The results were verified through field investigations of the modeled reaches.

The major component of a 2-D hydraulic model is well-defined stream channel geometry. This type of data can be difficult to obtain, particularly for long study reaches. To resolve this issue, water penetrating airborne LiDAR was used to map approximately 153 river kilometers of bathymetry on the Naches and Yakima Rivers. This data was then combined with terrestrial LiDAR to create a complete surface with which to model hydraulics. The ability of airborne LiDAR bathymetry to map shallow water river environments is in early stages of development. The accuracy and precision of those measurements is summarized.

INTRODUCTION

Efforts to rehabilitate aquatic habitat can be greatly aided with the use of multi-dimensional hydraulic models to identify key habitat features with respect to hydraulics. Although much progress has been made in the ability to numerically represent complex hydraulic flow patterns, one of the problems that still exists is inadequate bathymetric terrain representation (Marks and Bates, 2000). This is especially true for study reaches longer than approximately five miles, where acquisition of dense channel bathymetry is difficult and time consuming. Recent advancements have been made in processing airborne LiDAR bathymetry (ALB) signals for shallow water river applications. ALB has been used for approximately 20 years for surveying coastal regions but has seen limited applications in shallow water riverine environments (Hilldale and Raff, 2007). ALB has been recently used in two-dimensional (2-D) hydraulic modeling studies by the Bureau of Reclamation (Reclamation) in the Yakima River Basin, Washington (Figure 1). The primary goal of the hydraulic modeling is to consistently quantify the available habitat types at various flow rates. These types include pool-riffle- glide habitat as well as off-channel and spawning habitat. Pool-riffle-glide and spawning habitat has been identified and categorized using the Froude number, which provides the ability to quantify the available habitat for comparison among various flow rates. Off channel habitat was identified as side channels become inundated with increasing discharge.

Purpose and Scope

The purpose of this study is to evaluate the effects of modifying flow releases from five Reclamation dams in the Yakima Basin for the year-round benefit of salmonid habitat and supplemental irrigation to those holding junior water rights during periods of drought. Providing increased storage in the basin is also being considered in order to meet the increasing demand for water. The primary tool chosen to evaluate the benefit to salmonid habitat is the Ecosystem Diagnostic and Treatment (EDT) model (Mobrand et al., 1997). EDT develops a working hypothesis to guide restoration efforts and includes an analytical model to quantify the biological potential of stream habitat for salmonid fish species (Greg Blair, Mobrand-Jones and Stokes Inc., written communication). Some of the input parameters required for the EDT model have been provided by two-dimensional (2-D) hydraulic models, which were constructed and run over a wide range of flows for selected reaches of the Yakima and Naches Rivers in the Yakima Basin. One of the specific inputs to EDT is a quantification of the amount of pool, riffle, and glide habitat types available at various discharges. Defining these habitat types forms the basis of this paper. Off channel and spawning habitat is discussed briefly.

Prior to modeling selected reaches of the Yakima and Naches Rivers for various habitat types, it was necessary to obtain river channel bathymetry of sufficient density to properly represent these features. Due to the large size of the project area ALB was considered, as conventional river surveys performed with acoustics and Real Time Kinematic (RTK) Global Positioning Survey (GPS) equipment would be very time consuming and less likely to have the desired point density. It was decided that ALB would be flown for approximately 153 river kilometers on the Yakima and Naches Rivers in the Yakima Basin. For the modeling effort discussed in this paper, 41.8 river kilometers of the ALB survey was used, divided among three reaches (Figure 1).

Site Description

The Yakima River Basin in Washington has a drainage area of 16,000 km^2 and produces a mean annual unregulated runoff of 158 m^3/s and a mean annual regulated runoff of 102 m^3/s (Mastin and Vacarro, 2002). The Yakima Basin headwaters are on the eastern slope of the Cascade Range and the Yakima River terminates at its confluence with the Columbia River (Figure 1). Basin elevations range from 122 to 2,440 m (Mastin and Vaccaro, 2002). Two reaches were modeled on the Yakima River, referred to as the Easton reach and the Kittitas reach. One reach on the Naches River was modeled, referred to as the Naches reach. Table 1 shows descriptions for each reach.

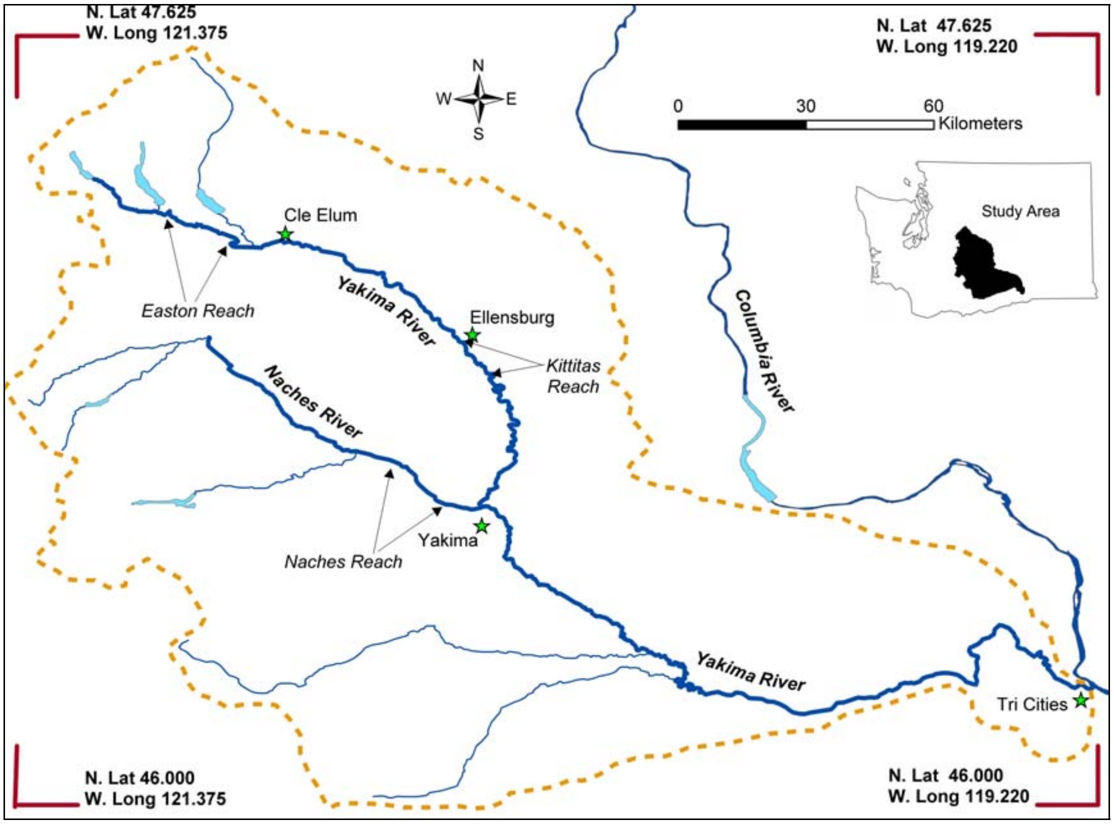

Figure 1: Site map of the Yakima Basin. Study reach locations are indicated.

