THE REACHES PROJECT:
ECOLOGICAL AND GEOMORPHIC STUDIES SUPPORTING NORMATIVE FLOWS IN THE YAKIMA RIVER BASIN, WASHINGTON

by

Jack A. Stanford
Eric B. Snyder
Mark N. Lorang
Diane C. Whited
Phillip L. Matson
Jake L. Chaffin

Flathead Lake Biological Station, The University of Montana, Polson, MT 59860
flbs@selway.umt.edu, www.umt.edu/biology/flbs

PRESENTED IN FOUR PARTS:

PART A - SUMMARY AND CONCLUSIONS

PART B - LINKING FLUVIAL PROCESSES TO FLOODPLAIN ECOLOGY OF THE YAKIMA RIVER, WASHINGTON

PART C - ASSESSING SALMONID HABITAT ON FLOOD PLAINS OF THE YAKIMA RIVER, WASHINGTON, USING REMOTE SENSING

PART D - DERIVATION OF NORMATIVE FLOWS FOR A DAMAGED FLOODPLAIN RIVER ECOSYSTEM

October 4, 2002

Final Report to

US Department of the Interior, Bureau of Reclamation
Yakima Office
1917 Marsh Rd.
Yakima, WA 98901

and

Yakama Nation
Yakama Tribal Council and Fisheries Resource Management Program
P.O. Box 151
Toppenish, WA 98948

TABLE OF CONTENTS

TABLE OF CONTENTS

PART A – SUMMARY

The Yakima River system historically produced robust annual runs of chinook, sockeye, chum and coho salmon and steelhead. Many different stocks or life history types existed because the physiography of the basin is diverse, ranging from very dry and hot in the high desert of the lower basin to cold and wet in the Cascade Mountains of the headwaters (Snyder and Stanford 2001). Habitat diversity and life history diversity of salmonids are closely correlated in the Yakima Basin. Moreover, habitat diversity for salmonids and many other fishes maximizes in floodplain reaches of river systems (Ward and Stanford 1995, Independent Scientific Group 2000). The flood plains of Yakima River likely were extremely important for spawning and rearing of anadromous salmonids (Snyder and Stanford 2001).

However, Yakima River flood plains are substantially degraded. Primary problems are: revetments that disconnect main and side channel habitats; dewatering associated with irrigation that changes base flow conditions and degrades the shallow-water food web; chemical and thermal pollution that prevents proper maturation of eggs and juveniles; and extensive gravel mining within the floodplain reaches that has severed groundwater-channel connectivity, increased thermal loading and increased opportunities for invasions of nonnative species. The Yakima River is too altered from its natural state to allow anything close to the historical abundance and diversity of anadromous fishes. Habitat loss, overharvest and dam and reservoir passage problems in the mainstem Columbia River downstream of the Yakima, coupled with ocean productivity variation, also are implicated in the loss of Yakima fisheries.

Nonetheless, in an earlier analysis, Snyder and Stanford (2001) concluded that a significant amount of physical habitat remains in the five floodplain reaches of the mainstem river because habitat-structuring floods do still occur on the remaining expanses of floodplain environment. Assuming main stem and ocean bottlenecks are not overriding, restoration of floodplain connectivity by elevating base flows throughout the corridor, removing revetments and refilling gravel pits by natural riverine transport of gravel where possible could be successful in substantially enhancing Yakima salmon and steelhead runs.

Hence, the overarching purpose of this research was to determine the ecology of major floodplain reaches of the Yakima River: Cle Elum, Kittitas, Naches, Union Gap and Wapato. Specifically, the study documented groundwater-channel connectivity and flow relations; use and quality of side channel and other floodplain habitats by salmonid fishes; and classification and analysis of floodplain habitat using remote sensing and documentation of geomorphic processes, required for a robust understanding of the feasibility of revetment removal and establishment of a normative flow regime for the mainstem river.

The study, hereafter referred to as the reaches project, was initiated in the fall of 1998 and was a collaborative effort between the Flathead Lake Biological Station (FLBS), a research center of The University of Montana, and the Department of Geography and Land Studies at Central Washington University (CWU). The reaches project was funded by the US Bureau of Reclamation (USBR) and the Yakama Nation (YN), and some of their personnel assisted with the project.

FLBS was charged with documenting floodplain ecological integrity and potential for geomorphic change in relation to sediment supply for each of five alluvial flood plains. We proposed that measures of hydrological connectivity between the main channel and the surrounding flood plain would provide a strong indication of the restoration potential of each individual flood plain. As such, we viewed measures of connectivity as integrators of both complex properties of channel morphology and channel avulsion and biological or ecological response to these habitat-forming processes.

CWU was charged with the assessment of historical and present connectivity, or lack thereof, via interpretation of aerial photographs (Eitemiller et al. 2002). This analysis shows that the Holocene expanse of floodplain area has been reduced by up to 70 percent by human activities.

Results of the FLBS work are presented herein in three parts in addition to this summary (Part A). Part B shows remote sensing is an effective tool for assessing habitat for each of the flood plains and in spite of significant change related to human activities, the flood plains retain a shifting habitat mosaic driven by cut and fill alluviation. Part C provides maps of areas of potential geomorphic change in context of sediment supply to each flood plain. This analysis underscores the point from remote sensing that the flood plains do retain considerable potential for natural enhancement of the shifting habitat mosaic. Part D analyzes existing relations between the regulated flow regime and biology of the five flood plains, ranks them in context of restoration potential and provides seasonal quantity and rationale for normative flows.

The major findings of the study taken as a whole may be summarized as follows:

1. Ground-surface water interactions were demonstrated for all five flood plains. Water table elevation in monitoring wells changed in direct relation to river stage (discharge). Water from the river circulates into the floodplain aquifers and back again as evidenced by presence of flowing springs flood channels at base flow. Moreover, in the Cle Elum and Kittitas reaches, amphibitic stoneflies were commonly collected in monitoring wells. These organisms are well known as indicators of strong connectivity between the river and its floodplain aquifer. However, amphibitic stoneflies were not present in the other flood plains probably due to the cumulative anthropogenic effects.

2. Localized temperature regimes were strongly influenced by patterns in upwelling ground water from the alluvial aquifers. In all reaches, spring brooks maintained thermal regimes that were more stable than the mainstem habitat.

3. The distribution and concentration of algae, macroinvertebrates and fish on the flood plains clearly demonstrated the importance of off-channel habitats including overflow channels, spring brooks and disconnected channels. For example, in the Wapato reach, several juvenile spring chinook were trapped in a spring brook that became disconnected at the onset of the irrigation season. Several of these fish were recaptured on successive dates and were found exclusively at the upper end of the spring brook, near an upwelling area that maintained cool water temperatures. However, remote sensing showed that off-channel habitats are flow dependent; they are dewatered substantially by reduced base

flow. This of course reduces productivity of the food web and thereby reduces habitat quality. Habitat quantity is determined by the extent to which the flood plains are subject to cut and fill alluviation mediated by flooding.

4. The Wapato Flood Plain is the most complex and physically intact, but it also is the most dewatered. Moreover, the primary channel system of the Wapato may be incising because of depleted sediment supply, perhaps related to retention by Sunnyside Diversion Dam, but more likely related to reduced bank erosion caused by depleted flows through this reach.

5. All five reaches have significant potential for restoration. However, the restoration potential is highest in the Union Gap reach, based on many factors including its size, location, current condition, willing sellers and especially, current water availability, being located just below the Naches tributary and not experiencing severe dewatering evident in the Wapato reach. Significant potential for the river to avulse above and below the Moxee bridge (Hwy. 24) exists if the revetments are removed and highways and other domestic infrastructure are properly relocated. The sediment budget of the reach is sufficient to fill the shallow gravel pits located within the active flood plain, creating normative habitat. However, the sediment supply for Union Gap comes from Naches and further revetment or other alteration of that reach could compromise a normative condition for Union Gap. The Wapato reach could be substantially restored by normative flows with little or no land acquisition because there is very little floodplain encroachment, except by the interstate highway and associated gravel pits. However, there is very little possibility of increased flows in this reach under the existing irrigation delivery scheme.

6. There is insufficient water in the Yakima system to meet current diversion rates and at the same time create normative conditions on any of the flood plains. Improvement in irrigation efficiency would potentially increase instream flows by less than 1%. This is not ecologically meaningful in terms of enhancing floodplain connectivity. Alternatively, leaving water currently diverted at Roza in the river would increase base flow in the Union Gap flood plain by 29% and increase the connection of off-channel habitat by 80%. Similar improvements would occur downstream at Wapato, particularly if diversions at Sunnyside could be reduced.

7. The only way to reach a normative flow condition in the Yakima River system is to increase water supply if the existing diversions are to be maintained. Constructing new storage reservoirs is not the solution because runoff is declining and the current flood flows are needed to maintain the existing shifting habitat mosaic. Moreover, the current flip-flop procedure required to deliver water to the diversion points first from the upper Yakima and later in the summer shifting to the Naches already is problematic ecologically, to say the least. Alternatively, exchanging Roza and Sunnyside diversions with water from the Columbia River is feasible according to several analyses, including a very recent assessment by USBR. This is an attractive solution not only because obviously it would allow the Yakima to free flow at nearly historical levels, but also

because base flows in the main stem could be augmented by flood control storage in the existing reservoirs.

The Yakima River ecosystem can be restored to a normative condition. The flood plain reaches retain some ecological integrity, but are substantially degraded and cannot sustain enhanced runs of salmon and steelhead with out restoring normative flows throughout the mainstem Yakima and Naches. Water volume required to restore channel and floodplain connectivity is far more than will be available from conservation measures alone. Pump exchange from the Columbia River is possibly the best solution. However, management of wild populations without harm from hatchery stocks and harvest within the Yakima River and downstream is required as well. The recommended approach is to allow natural processes including especially annual flooding and natural radiation of salmonid life history types. Restoring anadromous salmonid runs may take several decades to accomplish, but payoff may be expected within a few years for the wild spring chinook, fall chinook and steelhead stocks that currently return to the Yakima in some numbers annually.

REFERENCES

Eitemiller, D. J., C. P. Arango, K. L. Clark, M. L., and Uebelacker. 2002. The effects of anthropogenic alterations to lateral connectivity on seven select alluvial floodplains within the Yakima River Basin, Washington. Department of Geography and Land Studies, Central Washington University, Ellensburg, Washington, USA.

Independent Scientific Group. 2000. Return to the River 2000: Restoration of the Salmonid Fishes in the Columbia River Ecosystem. Northwest Power Planning Council Document 2000-12, Northwest Power Planning Council

Snyder, E. B., and J. A. Stanford. 2001. Review and synthesis of river ecological studies in the Yakima River, Washington, with emphasis on flow and salmon habitat interactions. Prepared for U.S. Department of the Interior, Bureau of Reclamation, Yakima, Washington. Open File Report 163-01. Flathead Lake Biological Station, The University of Montana, Polson, Montana.

Ward, J. V., and J. A. Stanford. 1995. Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. Regulated Rivers **11**:105-119.

PART B: LINKING FLUVIAL PROCESSES TO FLOODPLAIN ECOLOGY OF THE YAKIMA RIVER, WASHINGTON

by

Mark S. Lorang
mlorang@selway.umt.edu

Diane C. Whited
dwhited@selway.umt.edu

Phillip L. Matson
Pmatson@selway.umt.edu

and

Jack A. Stanford
stanford@selway.umt.edu

Flathead Lake Biological Station
The University of Montana
311 Bio Station Lane
Polson, MT 59860-9659
406-982-3301
www.umt.edu/biology/flbs

STATEMENT OF PROBLEM

This report covers research results completed between the periods of September, 2000 and March, 2002, aimed at linking fluvial geomorphic processes that create and maintain shallow water habitats in five key reaches (Fig. 1). The priority reaches are the five major floodplain units (Cle Elum, Kittitas, Naches, Union Gap and Wapato – see Fig. 1) of the Yakima River, Washington, identified as likely critical to salmon recovery (Snyder and Stanford 2001). The underpinning hypothesis is that the river can do the work of naturally restoring shallow water habitats in the five key reaches identified as critical for productivity of juvenile salmon and steelhead (Fig. 1). Key fluvial processes are channel avulsion and cut and fill alluviation. These processes shape the floodplain landscape resulting in a continual shifting mosaic of habitat both above and below ground. Maintaining this shifting habitat mosaic is dependent on the ability of the river to move freely about the historical flood plain and on the balance between stream power, to accomplish the geomorphic work of channel avulsions, and cut and fill alluviation. It is also dependent on a sufficient supply of sediment to build new bars and islands and to prevent channel incision that would disconnect important groundwater-surfacewater interactions. Hence, there were two main objectives for this work. One objective was to determine which areas of the flood plains had the highest potential to be reworked by fluvial processes; the other was to assess a sediment budget for each of the five reaches.

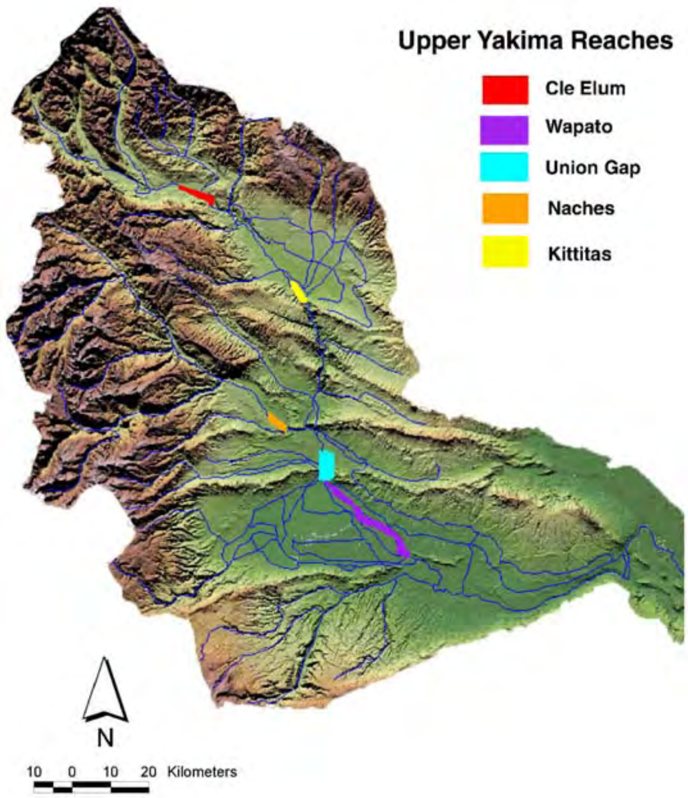


Figure 1. Extent of multispectral imagery acquired for each floodplain reach.

APPROACH

Stream flow and sediment loads were analyzed by linking remote sensing multispectral imagery with on the ground measures of flow velocity, water depth, substrate size and surface topography. The spatial distribution of stream power, shear stress, sediment mobility and volumetric flux, within the five reaches covered by multispectral imagery, were then modeled in a GIS. The results of those analyses formed the basis for the sediment budget and provided an objective methodology to quantifiably determine floodplain zones of both high and moderate potential for geomorphic work. Maps were produced that delineate these zones for each of the five floodplain reaches. Habitat restoration plans put forth by the Bureau of Reclamation in the Yakima River Basin call for floodplain land acquisition as one aspect of salmonid recovery. The goal is to secure land in the flood plain that is critical for productivity of juvenile salmon and steelhead. The maps integrate results from the analysis of modeled stream power and shear stress over various discharge regimes. However, they are only meant to serve as aids in the decision making process of prioritizing land acquisition efforts. This report outlines how the data were collected and used to develop the sediment budget and model the potential for geomorphic work as a function of various discharge stage levels across the five key reaches.

DATA ACQUISITION

Imagery

Airborne multispectral (blue, 0.46-0.55 μm; green, 0.52-0.61 μm; red, 0.61-0.70 μm; near-infrared; 0.78-0.92 μm) digital imagery were acquired in August 1999 for four of the flood plains (Cle Elum, Kittitas, Naches and Union Gap) and in August 2000 for the Wapato reach. The remote sensing imagery was acquired using an ADAR System 5500 digital camera on-board a light aircraft. Individual scenes covered a ground area of approximately 1.5 km^2 with a spatial resolution of 0.7 m and a 35% consecutive image overlap. Digital image mosaics were created for the entire image corridor for each reach using Digital Image Made Easy (DIME) software (Positive Systems ^{TM}), which uses a semiautomated textural analysis of overlapping images to assemble large amounts of spatial data into a single mosaic. The mosaics were then georeferenced using an US Geological Survey (scale - 1:2400) Digital Ortho-Photo data base. These data were used for image classification of flow velocity and water depth for all floodplain reaches.

Depth and Flow Velocity

The Sontek RS3000 Acoustic Doppler velocity-Profiler (ADP) was purchased from a research grant made by the Boise office of USBR to study the South Fork of the Snake River in southeastern Idaho. Acquisition of the ADP greatly increased the modeling capabilities of stream power and volumetric sediment flux for this project.

The Sontek RS3000 (ADP) uses 3 transducers to generate a pulse of sound at a known frequency. As the sound travels through the water, it is reflected in all directions by particulate matter (e.g., sediment, biological matter) being advected with the flow and is most strongly reflected from the bottom substrate. Some portion of the reflected energy travels back toward the transducer where the processing electronics measure the change in frequency referred to as a Doppler shift. The Doppler shift relates to the velocity of the water. By measuring the return signal at different times following the transmit pulse, the ADP measures water velocity at different distances from the transducer from just below the water surface to the bottom. This results in a measured velocity profile and depth of the water column. The profile of water velocity is divided into a range of 15 cm deep cells where each cell represents the average of the return signal for a given period of time. The ADP operates using three transducers generating beams with different orientations relative to the flow of water. The velocity measured by each ADP transducer is along the axis of its acoustic beam. These beam velocities are converted to XYZ (Cartesian) velocities using the relative orientation of the acoustic beams, giving a 3-D velocity field relative to the orientation of the ADP. Since it is not always possible to control instrument orientation, the ADP includes an internal compass and tilt sensor to report 3-D velocity data in Earth (East-North-Up or ENU) coordinates, independent of instrument orientation. Hence, it is possible to determine the mean flow velocity in separate cells through the water column oriented perpendicular to the flow field.

Velocity profile data are correlated spatially by using a Global Positioning System (GPS) receiver co-located with the position of the ADP. Both ADP and GPS data are recorded simultaneously on a field lap top with the SonTek River Surveyor software (Fig. 2A & B). Those data are then related to individual pixels from the airborne multispectral digital imagery. In this way, pixel intensity can be correlated to flow velocity and water depth.

Figure 2A. Picture showing ADP and GPS mounted on the front of a Jet Boat.

Figure 2B. Picture showing ADP and GPS mounted on the side of a raft.

The ADP surveys were collected for three of the reaches (Cle Elum, Kittitas and Union Gap). The Union Gap reach ADP data was obtained with the ADP and GPS deployed from a jet boat (Fig. 2A) on April 23, 2001 with a discharge of 59 $m^3 s^{-1}$ (August, 1999 imagery discharge of 64 $m^3 s^{-1}$), while the Kittitas (discharge of 88 $m^3 s^{-1}$, imagery discharge of 104 $m^3 s^{-1}$) and Cle Elum (discharge of 77 $m^3 s^{-1}$, imagery discharge of 92 $m^3 s^{-1}$) reaches were surveyed on August 21 and 22, 2001, respectively with the ADP and GPS deployed from a raft (Fig. 2B). The ADP surveys provided additional data on depth and velocities throughout the reaches that could not have been recorded by any other means. For example, in the Union Gap reach over 800 depth and velocity measurements were collected. However, budget constraints did not allow for ADP data collection on the other two reaches (Naches and Wapato) as such detailed measures of flow and depth were not included as part of the scope of work in the original proposal.

Topography and Substrate

All topography data was collected using a Leica TC 600 Total Station. Substrate size data was collected with a digital camera and analyzed with Image Pro Plus software. As part of our contract, we were to try and utilize existing software to develop an image processing system to automate the analyses of particle size data. This aspect was only partially successful in that we were not able to get sufficiently accurate results from the automated size analysis. This meant that we had to manually digitize projection surface areas of individual rocks from the 54 photo-sieve samples taken from the various reaches. The positive side of this was that taking digital photos of the substrate rather than having to measure in the field cut the number of field days required in half. In conclusion, the photo-sieving technique needs considerably more development to become automated. However, the ability to sample substrate rapidly in the field and then analyze the data in the lab greatly saves field time. Therefore, the application of the methodology was economically beneficial.

MODELING STREAM POWER

The first step in modeling stream power is to estimate water depth and flow velocity for every square meter of main channel water surface captured in the multispectral imagery for each reach. An integrated velocity measure was calculated (i.e., average velocity for the water column) and co-located to the imagery with the GPS data for each ADP measured profile (Fig. 3). The integrated velocity and depth, corresponding to a specific area of water surface captured by the imagery, were then used to train the multispectral imagery to classify the flow velocity and depth for all pixels in the reach image (see Whited et al. (in press) for detailed descriptions of the methodology). The imagery captures a measure of spectral reflectance for every square meter that can be related to physical attributes of water, such as differences in the color and surface roughness of the water. While floating a river one can see differences between, smooth water, riffles, rapids, boils and other forms of surface roughness related to various degrees of turbulence and different colors of water related to depth. Similarly, multispectral imagery can be used to reasonably estimate water depths and flow velocities based on differences observed in the spectral reflectances associated with changes in water roughness and color.

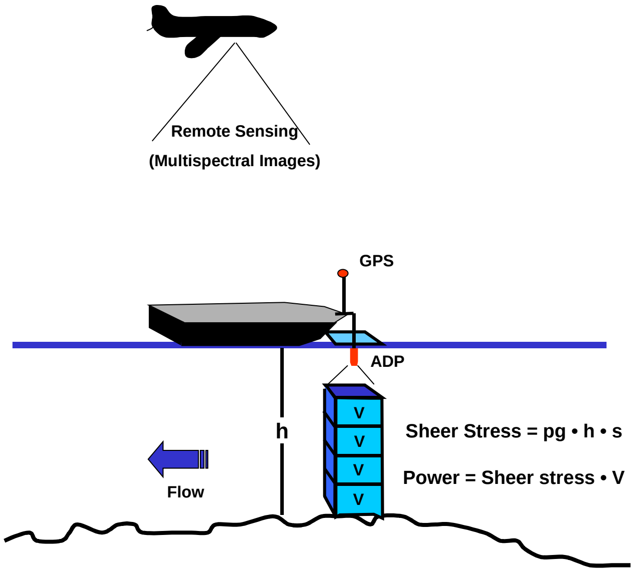


Figure 3. A schematic showing the correlation of multispectral imagery over a square area of water surface with flow velocity (V) and depth (h) data measured with the ADP. Shear stress and stream power can then be calculated once the slope (S) has been estimated.

We used the 30 m^2 DEM (Digital Elevation Model) data available from the U.S.G.S. to estimate slope of the water surface (Fig. 4). It is only a rough estimate that captures the general slope inflections along the river. Some of the steeper slopes associated with rapids at the ends of bars and pools-riffle sequences are lost at this resolution of slope estimation. To more accurately measure the water surface slope, one would have to either run a level survey down the river or use another Remote Sensing tool like LIDAR. Both of those options are expensive and were beyond the scope of this project. However, using the USGS 30 m^2 DEM confidently satisfies the scope of this project.

Figure 4. 1 meter contour intervals derived from the 30 m^2 DEM data available from the U.S.G.S overlain on the multispectral imagery from the Union Gap reach. The contour intervals that overlay the water surface allow a first order estimate of river slope.

Once slope (S), water depth (h) and flow velocity (V) are known, a GIS can be used to calculate an estimate of stream power (P) in Watts/m of stream width for every pixel in the multispectral image using the following equation

$$P = \rho g h S V \tag{1}$$

where ρ and g are the density of water and the gravitational constant respectively. The absolute value of stream power is not as important as the spatial pattern of power variance because we are not balancing the absolute value of stream power with some measure of bank or bed resistance. A map of the standard deviation of high stream power is simply used to show spatially where along the river corridor stream power is high or low relative to the mean (Fig. 5).

