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Identifying Stream Habitat Features With a Two-Dimensional Hydraulic Model

A component of

Yakima River Basin Water Storage Feasibility Study, Washington

Cle Elum River

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

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Yakima River Basin Water Storage Feasibility Study, Washington

Identifying Stream Habitat Features With a Two-Dimensional Hydraulic Model

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Chapter 1.0 INTRODUCTION

The Yakima River Basin Storage Study is investigating the need and benefit of increasing water storage in the Yakima Basin to provide beneficial flows for habitat and still meet irrigation demands. Presently, flow releases for irrigation do not coincide with the flows required for adequate aquatic habitat, in particular for salmonid fish species. The major thrust of the storage study is to shape annual hydrographs to more closely resemble the flow patterns that existed prior to regulation. With limited storage volumes in the basin, meeting the demands of both habitat and irrigation is challenging. This report details one aspect of the storage study, determining habitat availability at various flow rates using the two-dimensional (2-D) hydraulic model titled, Generalized Sediment Transport for Alluvial Rivers and Watersheds (GSTAR-W).

The Ecosystems Diagnostic and Treatment (EDT) model is being utilized (Mobrand, et al., 1997) to assess the benefit of modifying flow releases at certain times throughout the year. 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, written communication). To address some of the more specific input needs for the EDT model, two-dimensional (2-D) hydraulic models were constructed and run over a wide range of flows for selected reaches of the Yakima and Naches Rivers. A two-dimensional model provides continuous hydraulic data over an entire reach of interest, as opposed to one-dimensional (1-D) hydraulic models, which provide cross-sectional average hydraulic properties at discrete locations. Outputs of the 2-D models are flow depth, depth-averaged velocity, water surface elevation and Froude number. Identification of pool, riffle and glide habitat types used the Froude number. Additionally, the quantity and quality of side channel habitat can be evaluated over the given range of flows. The 2-D models discussed in this report were run over a range of flows from the lowest anticipated discharge to approximately 130% of bankfull discharge. The model results can be displayed and mathematically manipulated in a Geographical Information System (GIS) to categorize areas for each EDT reach.

1.1 EDT Attributes Provided by Hydraulic and Sediment Models

Many EDT attributes can be obtained with 1-D models, such as channel length, width, gradient and confinement, either natural or anthropogenic. The attributes requiring 2-D modeling are continuous values of depth averaged velocity, flow depth, and habitat types, such as pools (both in-channel and backwater), glides, and riffles. Additionally, off-channel and side channel habitat areas can be quantified using 2-D model results. An important aspect of evaluating side channels is the flow rate at which individual side channels become inundated.

1.2 Description of Modeled Reaches

Five reaches were chosen for a 2-D hydraulic model to obtain a data set with higher habitat resolution than a 1D model. The reaches were chosen based primarily on habitat characteristics outlined by Stanford, et al. (2002), who stated that restoration efforts in the Cle Elum, Kittitas, Naches, Gap-to-Gap, and Wapato Reaches provide the greatest potential for improvement to salmon and steelhead populations. It was decided by the Storage Study Technical Committee to replace the Cle Elum Reach with the Easton Reach, which is considered to be of biological significance. Three of the reaches were modeled by Reclamation (Hilldale & Mooney) and two reaches were modeled by the USGS (Hatton) (Figure 1). The reaches modeled by Reclamation are referred to as Easton (RM 193 to 203.5) and lower Kittitas (RM 149 to 153.5) on the Yakima River and Naches (RM 4 to 14) on the lower Naches River. The reaches modeled by the USGS are referred to as the Gap-to-Gap Reach (RM 109 to 118) and Wapato (RM 82.5 to 91.5) on the Yakima River. The USGS is responsible for reporting results for the Gap-to-Gap and Wapato Reaches.

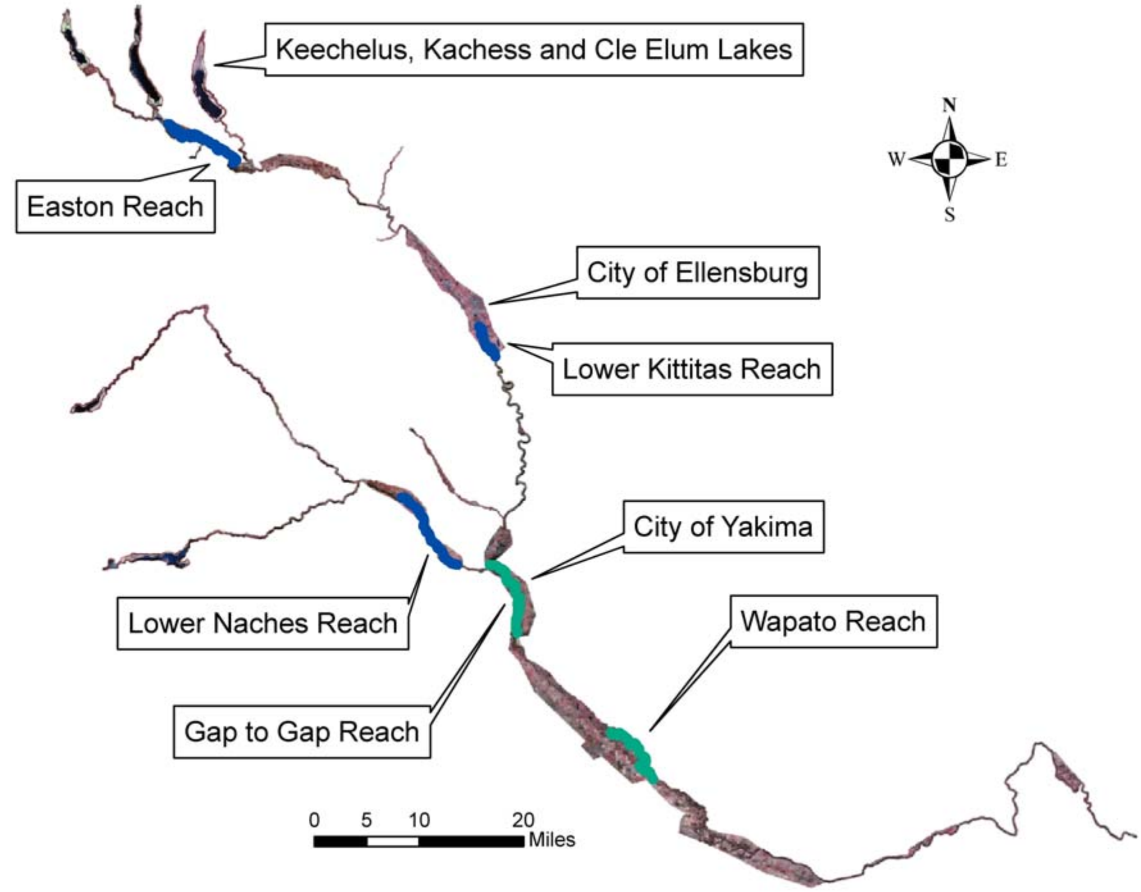

Figure 1. Aerial photograph of the Yakima Basin including the Yakima, Naches and Tieton Rivers. The 2-D hydraulic model reaches are shown in blue (Reclamation) and green (USGS).

1.2.1 Easton Reach (Yakima River)

The Easton Reach of the Yakima River begins just downstream of Easton Dam near River Mile 203.5 and continues downstream to the Interstate 90 Bridge at River Mile 193 (Figure 2). The upstream end of this reach (RM 199 to RM 203) is characterized as anastomosed, with the remaining portion of the river being single-thread. A few locations in this reach are vertically controlled by bedrock. Flow rates in this reach are typically much less than downstream of the Cle Elum River mouth. Flows modeled in this reach range from 250 to 2,000 ft^3/s. The characteristic slope of this reach is 0.24%. This reach contains more large woody debris than the other two reaches modeled by Reclamation.

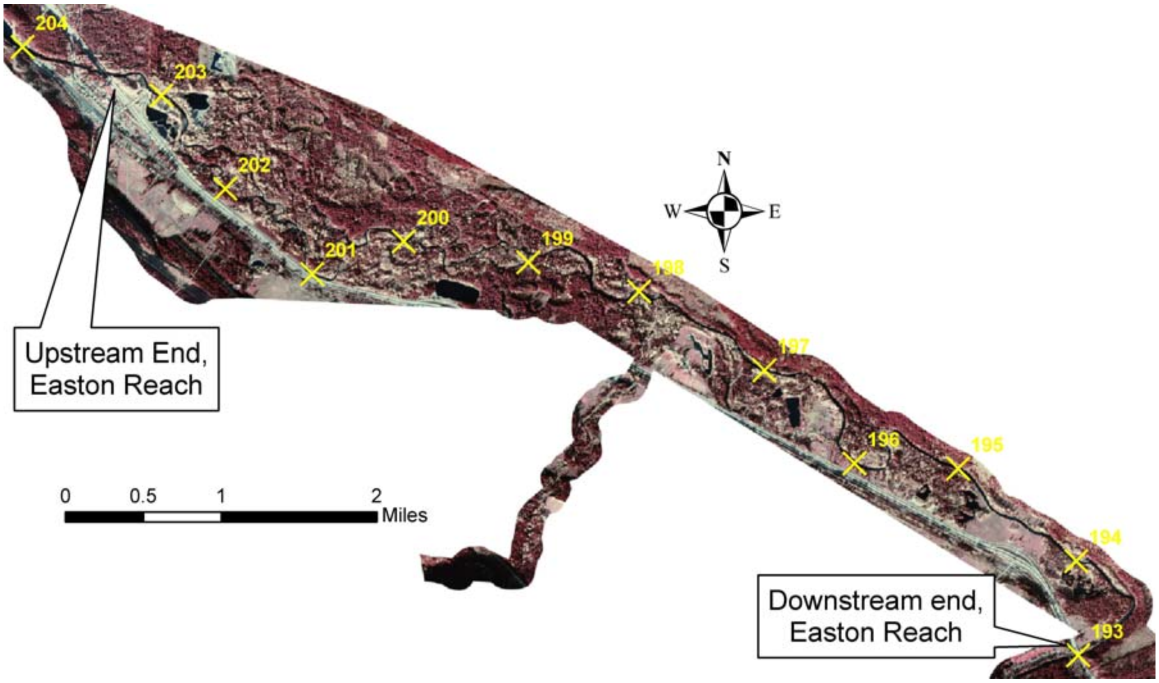

Figure 2. Aerial photograph showing the Easton Reach (river miles are shown in yellow).