Table 1: Descriptions of the modeled reaches.

Reach Name	Modeled Length (kilometers)	Modeled Discharges (m^3/s)	Characteristic Slope (%)
Easton	19.3	7.1 – 56.6	0.24
Kttitas	6.4	15.3 – 283	0.25
Naches	16.1	7.1 – 226.5	0.53

TERRAIN SURFACE GENERATION

Bathymetric LiDAR

Bathymetric LiDAR was obtained for the Easton and Kittitas reaches in September, 2004 and the Naches reach in May, 2005. Ground surveys of the underwater portion of the channel were obtained concomitantly with the ALB surveys and used to determine the accuracy and precision of the ALB surveys. A more detailed discussion regarding the ALB surveys is contained in Hilldale and Raff (2007).

Error statistics were obtained by comparing the ground survey point elevations to a common horizontal position of a kriged raster surface generated with the ALB survey data. Table 2 shows the error statistics of this comparison.

Table 2: Error statistics of the ALB data compared to ground surveys (taken from Hilldale and Raff, 2007). Error shown is from field measured values.

Reach Name	Mean (m)	Median (m)	Standard Deviation (m)	Number of samples
Easton	0.15	0.14	0.22	163
Kittitas	0.24	0.26	0.35	56
Naches	0.26	0.27	0.11	341

As seen in Table 2, a persistent positive bias is present, indicating an overestimation of the bed elevation by the LiDAR. The removal of bias in the ALB data is desirable before it is to be combined with other surveys. Table 3 shows bias adjusted data for the three study reaches. The data adjustment in this case was applied evenly across all bathymetric LiDAR points (block adjusted) by subtracting the mean error from the elevation provided by the ALB survey.

Table 3: Error statistics following an adjustment for bias (taken from Hilldale and Raff, 2007). Error shown is from field measured values.

Reach Name	Mean (m)	Median(m)	Standard Deviation (m)	Min. (m)	Max (m)
Easton	0.00	0.00	0.22	-1.11	0.56
Kittitas	0.00	0.02	0.35	-1.03	0.55
Naches	0.00	0.00	0.11	-0.35	0.29

Combining data sets to form a surface

Following the completion of the error analysis of the ALB data, it was combined with terrestrial LiDAR flown previously. The two point data sets were combined in Arc GIS (ver. 9.0, ESRI, Redlands, CA) to form a complete surface including the floodplain and channel. This surface was then converted to a format used by the Surface water Modeling System (SMS, EMS-I, Salt Lake City, UT) to be interpolated to the model mesh.

THE HYDRAULIC MODEL

The 2-D hydraulic model used for this project is GSTAR-W (Generalized Sediment Transport for Alluvial Rivers and Watersheds). GSTAR-W is a 2-D hydraulic, erosion and sediment transport model for rivers and watersheds developed by Lai (2006). GSTAR-W makes use of the arbitrarily shaped element method (ASEM) of Lai (2000), which is an unstructured meshing strategy providing a great deal of ease and flexibility in mesh representation. A diffusive wave solution was applied for this modeling effort using an implicit scheme. The diffusive wave solution assumes that the convective and diffusive transports of water are in equilibrium (Lai, 2006).

The meshes used in the three models were developed in SMS, the recommended software for mesh generation in GSTAR-W. The mesh is a combination of structured and unstructured elements (Figure 2). The structured portion of the mesh represents the active portion of the channel while the unstructured portion of the mesh represents the floodplain. Within the mesh, polygons are created to represent various roughnesses. After the mesh is constructed, a scatter point file containing elevation information from the surface generated in Arc GIS is interpolated to the mesh. In the active channel portion of the mesh, cell size varied from 2 to 3 meters in the lateral dimension and 3 to 6 meters in the longitudinal direction. The channel mesh cells are built in this fashion because there is generally less bed elevation change with respect to distance in the longitudinal direction, saving computational time without significant sacrifice in resolution.

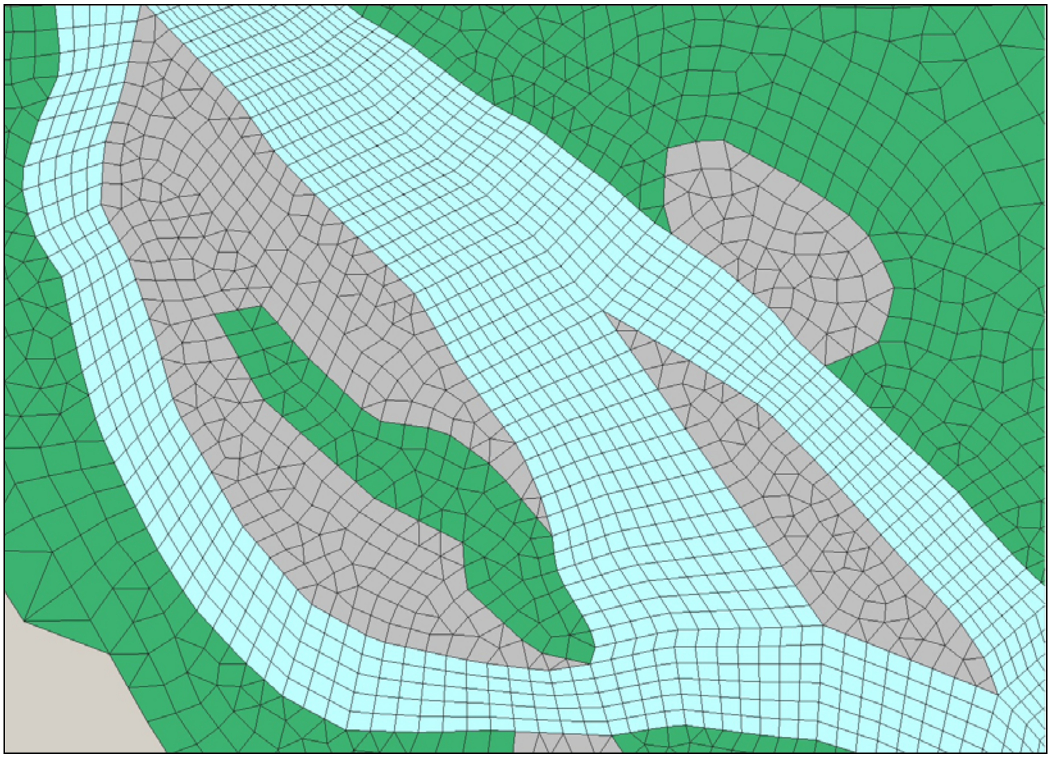

Figure 2: Example of the structured (light blue) and unstructured (green and gray) portions of the mesh. Colored regions represent different roughness values.