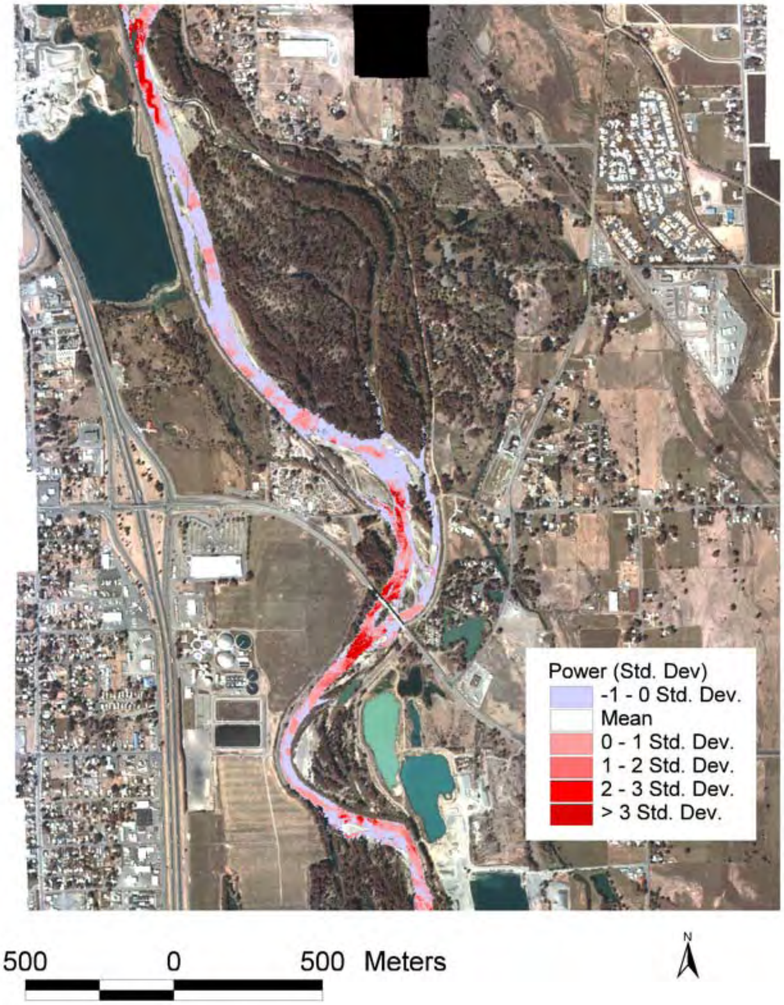


Figure 5. A plot of the standard deviation of stream power, within the main channel of the Union Gap reach, modeled with a GIS using multispectral imagery, ADP data and slope derived from USGS 30m^2 DEM data.

Although stream power itself can not be used directly to estimate bank erosion until bank resistance is calibrated, we have shown on our studies of the Nyack flood plain in Northwest Montana that areas of high stream power correlate well with eroding banks and channel migration (Fig. 6). Therefore, modeling the spatial distribution of stream power provides a valuable tool for predicting where channel avulsions are likely to occur, as well as where processes of cut and fill alluviation are apt to be more active. Stream power was modeled in this manner for each of the five flood plains shown in Figure 1.

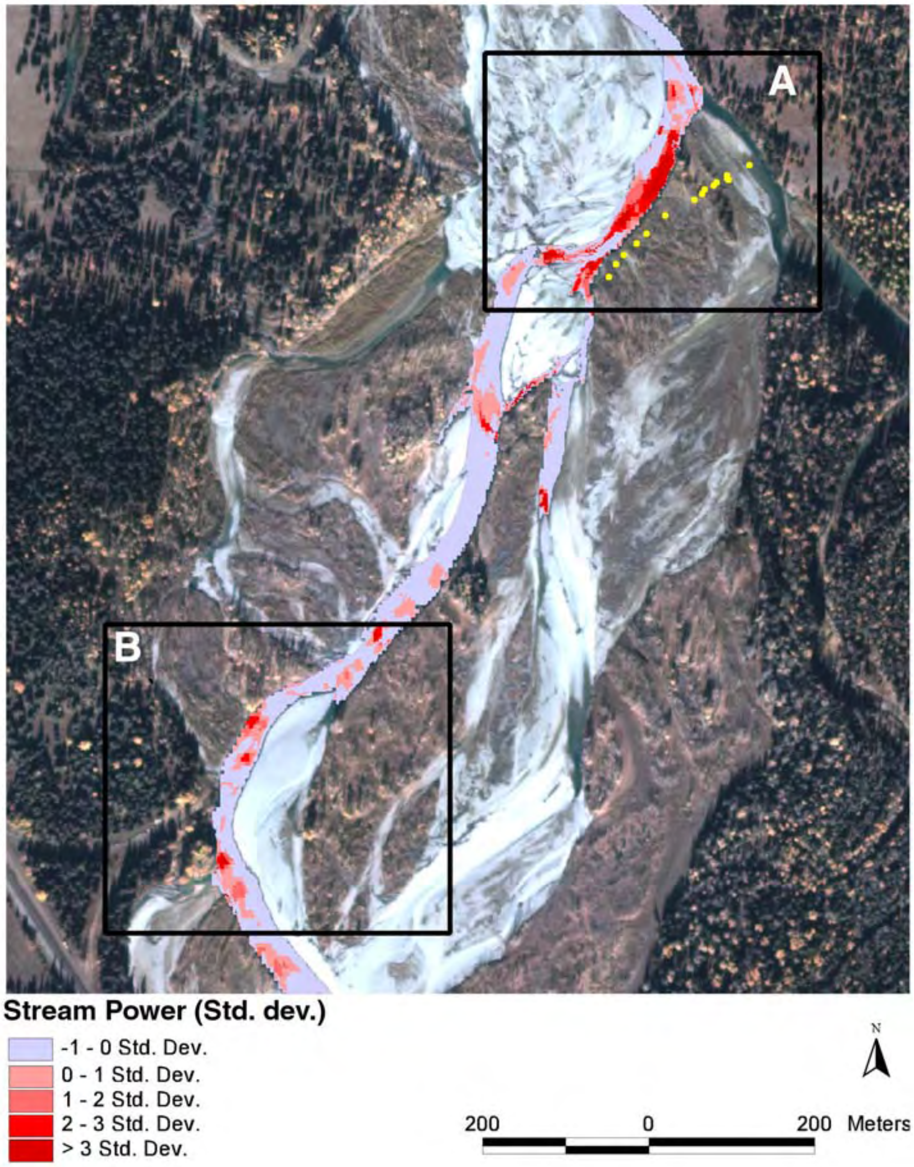


Figure 6. Stream power modeled from 1999 multispectral imagery for the Nyack flood plain in Northwest Montana. The yellow dotted line within box A shows the position of the 2001 channel bank due to erosion in the area of highest relative stream power. Bank erosion is also active in areas of high relative stream power plotted in box B.

This modeling effort provided the first step in assessing which areas of the flood plain had the highest potential for geomorphic work to be accomplished within the five reaches. Step 2 involved modeling shear stress across the flood plain and over various discharge stage levels.

MODELING SHEAR STRESS ACROSS THE FLOOD PLAIN

It is not possible at this time to estimate stream power at any other stage of discharge then that when the images were collected. However, to further delineate what portions of flood plain are likely to be reworked during floods, it is necessary to objectively assess that potential in a quantitative manner. We can estimate shear stress with only the water depth and slope as input variables. Therefore, if we know the topography of the flood plain, it becomes possible to model water depth above some reference point. We used the discharge stage level during image acquisition as our relative elevation of reference.

One meter contour intervals derived from the 30 m^2 DEM data available from the U.S.G.S can be overlain on the multispectral imagery and allow for a first order estimate of slope to be made (Fig. 5). However, this level of topographic information is not of a sufficient resolution to delineate floodplain topography, especially important features like backwater channels that may provide new channels following a future avulsion. It is also not feasible to use traditional survey methods to measure the topography adequately over many kilometers of a river corridor. To obtain sufficient topographic information to model shear stress during various flood discharge stage levels, we have combined topographical surveys with the multispectral imagery to delineate areas within the flood plain with similar elevations. We ran cross-sectional topographic surveys from wells installed to monitor chemistry and biota (see Part D) through the floodplain vegetation to the main channel of the river (Fig. 7).

In the process, we attempted to gather as much varied topography across as many cover type features as possible. We also surveyed relative elevations between gravel bars, water surface and bank top elevations throughout the floodplain reach. The multispectral imagery was then used to classify certain cover type features, including vegetation (e.g., grass/forest), side channels, spring brooks, cobbles, terraces and others (Fig. 7). The survey data was then overlaid on the various classified cover types and assigned a relative elevation to the main channel, as well as a typical slope value, to characterize the transition from one cover type to the next (Fig. 7). With this combination of data, we were able to assign relative elevations for the flood plain that were smooth, not blocky in nature, to produce a higher resolution DEM of the flood plain (Fig. 8 left panel).

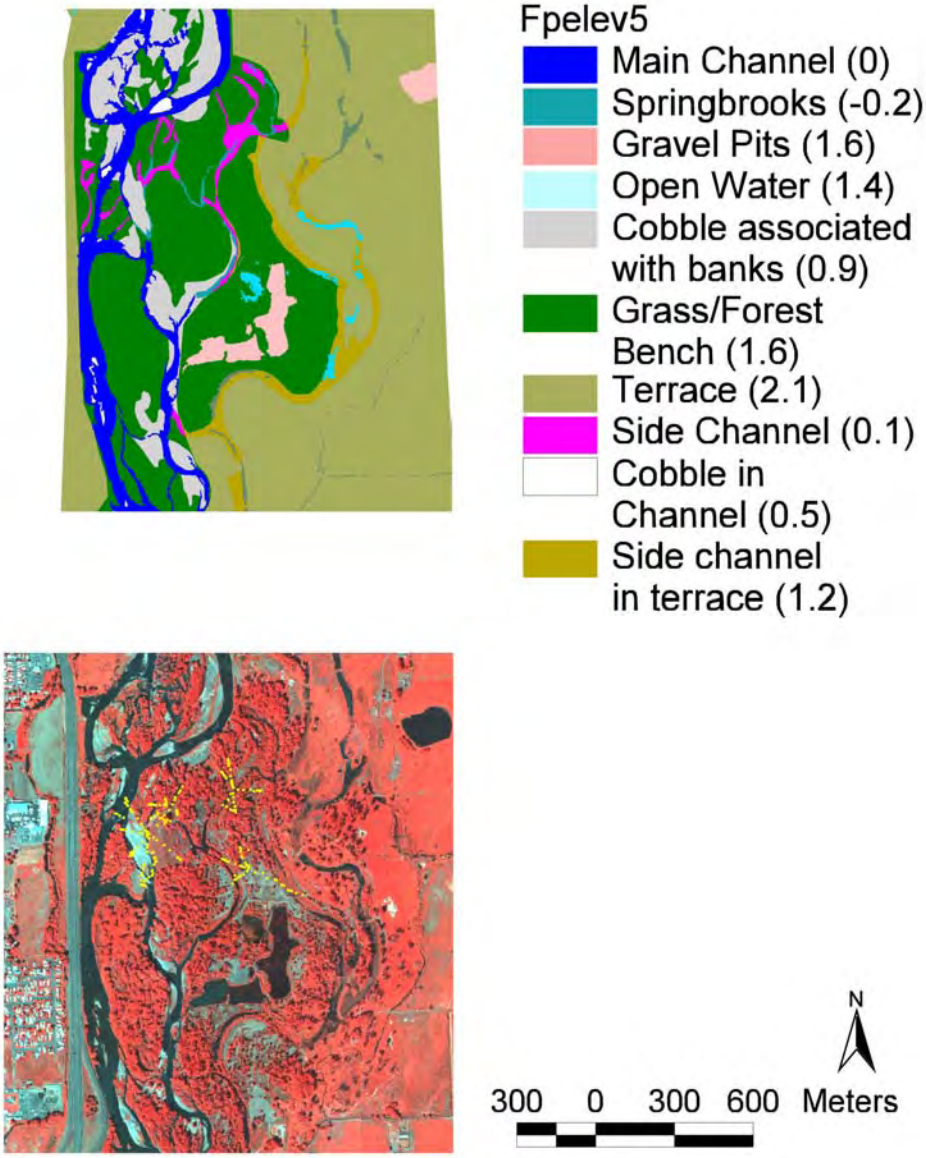


Figure 7. Example of survey transect lines (yellow dots) covering various habitat features easily classified with the multispectral imagery to enable a correlation of elevation relative to the water surface of the main channel and slope between cover type features.

By using the new higher resolution DEM, we modeled inundation of the flood plain at progressively higher (10 cm) increments (Fig. 8 middle panel). Comparing the modeled flood inundation (1.5 m stage above image discharge) with the inundation depicted in the 1996 georectified photograph taken during the 1996 flood, we can show that the modeled topography and simulated flood compare very closely (Fig. 8 middle panel). Once flood inundation was simulated for each stage increment, water depths for the inundated areas could also be calculated. Using the water depths and the slope of the flood plain (Fig. 8 left panel), it was possible to calculate shear stress (Fig. 8 right panel) throughout the floodplain reach. Displaying the spatial distribution of shear stress in this manner allows a qualitative comparison between shear stress in the main channel and shear stress in the flooded off channels for that particular stage level of discharge. If shear stress in an off channel has a similar magnitude as in the main channel (see Fig. 8 right panel), one could conclude that similar levels of geomorphic work could be accomplished in the off channel. Using this approach, we were able to model shear stress at bank full discharge stage and above for all of the five reaches.

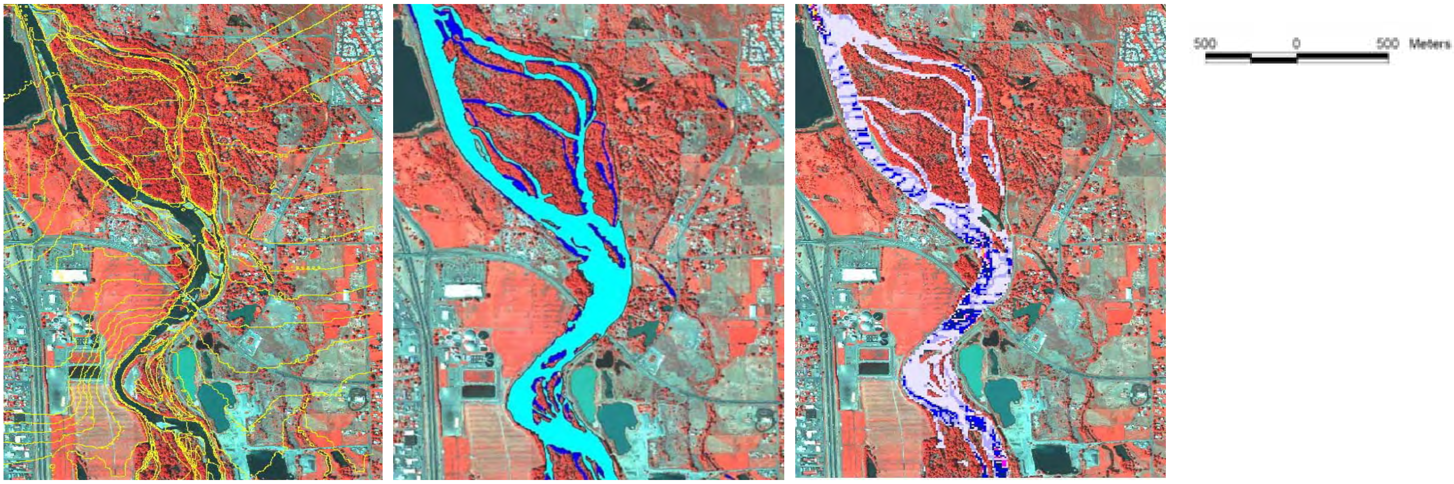


Figure 8. A multispectraltral image showing an overlay of modeled topography (far left panel). A comparison of a modeled flood discharge (dark blue) to actual flood of 1996 (light blue) based on the modeled topography (middle panel). The spatial distribution of shear stress in the flood plain corresponding to the modeled flood discharge shown in the middle panel (far right panel).

ZONAL DELINEATION OF POTENTIAL FOR GEOMORPHIC WORK

Plotting the results of the stream power analysis alone without the underlying aerial photography provides a clear picture of the spatial distribution of where erosion to both the main channel bed and banks is likely to occur (Fig. 9 top left panel). Likewise, plotting the results of shear stress at a bank-full discharge without the underlying aerial photography provides a clear picture of the spatial distribution of where erosion is likely to occur across the flood plain and the level of connectivity between floodplain channels (Fig. 9 top right panel). Areas where the main channel becomes a single wide channel, lacking high relative shear stress (Fig. 9 (A) top right panel) may indicate an area where the river is depositing its sediment load and aggrading in response to the reduced shear stress.

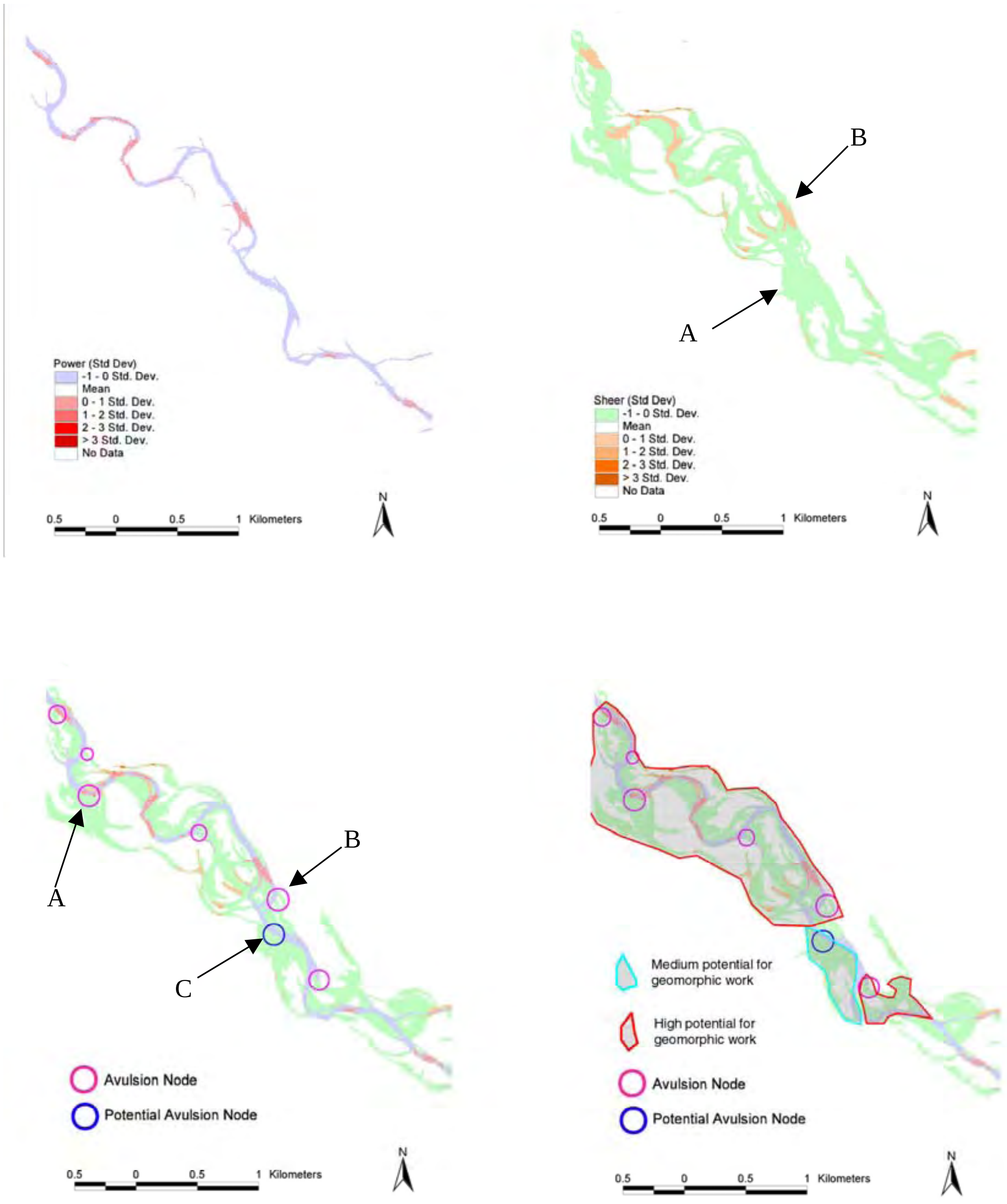


Figure 9. A schematic of the methodology used to combine the stream power modeling with that of shear stress using the Wapato reach as an example. The top left panel represents just stream power. The top right panel represents modeled shear stress at bank full with arrows depicting different zones of relative shear stress. The lower left panel shows an overlay of stream power and shear stress at bank-full with the relative position of avulsion nodes A and B and potential avulsion nodes C shown. The lower right panel shows the delineation of areas with high and moderate potentials for geomorphic work.

This area may also be a deposition zone for large wood that further induces scour holes and pools to form which are important shallow water floodplain habitats. In contrast, areas where there are several floodplain channels connected to the main channel and have high relative shear stress (Fig. 9 (B) top right panel) may indicate significant geomorphic work being done in those off channels. This level of geomorphic work would likely scour the bed resulting in the creation and or maintenance of a spring brook at lower discharge levels. These are just examples of how the geomorphic modeling efforts can be used to quantify objectively where various types of fluvial process may be active in a flood plain and how they can help interpret what level of ecological benefit could occur.

Combining stream power and shear stress modeling results can also be used to identify potential avulsion nodes and hence, further delineate areas of the flood plain with high, moderate or low potentials for geomorphic work. By overlaying the stream power results on to the shear stress at bank full, one can correlate where bank erosion and flood channel connectivity are likely. Areas where flood flows connect floodplain channels with the main channel in a zone of high stream power have the highest potential for an avulsion node to form (Fig. 9 (A) lower left panel). Areas where flood flows connect floodplain channels with the main channel in a zone of lower stream power but occur along the <u>outside</u> of a channel bend also have a high potential for an avulsion node to form (Fig. 9. (B) lower left panel). Likewise, areas where flood flows connect floodplain channels with the main channel but in a zone of low relative stream power and not along an outside bend of the main channel have a lower or moderate potential (Fig. 9. (C) lower left panel). Connecting the avulsion node at the top to with the lateral extent of flooding and to where the flood channels join back to the main channels provides a limit to defining zones of potential geomorphic work (Fig. 9 lower right panel). This represents the final end product for our first objective (Fig. 10) and large maps of this type have been prepared for each of the reaches.