1.2.2 Lower Kittitas Reach (Yakima River)

The lower Kittitas Reach begins 2 miles downstream of the Irene Reinhart boat launch and terminates near the head of the Yakima Canyon (Figure 3). The Reaches Report (Stanford et al., 2002) identifies this area as the reach of the Yakima River with the highest habitat channel complexity. The range of flows modeled in this reach were 540 to 10,000 ft^3/s. The characteristic slope for this reach is 0.25%. Significant side channel habitat exists throughout the reach.

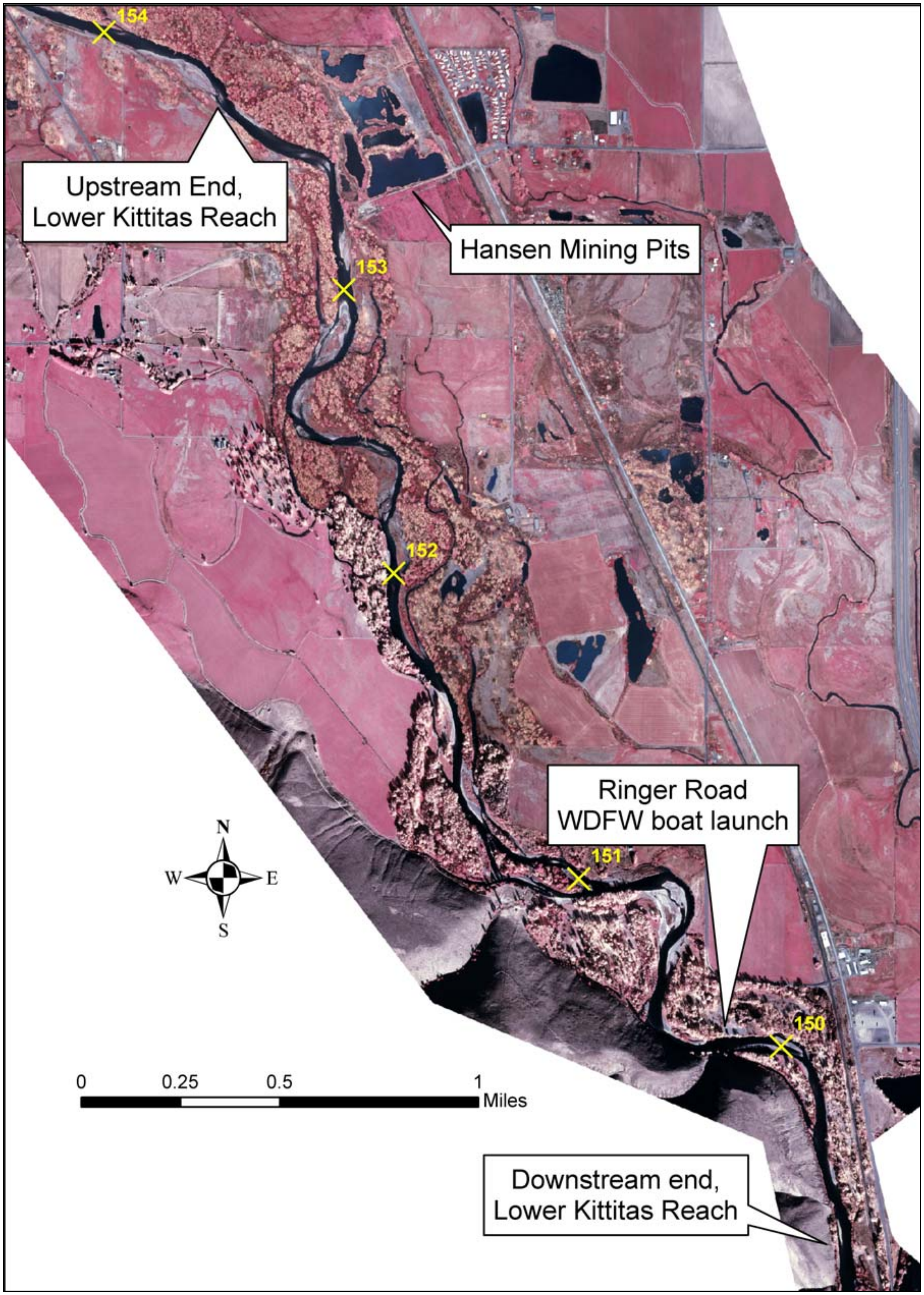

Figure 3. Aerial photograph of the lower Kittitas Reach (river miles are shown in yellow).

1.2.3 Lower Naches Reach (Naches River)

The Naches Reach begins at the Naches Bridge in the town of Naches (RM 14) and terminates near the Highway 12 twin bridges (RM 4) (Figure 4). This reach of the Naches River is subject to numerous irrigation diversions and returns, which were not accounted for in the model. It was decided that the additional effort of accounting for the many diversions and returns would not significantly alter the analysis of habitat in this reach. In the lower Naches River, there are many locations where the water surface varies across the cross section. This typically occurs at locations that have split channel morphology, where riffles exist on both sides but in different locations longitudinally. Many of these locations were noted during a raft trip down the reach. A check of the modeled water surface elevations at these locations verified that this type of feature was properly duplicated in the model. The flows modeled for this reach ranged from 250 to 8,000 ft^3/s.

1.2.4 Data Sources

The data used to build the model terrain and bathymetry was obtained from two sources. Terrestrial Light Detection and Ranging (LiDAR) was collected aerially in November 2000. The underwater portion, or bathymetry, was collected with water-penetrating LiDAR in September 2004 for the Easton and lower Kittitas Reaches and May 2005 for the Naches Reach. The point data from both LiDAR sets and contour lines generated from the terrestrial LiDAR were used to construct a continuous surface of above- and below-water terrain using Arc GIS. In many locations break lines had to be added along contours and adjusted to create a smooth transition from underwater to above-water terrain where the two sets of points met. However, the two data sets merged quite well with the exception of a few locations on the Naches River. In those locations, the river had migrated in the time between the terrestrial and bathymetric data collection, making it necessary to eliminate some of the terrestrial data points and use the bathymetry data. The complete set of bathymetric and terrestrial data points and contours were used to create a Triangulated Irregular Network (TIN). This surface was then converted to feature points for interpolation to the mesh, discussed in the next section.

The spot spacing for the bathymetry data is at a resolution of no greater than 6.5 feet. This is the greatest resolution provided by the LiDAR Bathymeter. For more information regarding the bathymetric LiDAR data, see Hilldale and Raff (2007).