The models were verified with water surface elevation surveys at various locations throughout the reach at two different discharges. The surveys were performed with Real Time Kinematic (RTK) Global Positioning Satellite (GPS) survey equipment. The model error is shown in Table 4.

Table 4: Table of verification data comparing water surface elevations. The mean error and standard deviation are statistics on the differences between modeled and surveyed water surface elevations (modeled value minus surveyed value). (Taken from Hilldale and Mooney, 2006.)

Reach	Flow Rate (m^3/s)	Mean Error (cm)	Std. Deviation (cm)	Number of locations
Easton	7	-0.61	10.0	7
Easton	14	5.49	8.2	4
Kittitas	89	-1.22	13.1	continuous
Kittitas	29	7.0	14.9	4
Naches	20	0.3	11.0	5
Naches*	76	11.0	10.1	4

*Flows at the Naches Gage @ Naches fluctuated 2.3 m^3/s during this survey. Additionally, discharge fluctuated spatially throughout the reach by 1.8 m^3/s due to multiple irrigation diversions and returns. These were not considered in the model. An average of the estimated flows at each location was used for the modeled flow rate.

IDENTIFYING POOL-RIFFLE-GLIDE HABITAT WITH THE FROUDE NUMBER

Methodology

The primary use of the model output was to identify habitat types at various discharges. Jowett (1993) performed an analysis whereby habitat types were numerically determined using a variety of methods to increase replicability and predictability in river studies. Jowett (1993) evaluated habitat using the Froude number, slope, velocity/depth ratio and combinations of these values. For the present study, it was determined that the Froude number better defined the habitat types when compared to field data.

Using the model output at all flow rates, the Froude number $\left(F_r = \frac{V}{\sqrt{gh}}\right)$, where V is depth averaged velocity, g is the gravitational constant and h is the flow depth, was used to determine the locations comprising pools, glides and riffles. Determining the Froude values at which the habitat changes from one type to another was initially set to those values determined by Jowett (1993). The breaks in the Froude habitat classification were then adjusted to match field surveys of identified habitat types in all reaches modeled. Generally speaking, the Froude number changes gradually from one mesh cell to another, creating clusters of mesh cells corresponding to pools, glides or riffles. The following piecewise function was used for habitat determination:

pool → $F_r < 0.09$

glide → $0.09 \le F_r \le 0.42$

riffle → $F_r > 0.42$

The break in Froude number between pools and glides used in this study ($F_r = 0.09$) differs from that used by Jowett (1993), who used $F_r = 0.18$ but is very similar to that used by Reuter et al. (2003), $F_r = 0.10$. The break between glides and riffles used in this study was determined to be $F_r = 0.42$, similar to both Jowett (1993) and Reuter et al. (2003), who used $F_r = 0.41$ and $F_r = 0.40$, respectively.

Froude number values were categorized according to the piecewise function above and assigned an integer value 1 (pool), 2 (glide), 3 (riffle), or 4 (dry cells). A Triangulated Irregular Network (TIN) was then created in Arc GIS to display wetted areas as pools, glides, or riffles, with dry cells not displayed. In the process of creating a TIN, adjacent cells are interpolated between discrete habitat cell values. The interpolation results in decimal values between the integer values assigned each habitat type (e.g. the line of cells between a glide and a riffle will have a value between 2 and 3). These interpolations create a border one cell wide bounding each habitat classification. These borders are interpreted as transition zones between the habitat types. For calculations of habitat area, these transition zones were neglected.

Verification

Field verification of the Froude habitat classification was performed from a raft using a hand-held Trimble GPS to mark the beginning and end of visually identified pools, glides and riffles throughout the reach. The intent was to continuously map the reach, however there were many instances where identifying the beginning or end of a specific feature was unclear. Identifying pools, riffles and glides continuously in the field is a rather subjective process and led to some unidentified portions of the stream. Moreover, pools, glides and riffles are not the only identified features in a stream. Some researchers (e.g. Reuter et al., 2003) identify edge habitat, races and tailouts with this method, although this study did not call for these features.

Figures 3, 4 and 5 show the modeling results compared to field verification for sections of the lower Kittitas, Naches and Easton reaches. The results used in these figures are typical of results throughout each of the reaches. It was observed that identifying the habitat features (pool, glide and riffle) in the Naches reach was much less ambiguous than in the Easton and Kittitas reaches. This can be seen in Figures 3 – 5 where there are gaps between the field identified features. Another interesting observation is that features in the Easton reach average 60 meters in length while features in the Naches and Kittitas reaches average 121 and 117 meters, respectively. This result is probably a function of scale. A smaller channel with lower discharge is likely to have smaller features, as is the case with the Easton reach of the Yakima River.