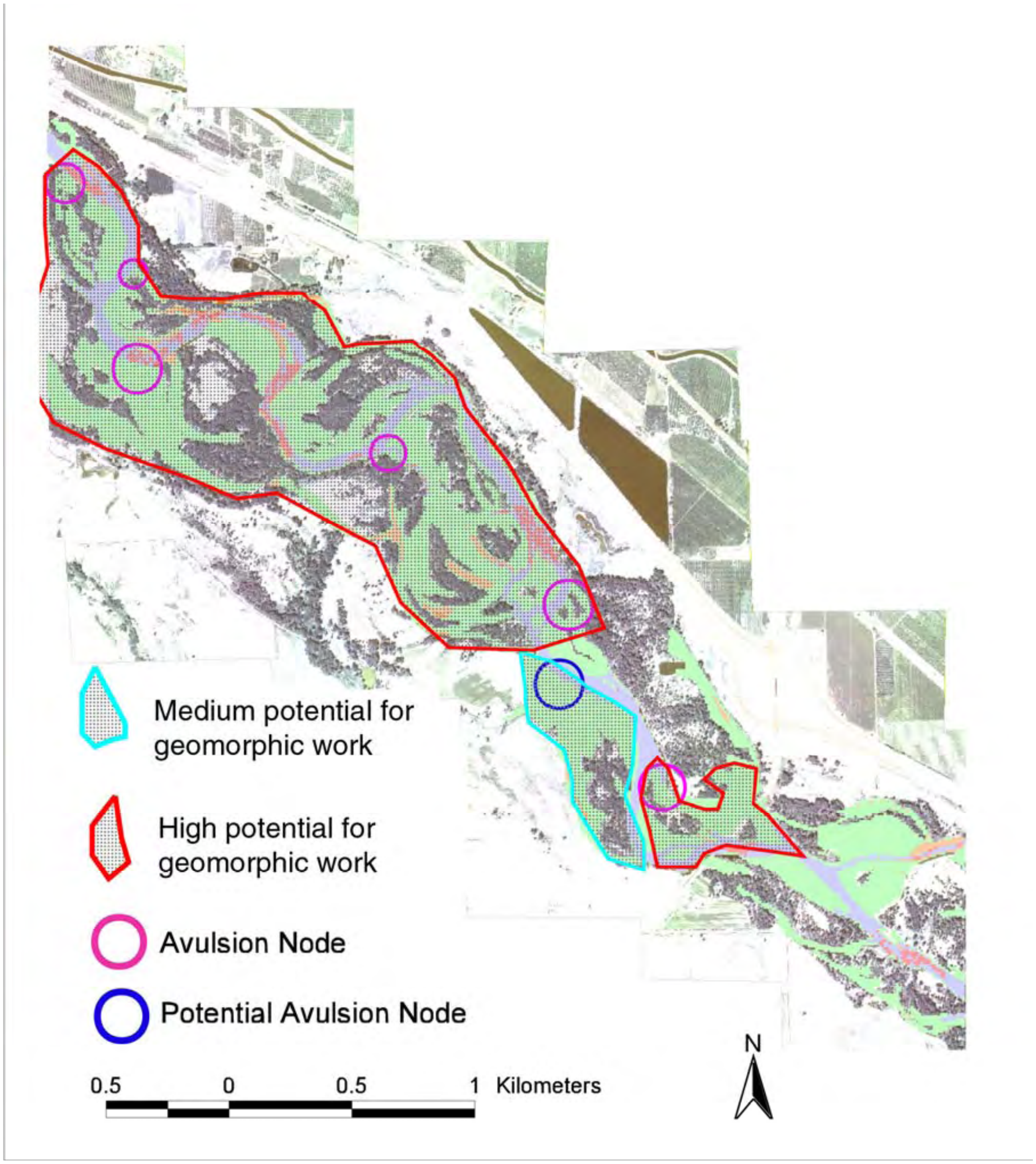


Figure 10. An example of a final map for the Wapato reach with the avulsion nodes and zones of potential geomorphic work overlaid on to the multispectral image.

THE SEDIMENT BUDGET

Floodplain Sediment Storage

The total volume of sediment in each flood plain was determined by using the high resolution DEM's created for the shear stress modeling. The edge of the riparian vegetation and high terraces defined the lateral boundaries (see Fig. 11 for an example) and scour pool depth was used as the vertical constraint for the volume estimation. This represents the total volume of sediment available to the river through natural fluvial processes. Each flood plain may have much deeper deposits of gravel, but those reserves below the maximum depth of scour are not available to the river system.

The Kittitas reach has the highest volume of available sediment per kilometer of river compared with the other reaches (Table 1). From a computation perspective, this is due to the relatively large area of high-forested terraces combined with deep scour holes. The same is true for the Cle Elum reach. The Wapato reach has a high available volume due to its wide flood plain rather than depth of scour. The Naches and Union Gap reaches have the least amount of available sediment per river kilometer. The computation reason for this is the larger percentage of para-fluvial zone (i.e., annual scour zone between low water and bank-full) composed of low elevation gravel bars relative to high-forested terraces.

The differences in sediment volume observed in the various reaches can be explained by the varying degrees of fluvial processes occurring within each reach. Recent fluvial processes are more active in the Union Gap and Naches reaches than the other three as expressed by their wider para-fluvial zones and lower available sediment per river kilometer. However, because they have wider para-fluvial zones, they have a large amount of immediately available sediment while the other reaches require significant bank erosion to release their stored reserves.

Georectified historical photos were used to provide an estimate of channel migration and to calculate the volume of sediment that has been cut through the historical flood plains to form the present river channel positions (Fig. 12). These cut-volume estimates provide a means of scaling relative historical fluvial activity. We scaled the amount of sediment in the flood plain to the cut-volume of sediment. In this way, we can make a first order comparison of historical fluvial activity. The present river channels for the Kittitas and Cle Elum reaches occupy much of the same historical channel positions compared with Naches and Union Gap which have nearly cut completely new channels. Therefore, fluvial processes have been more active in the Union Gap and Naches reaches as demonstrated by the higher percentage of cut-volume relative to total floodplain volume (Table 1). A possible explanation for this is that the Cle Elum and Kittitas reaches have become more incised in their channels. This may also be related to the relative supply of sediment from upstream being greater in the Naches and Union Gap than the Cle Elum and Kittitas reaches. Historical photographs for the Wapato reach were not available and those used for comparison on the other reaches were georectified and compiled by the Central Washington Reaches Group (Eitemiller 2002).

Figure 11. The 1999 multispectral image of the Naches flood plain showing the area within the red lines used to determine the volume of sediment. Modeled topography, the above lateral boundaries and depth of the deepest scour pool were used as constraints in the volume estimation.

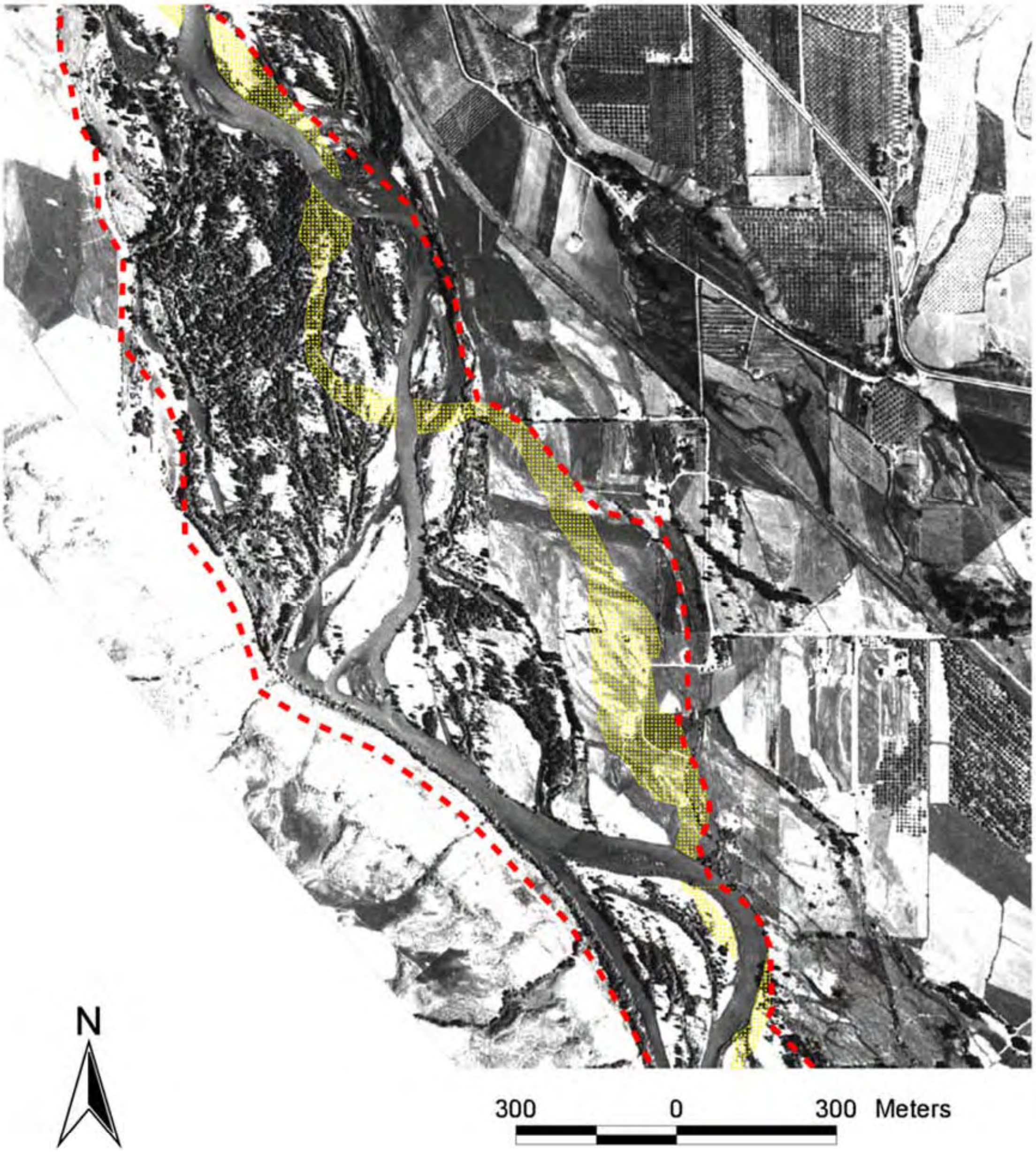


Figure 12. A 1942 photograph of the Naches flood plain showing an overlay of the 1999 present channel (yellow stippled area). The cut-volume of sediment was estimated for those areas corresponding to the present channel positions that cut through the 1942 flood plain. Those historical volume estimates are listed in Table 1.

Table 1. A comparison of the total volume of sediment in each reach (see Fig. 11 example) with cut-volume associated with the 1999 channel position (see Fig. 12 example).

Reach	River Length (km)	Total Volume (m^3)	Normalized Vol. (m^3/km)	Cut Volume (m^3)	Cut % of Total (%)
Cle Elum	11.2	12,375,535	1,101,026	794,094	6.4
Kittitas	8.5	14,599,497	1,715,570	794,097	5.4
Naches	11.9	10,776,689	904,844	2,394,482	22.2
Union Gap	9.7	8,529,963	883,934	1,696,542	19.9
Wapato	41.4	60,116,120	1,450,679	NA	NA

Sediment Supply from the River Banks and Channel-bed

Natural floodplain restoration is dependent on a sufficient supply of sediment to build new bars and islands and to prevent channel incision. Two important sources of sediment are that stored in the banks and beds of the present channel. They are important sources because the deposition of sediment, supplied through erosion of the banks and channel-beds, is what creates new geomorphic surfaces and what allows for the potential recolonization of riparian vegetation on short (annual to decade) time scales. However not every meter of channel bank or bed erodes on an annual basis, therefore it is important to estimate how much sediment is potentially available from banks associated with estimated high stream power, as well as, the total amount of sediment stored along the entire length of floodplain banks.

We use the high resolution floodplain DEM to calculate the amount of sediment stored in the channel-bed and banks by putting a 1m lateral limit on the erosion and limiting the depth to that of the deepest scour pools (Fig. 13). The other limiting factor was stage level corresponding to discharge regimes (Fig. 13). The volume of stored sediment available to bed and bank erosion for all reaches at a bank-full stage level is listed in Table 2. In general, that volume represents around 5 % on average of the total available sediment in the flood plain.

The frequency of bank-full discharge varies for different rivers but on average occurs about every 1.5 years (Williams, 1978). Therefore, for scaling purposes the bank erosion alone represents grossly about a 40-year supply which underscores the importance of a long-term resupply of sediment from upstream for each reach. A loss or reduction of up stream sediment will induce channel incision, a reduction in channel complexity and disconnection of groundwater-surface water interaction. Such scaling exercises provide a quantitative base to assess the potential impact in the critical reaches due to river capture by floodplain gravel pits and bank stabilization efforts upstream.

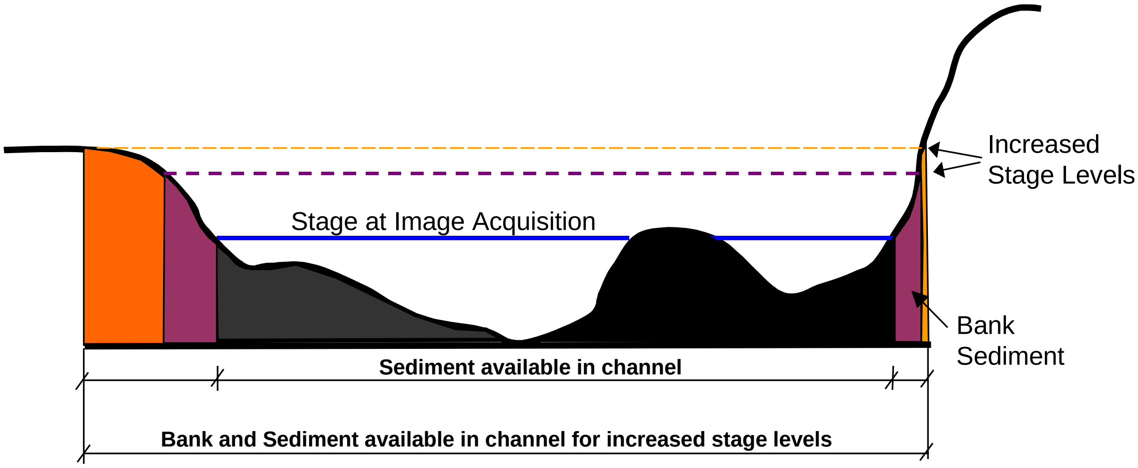


Figure 13. A schematic depicting how the available volume of sediment was estimated for the channel and the banks for various stage levels corresponding to discharges above that during image acquisition.

Bank-full discharge events do not erode the entire length of river bank and channel bed. However, we found a good correlation between modeled stream power and bank erosion in the Nyack flood plain (Fig. 6). Therefore, a more conservative estimate for the amount of sediment potentially released during bank-full discharge was calculated only for those banks that correlated with relatively high stream power (Fig. 14). The percentage of total sediment released from high power banks is low (i.e., <1%, see Table 2) of the total volume stored in the flood plain, but the absolute amount equates to an area of about 1 hectare. Clearly, not all eroded sediment goes to forming 1 hectare of new bars or islands in each reach after every bank-full discharge. However, it does scale the important role bank erosion plays on an annual time scale in maintaining a balance to the shifting habitat mosaic. Moreover, it points out the potential immediate impact due to local bank stabilization efforts, like construction of riprap and spur dikes, within the critical reaches (Fig. 1).

Table 2. A comparison of the total volume of sediment from the channel and the banks at bank-full stage (Fig. 13 example) and those from the bank correlated with high stream power (Fig. 14 example) for all five reaches. Also included is a percent comparison of channel plus bank-full volumes to the total flood plain volume. The volume of sediment correlating to areas of high power is compared to the total bank volume and total floodplain volume.

Reach	Channel (m^3)	Bankfull (m^3)	Chan+BF/Total (%)	High Pwr Bank (m^3)	HPwr / Bankfull (%)	HPwr / Total (%)
Cle Elum	385,067	78,782	3.7	13,115	16.6	0.11
Kittitas	497,212	76,678	3.9	9,890	12.9	0.07
Naches	424,527	89,225	4.8	16,844	18.9	0.16
Union Gap	644,991	86,690	8.6	15,720	18.1	0.18
Wapato	1,513,881	320,998	3.1	42,721	13.3	0.07

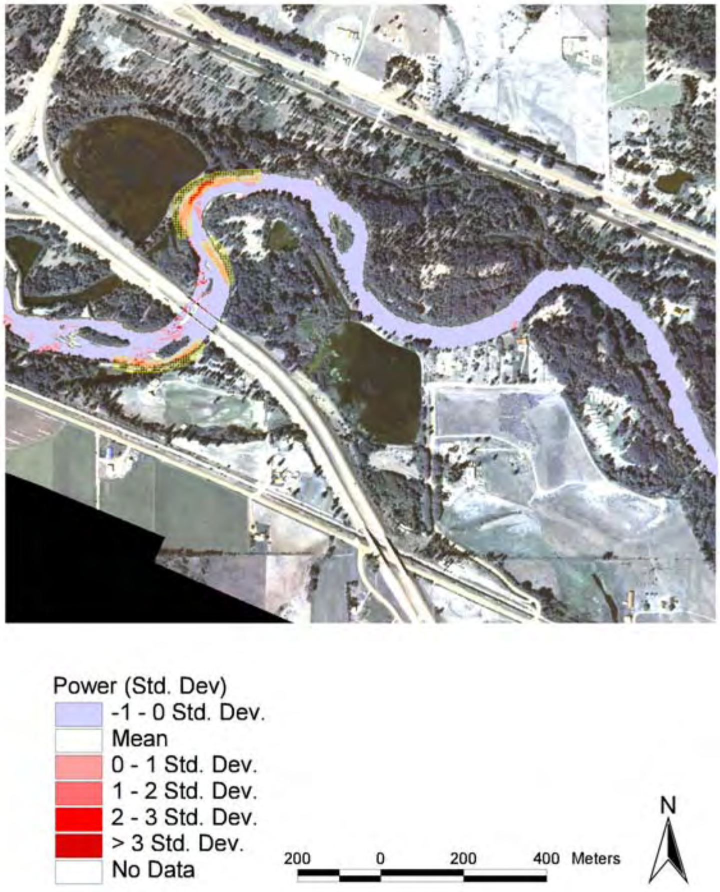


Figure 14. A photograph from the Cle Elum reach showing areas of high relative stream power and the corresponding length of bank (yellow stippled area). The volume of sediment available from these bank areas was estimated for bank-full discharge for each reach assuming 1 m of lateral erosion.

Analysis of Sediment Mobility

When qualitatively describing channel behavior it is common for channel reaches to be segmented into supply, transport and depositional segments (Montgomery and Buffington 1998). The remote sensing based, GIS models developed in this project have for the first time provided a quantitative, high-resolution method for mapping, on the reach scale, where sediment is coming from and where it will likely deposit (Fig. 15). An important step in analyzing channel sensitivity to morphological change is to estimate the mobility potential of the bed sediments. That requires estimating the forces applied to the bed by flowing water and the threshold level of sediment entrainment.

The force that flowing water exerts on the channel bed to initiate sediment transport is called the bottom boundary shear stress, τ_o and for a particular square meter of channel bottom can be estimated with the following equation

$$\tau_o = \rho \ ghS \tag{2}$$

where *h* is the water depth and *S* is the local slope of the bed. Thus, as water depth, *h*, increases or the down-slope component of gravity ($g \cdot S$) increases, so does the *potential* shear stress at a single point where depth is being considered. This is a useful approach to estimating τ_o because a spatial distribution of shear stress for any discharge can be calculated for every square meter of the channel and flood plain, as long as water depth and slope are known. This is what was done to help delineate zones of the flood plain with a high potential to be reworked (Fig. 8 and 9).

The critical shear stress, τ_{crit} , is the shear stress at which threshold entrainment occurs and every particle size has an individual critical shear stress. Over the last eight decades, threshold entrainment has been evaluated by relating estimates of shear stress from measures of depth, slope and/or velocity to the size of the largest particles set in motion resulting in equations to estimate critical shear stress (Buffington and Montgomery 1997). Komar (1987a) modified the original Shields (1936) entrainment expression to account for a natural bed composed of a mixture of particle sizes, to derive the following equation

$$\tau_{crit} = \theta(\rho_s - \rho)gD_{50}^{0.6}D_{\max}^{0.4} \tag{3}$$

where θ is a constant, D_{50} is the mean particle diameter , D_{max} is the maximum diameter. Buffington and Montgomery (1997) compiled 6 decades of flow competence work and found that θ_{crit} values range from 0.03 to 0.07. Andrews (1984) found a θ_{crit} value of 0.031 for gravel-bed rivers where the mean substrate diameter was 2.3 cm to 12.0 cm which is close to the range of gravel material measured in the Yakima River reaches and hence, the value used here. This and similar equations have been used extensively by fluvial geomorphologists and engineers to evaluate sediment threshold entrainment (Hjulstrom 1935, 1939, Shields 1936, Lane 1955, Kellerhals 1967, Ridder 1967, Scott and Gravlee 1968, Helley 1969, Baker and Ritter 1975, Miller et al. 1977, Bradley and Mears 1980, Costa 1983, Andrews 1983, 1984, Komar 1987a, 1987b, 1988, 1989, Komar and Carling 1991, O'Connor 1993). More recently, stream ecologists have used equation (2) to evaluate stream stability (Downes et al. 1997, Townsend et al. 1997, Duncan et al. 1999, Lorang and Hauer 2002). Lorang and Hauer, 2002 combined equations (2) and (3) into a single expression to estimate potential sediment mobility

$$\xi = \frac{\rho g h S}{\theta(\rho_s - \rho) g D_{50}^{0.6} D_{\max}^{0.4}}. \qquad (4)$$

When ξ >1, the basal shear stress applied to the bed by the flowing water is greater than the critical shear stress required for threshold entrainment of the bed sediments. At this stage, sediment mobility is theoretically achieved. In gravel- and cobble-bed rivers, the bank-full stage accomplishes most of the geomorphic work associated with sediment transport and hence, establishes channel morphology (Leopold et al. 1964, Williams 1978, Andrews 1984, Montgomery and Buffington 1998). Therefore, for each reach the sediment mobility ratio ξ was calculated for every square meter at a bank-full discharge and every pixel where ξ >1 was plotted in red (Fig. 15). This type of plot shows a clear segmentation of the reaches into areas where sediment transport is expected and where that sediment should deposit.

It is important to keep in mind that these patterns are based on statistical representations of the particle sizes (i.e., D_{50} is the mean particle diameter, D_{max} is the maximum diameter) for the whole reach. Clearly, better estimations would be achieved if the actual spatial variation in particle size were known. The Kittitas reach provides an example of distinct segmentation of transport and depositional stretches. However, the lower section of the reach is mapped as completely mobile during bank-full flow (Fig. 15 see yellow box). This section of the river channel has historically remained in the same position and is presently steep and armored with larger cobbles. For these reasons, sediment mobility is over predicted and the area within the yellow box is a segment of the reach that is a transport zone where smaller sized gravel is transported through and into the lower canyon reach. The areas above show alternating segments of transport and deposition defining an aggrading zone of the reach with active fluvial processes of cut and fill alluviation and a higher potential for avulsions to occur. The Cle Elum reach shows a similar spatial distribution of a transport segment just as the reach exits into a steep canyon reach. This is one feature that separates the Kittitas and Cle Elum reaches from the other three. The Union Gap and Wapato reaches have alternating small stretches of transport and depositional segments through out the reach and in particular near the bottom.

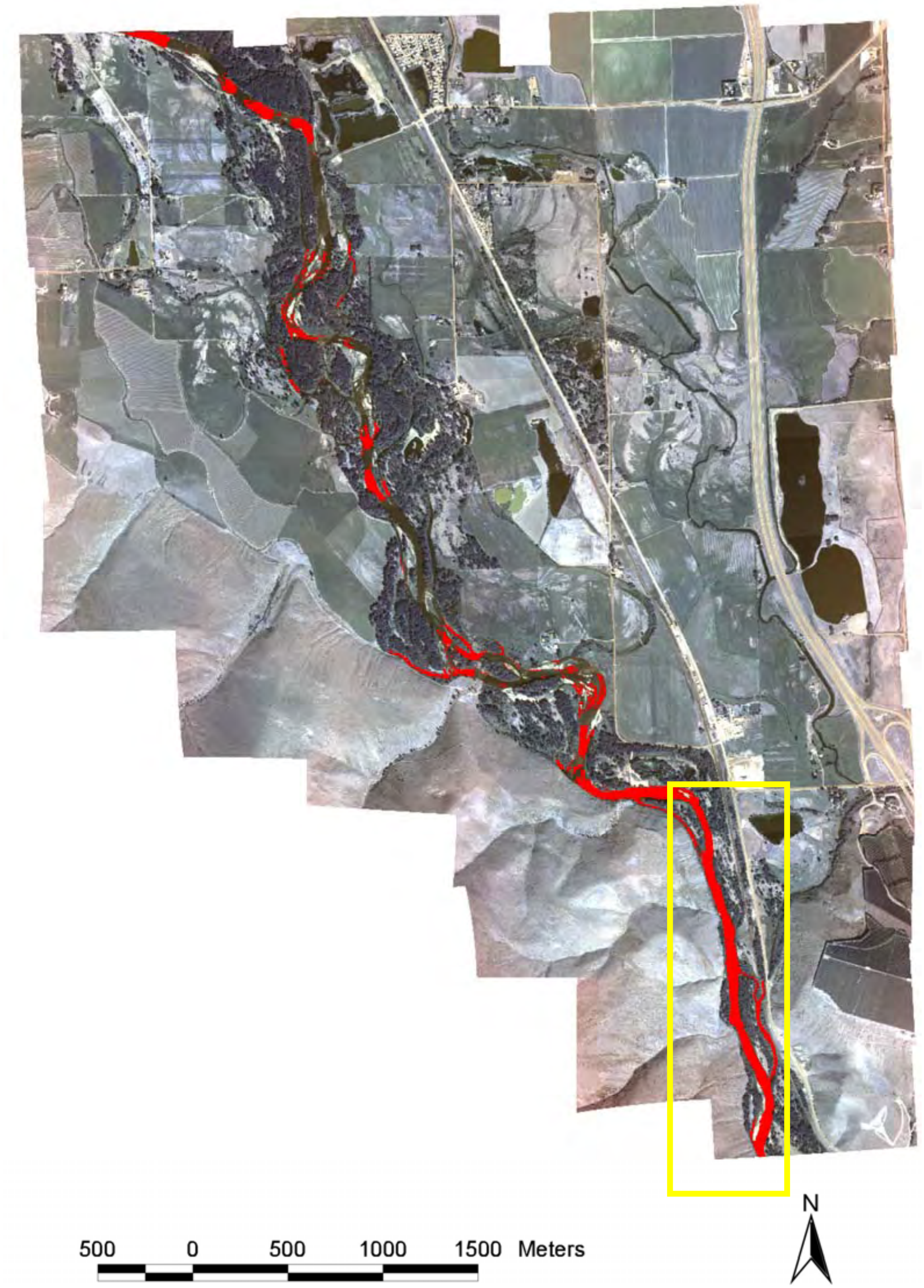


Figure 15. A plot of the spatial distribution of potential mobility during bank-full discharge for the Kittitas reach. The red areas are where $\xi =\geq 1$ indicating the potential for sediment movement. The yellow box is an area where the channel is steep and armored with larger cobbles and hence, mobility is over predicted.