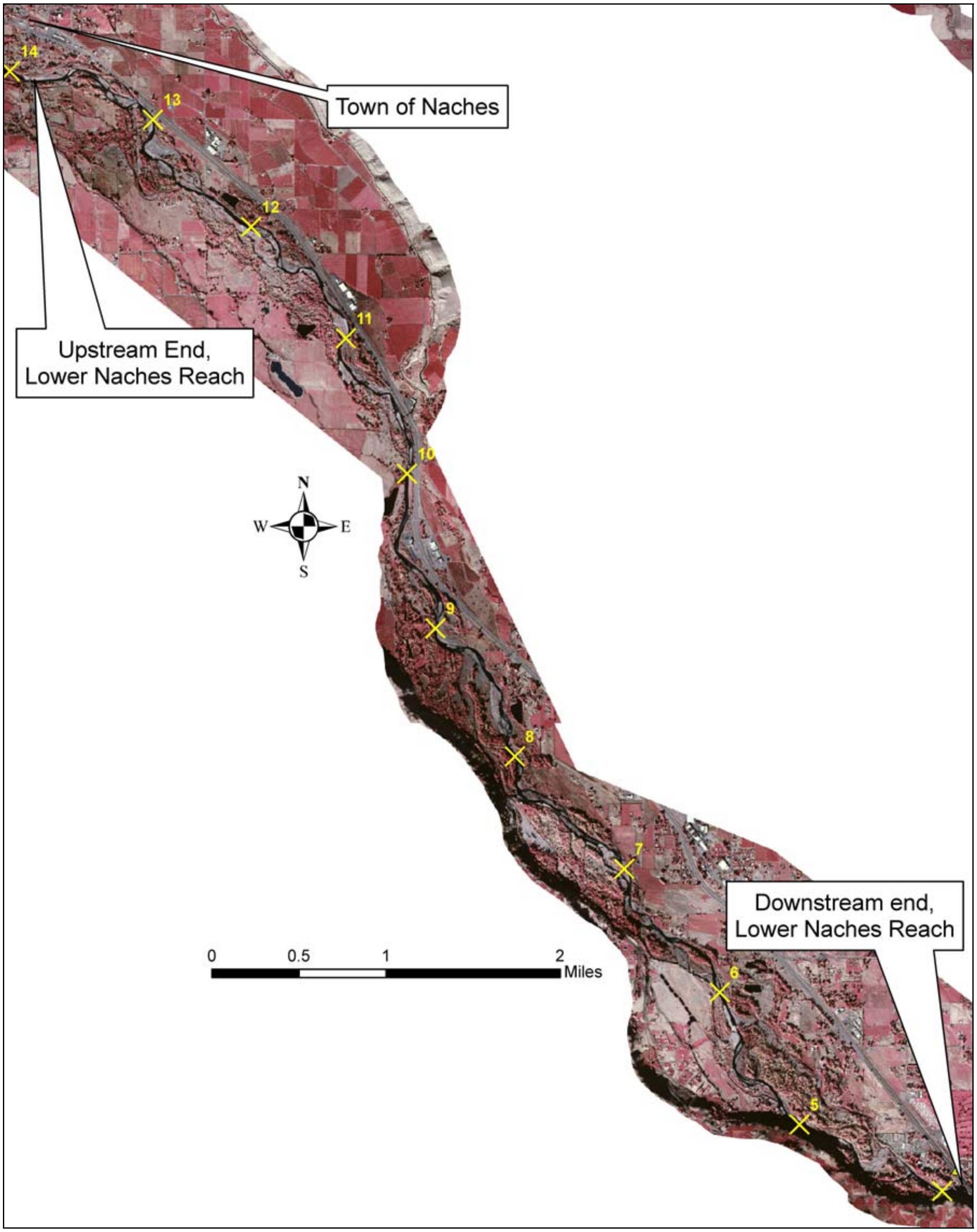

Figure 4: Aerial photograph of the lower Naches Reach, Naches River (river miles are shown in yellow).

Chapter 2.0 MODEL SPECIFICS

2.1 Mesh Generation

The finite element mesh used for the model was created using the Surface-water Modeling System (SMS) software package. The mesh combines structured and unstructured regions. The structured portion of the mesh represents the channeled portions of the terrain. The unstructured portion represents the overbank areas of the terrain (Figure 5).

The structured portions of the mesh represent the channel using rectangular cells with the long dimension coincident with the upstream/downstream direction. The unstructured portion of the mesh consists of three-, four- or five-sided polygons. At greater distances from the channel the unstructured mesh resolution decreases (cell size increases) in order to reduce the overall number of mesh cells. This type of mesh greatly reduces computing time while maintaining sufficient resolution in areas of greater interest. The resolution of the structured mesh is generally consistent throughout each model and typically varies in the width (short dimension) as the active channel changes width. Structured meshes require the same number of nodes across the channel at each end of a region. Where there are significant changes in active channel width, regions were created in such a way that the number of nodes across the channel could be adjusted to maintain a mostly consistent resolution. For all reaches, the cell sizes in the active channel varied from approximately 6 to 10 feet in the lateral direction and 10 to 20 feet in the streamwise direction. The mesh cell size is related to the resolution of the survey data.

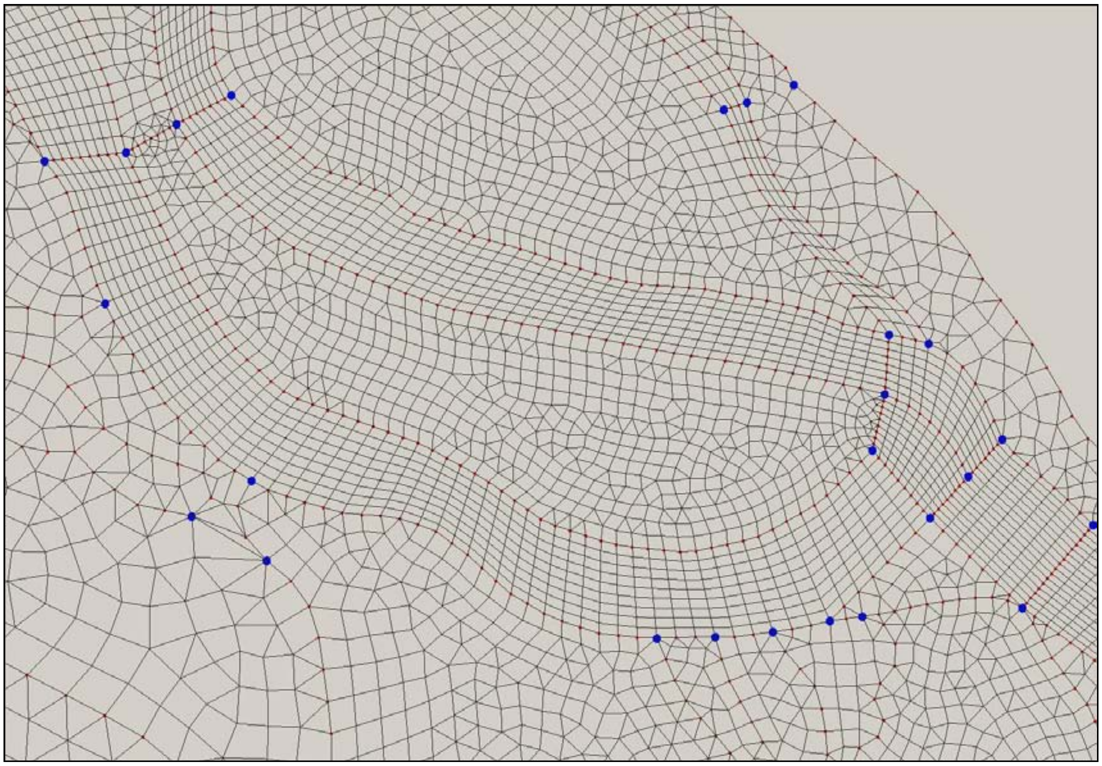

Figure 5: Example of the structured and unstructured mesh used in the 2-D models. The rectangular shaped cells represent the active portion of the channel, while the irregular polygons represent the floodplain. Note that the resolution is higher in and around the active channel and decreases with increasing distance from the active channel.

2.2 Hydraulic Model

The following excerpt is a comprehensive description of the GSTAR-W model, taken from the User's Manual for GSTAR-W (Lai, 2006b).

> GSTAR-W, Generalized Sediment Transport for Alluvial Rivers and Watersheds, is a two-dimensional (2D) hydraulic and sediment transport model for river systems and watersheds. It has been developed primarily for use by Reclamation engineers to solve various hydraulic and sedimentation problems; and it has been applied successfully to many projects at Reclamation.
>
> GSTAR-W is a 2D model that may be used to predict water flow and sediment transport for river reaches or water runoff and sediment delivery for a watershed. GSTAR-W adopts an approach for coupled modeling of channels, floodplains, and overland flow. Major features include the following:

Hybrid Zonal Modeling: GSTAR-W divides a watershed or river reaches into modeling zones. A zone may represent a 1D river reach or a 2D feature that may be solved with suitable models and algorithms. This layered hybrid approach facilitates the use of most appropriate models and solvers for each zone; it also extends the model to larger spatial and time scales.

Geometry Representation: The arbitrarily shaped element method (ASEM) of Lai (2000) is adopted for geometry representation. This unstructured meshing strategy is very flexible and facilitates the implementation of the hybrid zonal modeling concept. It essentially allows the use of most existing meshing methods available. For example, it allows a natural representation of a channel network in 1-D or 2-D, as well as the surroundings (flood plains or watersheds). With ASEM, a tight integration between watershed and channel system is achieved and a truly mesh-convergent solution may be obtained.

Major capabilities of GSTAR-W are listed below:

- GSTAR-W solves the 2-D form of the diffusive wave or dynamic wave equations. The dynamic wave equations are the standard St. Venant depth-averaged equations;

- Both diffusive wave and dynamic wave solvers use the implicit scheme so that solution robustness and efficiency may be achieved for a majority of applications;

- Both steady or unsteady flows may be simulated;

- Unstructured or structured 2-D meshes, with arbitrary element shapes, may be used with GSTAR-W. In most applications, a combination of quadrilateral and triangular meshes works the best. A Cartesian or raster mesh is a special mesh that may also be used by GSTAR-W;

- All flow regimes, i.e., subcritical, transcritical, and supercritical flows, are simulated simultaneously;

- Solution domain may include a combination of main channels, floodplains, and overland;

- Both steady and unsteady sediment transport may be simulated with the nonequilibrium approach for nonuniform sediment transport;

- Sediment transport module includes more than 10 non-cohesive sediment transport capacity formulae that are applicable to a wide range of hydraulic and sediment conditions.

- Fractional sediment transport with bed sorting and armoring.

> GSTAR-W is a 2-D model and it is particularly useful for problems where 2D effect is important. Examples include flows with in-stream structures, through bends, with perched rivers, and for multiple channel systems. A 2-D model may also be needed if one is interested in local flow velocities and eddy patterns.