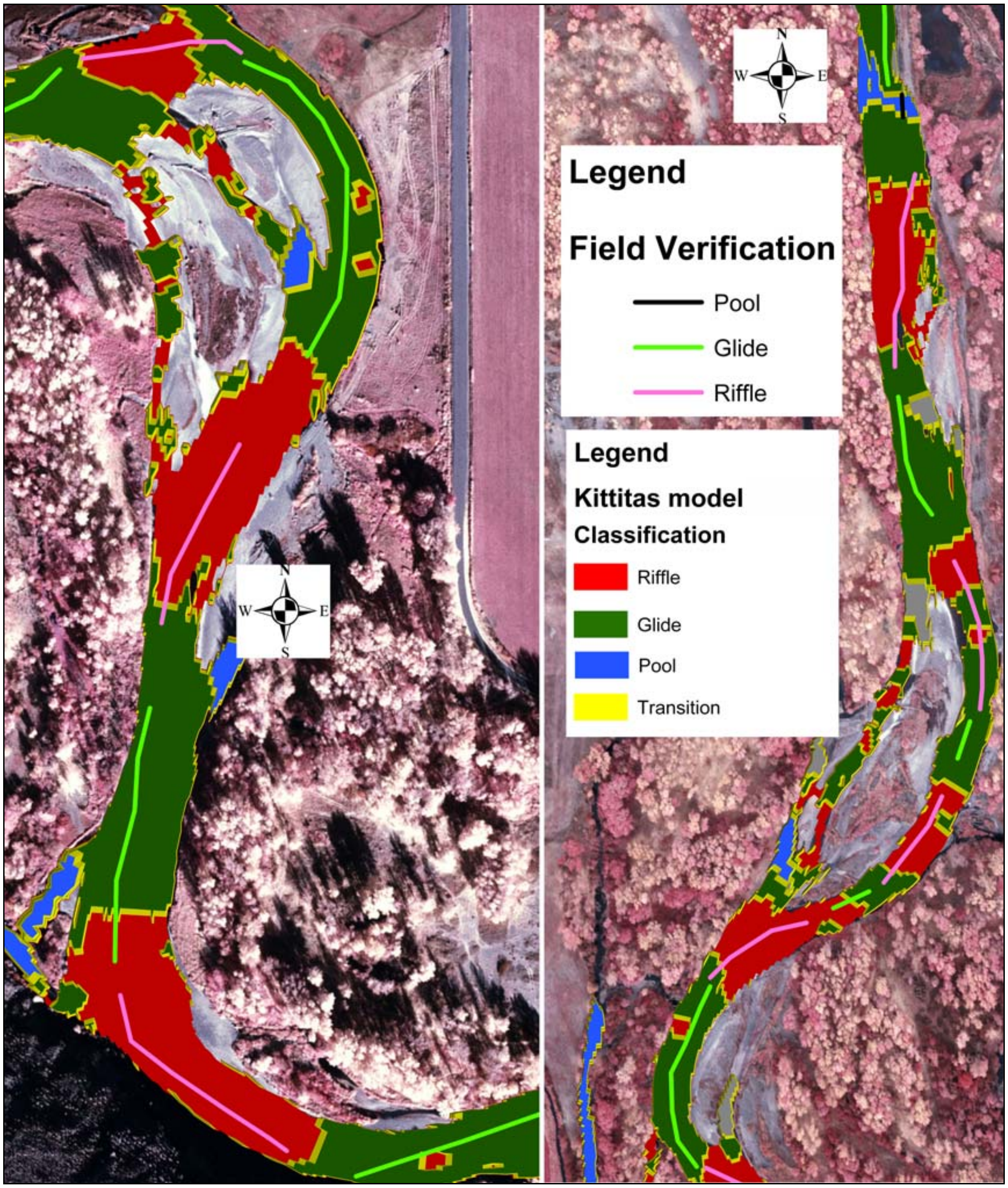

Figure 3: Aerial photograph (2000) with the habitat results TIN showing the modeled Froude classification and field verification. Two sections of the Kittitas reach are shown at 22.7 m^3/s (Flow direction is north to south). Missing data between field verification data lines is a result of ambiguity regarding classification.

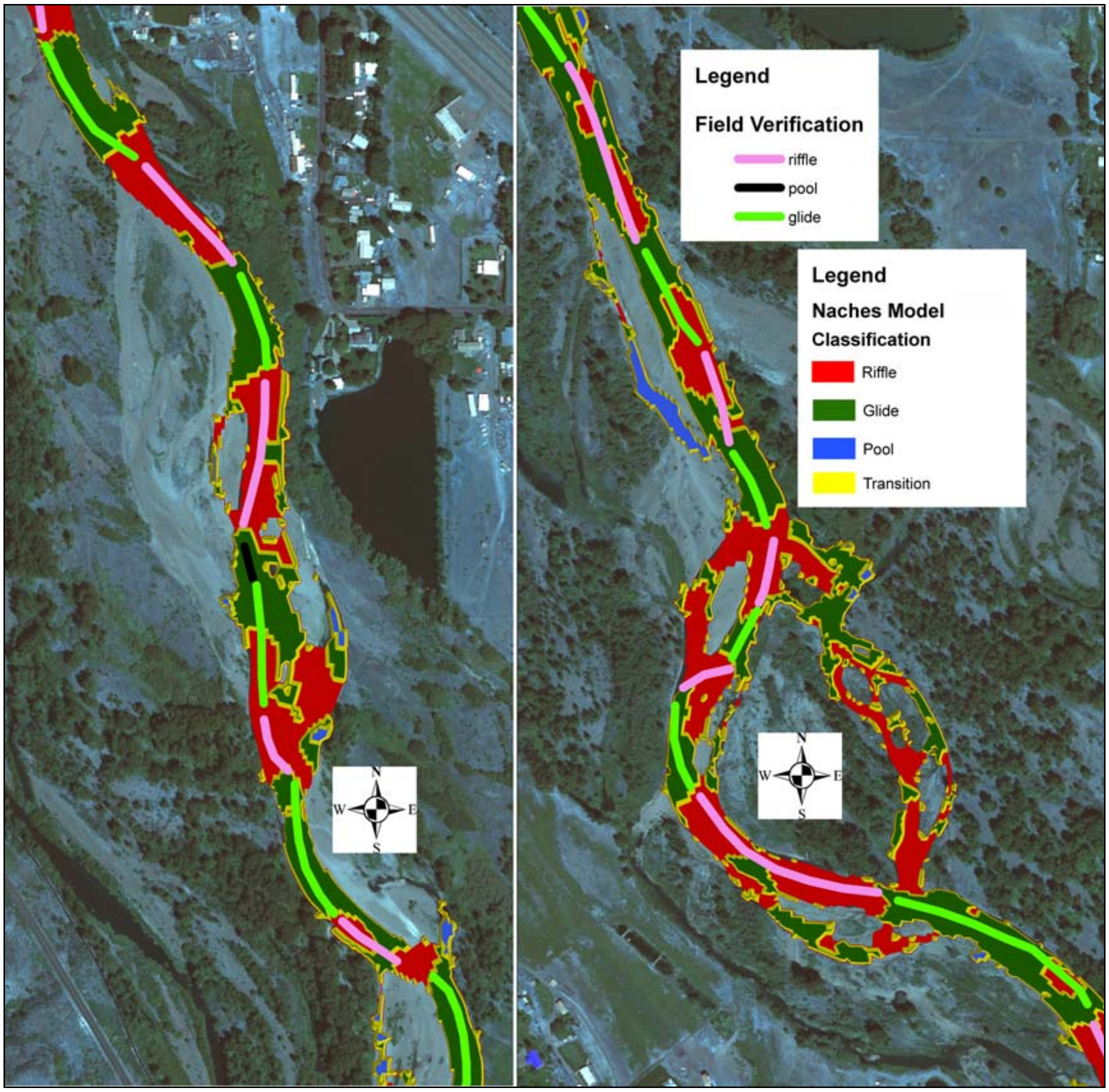

Figure 4: Aerial photograph (2003) with the habitat results TIN showing the modeled Froude classification and field verification. Two sections of the Naches reach are shown at 20.4 m^3/s (flow direction is north to south).