The Naches reach is unique from the others in that sediment transport zones dominate. Historically, it is characterized by major channel avulsions followed by broad scour of the para-fluvial zone. Clearly, to maintain this behavior and also the creation of new-forested riparian areas there must be a large influx of sediment from the upstream headwaters. Given this relatively high proportion of mobile areas determined from the mobility analysis and the highest percent of cut-volume (22% Table 1) supports the conclusion that the Naches reach is a major source of sediment for the Union Gap reach. Therefore, bank stabilization in the Naches reach will impact the viability of the Union Gap reach.

Analysis of Sediment Bed Load Flux Rate

Once sediment threshold entrainment has been achieved it is the volumetric flux of sediment that is important. For gravel-bed rivers, the volumetric flux of sediment that causes major changes in channel morphology is mainly a function of the bed load. Many variations of bed load discharge equations have been put forward and used to varying degrees of success (Bathurst et al. 1987). Pitlick and Van Streeter (1998) used the empirical bed load function of Parker et al. 1982,

$$Q_b = W^* \frac{\sqrt{g}\left(hS\right)^{2/3}}{\left(\left(\rho_s/\rho\right)-1\right)} \tag{5}$$

where Q_b is the bed load discharge rate and W^* is an empirical coefficient, to assess discharge regimes on the Colorado River that were best for maintaining habitat for the endangered Colorado squawfish. Equation (5) has functional similarity with the mobility ratio equation (4) but with units of $m^{1.5}$ for W^* to obtain the proper units (m^3/s) for Q_b. Values for W^* are dependent on particle size data from both the surface layer and the subsurface and therefore are difficult and time consuming to obtain. We did not use this expression in our assessment of bed load discharge given the additional time needed to collect the necessary particle size data.

More classic approaches to bed load discharge stem from the seminal work by Bagnold (1966) where he established the general relation

$$q_b = C\left(q - q_c\right)S \tag{6}$$

where q_b is the bed load discharge per unit stream width, q unit discharge, q_c is the critical unit discharge that entrains sediment and C is an empirical coefficient. Many authors have built upon this relation that says the bed load discharge is proportional to the unit discharge of water above the critical threshold limit and the slope. They have reduced the equations down to yet simpler forms dependent on slope and the mean particle size,

$$q_b = C D_{50}^{a} \sqrt{g} S^{b} \tag{7}$$

(Bathurst et al. 1987). The coefficients are empirical and vary widely as a function of the data sets from which they were derived and methods of measuring the actual flux of sediment. We were initially attracted to these equations because the data collection needs were simple and they are easy to calculate in a GIS for every square meter of river channel in our multispectral images. However, after testing the range published coefficients we found volumetric flux rates in units of m^3/s that exceeded the total available sediment stored in the flood plains.

The outcome of this testing occasioned us to derive our own equation for bed load discharge and scaling the results from modeling the equation against actual historical flood events that have occurred in the Yakima River with the estimates of sediment storage in the flood plain. That derivation is presented below followed by discussion of the results.

Derivation of a Bed Load Discharge Equation for Gravel-bed Rivers

Bed load discharge should be related physically to some assessment of threshold entrainment, unit area of the bed and the mean particle transport velocity. Conceptually, this is straight forward and can be written mathematically as a proportionality relation as follows

$$q_b \propto \xi A \overline{U}_b \qquad (8)$$

where ξ is the mobility ratio (equation 4), A is unit area of the bed under transport and $\overline{U}_b$ is the mean advection or transport velocity of the bed load. Substitution of equation 4 into equation 8 and using a nondimensional proportionality coefficient, K, yields the following bed load transport equation

$$q_b = K\left(\frac{\rho g h S}{\theta(\rho_s - \rho) g D_{50}^{0.6} D_{\max}^{0.4}}\right) A \overline{U}_b \qquad (9)$$

where q_b is the volumetric bed load transport rate per area of the bed in units of m^3/s.

We do not know the mean advection velocity, so we cannot plug values into equation (9). However, Bagnold (1966) working in flume experiments with sand and pebble size material found that $\overline{U}_b$ was proportional to the mean flow velocity $\overline{U}$

$$\overline{U}_b = a\overline{U} \qquad (10)$$

and that the proportionality coefficient (a) in this relation can have values as high as 0.3. Therefore, we used that value in our bed load modeling even though it is probably quite high for gravel to cobble size material. It would be best to evaluate the variance of (a) over a range of flow discharges because transport intensity and advection velocity will increase as discharge increases. However, the coefficient (a) will vary much less then K, which can vary by an order of magnitude. The goal here is to not calibrate K and (a) to precisely estimate bed load, but rather to roughly assess the bed load flux by using constant values and scaling the results against sediment stores in a first order sediment budget.

Substitution of equation (10) into (9) yields the form of the bed load equation modeled here:

$$q_b = K\left(\frac{\rho g h S}{\theta(\rho_s - \rho) g D_{50}^{0.6} D_{\max}^{0.4}}\right) A\left(\overline{U} a\right). \tag{11}$$

The equation above is essentially in a form that proportionally relates normalized stream power to bed load flux, which is a physically correct approach common to sediment transport problems in rivers, sand dunes and on beaches. Moreover, the equation is dimensionally correct without the insertion of dimensional coefficients to balance the units and all the values are easily measured and modeled in a GIS. However at this point, we are still left with determining what value(s) to use for *K*. The goal here was to use scaling arguments to justify values for *K* in estimating bed load flux on the Yakima River reaches. It is common in GIS soil erosion models to use proportionality coefficients in sediment transport relations of similar form to *K* that vary 6 orders of magnitude (Wilson and Lorang 1999).

The coefficient *K* in equation (11) proportionally scales the intensity of the transport rate in a similar fashion to how flow resistance or drag is scaled. It is therefore useful to compare the range of values for other similar proportionality coefficients used in general expressions for turbulent shear stress

$$\tau = C_d \rho \overline{U}^2 \tag{12}$$

where C_d is a drag coefficient that relates to differing particle sizes and or bed forms. Sternberg (1972) determined values of C_d at 0.002 to 0.003 for coarse sand and pebbles (<0.01m diameter material). Voulgaris et al. (1994) determined values in the same range for a gravel-bed tidal channel.

Another form of drag is that associated with flow resistance in rivers. The Darcy-Weisbach equation is a widely-used flow resistance equation

$$U = \sqrt{\frac{8}{f_r} g R S_f} \tag{13}$$

where, *R* is the hydraulic radius, S_f is the energy gradient or friction slope and f_r is the dimensionless Darcy-Weisbach friction coefficient, which relates to the bottom drag in a river that induces flow resistance. In this equation, frictional coupling, f_r, has a nondimensional proportionality relation to the product of channel dimension and water depth, *R*, the friction slope, S_f, and the driving force of gravity, *g*, similar to the *K* coefficient in equation (11). Lorang and Hauer (2002) developed regression equations to estimate the Darcy-Weisbach friction coefficient determined with data from gravel-bed rivers in New Zealand similar in size, slopes and bed material. Using those regression equations for the Yakima, we found values for

f_r ranging from 0.001 to 0.01. We used values for *K* in equation (11) that spanned this range as scaling factors related to how efficiently the river transports sediment. Frictional resistance will increase as a function of an increase in either the energy gradient or bed slope. Therefore, we use values for *K* of 0.001 for the steep slope reaches Cle Elum and Naches and 0.01 for the others given that slope differed by a factor of 2.

Scaling *K* in this manner produced reasonable daily bed load discharge rates when compared with stored volumes of sediment (Table 4). We also found a favorable comparison between modeled bed load flux and measured deposits following the February flood of 1996. Norman et al. (1998) reported that approximately 400,000 cubic yards of gravel was deposited in a breached gravel pit in Selah Gap and on the bars of the Yakima River immediately upstream from the pits during the February 1996 flood. Using the flux rate for Union Gap reach (Table 4) and modeling the February 1996 flood, we came up with an estimate of 555,361 cubic yards for the extent of river (3 km) covered by our multispectral imagery. These arguments support the conclusion, at least to first order, that our estimates of sediment flux (Table 4) using equation (11) are reasonable and that no further adjustments need to be made in the coefficients.

Table 4. Estimated bed load sediment flux rates under bank-full discharge conditions for each of the reaches. Included are values used for particle size, average reach slope and bank-full stage above stage at image acquisition.

Reach	Bankfull Stage (m)	D_{50} (cm)	D_{max} (cm)	Slope ND	Reach Flux (m^3/day)	Flux/River km ($m^3 day^{-1} km^{-1}$)
Cle Elum	1.2	7	15	0.0054	31,238	2,779
Kittitas	1.6	10.2	20	0.0038	39,447	4,635
Naches	1.6	17.1	31	0.0078	29,862	2,507
Union Gap	1.6	17.1	31	0.0037	151,763	15,727
Wapato	1.4	5	15	0.0028	601,785	14,522

The Wapato reach had the highest total flux rate which is expected given it is the largest. However, the Union Gap reach had the highest level of bed load flux per river km. What is interesting here is that the Union Gap reach had a flux rate per river km nearly three times as large as the Kittitas reach. Both of these reaches have similar slopes, bank-full stage depths and reach lengths. The particle sizes are slightly larger in Union Gap, which would tend to reduce the flux rates when other driving variables are similar. The difference is due to two reasons. First, the Union Gap reach has a much larger para-fluvial zone (greater source area) than the Kittitas and second, more of that area is mobilized during bank-full flow (i.e., $\xi > 1$). The Naches reach also has a large para-fluvial zone, however, due to its steep slope the *K* value used was 0.001 rather than 0.01, which greatly reduces the flux rate. The normalized flux rate for the Wapato reach was also rather large. The reason was its smaller particle size and perhaps, a lower elevation relative to the bank elevation which would cause *h* in equation (11) to be relatively higher than the other reaches (i.e., a higher percentage of the pixels covering the para-fluvial zone would have ξ values > 1). If this is true, the Wapato reach may very well be incising due to a depleted supply of sediment trapped behind Sunny Side dam and because irrigation withdrawals, by decreasing stream power, may be reducing bank erosion and hence, reducing the supply of sediment from that source.

The relevance of this discussion is that comparison of flux rates for the different reaches in light of the driving variables in equation (11) lends insight into the fluvial processes active within each reach more than estimating the absolute volumetric flux of sediment. In that light, we can conclude the Union Gap reach is the most fluvially active reach and the Wapato reach may be experiencing significant incision due to processes that lead to a large difference between bar top and bank top for the given range in sediment sizes.

To further examine the sediment budget for the reaches, we estimated the cumulative bed load flux during all significant flood events since 1966 for all reaches. We can do this by simply summing the number of days above some threshold discharge and multiplying that number by the daily bed load flux for each reach (Table 4). Our first assumption is that these flood events were geomorphic threshold crossing events where significant bed transport and channel shaping occurred. Secondly, we assumed that each of those events were also basin wide and therefore, we could use the USGS gauging station #12500450 from the Union Gap reach to determine the duration of each flood.

Our bank-full flood-stage modeling of the Union Gap reach compared well with aerial photographs taken at a discharge of approximately 15,000 cfs on Febrary 8th (Fig. 8.) Therefore, we arbitrarily choose 15,000 cfs as our threshold crossing discharge from which to determine the number of days since 1966 (start of complete discharge record for station #12500450) where discharge met or exceeded that value (Table 5). This geomorphic discharge level would be different for each of the reaches (e.g., ~7,500 cfs for Kittitas), however, the duration would be similar. Knowing the number of days allowed us to estimate the volume flux for each of the floods expected to have transported significant volumes of sediment.

We compared bed load discharge estimates as percentages of the total available volume of sediment in each reach and for each flood year (Table 5). Those numbers scale well with the estimates of bank erosion volumes associated with zones of relatively high stream power (Table 2 and Fig. 14). This is expected since equation (11) is a proportionality relation between stream power and bed load transport. It also validates the use of 15,000 cfs as a reasonable choice for the geomorphic threshold crossing discharge to use in determining duration. Had we used a smaller discharge, the total flux values for each reach would have been exceedingly high. Or, had we chosen a higher threshold discharge, the total flux would have been too low. If the values had scaled more closely to the volume estimates, determined from eroding all the banks and channel bed, than that would indicate too low of a threshold discharge had been chosen. One would expect most of the sediment would come from erosion in areas where stream power was highest the close scaling to those estimates of volume flux further validates equation (11), the values used for the variables and the chosen threshold discharge level.

The most sediment moved in a single year occurred in 1971 for all reaches due to the high duration of bank-full discharge (Table 1). It is interesting to compare water year 1971 with 1995 when the largest flood of record occurred in the Yakima Basin (Fig. 16). Because the flood was so much larger in February 1996 than other years, the actual volume of sediment moved could have been considerably more than what is estimated (Table 5). This is due to the fact that we are holding the *K* value constant for all floods. As flood magnitude increases, one would expect the intensity or efficiency of sediment transport to increase and hence, *K* should increase as well. Larger floods like 1996 also cover more areas and conceivably acquire more sediment from a larger area. However, precisely estimating the volume flux is not possible until a reasonable argument from either empirical or theoretical grounds or both can be made to address the proper *K* values to use for higher discharges. However, the value for (*a*) was held at a constant high value, which would tend to overestimate bed load discharge at near threshold conditions and more closely approximate the actual bed advection rate at higher discharges.

Table 5. A comparison of the estimated volumetric flux of gravel for each reach expressed as a percentage of the total available volume of sediment in the reach, relative to the number of days of discharge above bank-full conditions since 1968. The volume flux sum total for the period of record is listed at the bottom of each column.

Water Year	# of Days > BF	Cle Elum % Total	Kittitas % Total	Naches % Total	Union Gap % Total	Wapato % Total
1968	2	0.5	0.5	0.6	0.9	0.5
1970	1	0.3	0.3	0.3	0.4	0.3
1971	30	7.6	8.1	8.3	13.5	8.1
1973	16	4.0	4.3	4.4	7.2	4.3
1975	5	1.3	1.4	1.4	2.2	1.4
1977	6	1.5	1.6	1.7	2.7	1.6
1980	4	1.0	1.1	1.1	1.8	1.1
1981	1	0.3	0.3	0.3	0.4	0.3
1982	1	0.3	0.3	0.3	0.4	0.3
1983	2	0.5	0.5	0.6	0.9	0.5
1990	2	0.5	0.5	0.6	0.9	0.5
1995	12	3.0	3.2	3.3	5.4	3.2
1996	19	4.8	5.1	5.3	8.5	5.1
Total		25	27	28	45	27

Overall, we can see that the total 30-year volume flux for most of the reaches is around 25 percent of the total available sediment in the flood plain except for the Union Gap which is 45 percent (Table 5). Therefore, each reach is greatly dependent on an influx of upstream sediment to maintain production of new geomorphic surfaces because the values are greater than the historical cut-volumes estimated earlier (Table 1) by a factor of 2 to 5. Annually, the volume flux rates (Table 5) scale closely with estimates from within reach bank erosion (Table 2). However, during large flood events where duration above a geomorphic threshold level is sustained for long time periods (e.g., 1971 see Fig. 16), sediment bed load flux rates greatly exceed within reach bank supply. This scalar evaluation points out the sensitive nature of all of the reaches to the upstream sediment supply in order to maintain a shifting habitat mosaic Hence, upstream bank stabilization can have significant impacts to the ecological functioning of these critical reaches over a decade scale time frame.

The Union Gap reach depends on sediment from the Naches reach. Sediment influx to the Union Gap reach from Selah is limited due to extensive gravel mining that has occurred there and the fact that Roza Dam has stopped all bed load sediment from being transported from the upper reaches of the Yakima. Another risk is avulsion capture of bed load by existing gravel pits. Pit capture of the river by some of the very deep gravel pits (~ 15 m) could disconnect groundwater-surfacewater interaction across the flood plain for periods of several decades.

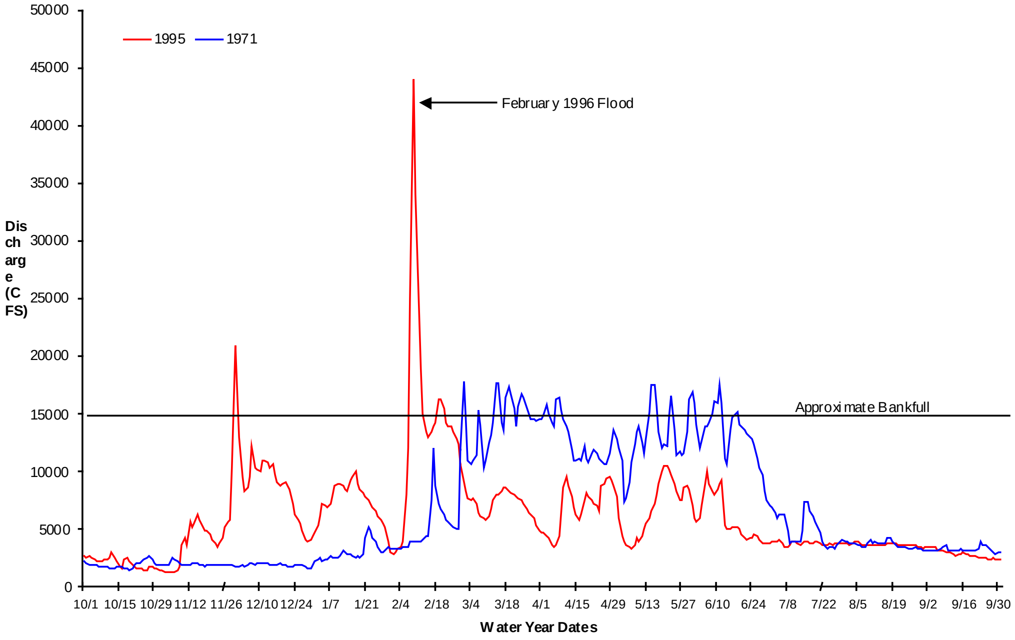


Figure 16. A graph comparing the discharge record for water years 1971 and 1995 for the Union Gap reach with data from USGS gauging station #12500450. The horizontal line defines the geomorphic threshold discharge of 15,000 cfs which approximates bank-full conditions.

SUMMARY AND CONCLUSIONS

The underpinning hypothesis of this project is that the river can do the work of naturally restoring shallow water floodplain habitats essential to maintaining the ecological health of the river system and salmonid recovery in the Yakima River, Washington. Key fluvial processes are cut and fill alluviation and channel avulsion. These processes shape the floodplain landscape resulting in a continual shifting mosaic of habitat both above and below ground. Maintaining this shifting habitat mosaic is dependent on the ability of the river to move freely about the historical flood plain and on the balance between stream power, to accomplish the geomorphic work of channel avulsions, and cut and fill alluviation. It is also dependent on a sufficient supply of sediment to build new bars and islands and to prevent channel incision that would disconnect important groundwater-surfacewater interactions.

There were two primary objectives for this work. One was to objectively and quantitatively map areas of the flood plains that have the highest potential to be reworked by fluvial processes; the other was to assess the long-term geomorphic viability of the flood plains by assessing sediment supply from a rough sediment budget approach. These objectives were successfully completed for the five key reaches (Cle Elum, Kittitas, Naches, Union Gap and Wapato) identified as critical for productivity of juvenile salmon and steelhead of the Yakima River, Washington.

Objective 1: Assess the Geomorphic Work Potential

We have successfully developed a new technique to objectively and quantitatively assess the potential of the river to do geomorphic work within the five critical reaches. To accomplish this task required the completion of three separate but related tasks. The first was to map out the spatial distribution of stream power within the main channel for each reach. The second step was to develop a high resolution DEM of the flood plain in each reach and then model the spatial distribution of shear stress for various flood discharge regimes. The third step was to combine the results from steps 1 and 2 to delineate zones of both moderate and high potential for geomorphic work and produce large-scale maps of those results.

Step One: Main Channel Stream Power Assessment. To map out the spatial distribution of stream power, we combined multispectral imagery with on the ground measures of water depth and flow velocity, using an ADP combined with position measures obtained with a GPS (Fig. 3). We then used estimates of river slope from existing USGS DEM's (Fig. 4) to model stream power for every square meter of the river surface corresponding to the discharge at image acquisition (Fig. 5). This analysis provided an objective and quantitative assessment of the spatial distribution of important fluvial processes, mainly location of potential avulsion nodes and areas of cut and fill alluviation.

Step Two: Floodplain Shear Stress Assessment. In order to estimate shear stress across the flood plain, we needed to develop an accurate DEM of the floodplain topography. We combined the ability to automatically make cover type maps of vegetation, gravel bars, off-channel water and other easily distinguished features from the multispectral imagery with on the ground topographic surveys through those units (Fig. 7). Hence, we completed topographic survey transects near project monitoring wells and along the banks and bars in each reach. This data collection scheme allowed us to use a GIS to develop a high-resolution topography map (10cm DEM) for each reach by assigning relative elevation and slope relationships for each cover type. We then used the new DEM's to model shear stress across the flood plains for various flood stage levels (Fig. 8).

Step Three: Zonal Delineation of Potential Geomorphic Work. Combined stream power and shear stress modeling results were used to identify potential avulsion nodes by overlaying the results from the stream power and shear stress analysis to correlate where bank erosion and flood channel connectivity are likely. Areas where flood flows connect floodplain channels with the main channel in a zone of high stream power have the highest potential for an avulsion node to form (Fig. 9 (A) lower left panel). Areas where flood flows connect floodplain channels with the main channel in a zone of low relative stream power but along the outside of a channel bend also have a high potential for an avulsion node to form (Fig. 9 (B) lower left panel). Likewise, areas where flood flows connect floodplain channels with the main channel but in a zone of low relative stream power and not along an outside bend of the main channel have a lower or moderate avulsion potential (Fig. 9 (C) lower left panel). Connecting the avulsion node at the top with the lateral extent of flooding and where the flood channels join back to the main channels provides a limit to defining zones of potential geomorphic work (Fig. 9 lower right panel). This represents the final end product for our first objective (Fig. 10) and large maps of this type have been prepared for each of the reaches.

Objective 2: Assess Sediment Supply

We used a sediment budget approach to quantitatively assess how much sediment is stored in the flood plain compared with estimates of bed load flux rates. We evaluated a sediment budget for each reach over long time scales (decades) to make first order assessments of the relative importance of the influx of sediment into the critical reaches from upstream. We also assess the relative importance of the supply of sediment from within each reach for the formation of new geomorphic surfaces coming from local bank and channel erosion on a more short-term (annual) scale.

The first approach was to make scalar comparisons between how much sediment is stored in the total flood plain for each reach and how much sediment was removed from the historical flood plain to account for the present channel volume. Secondly, we estimated how much sediment is stored in the main channel-bed and banks and compared that with the sediment volume immediately available, by erosion of the main channel-bed and bank in areas of predicted high stream power. Lastly, we modeled spatial distribution of potential sediment mobility as a function of sediment size and applied shear stress during bank-full discharge and calculated the associated bed load flux rate. This analysis allowed us to make first order quantitative estimates of where sediment is coming from and where it is likely to deposit.