The 2-D channel network portion of GSTAR-W was used for modeling the reaches in this report using a diffusive wave solution with an implicit scheme. The diffusive wave solution assumes the convective and diffusive transports of water are in equilibrium. Eddies and flow separation are not considered, resulting in a loss of the ability to calculate micro- and meso-scale flow conditions that might occur in the vicinity of large instream boulders or woody debris. The scale of the survey data, on the order of 6.5 feet, does not provide proper resolution to define such meso-scale stream structure, much less the micro-scale. Although the diffusive wave solver can calculate sub-, super-, and trans-critical flow, a hydraulic jump is transitionally smoothed. For the purpose of this modeling effort, these properties are not crucial. For the diffusive wave solver, the Manning roughness coefficient should be interpreted as the energy loss coefficient. Additional losses due to eddies, separations, and hydraulic jumps are lumped together within this coefficient. These roughness values are on the order of traditional 1-D models.

The outputs available from this model are spatially rectified values of x-velocity, y-velocity, magnitude velocity, depth, water surface elevation, bed elevation, and Froude number. This data can be manipulated and presented in a number of ways, including shape files in Arc GIS.

2.2.1 Roughness

Various roughness values were assigned to specific regions of the model via polygons while creating the mesh (Figure 6). In all models there were five primary roughness categories used to represent the various conditions: main channel; littered gravel bars; side channels; cultivated floodplain; and forested regions. The Manning's roughness value of the side channels and littered gravel bars increased by 0.005 over the main channel roughness. It is common for debris to collect and small vegetation to grow inside channels, slightly increasing the roughness. The same applies to gravel bars where low vegetation growth and forest litter can slightly impede flow. The forested portions of the floodplain were given the highest roughness (Table 1).

Table 1: Table of Manning's Roughness Values Used in the 2-D Models.

Main channel	Side channel/ littered gravel bar	Cultivated field areas	Forested areas
0.03-0.035	0.035-0.045	0.04-0.045	0.055-0.07

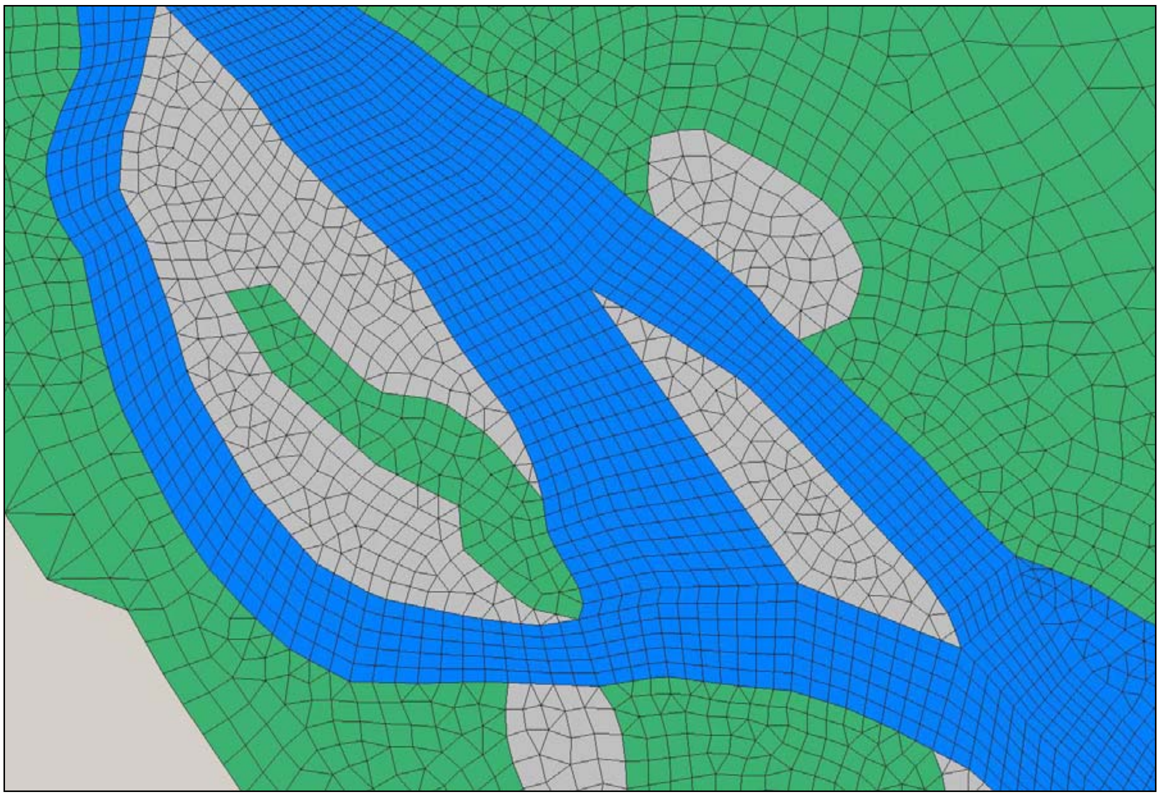

Figure 6: Example of the mesh used in the 2-D models. The colored areas represent specific roughness values. Blue represents main channel roughness, grey represents a gravel bar somewhat rougher than the main channel, and green represents forested portions of the floodplain.

2.2.2 Boundary Conditions

The models include three types of boundary conditions—upstream, downstream, and a slip boundary. The upstream boundary is the incoming flow rate. The downstream boundary is a fixed water surface elevation. The slip boundary is essentially a friction-free 'wall' built around the model. Ideally the flow should not meet the slip boundary.

The downstream boundary condition requires knowledge of the water surface elevation at various flow rates. A rating curve can be developed over a wide range of measured flow rates and corresponding water surface elevations. In the absence of adequate measured data, a 1-D hydraulic model can be constructed for the downstream-most portion of the reach, from which a stage-discharge rating curve can be developed. The latter method requires at least one or two known water surface elevations to verify the 1-D model results.

The downstream boundary condition for all three models used water surface elevation values determined for each flow with a 1-D hydraulic model verified with surveys at two different flow rates.

2.2.3 Model Verification

Verification of the models was performed by matching surveyed water surface elevations with modeled water surface elevations at various locations throughout each reach for a minimum of two different flow rates. Surveys of water surface elevations were performed with RTK GPS surveying equipment at accessible locations along each reach.

Table 2: Table of verification data comparing water surface elevations. The mean value and standard deviation are statistics on the differences between modeled and surveyed water surface elevations (modeled value minus surveyed value).

Reach	Flow Rate (cfs)	Mean Error (ft)	Standard Deviation (ft)	Number of Locations
Easton	250	-0.02	0.33	7
Easton	500	0.18	0.27	4
Kittitas	3146	-0.04	0.43	N/A
Kittitas	1032	0.23	0.49	4
Naches	720	0.01	0.36	5
Naches	2680*	0.36	0.33	4

*Flows at the Naches Gauge @ Naches fluctuated 80 ft^3/s during the survey. Additionally, flows fluctuated spatially throughout the reach by 63 ft^3/s due to irrigation diversion and return. An average of the estimated flows at each location was used for the modeled flow rate.

Chapter 3.0 HABITAT VIA FROUDE NUMBER

A major component of this study was to use the model output to identify habitat types, i.e., pools, riffles, and glides, at various flow rates. 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 evaluated habitat using the Froude number, slope, velocity/depth ratio and combinations of these values. Although it was found that a velocity/depth ratio best described these habitats, the difference in success between the Froude number and velocity depth ratio was small. 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 areas comprising pools, glides and riffles. Determining the Froude values at which the habitat changes from one type to another was initially done by experiment, beginning with the values determined by Jowett (1993). The break in habitat Froude classification was then adjusted to match field surveys of identified habitat types in all reaches modeled. Generally, the Froude number changes very little 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:

$F_r < 0.09$ → pool

$0.09 \le F_r \le 0.42$ → glide

$F_r > 0.42$ → riffle.

The break in Froude number between pools and glides used in this study 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 Fr = 0.42, similar to Jowett (1993), who used Fr = 0.41. Reuter further defined a habitat category of races, 0.2 < Fr < 0.4, with riffles defined as having a Froude number greater than 0.40, similar to the findings of this study.

A TIN was created in Arc GIS to display the results. In the process of creating a TIN, neighboring cells are interpolated between discrete habitat cell values. These interpolations consist of one cell in each dimension bounding each cluster of habitat classifications. Habitat features naturally include transitions along the boundaries of pools, glides and riffles that exist in the stream. For calculations of habitat area, these transition zones are neglected.

3.1 Field Verification of Determining Habitat via the Froude Number

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. Joel Hubble, a fisheries biologist for Reclamation (Upper Columbia Area Office), assisted with the field habitat identification. The intent was to continuously map the reach; however, there were instances where identifying the habitat was unclear. Identifying pools, riffles and glides is a subjective and qualitative process and led to some unidentified lengths. This can be seen in the following figures where there is a measurable distance between some field classifications. Another cause of unidentified portions of the reach can also be attributed to the difficulty in marking the beginning or end of a specific feature while floating in a raft. There were occasions where a feature type was not realized until the raft had already passed the true beginning of the feature.