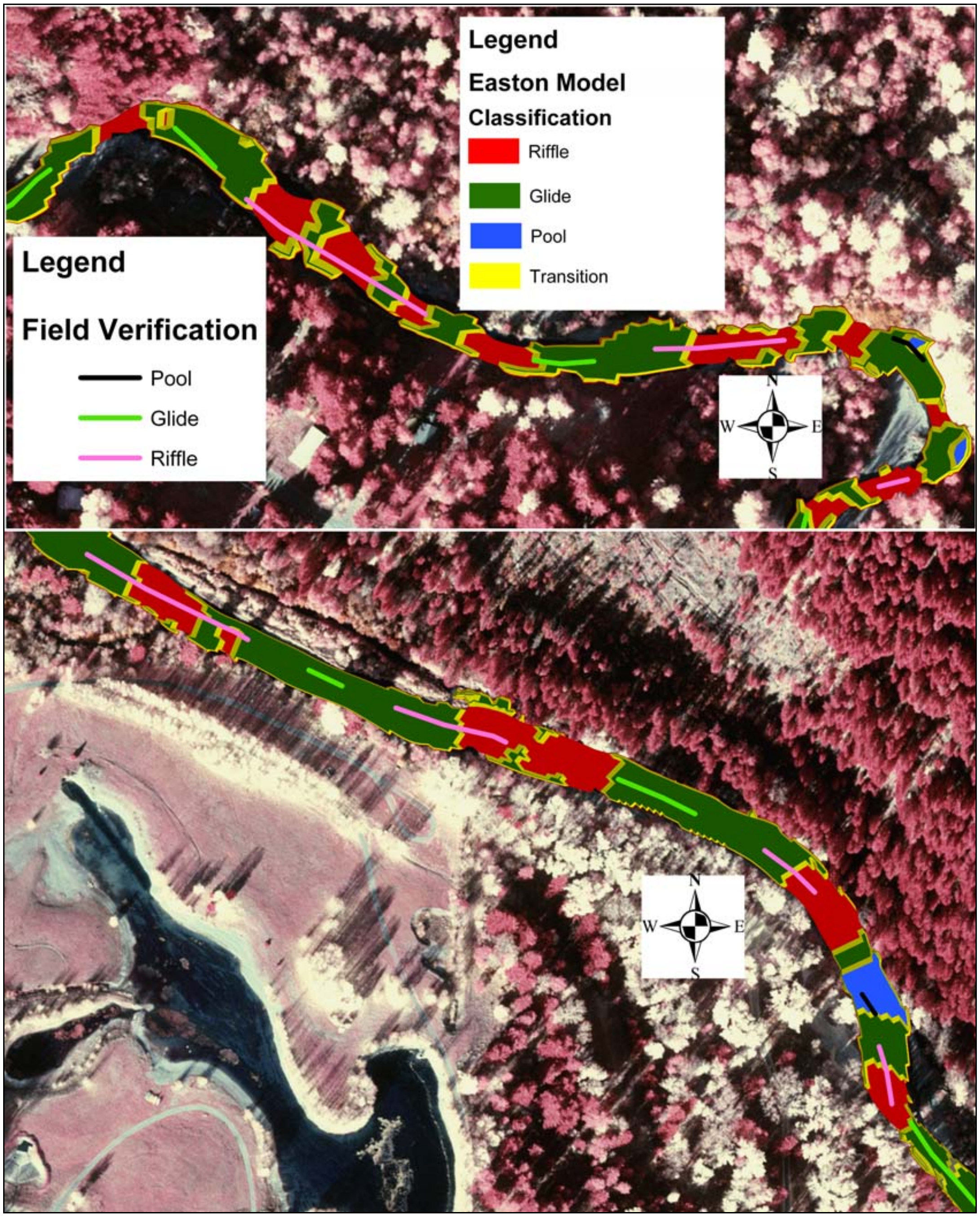

Figure 5: Aerial photograph (2000) with the habitat results TIN showing the modeled Froude classification and field verification. Two sections of the Easton reach are shown at 8.5 m^3*/s (flow direction is west to east). Missing data between field verification data lines is a result of ambiguity regarding classification.*

Measuring the Success of Modeling Habitat via the Froude Number

Measuring success of this method is somewhat difficult due to the subjective and discontinuous nature of the field verification. Additionally, the model determines location and spatial area of each feature while the field verification only measures the location and linear length of the features. The field verification did not account for identification of multiple features across the width of the channel. For this study, success was determined by measuring the length of each feature identified in the field and comparing that length to what was indicated in the model at a coincident location. An example of this type of measurement is shown in Figure 6, where there is a field determined glide that is completely represented by the modeled glide habitat. Also shown is a field determined riffle that has been modeled mostly as a riffle and partly as a glide. If the modeled habitat feature (i.e. pool, glide or riffle) was completely coincident with the same field identified feature, a score of 100% was given. When a field identified feature covered more than one modeled feature, the percentage of the field identified feature within a matching modeled feature was used. For example, Figure 6 shows a field identified riffle that lies partly over a modeled glide. The entire length of the field identified feature is 109.7 meters. The portion of the feature that lies outside the modeled riffle is 21.9 meters. The percent success for that modeled feature is $100 * \left(1 - \frac{21.9}{109.7}\right) = 80\%$. When a field identified feature crossed over a transition zone, the streamwise length of that transition zone was neglected.

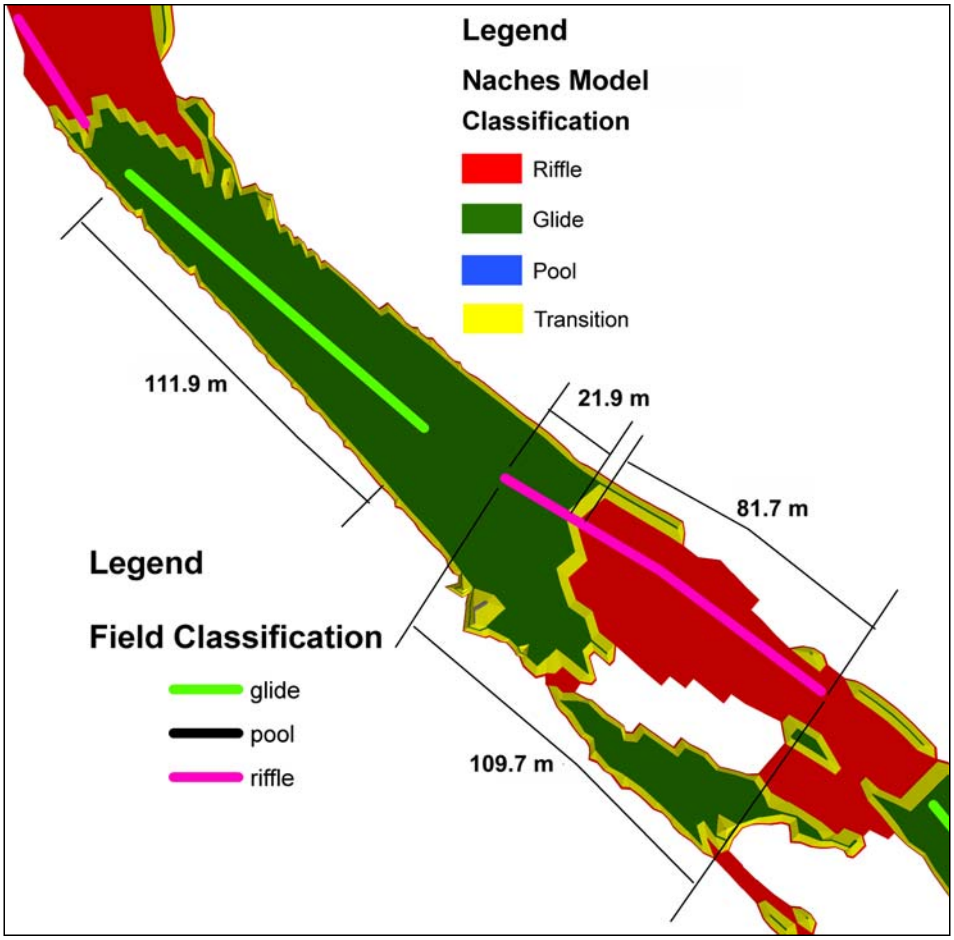

Figure 6: Example of measuring the field surveyed habitat type and comparing it to the modeled habitat type.