Floodplain Storage and Historical Flux

The Kittitas reach has the highest volume of available sediment per kilometer of river compared with the other reaches (Table 1). From a computation perspective, this is due to the relatively large area of high-forested terraces combined with deep scour holes. The same is true for the Cle Elum reach. The Wapato has a high available volume due to its wide flood plain rather than depth of scour. The Naches and Union Gap reaches have the least amount of available sediment per river kilometer. The computation reason for this is the larger percentage of para-fluvial zone (i.e., annual scour zone between low water and bank-full) composed of low elevation gravel bars relative to high-forested terraces.

These calculated differences have process based explanations associated with them. First of all recent, fluvial processes are more active in the Union Gap and Naches reaches than the other three as expressed by their wider para-fluvial zones and lower available sediment per river kilometer. However, because they have wider para-fluvial zones they more immediately available sediment while the other reaches require significant bank erosion to release their stored reserves. We can also conclude that the Union Gap and Naches reaches are more fluvially active due to the higher percentage of cut-volume related to total floodplain volume (Table 1). The present river channels for the Kittitas and Cle Elum reaches occupy much of the same historical channel positions compared with Naches and Union Gap which have nearly cut completely new channels. A possible explanation for this is that the Cle Elum and Kittitas reaches have become more incised in their channels then the Naches and Union Gap reaches. This may also be related to the relative supply of sediment from upstream is greater in the Naches and Union Gap then the Cle Elum and Kittitas reaches. Historical photographs for the Wapato reach were not available, and those used for comparison on the other reaches were georectified and compiled by the Central Washington Reaches Group (Eitemiller 2002).

Sediment Supply from the River Banks and Channel-bed

The volume of stored sediment available to bed and bank erosion for all reaches at a bank-full stage level represents around 5 % on average of the total available sediment in the flood plain. Therefore, bank erosion alone represents grossly about a 40-year supply, which underscores the importance of a long-term resupply of sediment from upstream for each reach. A loss or reduction of up stream sediment will induce channel incision, a reduction in channel complexity and disconnection of groundwater-surfacewater interaction. Such scaling exercises provide a quantitative base to assess the potential impact in the critical reaches due to river capture by floodplain gravel pits and bank stabilization efforts upstream.

A more conservative estimate for the amount of sediment potentially released during bank-full discharge was calculated only for those banks that correlated with relatively high stream power (Fig. 14). The percentage of total sediment released from high power banks is low (i.e., <1%, see Table 2) of the total volume stored in the flood plain, which equates to an area of about 1 hectare. Clearly, not all eroded sediment goes to forming 1 hectare of new bars or islands in each reach after every bank-full discharge. However, it does scale the important role bank erosion plays in maintaining a balance to the shifting habitat mosaic. Moreover, it points out the potential immediate impact due to local bank stabilization efforts, like construction of riprap and spur dikes, within the critical reaches (Fig. 1).

Analysis of Sediment Mobility and Bed Load Flux

All reaches show alternating segments of transport and deposition. The Union Gap and Wapato reaches have a high degree of alternating small stretches of transport and depositional segments through out the reach especially near the bottom of the reach. The Kittitas and Cle Elum reaches both have a large transport segment just as the reach exits into a steep canyon reach. The Naches reach is unique from the others in that sediment transport zones throughout the reach length dominate. Historically, it is characterized by major channel avulsions followed by broad scour of the fluvial zone. Clearly, to maintain this behavior and also the creation of new-forested riparian areas there must be a large influx of sediment from the upstream headwaters. Given this relatively high proportion of mobile areas determined from the mobility analysis and the highest percent of cut-volume (22% Table 1) supports the conclusion that the Naches reach is a major source of sediment for the Union Gap reach. Therefore, bank stabilization in the Naches reach will impact the viability of the Union Gap reach.

The Wapato reach had the highest total flux rate, which is expected given it is the largest. However, the Union Gap reach had the highest level of bed load flux per river km. The Union

Gap reach is the most fluvially active reach but is dependent on a supply of sediment from the Naches reach. The Wapato reach may very well be incising due to a depleted supply of sediment trapped behind Sunny Side dam and because irrigation withdrawals, by decreasing stream power, may be reducing bank erosion and hence, reducing the supply of sediment from that source.

We compared bed load discharge estimates as percentages of the total available volume of sediment in each reach and for each flood year (Table 5). Those numbers scale well with the estimates of bank erosion volumes associated with zones of relatively high stream power (Table 2 and Fig. 14). This is expected since equation (11) is a proportionality relation between stream power and bed load transport. It also validates the use of 15,000 cfs as a reasonable choice for the geomorphic threshold crossing discharge to use in determining duration.

Overall, we can see that the total 30-year volume flux for most of the reaches is around 25 percent of the total available sediment in the flood plain except for the Union Gap which is 45 percent (Table 5). Therefore, each reach is greatly dependent on an influx of upstream sediment to maintain production of new geomorphic surfaces because the values are greater then the historical cut-volumes estimated earlier (Table 1) by a factor of 2 to 5. On an annual basis, the volume flux rates (Table 5) scale closely with estimates from within reach bank erosion (Table 2). However, during large flood events were duration above a geomorphic threshold level is sustained for long time periods (e.g., 1971 see Fig. 16) sediment bed load flux rates greatly exceed within reach bank supply. This scalar evaluation points out the sensitive nature of all of the reaches to the up stream sediment supply in order to maintain a shifting habitat mosaic. Hence, upstream bank stabilization can have significant impacts to the ecological functioning of these critical reaches over a decade scale time frame.

The Union Gap reach depends on sediment from the Naches reach. Sediment in flux to the Union Gap reach from Selah is limited due to the extensive gravel mining that has occurred there and the fact that Roza Dam has stopped all bed load sediment from being transported from the upper reaches of the Yakima. Another risk is the avulsion capture of bed load by the existing gravel pits. Pit capture of the river by some of the very deep gravel pits (~ 15 m) could disconnect groundwater-surface water interaction across the flood plain for periods of several decades.

CONCLUDING STATEMENTS

Stream flow and sediment loads were analyzed by linking remote sensing multispectral imagery with on the ground measures of flow velocity, water depth, substrate size and surface topography. The spatial distribution of stream power, shear stress, sediment mobility and volumetric flux, within the five reaches covered by multispectral imagery, were then modeled in a GIS. The results of those analyses formed the basis for the sediment budget and provided an objective methodology to quantifiably determine floodplain zones of both high and moderate potential for geomorphic work. Maps were produced that delineate these zones for each of the five floodplain reaches. The maps integrate results from the analysis of modeled stream power and shear stress over various discharge regimes and are meant to serve as aids in the decision making process of prioritizing land acquisition efforts.

REFERENCES

Andrews, E. D. 1983. Entrainment of gravel from naturally sorted riverbed material. Bulletin of the Geological Society of America **94**:1225-1231.

Andrews, E. D. 1984. Bed-material entrainment and hydraulic geometry of gravel-bed rivers in Colorado. Bulletin of the Geological Society of America **95**:371-378.

Bagnold, R. A. 1966. An approach to the sediment transport problem from general physics. United States Geological Survey Professional Paper 422-I:1-37

Baker, V. R., and D. F. Ritter. 1975. Competence of rivers to transport coarse bedload material. Bulletin of the Geological Society of America **86**:975-978.

Bathurst, J. C., W. H. Graf, and H. H Cao. 1987. Bed load discharge equations for steep mountain rivers. Pages 453-491 *in* C. R. Thorne, J. C. Bathurst, and R. D. Hey, editors. Sediment transport in gravel-bed rivers. John Wiley and Sons Ltd., New York.

Bradley, W. C., and A. I. Mears. 1980. Calculations of flows needed to transport coarse fraction of Boulder Creek alluvium at Boulder, Colorado. Bulletin of the Geological Society of America **86**:1057-1090.

Buffington, J. M., and D. R. Montgomery. 1997. A systematic analysis of eight decades of incipient motion studies, with special reference to gravel-bedded rivers. Water Resources Research **33**:1993-2029.

Costa, J. E. 1983. Paleohydraulic reconstruction of flash-flood peaks from boulder deposits in the Colorado Front Range. Bulletin of the Geological Society of America **94**:986-1004.

Downes, B. J., A. Glaister, and P. S. Lake. 1997. Spatial variation in the force required to initiate rock movement in 4 upland streams: implications for estimating disturbance frequencies. Journal of the North American Benthological Society **16**:203-220.

Duncan, M. J., A. M. Suren, and S. L. R. Brown. 1999. Assessment of streambed stability in steep, bouldery streams: development of a new analytical technique. Journal of the North American Benthological Society **18**:445-456.

Eitemiller, D. J., C. P. Arango, K. L. Clark, M. L. and Uebelacker. 2002. The effects of anthropogenic alterations to lateral connectivity on seven select alluvial floodplains within the Yakima River Basin, Washington. Department of Geography and Land Studies, Central Washington University, Ellensburg, Washington, USA.

Helley, E. J. 1969. Field measurement of the initiation of large particle motion in Blue Creek near Klamath, California. United States Geological Survey Professional Paper 562-G:1-19.

Hjulstrom, F. 1935. Studies of the morphological activity of rivers as illustrated by the River Fyris. Bulletin of the Geological Institute of the University of Upsala **25**:221-528.

Hjulstrom, F. 1939. Transportation of detritus by moving water. Pages 5-31 *in* P. D. Trask, editor. Recent Marine Sediments, A Symposium. Special Publications of the Society of Economic Paleontologic Minerology, Tulsa, Oklahoma.

Kellerhals, R. 1967. Stable channels with gravel-beds. Journal of the Waterways and Harbors Division of the American Society of Civil Engineers **WW1**:63-84.

Komar, P. D. 1987a. Selective gravel entrainment and the empirical evaluation of flow competence. Sedimentology **34**:1165-1176.

Komar, P. D. 1987b. Selective grain entrainment by a current from a bed of mixed sizes: a reanalysis. Journal of Sedimentology and Petrology **57**:203-211.

Komar, P. D. 1988. Applications of grain-pivoting and sliding analyses to selective entrainment of gravel and to flow-competence evaluations. Sedimentology **35**:681-695.

Komar, P. D. 1989. Flow-competence evaluations of the hydraulic parameters of floods: an assessment of the technique. Pages 107-133 *in* K. Beven and P. Carling, editors. Floods: hydrological, sedimentological and geomorphological implications. John Wiley and Sons, New York.

Komar, P. D., and P. A. Carling. 1991. Grain sorting in gravel bed streams and the choice of particle sizes for flow-competence evaluations. Sedimentology **38**:489-502.

Lane, E. W. 1955. Design of stable channels. Transactions American Society of Civil Engineers **120**: 1234-1260.

Leopold, L. B., M. G. Wolman, and J. P. Miller. 1964. Fluvial Processes in Geomorphology. W. H. Freeman and Co., San Francisco.

Lorang, M. S., and F. R. Hauer. *In press*. Flow competence evaluation of stream-bed stability: an assessment of the technique and limitations of application. Journal of the North American Benthological Society.

Miller, M. C., I. N. McCave, and P. D. Komar. 1977. Threshold of sediment motion in unidirectional currents. Sedimentology **24**:507-528.

Montgomery D. R., and J. M. Buffington. 1998. Channel processes, classification, and response. Pages 13-42 *in* Naiman R. J. and R. E. Bilby, editors. River ecology and management. Springer-Verlag, New York.

Norman D. K., C. J. Cerderholm, and W. S. Lingley. 1998. Flood plains, salmon habitat, and sand and gravel mining. Washington Geology **26**:3-27.

O'Connor, J. E. 1993. Hydrology, hydraulics and geomorphology of the Bonneville flood. United States Geological Survey Professional Paper **274**:1-83.

Parker, G., P. C. Klingeman, and D. G. McLean. 1982. Bedload and size distribution in paved gravel-bed streams. Journal of Hydraulics **108**:544-571.

Pitlick, J., and M. M. van Steeter. 1998. Geomorphology and endangered fish habitats of the upper Colorado River 2. Linking sediment transport to habitat maintenance. Water Resources Research **34**:303-316.

Ridder, J. R. 1967. Bed-material movement, Middle Fork Eel River, California. United States Geological Survey Professional Paper 575-C:219-221.

Scott, K. M., and C. G. Gravlee. 1968. Flood surge on the Rubicon River. California: hydrology hydraulics and boulder transport. United States Geological Survey Professional Paper 422-M:1-38.

Shields, A. 1936. Anwendung der Aehnlichkeitsmechanik und der Turbulenz-forscgung auf die Geschiebewegung. Mitteilungen der Preuss.Versuchsanst fur Wasserbau und Schiffbau, Berlin.

Snyder E. B., and J .A. Stanford. 2001. Review and synthesis of data related to instream flow provision in the Yakima River ecosystem, Washington. U.S. Department of the Interior, Bureau of Reclamation.

Snyder, E. B. and J. A. Stanford. 2001. Review and synthesis of river ecological studies in the Yakima River, Washington, with emphasis on flow and salmon habitat interactions. Prepared for U.S.Department of the Interior, Bureau of Reclamation, Yakima, Washington. Open File Report 163-01. Flathead Lake Biological Station, The University of Montana, Polson, Montana.

Snyder, E. B., and J.A. Stanford. In preparation. Derivation of normative flows for a damaged floodplain river ecosystem. Draft report, U.S. Department of the Interior, Bureau of Reclamation, Upper Columbia Area Office, Yakima, Washington.

Sternberg, R.W. 1972. Predicting initial motion and bedload transport of sediment particles in the shallow marine environment. Pages 62-82 *in* D. J. P. Swift, editor. Shelf sediment transport: process and pattern. Hutchinson and Ross, Inc., Stroudsburg.

Townsend, C. R., M. R. Scarsbrook, and S. Dole`dec. 1997. Quantifying disturbance in streams: alternative measures of disturbance in relation to macroinvertebrate species traits and species richness. Journal of the North American Benthological Society **16**:531-544.

Voulgaris, G., Wilkin, M. P., and Collins, M. 1994. Shingle movement under waves and currents: an instrumented platform for field data collection. Pages 895-909 *in* A. S.

Arcilla, M.J.F. Stive, and N.C. Kraus, editors. Coastal Dynamics '94 : Proceedings of an International Conference on the Role of the Large Scale Experiments in Coastal Research: Universitat Polite. American Society of Civil Engineers.

Whited, D. C., J. A. Stanford, and J. S. Kimball. *In press*. Application of airborne multispectral imagery to quantify riverine habitats at different base flows. River Research and Applications.

Williams, G. P. 1978. Bank-full discharge of rivers. Water Resources Research **14**:1141-1154.

Wilson, J. P., and M. S. Lorang. 1999. Spatial models of soil erosion and GIS. Pages 83-103 *in* A. S. Fotheringham and M. Wegene, editors. Spatial Models and GIS - New Potential and New Models. Taylor and Francis, Chichester.

PART C: ASSESSING SALMONID HABIT ON FLOOD PLAINS OF THE YAKIMA RIVER SYSTEM, WASHINGTON, USING REMOTE SENSING

by

Diane Whited
dwhited@selway.umt.edu

Mark Lorang
mlorang@selway.umt.edu

Jack A. Stanford
stanford@selway.umt.edu

and

John S. Kimball
johnk@ntsg.umt.edu

Flathead Lake Biological Station
The University of Montana
311 Bio Station Lane
Polson, MT 59860-9659
406-982-3301
www.umt.edu/biology/flbs

STATEMENT OF PROBLEM

This report covers science activities from August, 2000 to December, 2001 for the following Bureau of Reclamation (USBR) contract: “Assessing salmonid habitat on flood plains of the Yakima River system, Washington, using remote sensing”. The objective of this work was to quantify habitat types in the six relatively intact flood plains (Cle Elum, Kittitas, Selah, Naches, Union Gap and Wapato reaches – see Fig. 1) in the upper Yakima River. Using similar remote sensing and GIS methodology described in the USBR report “Analysis of flow and habitat relations in the lower Yakima River, Washington, associated with proposed water exchange”, we quantified instream habitat for the six floodplain reaches.

We present herein a summary of research results for this investigation.

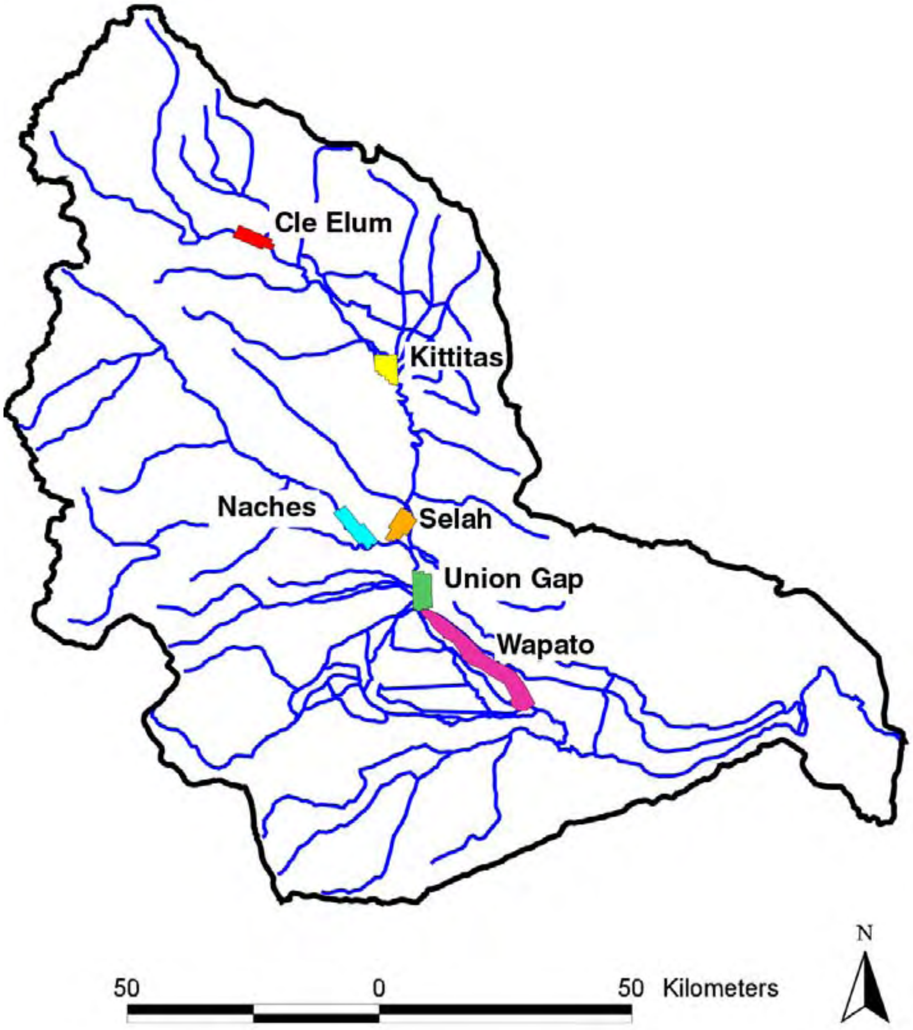


Figure 1. Extent of multispectral imagery acquired for each floodplain reach.

APPROACH

Regional mapping of instream habitats were investigated using an integrated system of airborne remote sensing, ground surveys and acoustic Doppler velocity profiler (ADP) surveys to assess instream habitat types.

Airborne multispectral digital imagery of six reaches were obtained at an approximate 0.7 m spatial resolution in August of 1999 and 2000 in conjunction with limited survey data of stream depth and point measures of flow velocity taken with a handheld flow meter.. Since these ground-based surveys were sparse (approximately 5 points per reach), ADP data collected in (2001) as part of the sediment study “Lorang and Stanford *Linking Fluvial Processes to Floodplain Ecology of the Yakima River Washington: Stream Flow, Sediment Loads and the Potential for Geomorphic Work”* were used for the classification of channel depth and flow velocity. For each floodplain reach, channel characteristics were quantified (e.g., channel complexity, number and size of habitats). Temperature and turbidity were also recorded.

Classification accuracies for islands and water surfaces were greater than 99%, while more detailed depth/flow classifications were less accurate (average of 70% for all reaches), primarily because of image bidirectional reflectance errors which negatively impacted classification accuracies and shadows.

DATA ACQUISITION

Imagery

Airborne multispectral (blue, 0.46-0.55 μm; green, 0.52-0.61 μm; red, 0.61-0.70 μm; near-infrared, 0.78-0.92 μm) digital imagery were acquired in August 1999 for five of the flood plains (Cle Elum, Kittitas, Selah, Naches and Union Gap) and in August 2000 for the Wapato reach. The remote sensing imagery was acquired using an ADAR System 5500 digital camera on-board a light aircraft. Individual scenes covered a ground area of approximately 1.5 km^2 with a spatial resolution of 0.7 m and a 35% consecutive image overlap. Digital image mosaics were created for the entire image corridor for each reach using Digital Image Made Easy (DIME) software (Positive Systems ^{TM}), which uses a semiautomated textural analysis of overlapping images to assemble large amounts of spatial data into a single mosaic. The mosaics were then georeferenced using a U.S. Geological Survey (scale - 1:2400) Digital Ortho-Photo data base. These data were used for image classification of selected habitat features for all floodplain reaches.

Habitat Data

Field measurements (flow velocity, water depth, temperature and turbidity, substratum conditions and habitat type) were obtained at 30 locations across all floodplain reaches. Field data was collected from August 20 – 22, 1999 for four of the reaches (Cle Elum, Kittitas, Naches and Union Gap) and on August 4, 2000 for the Wapato reach. These data were used for accuracy assessment and verification of corresponding digital remote sensing imagery. Riffles (includes riffles associated with vegetated sand bars, lateral cobble bars, cross bar channels and transverse bars fringing the channel), back bar channels and ponds, springbrooks, slack water (backwater habitat), eddies and pools were sampled as discrete habitats. At each survey site, geographic locations were recorded using a global positioning system (GPS) with a spatial accuracy of approximately ±3 m.

ADP

The Sontek RS3000 (ADP) uses 3 transducers to generate a pulse of sound at a known frequency. As the sound travels through the water, it is reflected in all directions by particulate matter (e.g., sediment, biological matter, bubbles) being advected with the flow and is most strongly reflected from the bottom substrate. Some portion of the reflected energy travels back toward the transducer where the processing electronics measure the change in frequency, referred to as a Doppler shift. The Doppler shift relates to the velocity of the water. By measuring the return signal at different times following the transmit pulse, the ADP measures water velocity at different distances from the transducer from just below the water surface to the bottom. This results in a measured velocity profile and depth of the water column. The profile of water velocity is divided into a range of 15 cm deep cells, where each cell represents the average of the return signal for a given period of time. The ADP operates using three transducers generating beams with different orientations relative to the flow of water. The velocity measured by each ADP transducer is along the axis of its acoustic beam. These beam velocities are converted to XYZ (Cartesian) velocities using the relative orientation of the acoustic beams, giving a 3-D velocity field relative to the orientation of the ADP. Since it is not always possible to control instrument orientation, the ADP includes an internal compass and tilt sensor to report 3-D velocity data in Earth (East-North-Up or ENU) coordinates, independent of instrument orientation. Hence, it is possible to determine the mean flow velocity in separate cells through the water column oriented perpendicular to the flow field.

Velocity profile data are correlated spatially by using a GPS receiver co-located with the position of the ADP with both ADP and GPS data recorded simultaneously on a field lap top with the SonTek River Surveyor software (Fig. 2A & B). Those data are then related to individual pixels from the airborne multispectral digital imagery. In this way, pixel intensity can be correlated to flow velocity and water depth.

Figure 2A. Picture showing ADP and GPS mounted on the front of a Jet Boat.

Figure 2B. Picture showing ADP and GPS mounted on the front of a raft.

The ADP surveys were collected for three of the reaches (Cle Elum, Kittitas and Union Gap). The Union Gap reach ADP data was obtained with the ADP and GPS deployed from a jet boat (Fig. 2A) on April 23, 2001 with a discharge of 59 $m^3 s^{-1}$ (imagery discharge of 64 $m^3 s^{-1}$), while the Kittitas (discharge of 88 $m^3 s^{-1}$, imagery discharge of 104 $m^3 s^{-1}$) and Cle Elum (discharge of 77 $m^3 s^{-1}$, imagery discharge of 92 $m^3 s^{-1}$) reaches were surveyed on August 21st and 22nd 2001, respectively with the ADP and GPS deployed from a raft (Fig. 2B). The ADP surveys provided additional data on depth and velocities throughout the reaches that could not have been recorded in any other means. For example, in the Union Gap reach over 800 depth and velocity measurements were collected.