Figure 7, Figure 8 andFigure 9 show 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 all the reaches. It was noted during the float surveys and data processing that the habitat features (pool, glide and riffle) in the Naches and Kittitas Reaches are much more easily defined than those in the Easton Reach, from the standpoint of both field identification and modeling. The habitat features in the Easton Reach are much more discontinuous. Evidence of this is shown in the average length of each feature identified in the field. Features in the Easton Reach average 196 feet in length, while features in the Naches and Kittitas Reaches average 397 and 384 feet, respectively. This result is probably a function of scale. A smaller channel with lower discharge is likely to have smaller features.

3.1.1 Measuring Success of Modeling Habitat with 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 length of the features. Field verification does not account for identification of multiple features across the width of the channel in one location. 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 10, where there is a modeled glide that is completely represented by the field determined habitat. Also shown is a field determined riffle that has been modeled partly as a riffle and partly as a glide. If the modeled habitat feature (i.e., pool, glide or riffle) was completely coincident with a like 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 10 shows a field-identified riffle that lies partly over a modeled glide. The entire length of the field-identified feature is 360 feet. The portion of the feature that lies outside the modeled riffle is 72 feet. The percent success for that modeled feature is:

$$100 * \left(1 - \frac{72}{360}\right) = 80\% .$$

When a field-identified feature crossed over a transition zone, that length was neglected. There were some instances where this occurred more than once per field-identified feature.

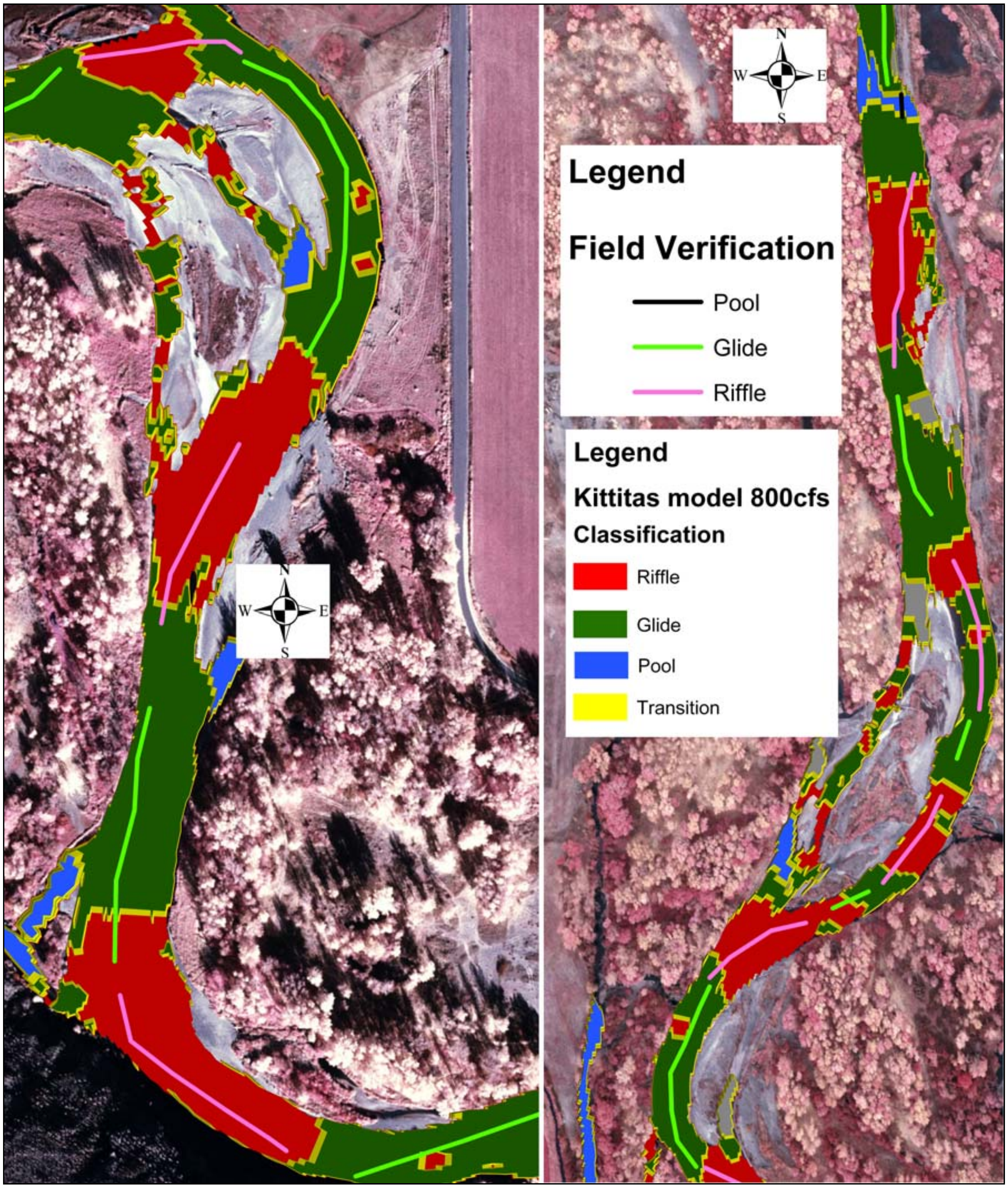

Figure 7. Aerial photograph (2000) with the habitat results TIN overlaid showing the modeled Froude classification and field verification. Two sections of the lower Kittitas Reach are shown at 800cfs (legend applies to both figures). Missing data between field verification data lines is a result of ambiguity regarding classification.

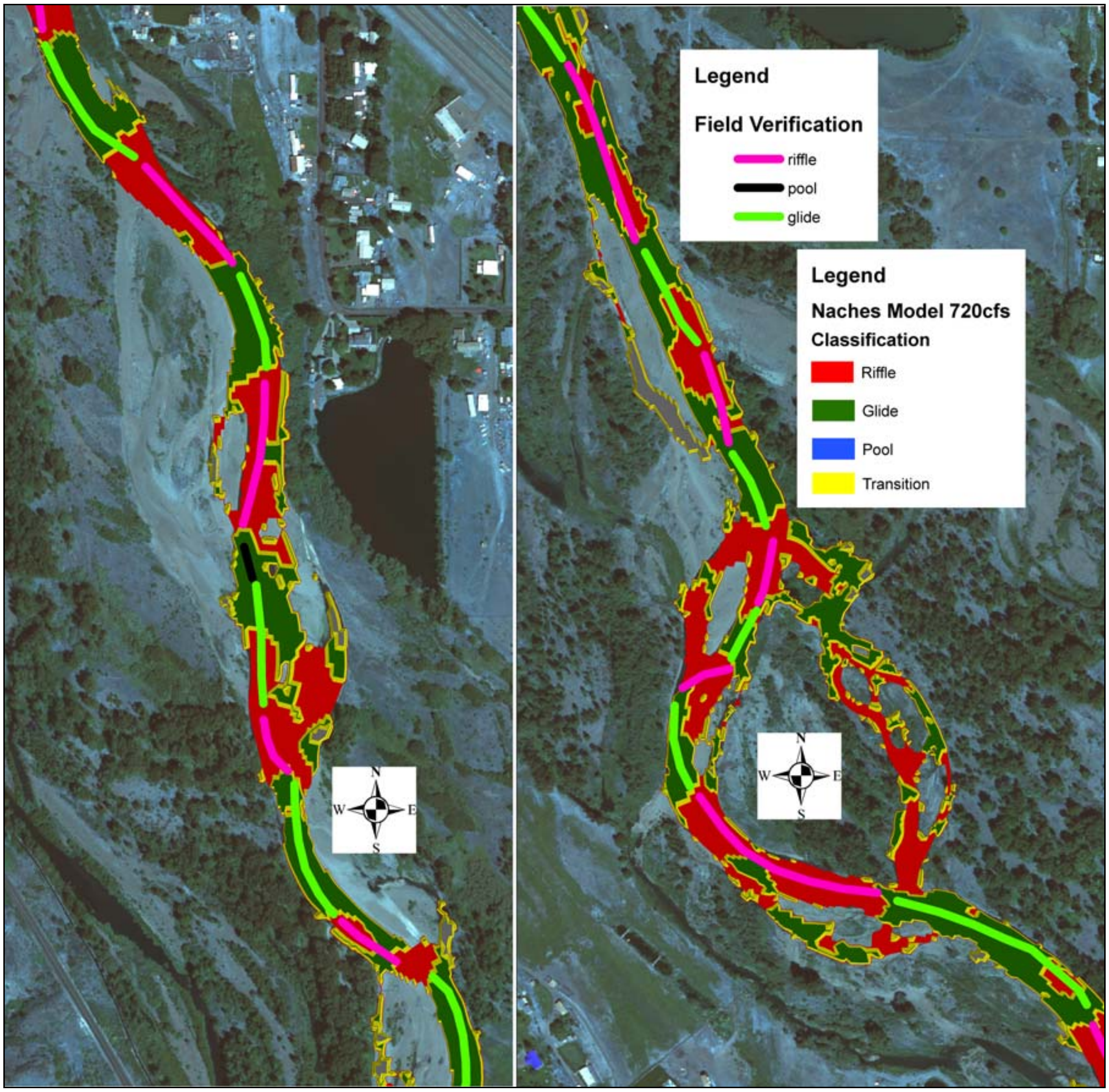

Figure 8. Aerial photograph (2003) with the habitat results TIN overlaid showing the modeled Froude classification and field verification. Two sections of the lower Naches Reach are shown at 720cfs (legend applies to both figures).