RESULTS

Overall, the modeled classification agrees well with the field verification. Table 5 summarizes the success. The number of pools identified by the model is not an appropriate representation of the total amount of pool habitat in each reach. The model can only account for large scale pool habitat and does not account for small or localized pool habitat created by structure such as woody debris, large boulder or bedrock features. The aerial survey of the bathymetry flown for this model has a horizontal spot spacing on the order of 2-x-2 meters, meaning that features on the order of 2 meters or less are not accurately represented. A significant contribution to pool habitat by large wood in the channel was noted during the float trips of all three reaches. It is not feasible that large wood in a stream be surveyed to the detail required for numerical modeling when the model covers many miles of river channel. Pool habitat also exists in the side channels and backwater areas that were not accounted for during the raft survey.

Table 5: Success of Froude habitat classification using GSTAR-W.

Reach	**Success for Riffles (%)**	**Success for Glides (%)**	**Success for Pools (%)**	**Number of Each Feature Identified in the Field**
Easton	63	87	64	69 Riffles. 66 Glides, 19 Pools
Kittitas	83	91	50	17 Riffles 15 Glides 2 Pools
Naches	87	77	0	34 Riffles 31 Glides 1 Pool

When pools, riffles, and glides are evaluated over various flow rates, their classifications gradually change. The length of pools becomes shorter with increasing flow as the features upstream and downstream encroach on the pool from each end until, occasionally, the entire pool feature becomes a glide. Figure 7 shows this procession over three discharges.

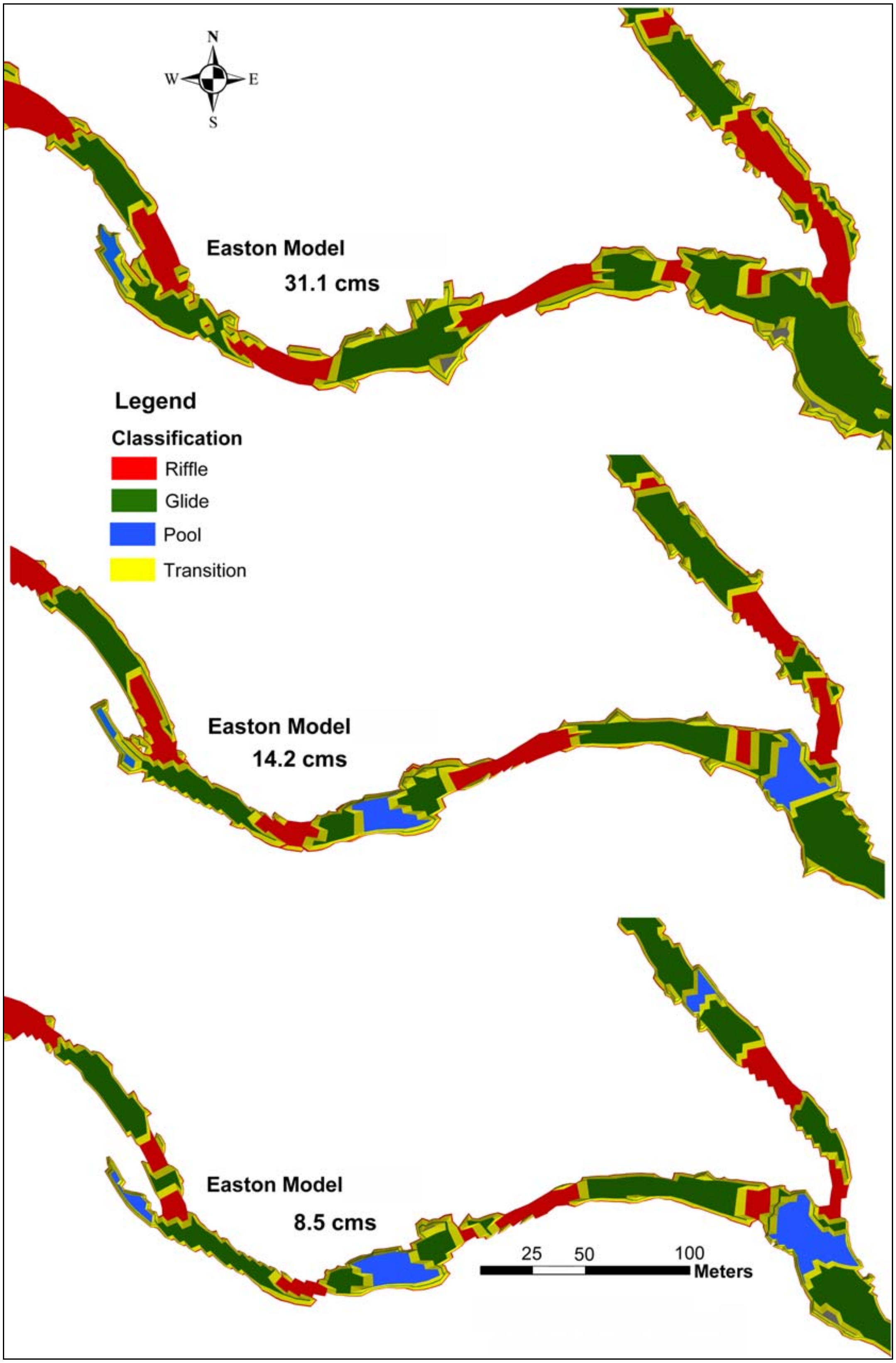

Figure 7: Example of the change in habitat types with a change in discharge (flow direction is west to east).