For each GPS location, an integrated velocity measure was calculated (i.e., average velocity for the water column) from the ADP data. The integrated velocity and depth were then used to train the multispectral imagery to classify the instream habitat for the Cle Elum, Kittitas and Union Gap reaches. An unsupervised classification approach (ISODATA, Iterative Self-Ordering Data Analysis, Tou and Gonzalez 1977) was used to generate similar categories of spectral reflectances. Once an unsupervised classification was generated, the ADP tracks were then overlaid on the unsupervised classification to aggregate classes and assign unique depth and velocity categories. For example, in the Union Gap reach the 24 classes defined by the unsupervised classification were aggregated into six depth categories and five velocity categories.

Figure 3 shows an example of an ADP run and subsequent velocity classification within the Union Gap reach. For the three reaches without ADP data (Selah, Naches and Wapato), instream habitat types were modeled from patterns observed in the three reaches with ADP data and adjusted for differences in discharge and slope observed in each floodplain reach. The field data then was used to perform the accuracy assessment for each reach. However no accuracy assessment was conducted for the Selah reach as no field data was collected.

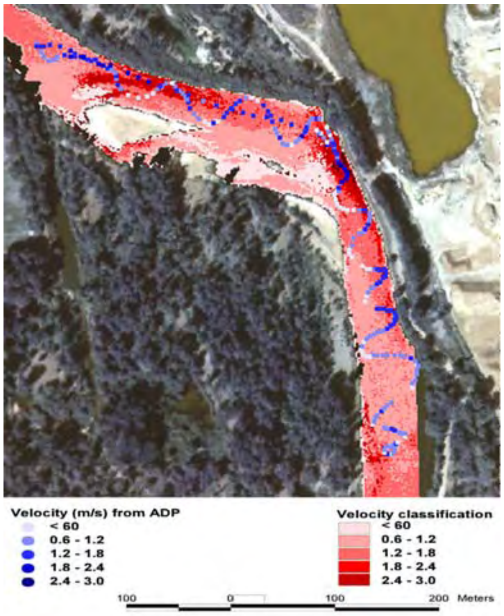


Figure 3. Example of ADP run and velocity classification within the Union Gap reach.

In addition to the depth and velocity classifications, habitat types were identified (i.e., main channel, islands, floodplain ponds, connected off-channel habitat, disconnected off-channel habitat, gravel ponds and other open water bodies) and a channel complexity metric was calculated. The channel complexity metric was developed to evaluate the extent of flow separations and convergences within the study reaches. For the main channel, the location of channel separations and convergences were documented as either separation or return nodes (Fig. 4). Similarly, if an off-channel habitat was connected to the main channel, it was recorded as an off-channel separation, as well as separations and returns within connected off-channel habitats.

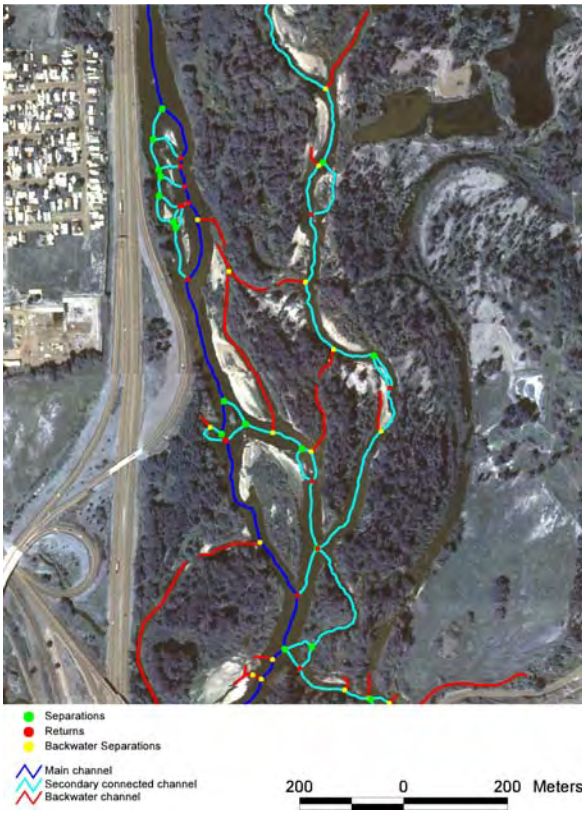


Figure 4. Example of channel complexity metric (separations and returns) as observed in the Union Gap reach.

RESULTS

Riverine habitats (flow depth, velocity and channel types) along with the channel complexity metric were efficiently and accurately identified throughout the reaches. Discrete habitats (main channel, islands within the main channel, floodplain ponds, connected off-channel habitat, disconnected off-channel habitat, gravel ponds, islands within ponds/back channels, canals and other water bodies) were identified and quantified. In addition, channel complexity was calculated, as well as channel lengths.

The accuracy of the depth and velocity classification was relatively high across all reaches with ground truth data (average of 70% correctly classified). However, due to the scarcity of ground truth data in these reaches, the overall accuracy may be inflated.

Obvious errors in classifications were usually caused by bidirectional errors. Figure 5 shows a typical bidirectional error observed in the Kittitas reach. These errors are caused by mosaicking individual scenes together with little attention to illumination differences between scenes.

Figure 5. Example of bidirectional reflectance error

A summary of each reach is discussed in detail.

Cle Elum Reach

Imagery was acquired for the Cle Elum reach on August 26, 1999 with a discharge of 92 m^3 s^{-1}. Turbidity averaged 1.02 (± 0.26) NTUs and temperature averaged 12.27(± 0.51) °C within the main channel. Table 1a and 1b describes the different habitat types (water body and channel types), channel complexity and instream depth and velocity classifications. Figures 6a shows the spatial extent of the different habitat types and figure 6b shows an example of the depth and velocity classifications.

Table 1a. Water and channel types and channel complexity measures for the Cle Elum reach.

Water body type	Number	Area (ha)	% of all water bodies
Main Channel	1	56.44	66
Islands within main channel	38	32.49	
Floodplain ponds	2	0.04	< 1
Connected off-channel habitat	12	1.61	2
Disconnected off-channel habitat	24	1.47	2
Gravel ponds	7	24.80	29
Islands within ponds/back channels	2	0.01	
Other open water	7	0.71	1

Chanel Type	Length (km)
Main Channel	11.24
Secondary Connected Channels	6.11
Back Channels	2.02

Channel complexity	Number
Separations	38
Returns	37
Backwater separation	13
# of separations per river km	3.38
# of returns per river km	3.29
# of b. separations per river km	1.16

Table 1b. Depth and velocity classification for the Cle Elum reach.

Depth (m)	ha	% of surface water area	Velocity (m/s)	ha	% of surface water area
Shadows	8.44	15	Shadows	8.44	15
0 - 0.25	2.29	4	0 - 0.25	2.29	4
0.25 - 0.5	2.20	4	0.25 - 0.5	2.20	4
0.5 - 1	10.97	19	0.5 - 1	10.97	19
1 - 1.5	18.29	31	1 - 1.5	17.35	30
1.5 - 2	12.87	22	1.5 - 2	13.38	23
> 2	3.00	5	2 - 2.5	0.93	2
			> 2.5	2.49	4

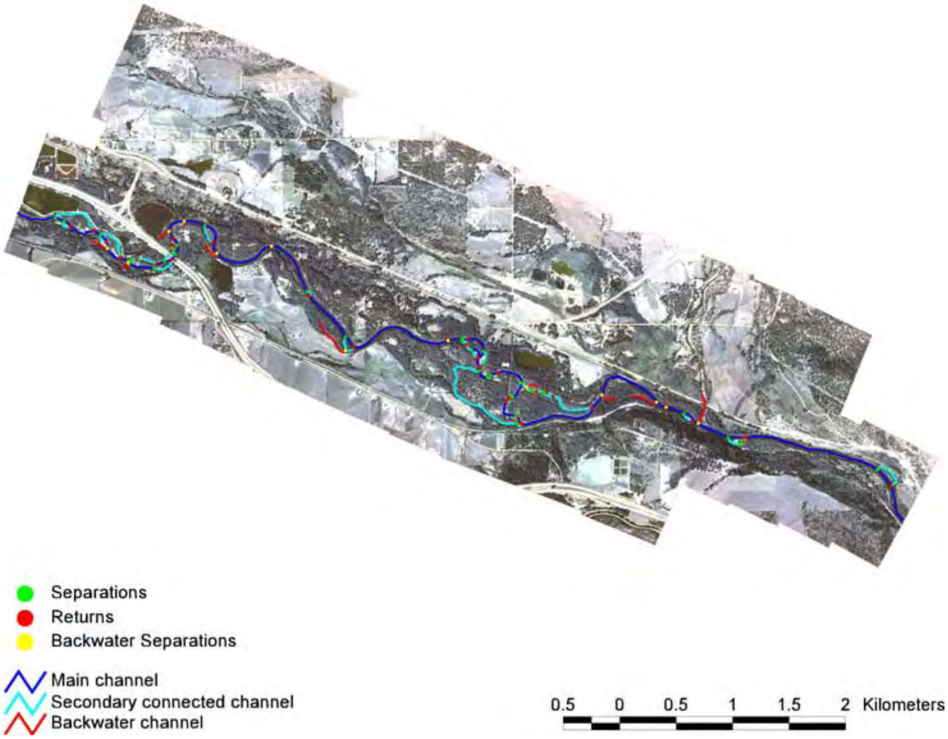
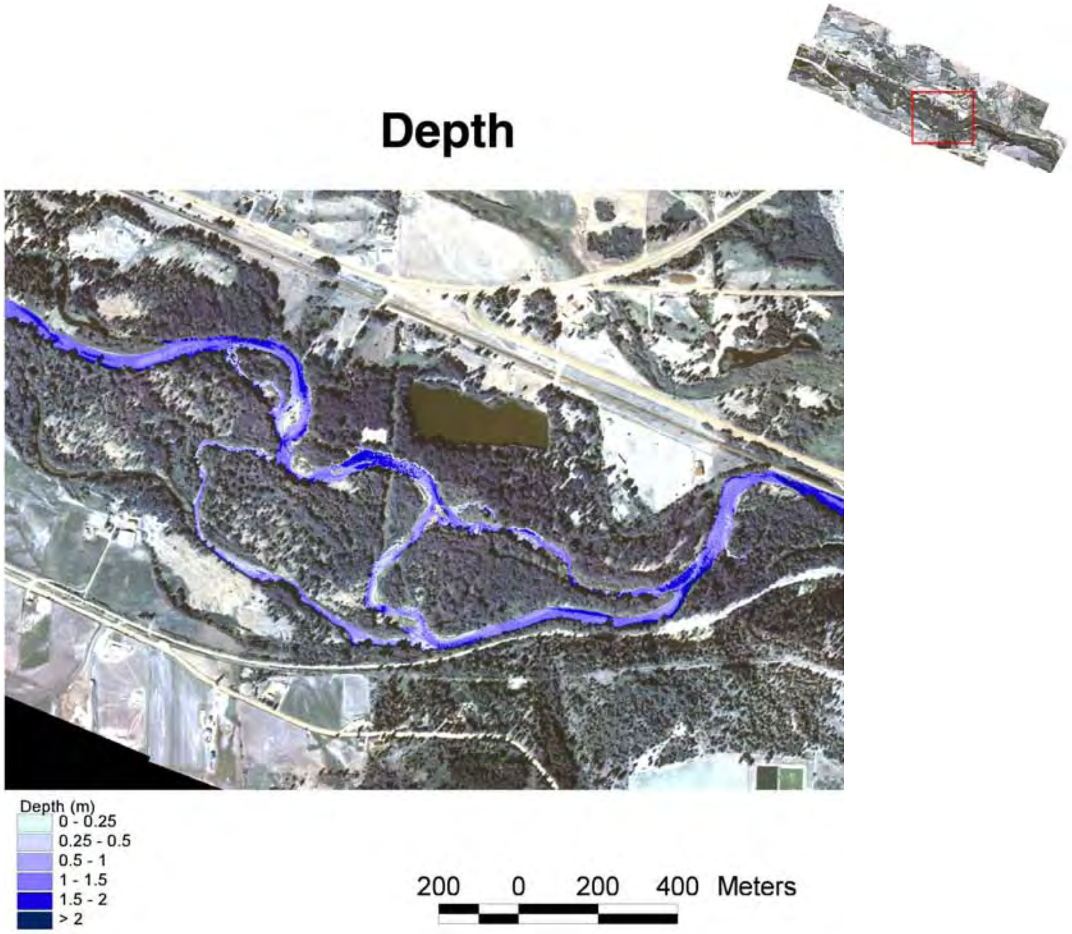


Figure 6a. Channel types and channel complexity measures.


Depth

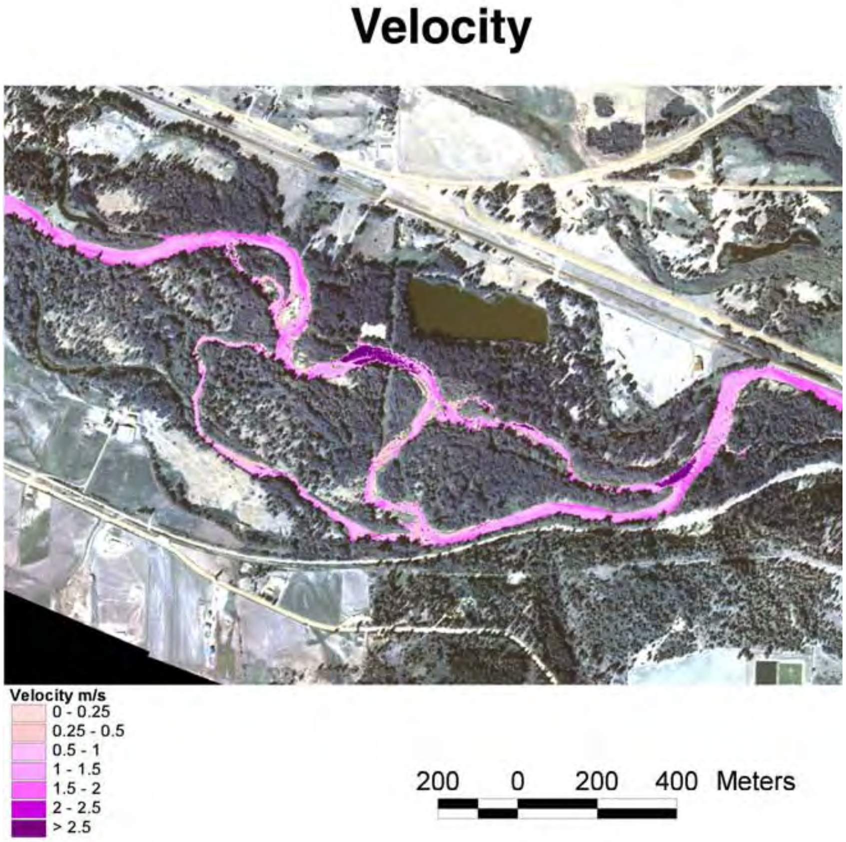

Velocity

Figure 6b. Example of depth and velocity classifications.

Kittitas Reach

Imagery was acquired for the Kittitas reach on August 26, 1999 with a discharge of 104 $m^3 s^{-1}$. Turbidity averaged 3.08 (± 0.49) NTUs and temperature averaged 12.9(± 1.66) °C within the main channel. Table 2a and 2b describes the different habitat types (water body and channel types), channel complexity and instream depth and velocity classifications. Figures 7a and 7b show the spatial extent of the different habitat types; Figure 7c shows an example of the depth and velocity classifications.

Table 2a. Water and channel types and channel complexity measures for the Kittitas reach.

Water body type	Number	Area (ha)	% of all water
Main Channel	1	48.16	44
Islands within main channel	69	14.34	
Floodplain ponds	6	0.02	< 1
Connected off-channel habitat	24	4.55	4
Disconnected off-channel habitat	128	9.21	8
Gravel ponds	26	45.45	42
Islands within ponds/back channels	11	0.47	
Other open water	13	1.04	1

Chanel Type	Length (km)
Main Channel	8.51
Secondary Connected Channels	7.63
Back Channels	4.16

Channel complexity	Number
Separations	75
Returns	66
Backwater separation	22
# of separations per river km	8.81
# of returns per river km	7.76
# of b. separations per river km	2.59

Table 2b. Depth and velocity classification for the Kittitas reach.

Depth (m)	ha	% of surface water area	Velocity (m/s)	ha	% of surface water area
Shadows	2.29	4	Shadows	2.29	4
0 - 0.5	3.40	6	0 - 0.5	3.40	6
0.5 - 1	27.38	52	0.5 - 1	27.38	52
1 - 1.5	9.50	18	1 - 2	9.50	18
1.5 - 2	9.70	18	> 2	10.14	19
> 2	0.43	1			

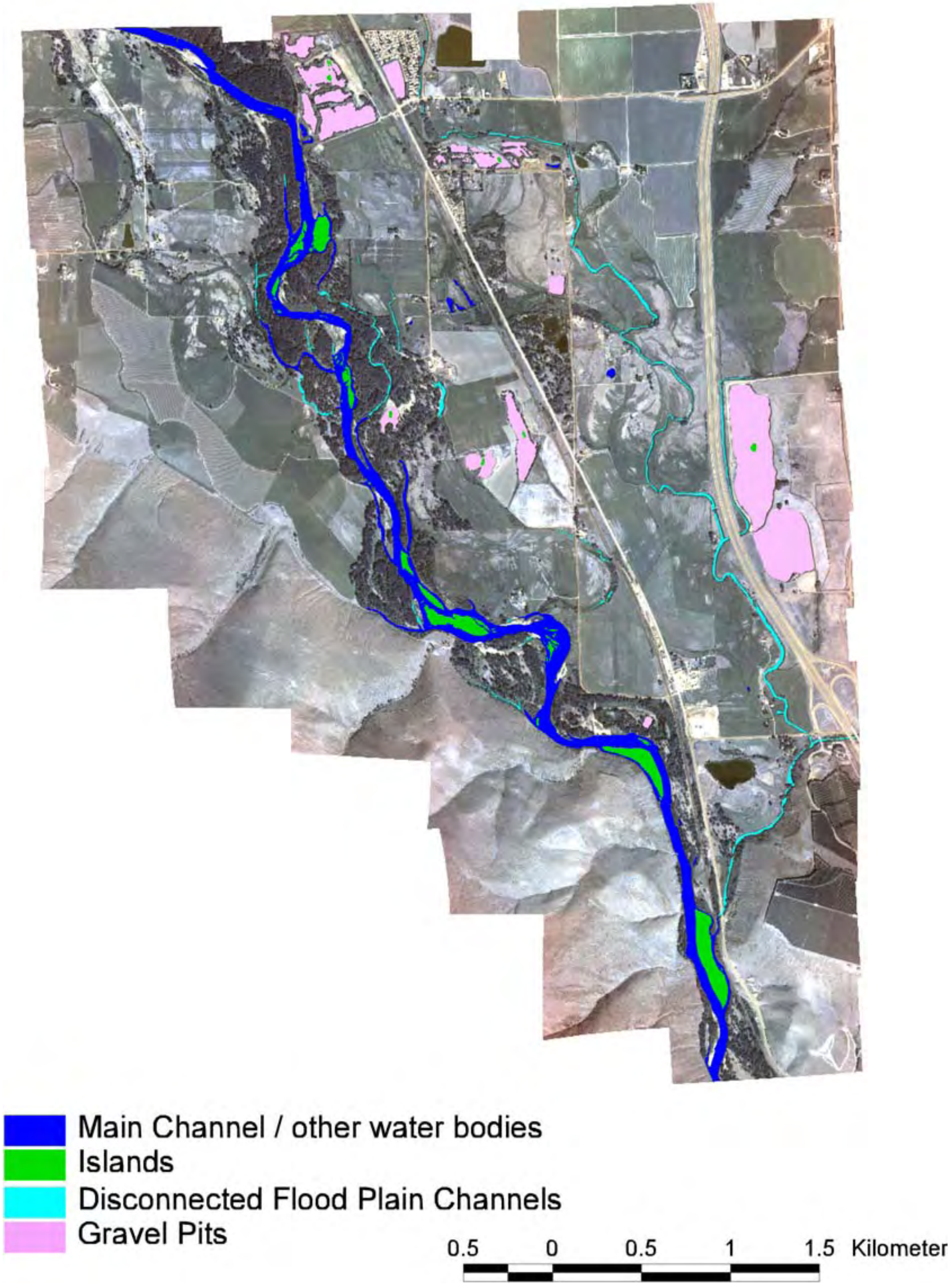


Figure 7a. Channel and water body types.

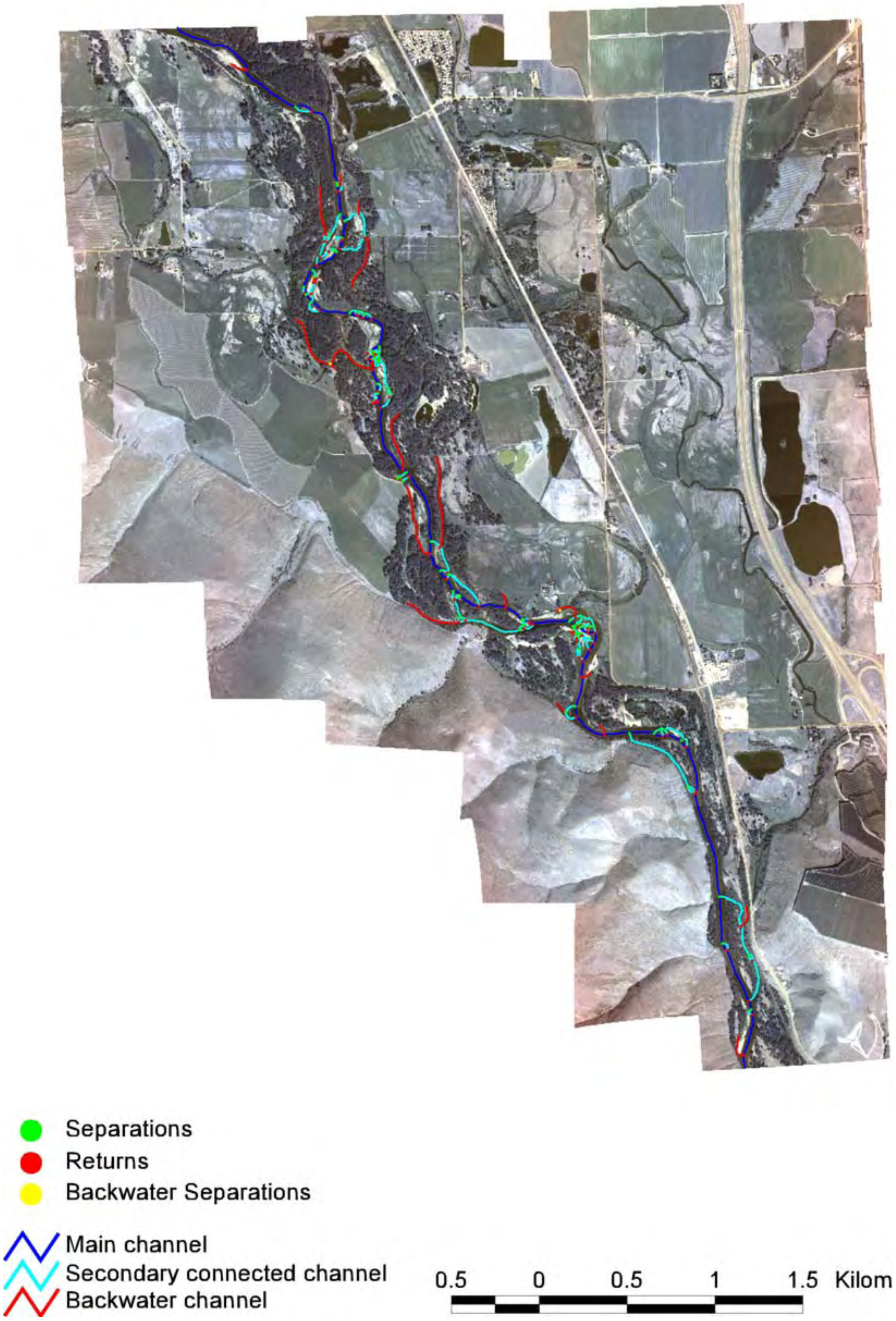


Figure 7b. Channel complexity measures.