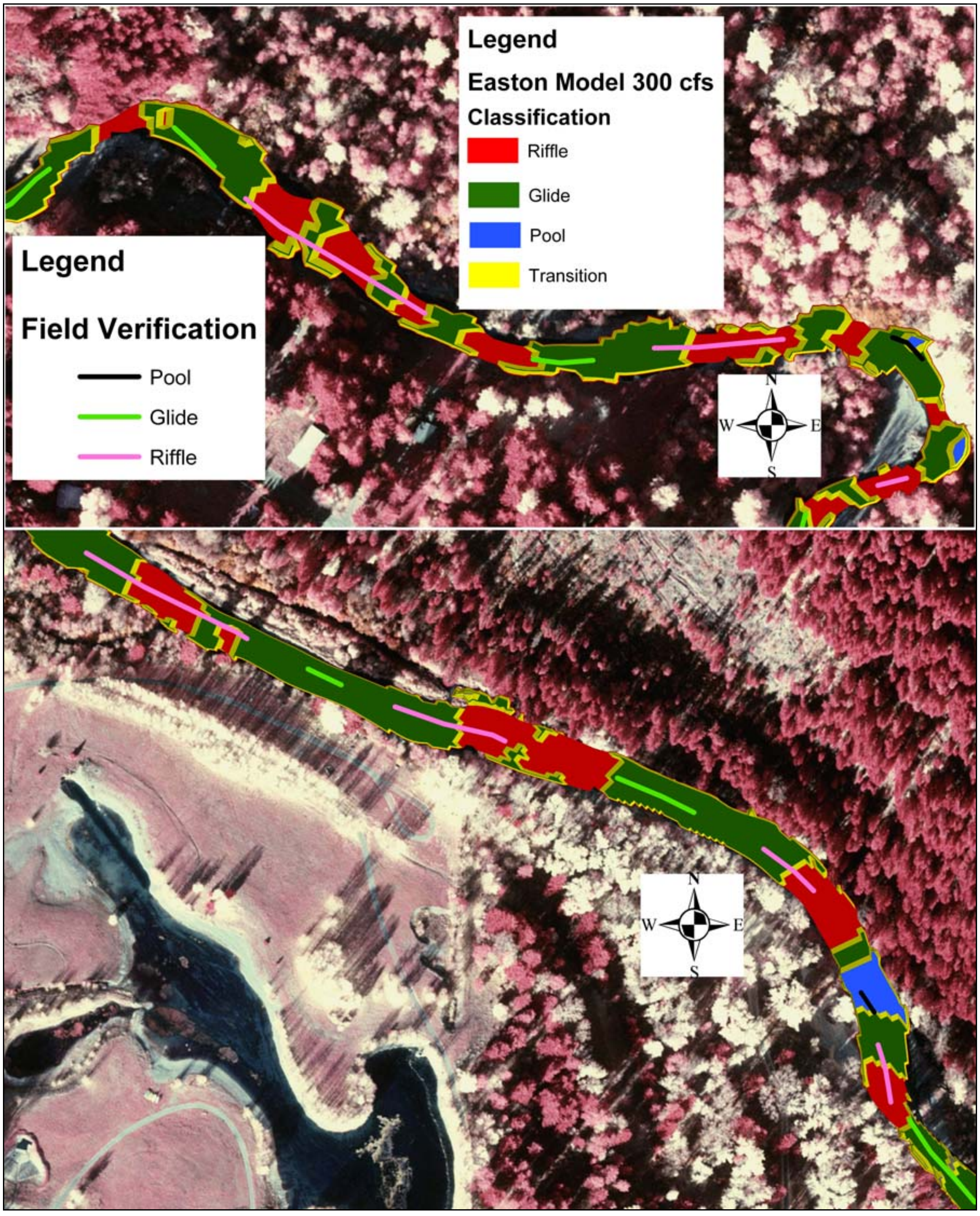

Figure 9. Aerial photograph (2000) with the habitat results TIN overlaid showing the modeled Froude classification and field verification. Two sections of the Easton Reach are shown at 300 cfs (legend applies to both figures).

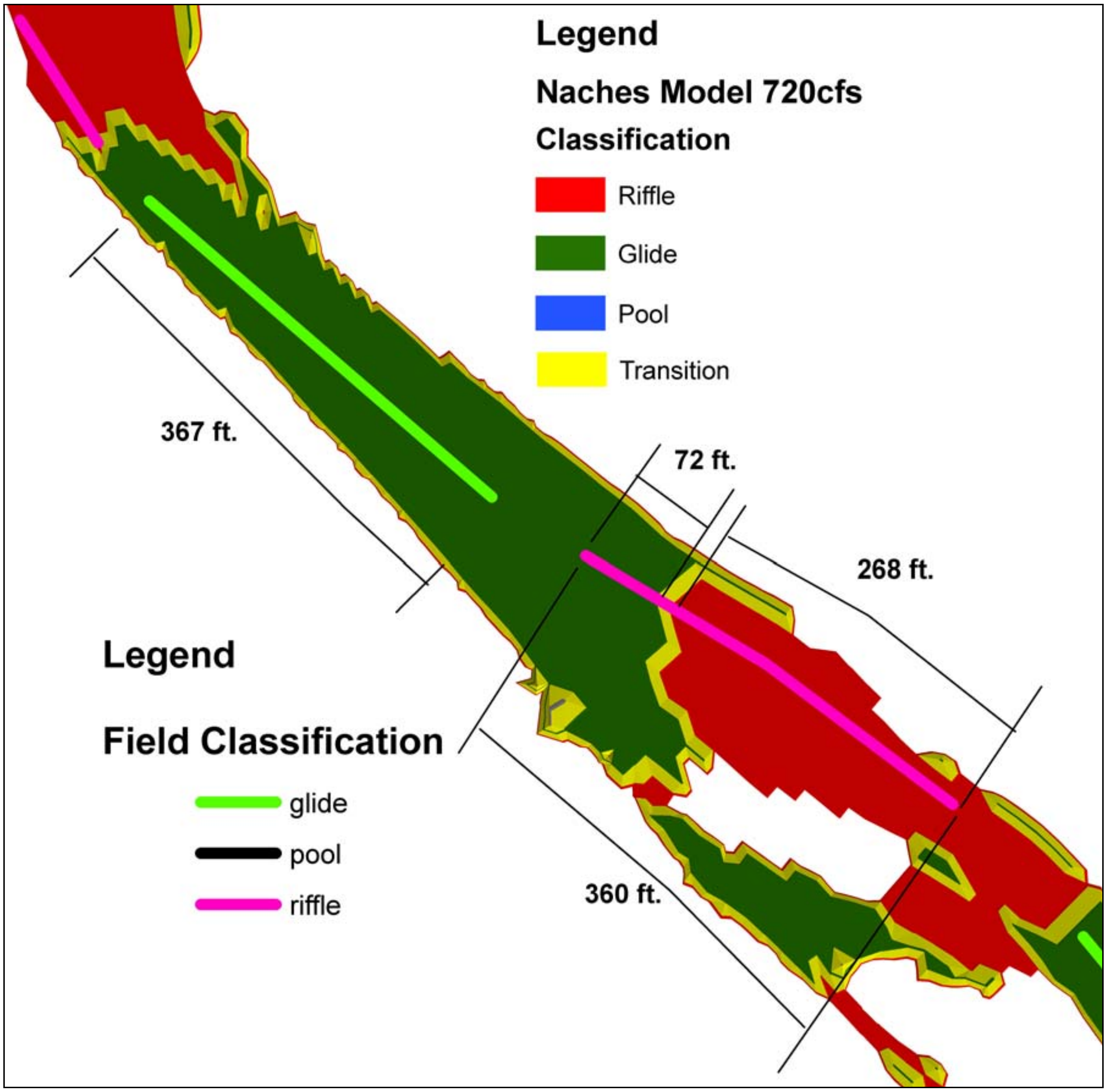

Figure 10. Example of measuring the field-surveyed habitat type and comparing it to the modeled habitat type. The field-indicated glide (light green line) coincides with the modeled glide, therefore this rating would score 100%. The modeled riffle (red area) mostly coincides with the field-surveyed riffle (pink line). This feature would score an 80% (1-[72/360]). Distances over the transitional areas were neglected.

Chapter 4.0 RESULTS

The results of the Froude number classification are displayed in detail in Appendix A. Table 3 summarizes the success.

Table 3. Success of Froude habitat classification using GSTAR-W.

Reach	Success for all features (%)	Success for Riffles (%)	Success for Glides (%)	Success for Pools (%)	Number of Each Feature Identified in the Field
Easton	73	63	87	64	69 Riffles, 66 Glides, 19 Pools
Kittitas	85	83	91	50	17 Riffles, 15 Glides, 2 Pools
Naches	81	87	77	0	34 Riffles, 31 Glides, 1 Pool

Overall, the modeled classification agreed very well with the field verification. 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 geomorphically created pool habitat and does not account for pool habitat created by woody debris. The float trips of all three reaches identified a significant contribution to pool habitat by large wood in the channel. 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. The aerial survey of the bathymetry flown for this model has a horizontal spot spacing on the order of 6.5 x 6.5 feet, meaning that features less than 6.5 feet in size are not accurately represented. The survey did not provide the level of detail required to account for large woody debris and associated pool habitat. Another important consideration is that the number of pools identified in the field habitat survey does not include the entire pool habitat of each reach. Pool habitat exists in the side channels and backwater areas that were not accounted for during the raft survey.