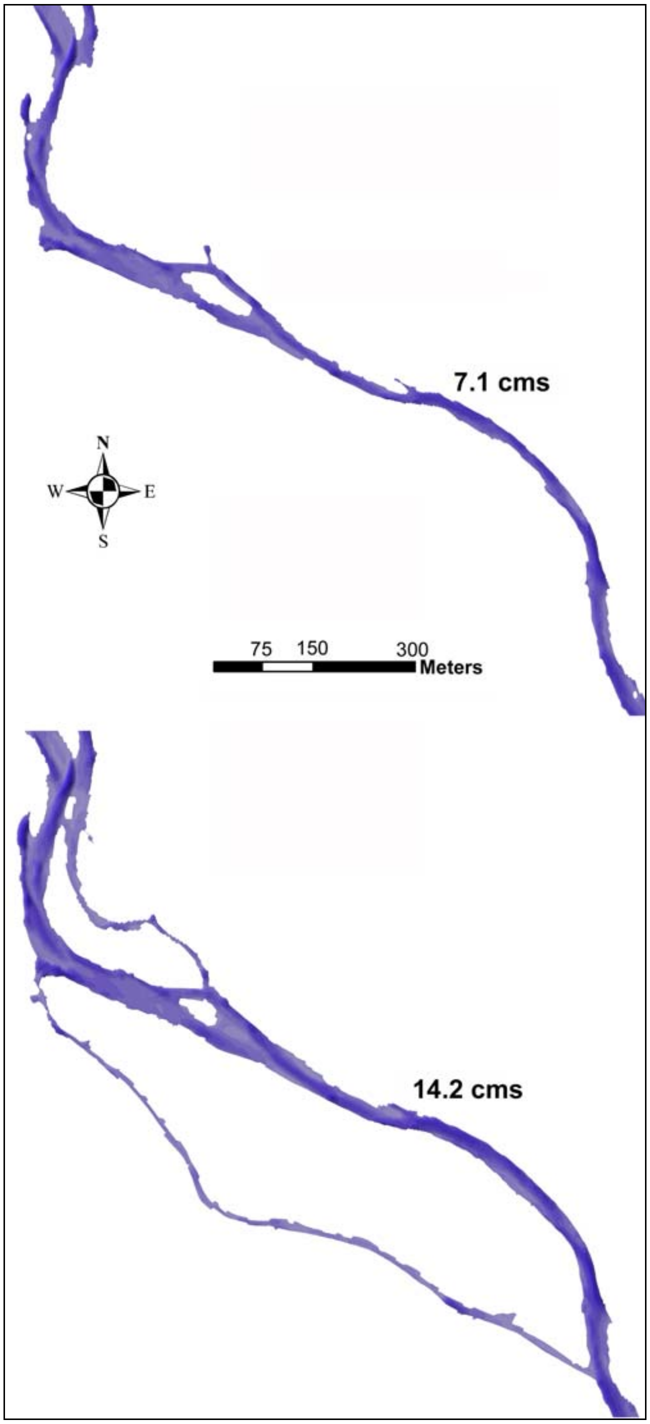

Figure 8: Map showing the same portion of the Naches Reach at 7.1 m^3/s and 14.2 m^3/s. Note that two side channels are only present at the higher discharge.

SIDE CHANNELS

Side channels have been identified as critical habitat for salmonids (Ring and Watson, 1999). It is therefore important to evaluate discharges at which side channels become active when evaluating overall habitat availability. This type of information is important when prescribing critical discharges for habitat in a regulated river. Figure 8 shows that two side channels form at discharges between 7.1 m^3/s and 14.2 m^3/s.

Not all side channels become active at similar discharges. Knowing the amount of available side channel habitat with discharge aids in optimization of flow releases at critical life stages of salmonids.

SPAWNING HABITAT

Following the completion of the modeling effort, it was discovered that spring Chinook (*Oncorhynchus tshawytscha*) redd locatations had been surveyed by the Northwest Fisheries Science Center (NOAA Fisheries, Seattle, WA) for the Easton reach. This data was made available and combined with the model results. Preliminary analyses correlating spawning habitat with the Froude number show promising results. When the location of spring Chinook redds are spatially combined with Froude number classifications, there is a strong correlation with Froude numbers between 0.3 and 0.6. Figures 9, 10 and 11 show the redd locations and Froude number classification for portions of the Easton reach. The legend in Figure 9 also applies to Figures 10 and 11.

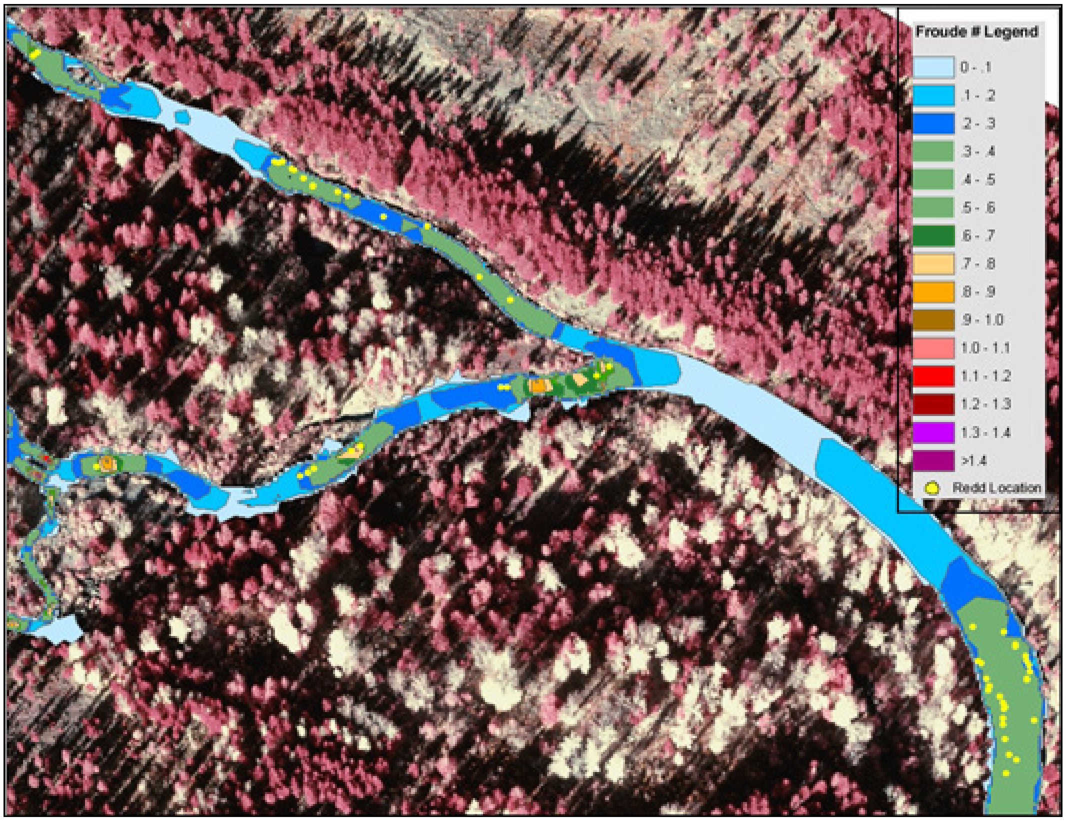

Figure 9: Aerial photograph of the Easton reach showing the Froude number classification and redd locations (yellow dots). Flow direction is west to east. (Figure courtesy of Ken Bovee.)