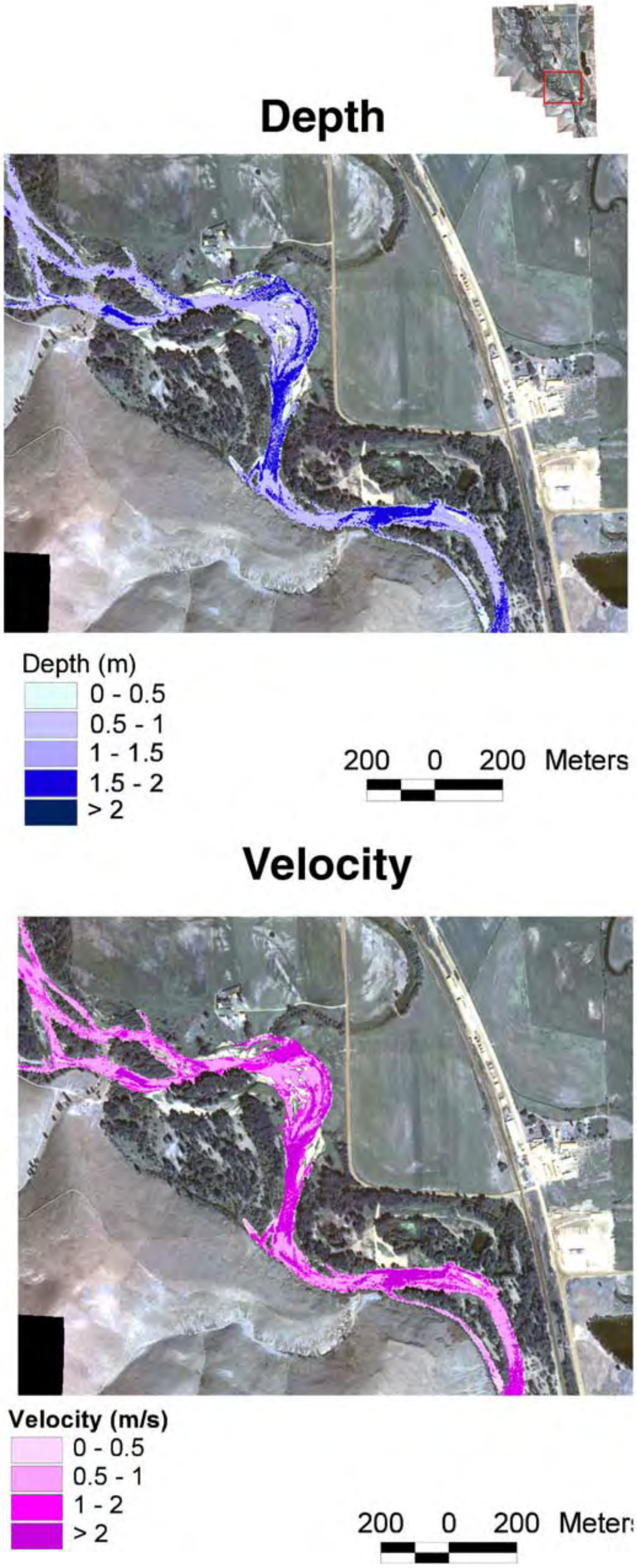


Figure 7c. Example of depth and velocity classifications.

Selah Reach

Imagery was acquired for the Selah reach on August 26, 1999 with a discharge of 52.3 m^3s^{-1}. No field data was collected for this reach during image acquisition nor was any ADP data recorded. Therefore, depth and velocity classifications were modeled from patterns observed in other reaches. Table 3a and 3b describes the different habitat types (water body and channel types), channel complexity and instream depth and velocity classifications. Figures 8a and 8b show the spatial extent of the different habitat types; Figure 8c shows an example of the depth and velocity classifications.

Table 3a. Water and channel types and channel complexity measures for the Selah reach.

Water body type	Number	Area (ha)	% of all water
Main Channel	1	41.61	35
Islands within main channel	12	2.77	
Floodplain ponds	1	0.00	0
Connected off-channel habitat	10	1.23	1
Disconnected off-channel habitat	17	0.43	<1
Gravel ponds	26	72.37	62
Islands within ponds/back channels	31	1.73	
Other open water	35	1.63	1

Chanel Type	Length (km)
Main Channel	8.66
Secondary Connected Channels	1.56
Back Channels	1.80

Channel complexity	Number
Separations	12
Returns	12
Backwater separation	19
# of separations per river km	1.39
# of returns per river km	1.39
# of b. separations per river km	2.19

Table 3b. Depth and velocity classification for the Selah reach

Depth (m)	ha	% of surface water area	Velocity (m/s)	ha	% of surface water area
Shadows	2.74	6	Shadows	2.74	6
0 - 0.5	1.52	4	0 - 0.5	1.52	4
0.5 - 1	2.77	6	0.5 - 1	2.77	6
1 - 1.5	24.06	56	1 - 1.5	28.57	67
1.5 -2	2.14	5	1.5 - 2	5.11	12
> 2	9.61	22	> 2	2.14	5

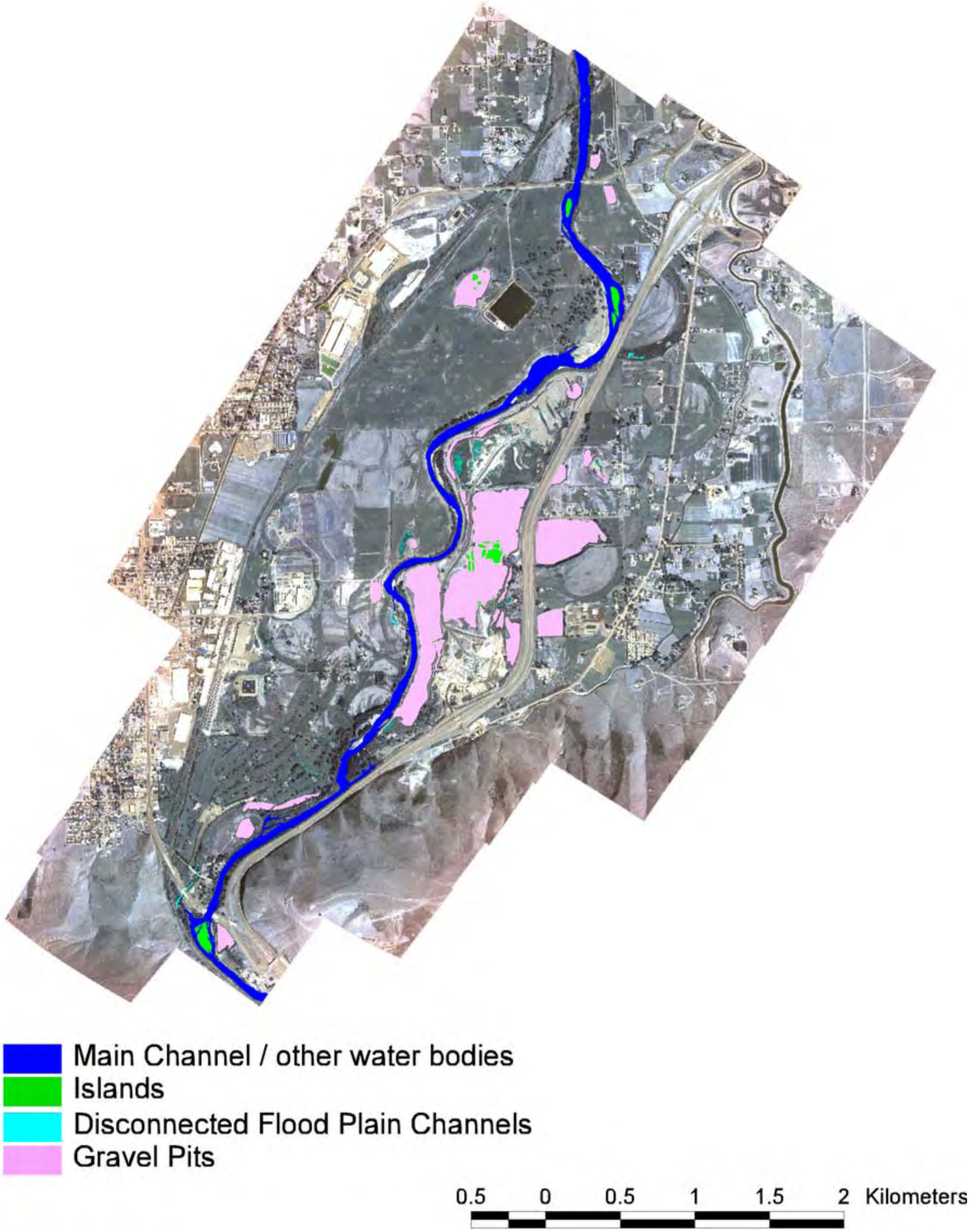


Figure 8a. Channel and water body types.

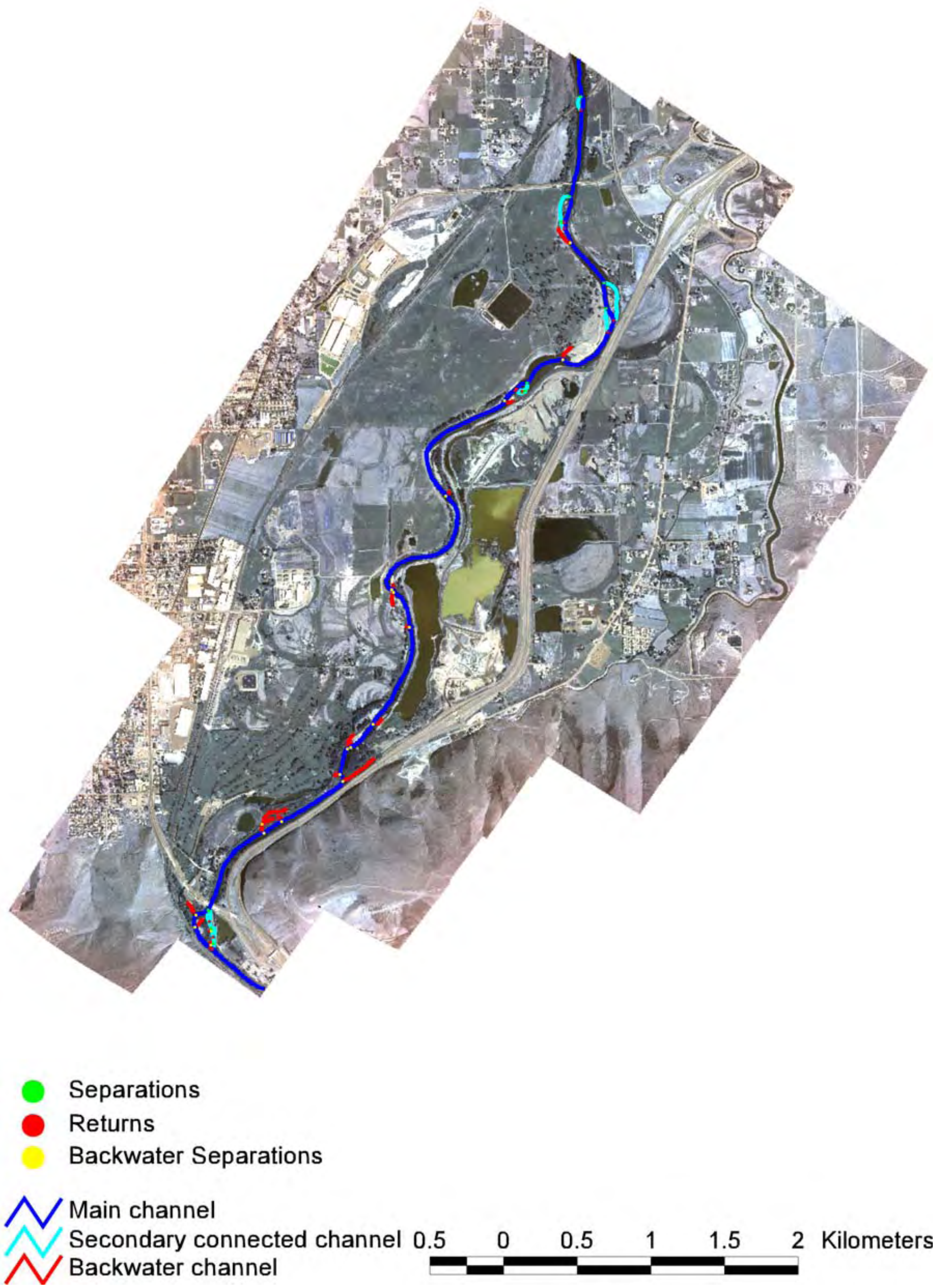
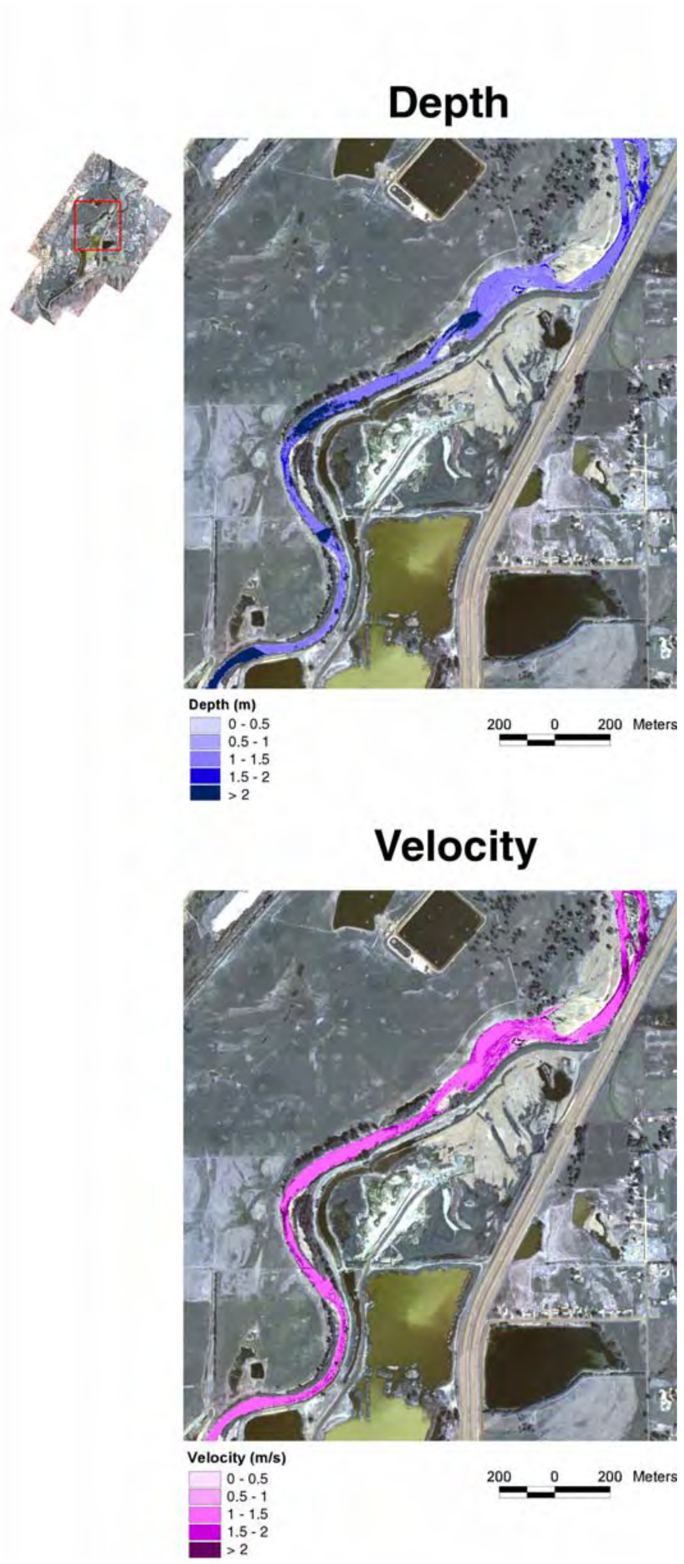


Figure 8b. Channel complexity measures.



-

Figure 8c. Example of depth and vevelocity.classifications.

Naches Reach

Imagery was acquired for the Naches reach on August 26, 1999 with a discharge of 14 m^3s^{-1}. Turbidity averaged 8.02 (± 1.85) NTUs and temperature averaged 14.68(± 1.06) °C within the main channel. Table 4a and 4b describes the different habitat types (water body and channel types), channel complexity and instream depth and velocity classifications. Figures 9a and 9b show the spatial extent of the different habitat types; Figure 9c shows an example of the depth and velocity classifications.

Table 4a. Water and channel types and channel complexity measures for the Naches reach.

Water body type	Number	Area (ha)	% of all water
Main Channel	11	48.52	75
Islands within main channel	76	26.91	
Floodplain ponds	1	0.00	0
Connected off-channel habitat	19	5.72	9
Disconnected off-channel habitat	28	4.39	7
Gravel ponds	4	4.57	7
Other open water	8	1.28	2

Chanel Type	Length (km)
Main Channel	11.91
Secondary Connected Channels	11.68
Back Channels	7.56

Channel complexity	Number
Separations	65
Returns	65
Backwater separation	59
# of separations per river km	5.46
# of returns per river km	5.46
# of b. separations per river km	4.96

Table 4b. Depth and velocity classification for the Naches reach.

Depth (m)	ha	% of surface water area	Velocity (m/s)	ha	% of surface water area
Shadows	3.12	6	Shadows	3.12	6
0 - 0.25	8.94	16	0 - 0.25	8.94	16
0.25 - 0.5	17.10	32	0.25 - 0.5	9.12	17
0.5 -1	3.35	6	0.5 - 1	11.67	22
1 - 1.5	11.67	22	1 - 2	10.06	19
> 1.5	10.06	19	> 2	11.33	21

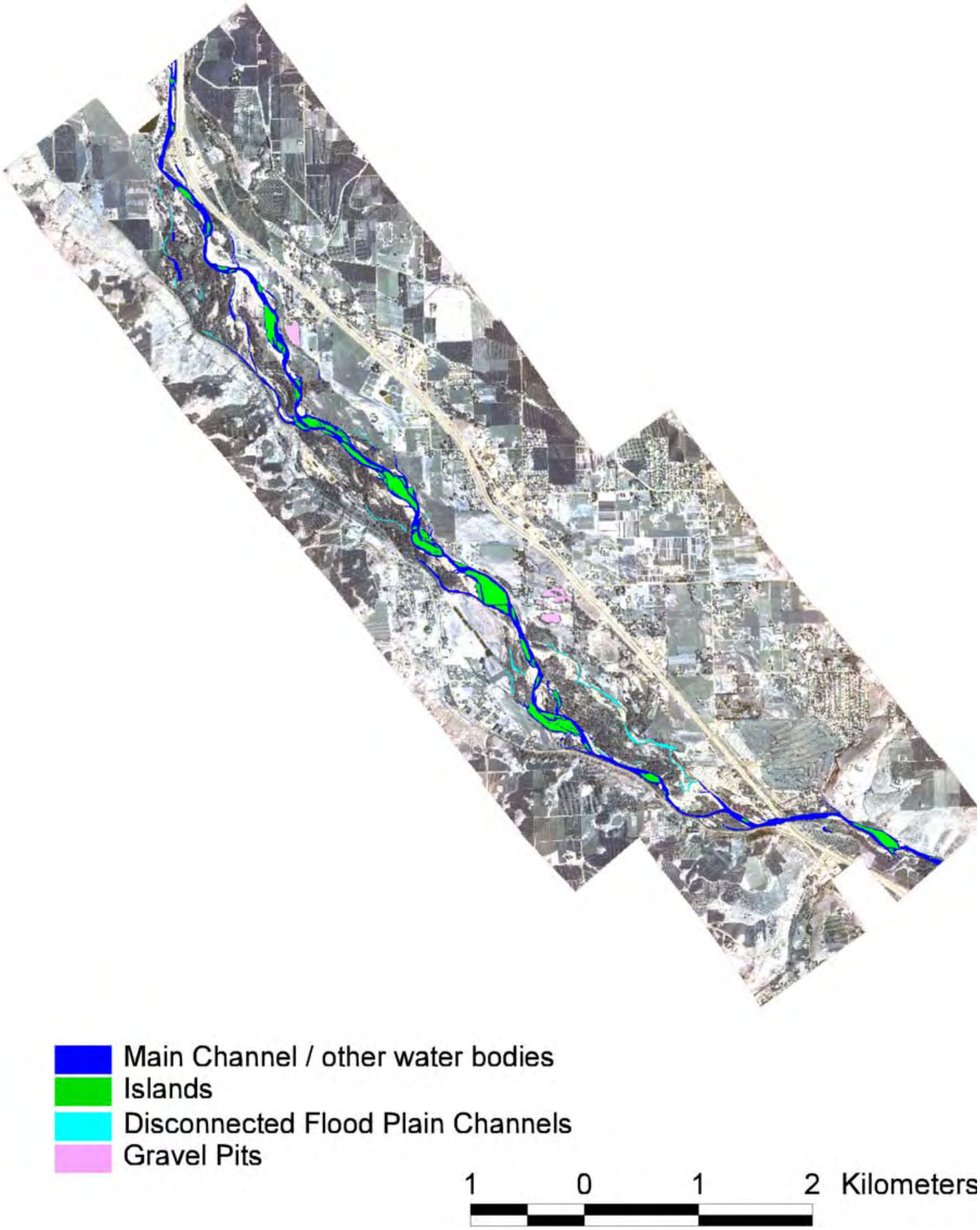


Figure 9a. Channel and water body types.

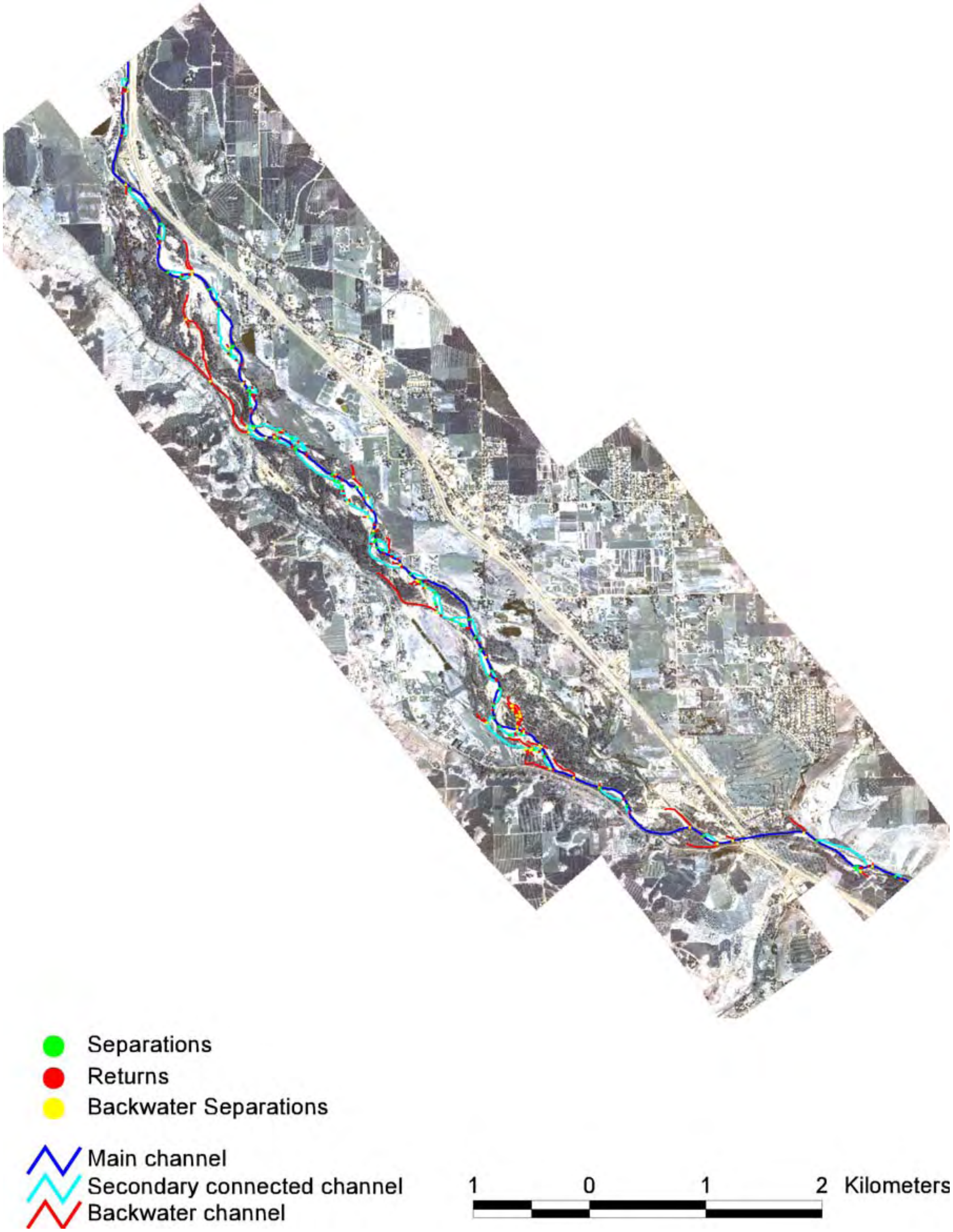


Figure 9b. Channel complexity measures.