When pools, riffles, and glides are evaluated over various flow rates, their classifications begin to change. The length of pools becomes shorter with increasing flow as the features upstream and downstream encroach on the pool from each end until the entire pool feature becomes a glide. Figure 11 shows the procession in two places. In some areas, a series of short riffles separated by short glides becomes one long riffle. With regards to glides and riffles, the greater tendency is for glides to transition into riffles with increasing flow, although this is not absolute. The ultimate determining parameter regarding this type of habitat is the water surface slope.

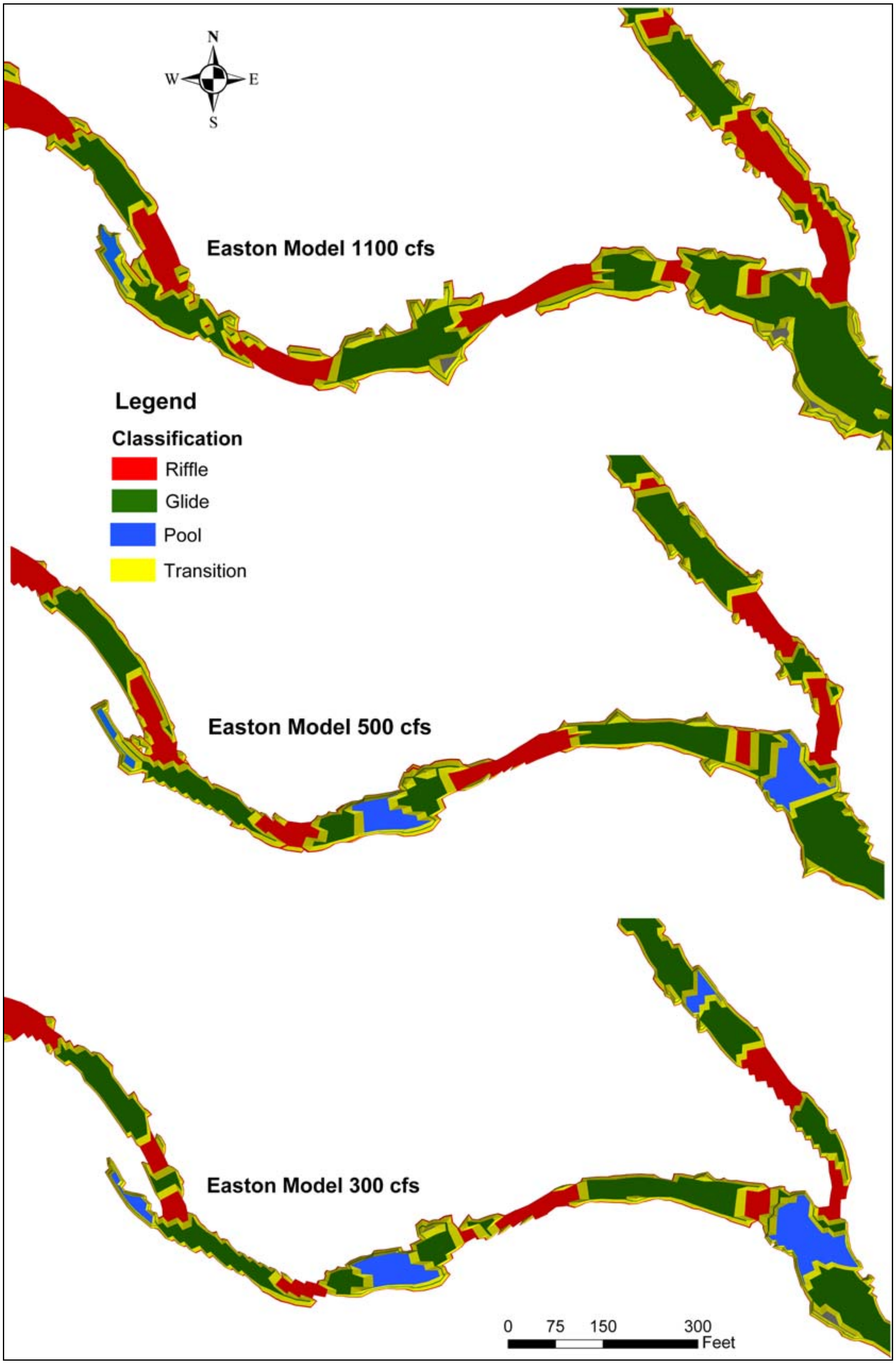

Figure 11. This figure shows habitat over the same short reach of the Yakima River, with a range of flows (300 cfs, 500 cfs, and 1,100 cfs).

In addition to habitat identified via Froude number, flow depth and velocity are also provided for use as input to the EDT model. An example of the velocity output is shown in Figure 12. Depth and velocity values throughout the models will build meso-habitat maps based on a range of flows for a Decision Support System tool that will be used in conjunction with EDT to evaluate different scenarios regarding flow rate. EDT will also use 2-D model results to determine which flows inundate individual side channels and measure wetted area, shown in Figure 13.

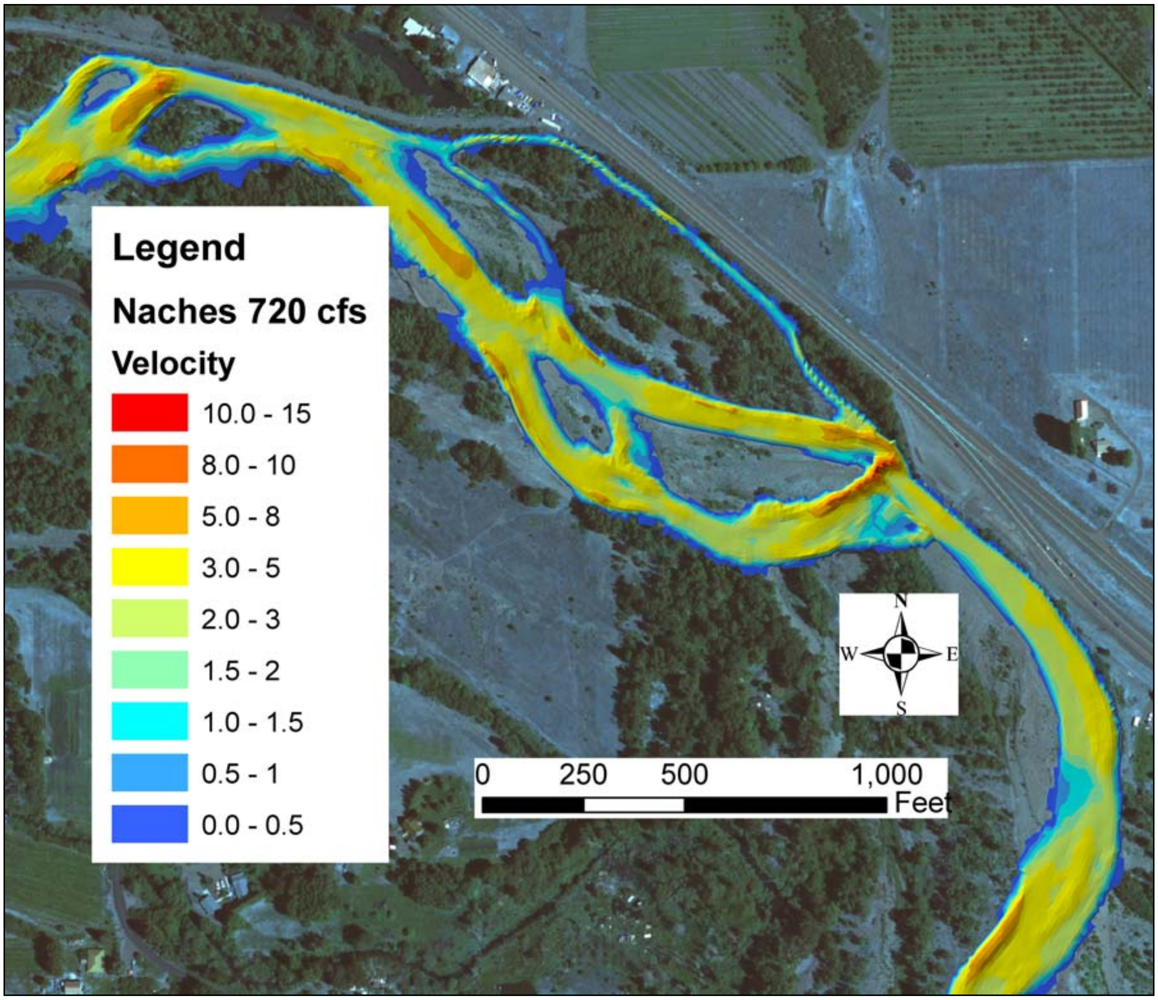

Figure 12. Example of velocity output from GSTAR-W. The Naches Reach is shown. Velocity is in feet per second.