Model results in Figures 9, 10 and 11 are shown at a discharge of 8.5 m^3/s. The exact discharge during spawning is not known. However due to the fact that the Yakima River is highly regulated in this reach, it is very likely that the discharge was between 7 - 10 m^3/s during spawning.

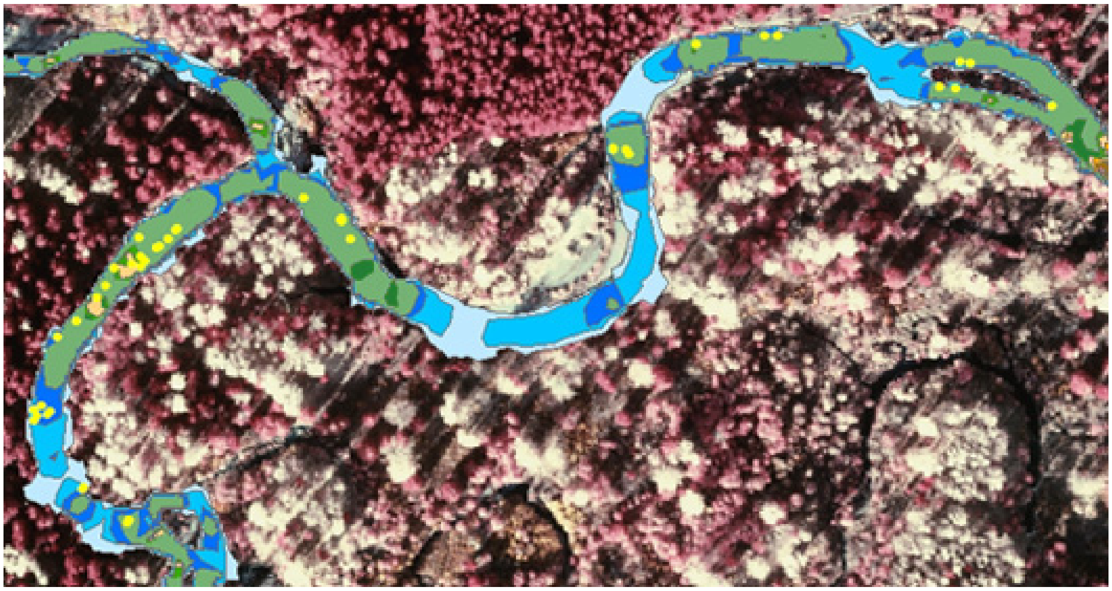

Figure 10: Aerial photograph of the Easton reach showing the Froude number classification and redd locations (yellow dots). Flow direction is west to east. The legend from Figure 9 applies. (Figure courtesy of Ken Bovee.)

Figure 11: Aerial photograph of the Easton reach showing the Froude number classification and redd locations (yellow dots). Flow direction is west to east. The legend from Figure 9 applies. (Figure courtesy of Ken Bovee.)

Although more analysis needs to be performed, preliminary results show it is likely that suitable spawning habitat can be modeled with respect to hydraulic conditions. It is hypothesized that portions of the river identified as suitable with respect to hydraulics may not have been utilized due to other requirements such as upwelling conditions and/or appropriate bed material size. Bedrock is exposed in some portions of this reach

It has been noted that the break between a glide and a riffle ($F_r = 0.42$) falls in the middle of the range where a vast majority of the redds exist ($0.3 < Fr < 0.6$). This range of Froude numbers coincides with what could be referred to as low gradient riffles or perhaps tailouts.

CONCLUSION

This report has shown that habitat can be modeled, with respect to hydraulic conditions, using detailed bathymetry, such as that obtained with airborne LiDAR, and a 2-D hydraulic model. Results of modeled habitat can range from the simplistic pool-glide-riffle analysis to a more detailed classification such as spawning habitat. It is possible that hydraulic conditions for other habitat types or life stages can be similarly modeled. Further research using similar data on different rivers will help show whether or not this method can be applied to other streams. A statistical analysis of the correlation between the redd data and the Froude number is planned as well as bed material analysis in areas where spawning did and did not occur. The success thus far regarding habitat analysis provides an indication that the airborne LiDAR bathymetry has captured the bed topography well enough perform habitat modeling on this scale.

ACKNOWLEDGEMENTS

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REFERENCES

Hilldale, R.C. and Mooney, D.M. (2007). Identifying stream habitat features with a two-dimensional hydraulic model. Prepared for the Yakima River Basin Water Storage Feasibility Study, Bureau of Reclamation, Technical Service Center, Denver, CO, January.

Hilldale, R.C. and Raff, D. (2007). "Assessing the ability of airborne LiDAR to map shallow river bathymetry." In press, *Earth Surface Processes and Landforms*.

Jowett, I.G. (1993). "A method for identifying pool, run and riffle habitats from physical measurements." *New Zealand J. of Marine and Freshwater Research*, 27, 2421 – 248.

Lai, Y.G. (2006). "User's Manual for GSTAR-W, ver. 1.0" Sedimentation and River Hydraulics, Bureau of Reclamation Report, Technical Service Center, Denver, CO. Available on line at www.usbr.gov/pmts/sediment.

Lai, Y.G. (2000). "Unstructured Grid Arbitrarily Shaped Element Method for Fluid Flow Simulation," *AIAA Journal*, 38(12), 2246-2252.

Marks, K. and Bates, P. (2000). “Integration of high-resolution topographic models with floodplain flow models”. *Hydrological Processes*, 14, 2109-2122.

Mastin, M.C. and Vaccaro, J.J. (2002). Watershed models for decision support in the Yakima River Basin, WA. USGS Open File Report 02-404, Tacoma, WA.

Mobrand, L.E., Lichatowich, J.A., Lestelle, L.C. and Vogel, T.S (1997). “An approach to describing ecosystem performance ‘through the eyes of salmon’.” *Can. J. Fish. Aquat. Sci.* 54, 2964–2973.

Reuter, J.M., Jacobson, R.B., and Elliot, C.M. (2003). “Physical stream habitat dynamics in lower Bear Creek, northern Arkansas.” Biological Sciences Report USGS/BRD/BSR-2003—002, Columbia Environmental Research Center, Columbia, MO.

Ring, T. E. and Watson, B. (1999). “Effects of geologic and hydrologic factors and watershed change on aquatic Habitat in the Yakima River Basin, Washington”. In: Watershed Management to Protect Declining Species, Rodney Sakrison and Peter Sturtevant, eds. American Water Resources Association, Middleberg, VA, TPS-99-4, p. 191 – 194.