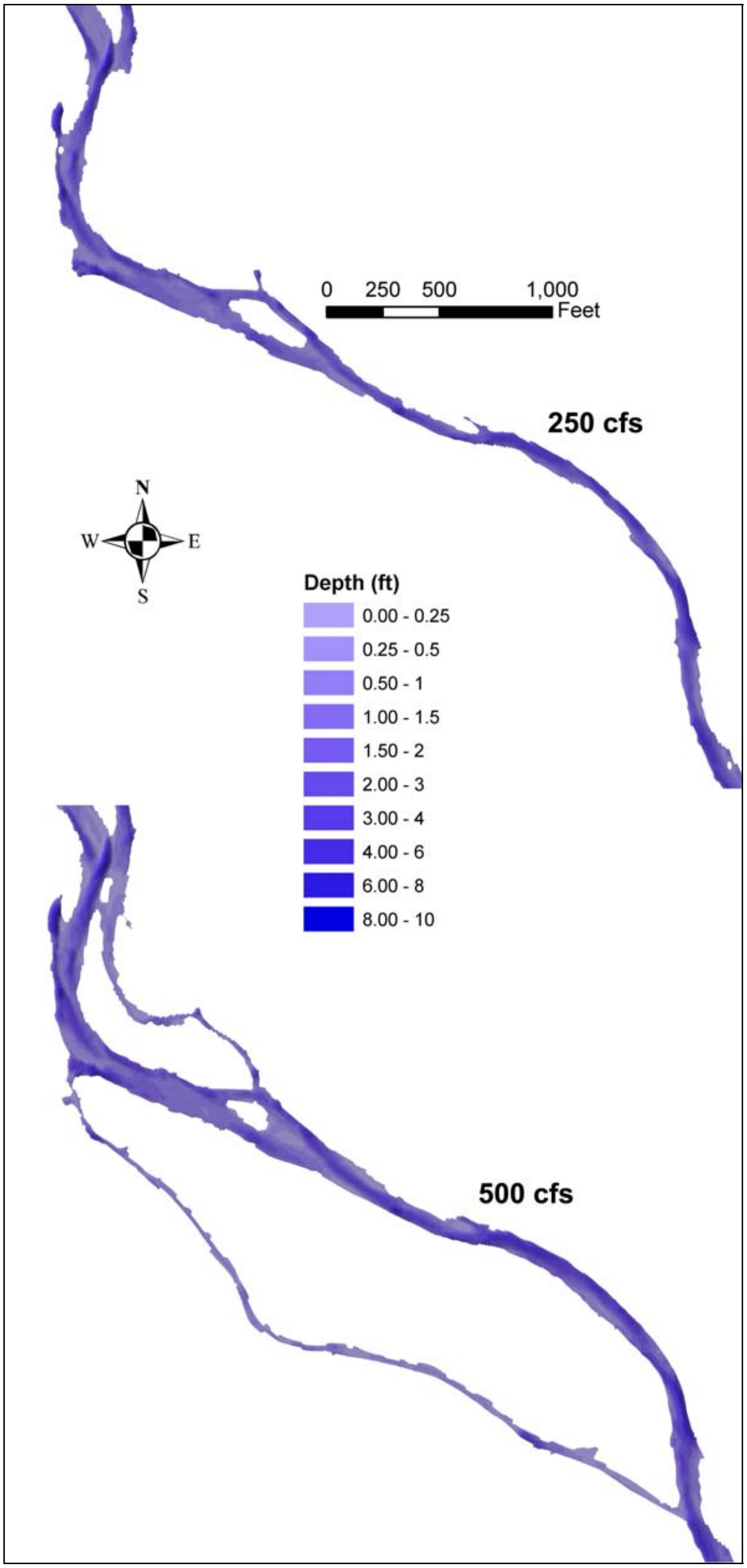

Figure 13. Figure showing two side channels becoming activated at 500 cfs that were not active at 250 cfs in the same reach.

Chapter 5.0 CONCLUSION

The use of GSTAR-W in combination with terrestrial and bathymetric LiDAR has been shown to be effective in determining aquatic habitat for input to EDT.

The combination of bathymetric LiDAR with the terrestrial methods provided a more detailed representation of the terrain than traditional boat survey methods. The resolution captured geomorphic channel features that cross section techniques might miss.

GSTAR-W allows contiguous 2D hydraulic simulation over lengths and resolutions beyond the capabilities of most other 2D models. Two-dimensional results provided depths and velocities over and around complex channel features including laterally varied riffles, pools, and glides as well as side channels.

Froude number classification of pools, riffles, and glides provides an objective and repeatable means of quantifying aquatic habitat. Field verification at different flow rates provided support for the method. Classification did not include features formed by woody debris or features smaller than the mesh resolution.

Classification of Froude number habitat may be expanded beyond that described in this paper. Reuter et al., (2003) have classified more meso-habitat features beyond pools, rifles and glides classified in this report To date, an effort to classify spawning habitat has shown some very promising results (Ken Bovee, USGS, pers. comm.). Additionally, habitat for other life stages may be possible.

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APPENDIX A SUCCESS CALCULATIONS FOR VERIFICATION OF HABITAT VIA THE FROUDE

For all feature identifications of the field classification; r = riffle, g = glide, p = pool.

The length indicated under 'Field Classification' is the length of the feature identified in the field. The length of each modeled feature was measured along a line coincident with that measured in the field. See Figure 10 for details.

Kittitas Reach

Field Classification		Modeled Classification			
Feature	Length	Riffle Length	Glide Length	Pool Length	calculated success
	(ft)	(ft)	(ft)	(ft)	(%)
r	130	130			100
g	308		308		100
p	70			70	100
r	545	432	94		83
g	350		350		100
r	440	118	266		40
g	118		118		100
r	302	253	35		88
g	120	52	57		57
r	325	265	40		88
g	554		554		100
r	211	211			100
r	592	276	272		54
r	696	387	155		78
g	676	312	316		54
r	447	447			100
g	455	36	409		92
r	635	492	110		83
g	148		148		100
g	284		284		100
r	323	257	51		84
g	512		512		100
r	560	362	164		71
r	566	408	94		83
g	144	23	84		84
r	123	123			100
p	304		304		0
g	158		158		100
r	345	247	80		77
g	727		727		100
r	415	362	38		91
g	535	85	418		84
r	498	498			100
g	428		428		100

Naches Reach

Field Classification		Modeled Classification			
Feature	Length	Riffle Length	Glide Length	Pool Length	calculated success
	(ft)	(ft)	(ft)	(ft)	(%)
r	128	128			100
g	371		371		100
r	364	270	70		81
g	819		819		100
r	196	196			100
g	108		108		100
r	339	339			100
g	1178	27	1131		98
r	383	298	35		91
g	501	27	445		95
r	277	277			100
g	467	69	360		85
r	413	413			100
g	306	306			0
r	454	454			100
p	109		109		0
g	383	266	135		31
r	189	189			100
g	440	27	360		94
r	223	153	34		85
g	563		563		100
r	144	108	23		84
g	301		301		100
r	243	126	57		77
g	287	53	207		82
r	372	235	119		68
g	740		740		100
r	557	504	36		94
g	316	19	289		94
r	620	620			100
g	622	79	512		87
r	1010	710	159		84
g	252	252	0		0
r	274	155	63		77
g	191	148	23		23
r	566	366	169		70
r	306	246	26		92
r	688	629	19		97
g	682	244	403		64
r	463	407	36		92
g	296	79	196		73
r	288	215	54		81
g	203		203		100
r	595	387	135		77
g	332	193	128		42
r	290	199	40		86
g	255		255		100
r	206	206			100
g	173		173		100
r	165	165			100
g	273		273		100
r	672	672			100
g	703	131	551		81
r	326	326			100
g	782	410	320		48
r	239	66	155		35
g	387		387		100
r	280	280			100
g	241	7	223		97
r	163	94	60		63
g	501	304	183		39
r	390	291	87		78
g	175	122	37		30
r	224	97	108		52
g	581		581		100
r	583	510	57		90
g	446		446		100

Easton Reach

Field Classification		Modeled Classification			
Feature	Length	Riffle Length	Glide Length	Pool Length	calculated success
	(ft)	(ft)	(ft)	(ft)	(%)
g	68		68		100
r	58	58			100
g	235		235		100
r	227	227			100
g	726	316	354		56
r	105	36	59		44
g	167	116	38		31
r	76	76			100
g	192	35	128		82
r	315	246	52		83
g	136	56	61		59
r	178	121	40		78
g	439	82	331		81
g	95		95		100
r	331	207	57		83
g	99		99		100
r	201	142	44		78
r	51	51			100
g	400	160	188		60
r	101	101			100
g	210		210		100
r	73	73			100
g	145	32	103		78
p	48			48	100
r	50		50		0
p	69		69		0
g	98		98		100
r	65	65			100
g	352	24	311		93
r	39	0	39		0
g	91	63	11		31
r	110		110		0
p	79			79	100
g	82		82		100
r	77	77			100
g	46		46		100
p	38			38	100
g	71		71		100
r	80		80		0
g	44	44			0
r	48		48		0
g	230		230		100
r	152	152			100
p	61		61		0
g	159	12	138		92
g	159		159		100
r	69		69		0
r	1665	165			100
g	128	56	47		56
g	123		123		100
r	207	207			100
g	290		213	54	81
r	71	35	24		66
g	36		36		100
p	42			42	100
r	70	70			100
g	201	82	100		59
r	217	53	144		34
g	570	375	133		34
r	274	81	185		32
r	102	64	30		71
r	174	174			100
r	438	438			100
g	127		127		100
g	148		148		100
r	86	60	20		77
g	74		74		100
r	88	40	32		64
r	106		106		0
g	136	15	97		89