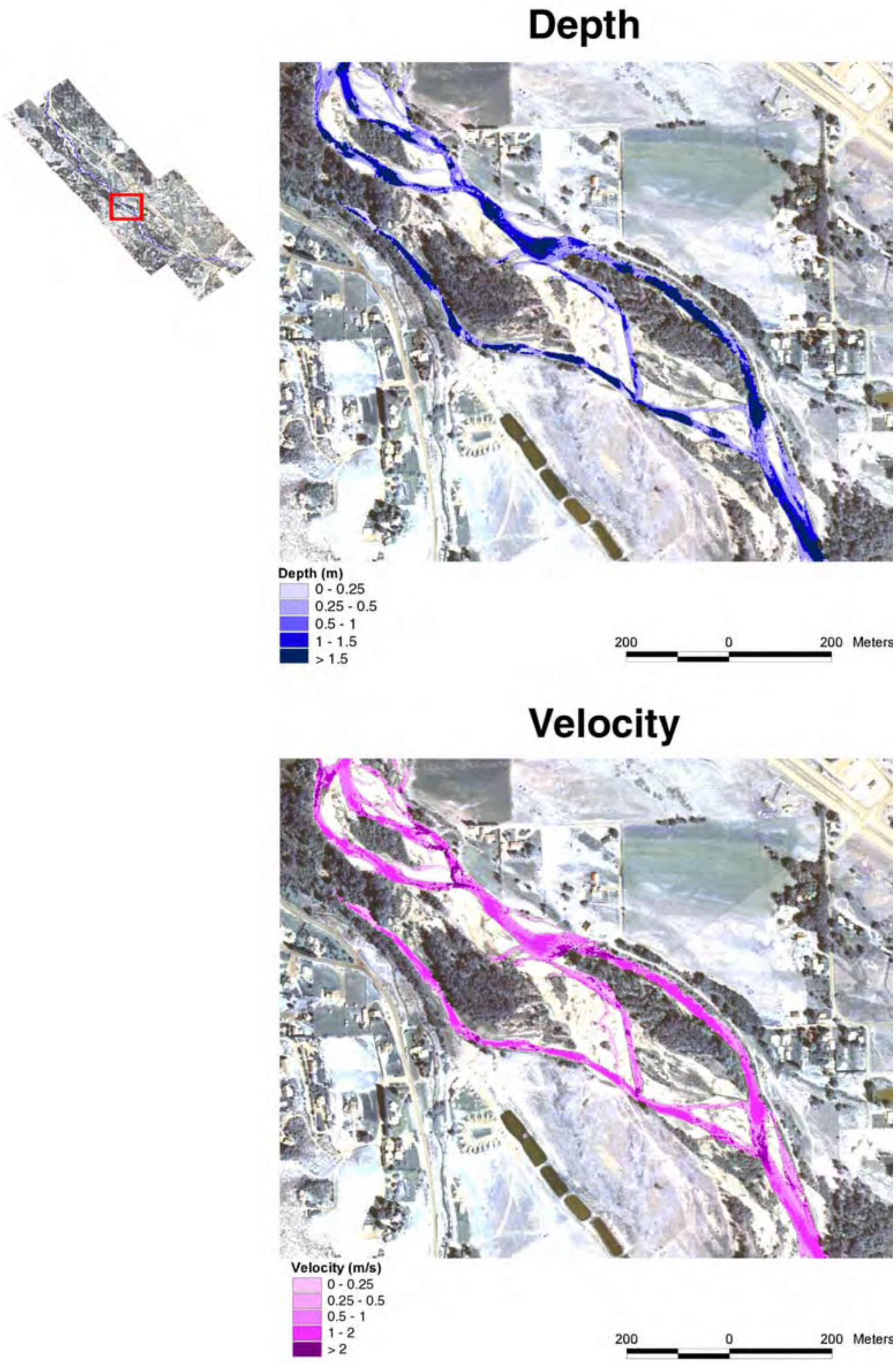


Figure 9c. Example of depth and velocity classification for the Naches reach.

Union Gap

Imagery was acquired for the Union Gap reach on August 24, 1999 with a discharge of 74 $m^3 s^{-1}$. Turbidity averaged 8.02 (± 1.85) NTUs and temperature averaged 27.9(± 1.60)°C within the main channel. Table 5a and 5b describes the different habitat types (water body and channel types), channel complexity and instream depth and velocity classifications. Figures 10a and 10b show the spatial extent of the different habitat types; Figure 10c shows an example of the depth and velocity classifications.

Table 5a. Water and channel types and channel complexity measures for the Union Gap reach.

Water body type	Number	Area (ha)	% of all water
Main Channel	3	69.21	46
Islands within main channel	58	56.33	
Floodplain ponds	14	0.38	<1
Connected off-channel habitat	23	3.73	3
Disconnected off-channel habitat	219	13.84	9
Gravel ponds	34	56.37	38
Islands within ponds/back channels	25	0.57	
Other open water	45	5.53	4

Chanel Type	Length (km)
Main channel	9.65
Secondary Connected Channels	10.63
Back channels	6.19

Channel complexity	Number
Separations	49
Returns	46
Backwater separation	58
# of separations per river km	5.08
# of returns per river km	4.77
# of b. separations per river km	6.01

Table 5b. Depth and velocity classification for the Union Gap reach.

Depth (m)	ha	% of surface water area	Velocity (m/s)	ha	% of surface water area
Shadows	3.65	5	Shadows	3.65	5
0 - 0.6	14.62	20	0 - 0.6	14.62	20
0.6 - 1.2	22.49	31	0.6 - 1.2	22.49	31
1.2 - 1.8	19.43	27	1.2 - 1.8	19.43	27
1.8 - 2.4	5.25	7	1.8 - 2.4	5.25	7
2.4 - 3	6.68	9	> 2.4	7.51	10
> 3	0.83	1			

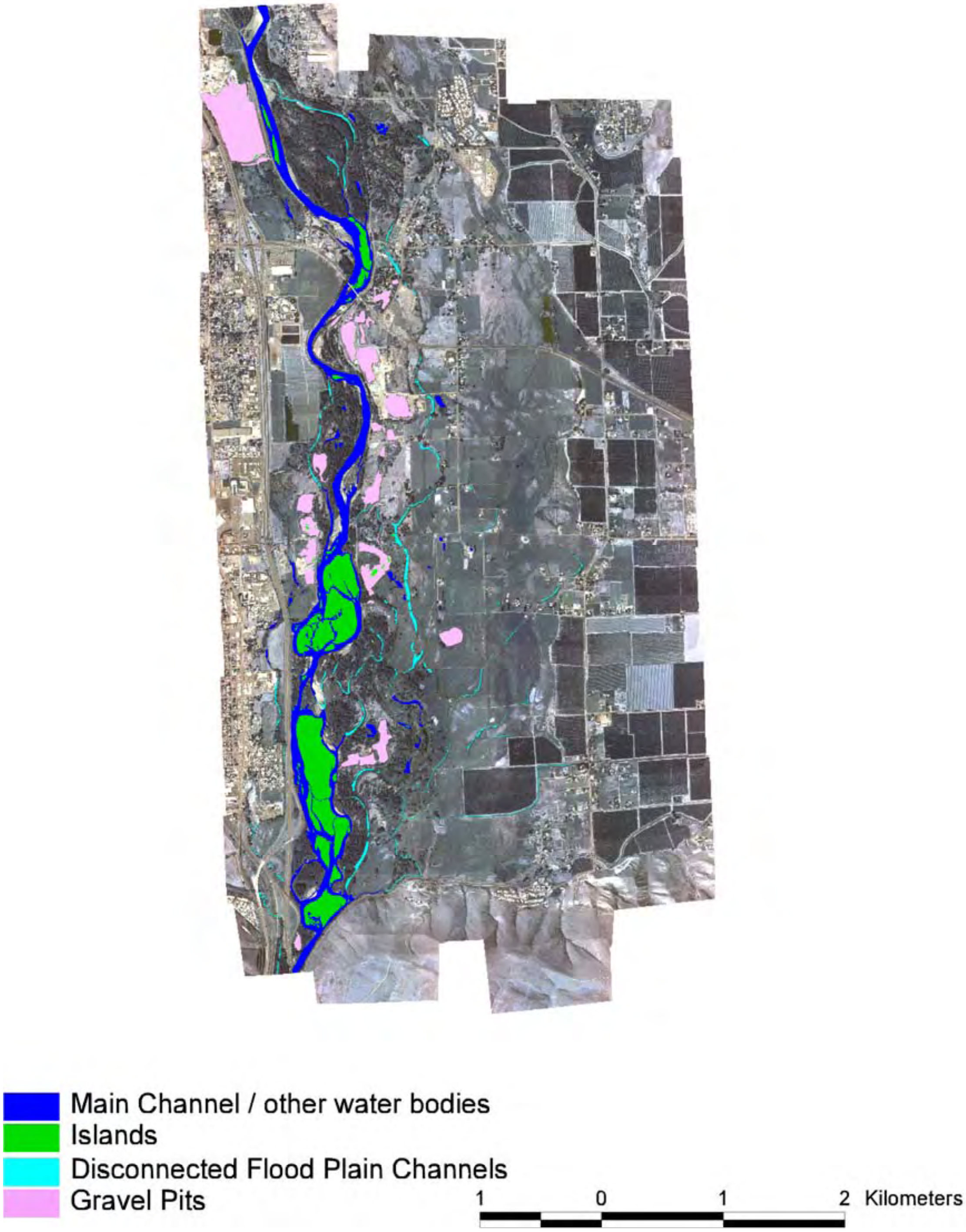


Figure 10a. Channel and water body types.

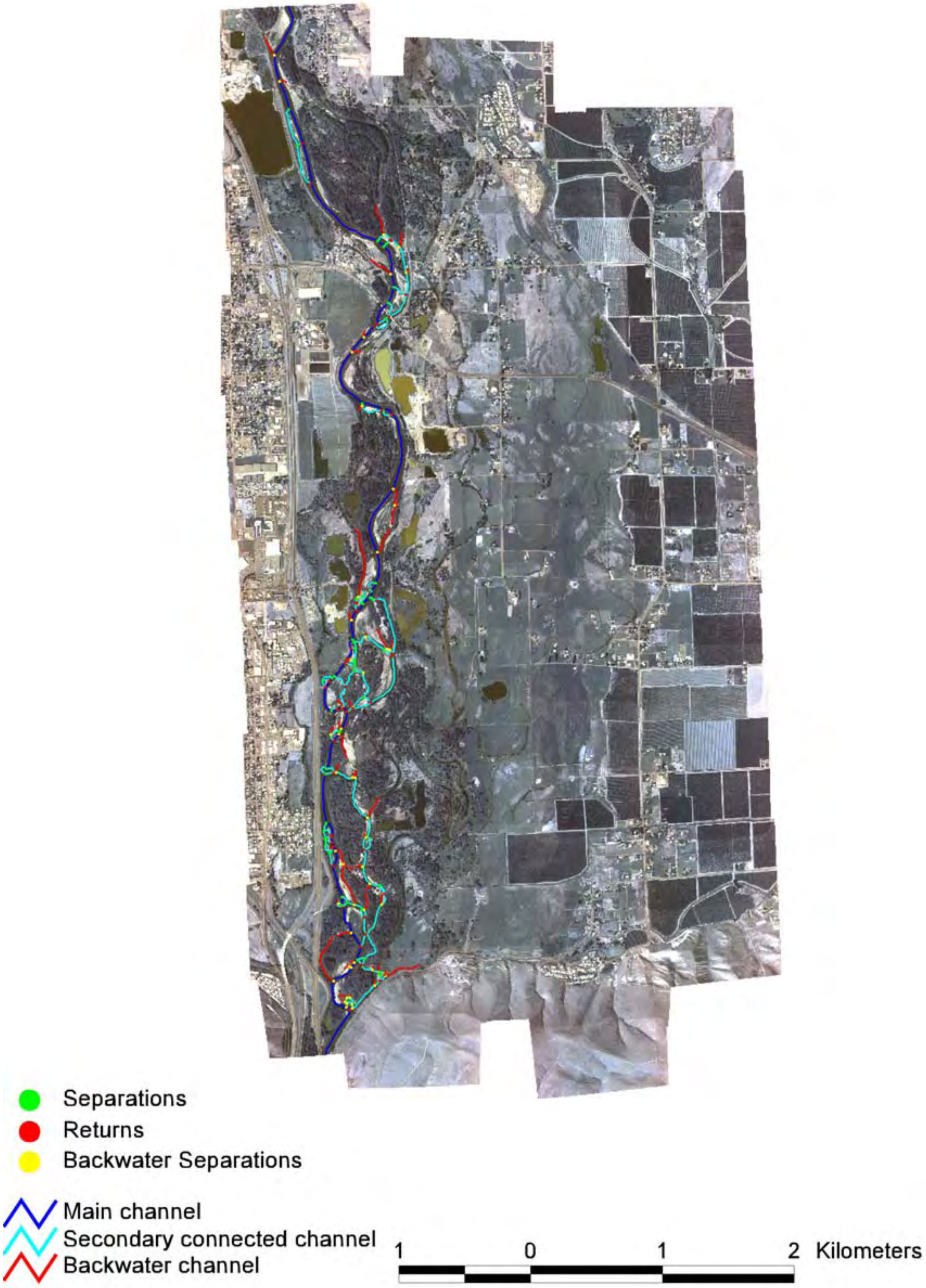


Figure 10b. Channel complexity measures.

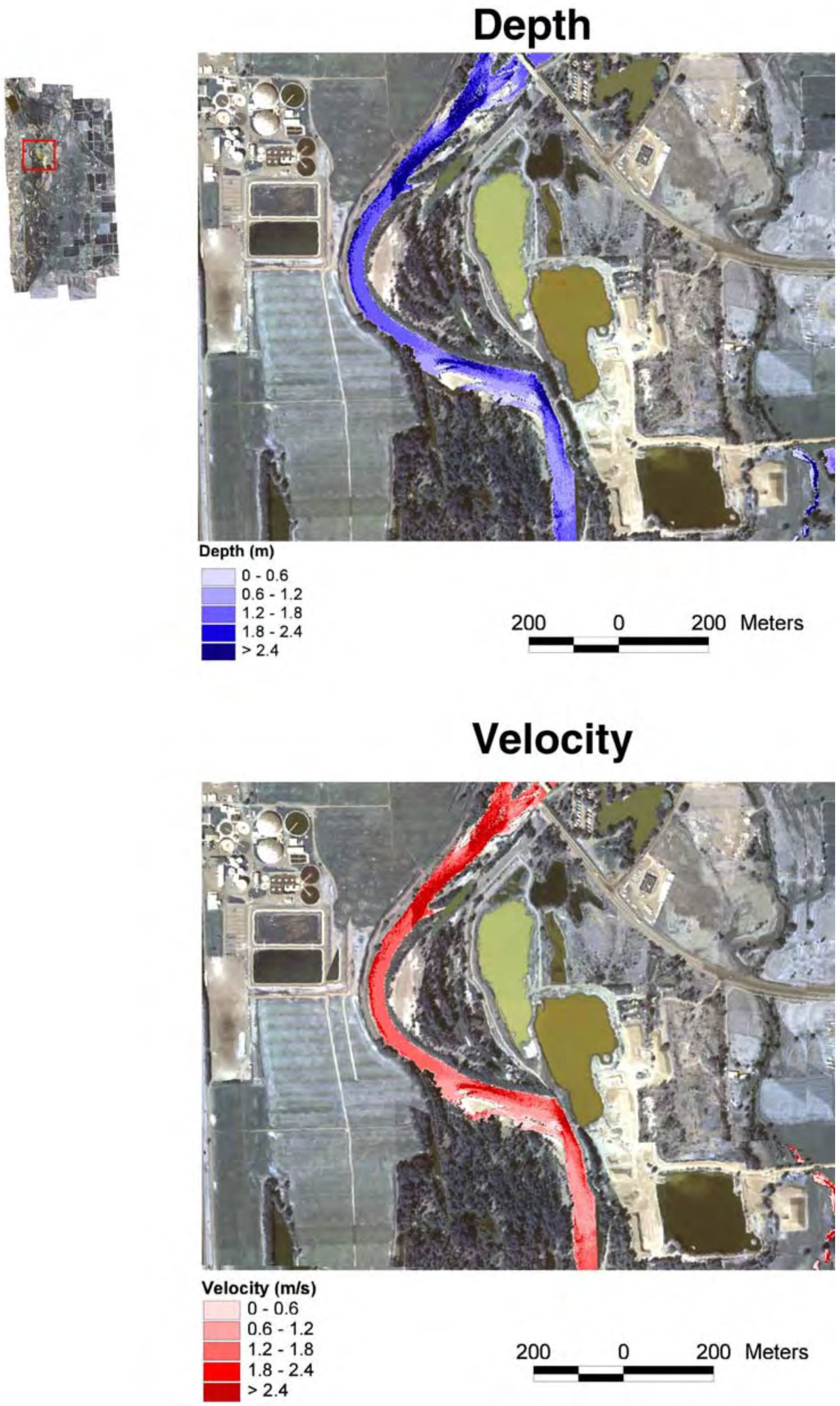


Figure 10c. Example of depth and velocity

Wapato Reach

Imagery was acquired for the Wapato reach on August 12, 2000 with a discharge of 15 $m^3 s^{-1}$. No field data was collected for this reach during image acquisition nor was any ADP data recorded. Therefore, depth and velocity classifications were modeled from patterns observed in other reaches. Table 6a and 6b describes the different habitat types (water body and channel types), channel complexity and instream depth and velocity classifications. Figures 11a – 11d shows the spatial extent of the different habitat types; Figure 11e shows an example of the depth and velocity classifications.

Table 6a. Water and channel types and channel complexity measures for the Wapato reach.

Water body type	**Number**	**Area (ha)**	**% of all water**
Main Channel	1	214.96	61
Islands within main channel	320	98.69	
Floodplain ponds	134	4.03	1
Connected off-channel habitat	49	14.84	4
Disconnected off-channel habitat	429	28.84	8
Gravel ponds	32	71.26	20
Islands within ponds/back channels	51	1.31	
Other open water	103	11.90	3
Canals	18	6.27	2

Chanel Type	**Length (km)**
Main channel	41.44
Secondary Connected Channels	27.68
Back channels	20.00

Channel complexity	**Number**
Separations	275
Returns	271
Backwater separation	143
# of separations per river km	6.64
# of returns per river km	6.54
# of b. separations per river km	3.45

Table 6b. Depth and velocity classification for the Wapato reach.

Depth (m)	**ha**	**% of surface water area**	**Velocity (m/s)**	**ha**	**% of surface water area**
shadows	6.51	3	shadows	6.51	3
0 - 0.25	24.06	10	0 - 0.25	24.06	10
0.25 - 0.5	33.04	14	0.25 - 0.5	33.04	14
0.5 - 1	86.41	38	0.5 - 1	75.36	33
1 - 1.5	46.94	20	1 - 1.5	32.85	14
> 1.5	32.85	14	1.5 - 2	41.90	18
			> 2	16.09	7

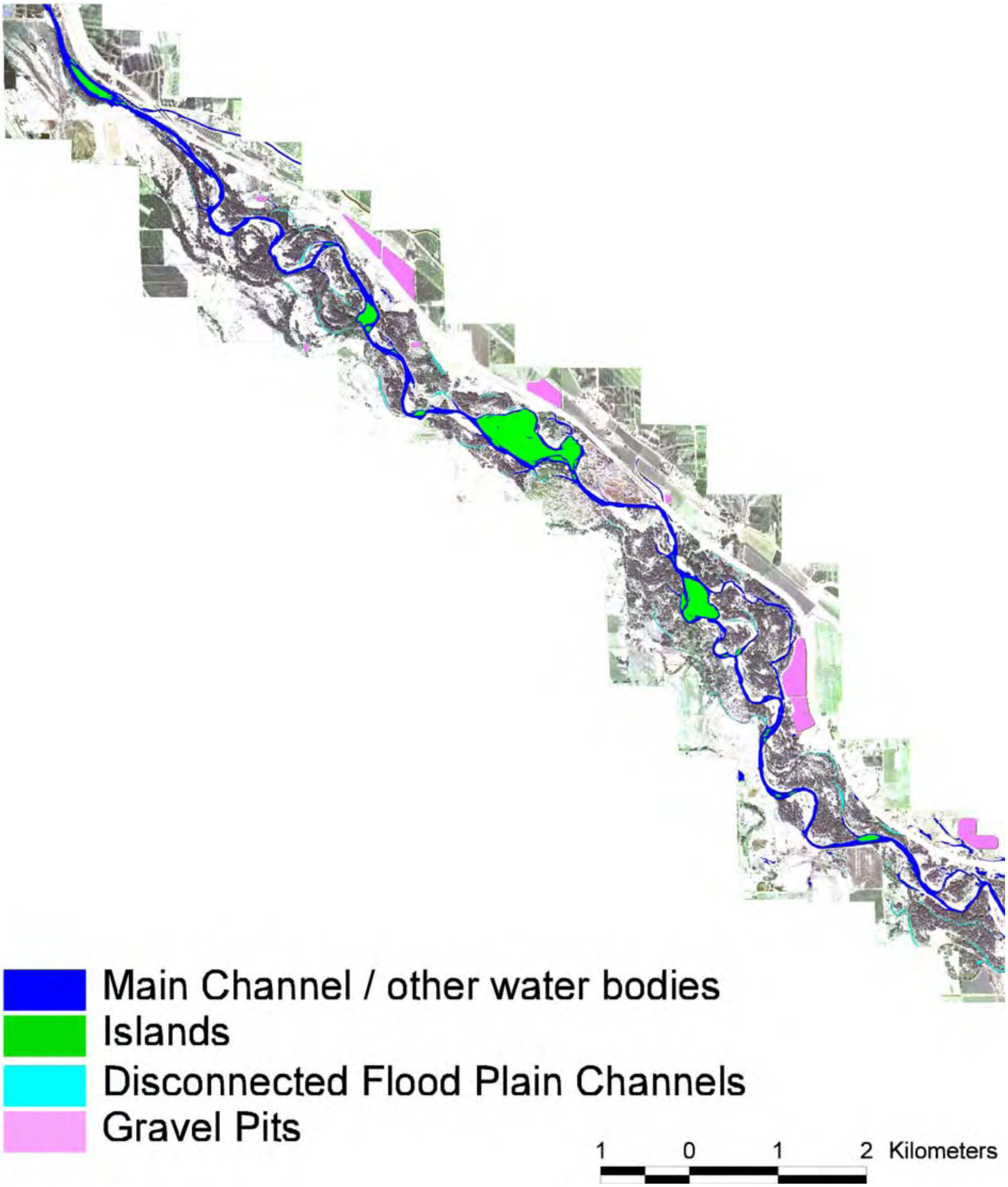


Figure 11a. Channel and water body types for the Wapato (north) reach.

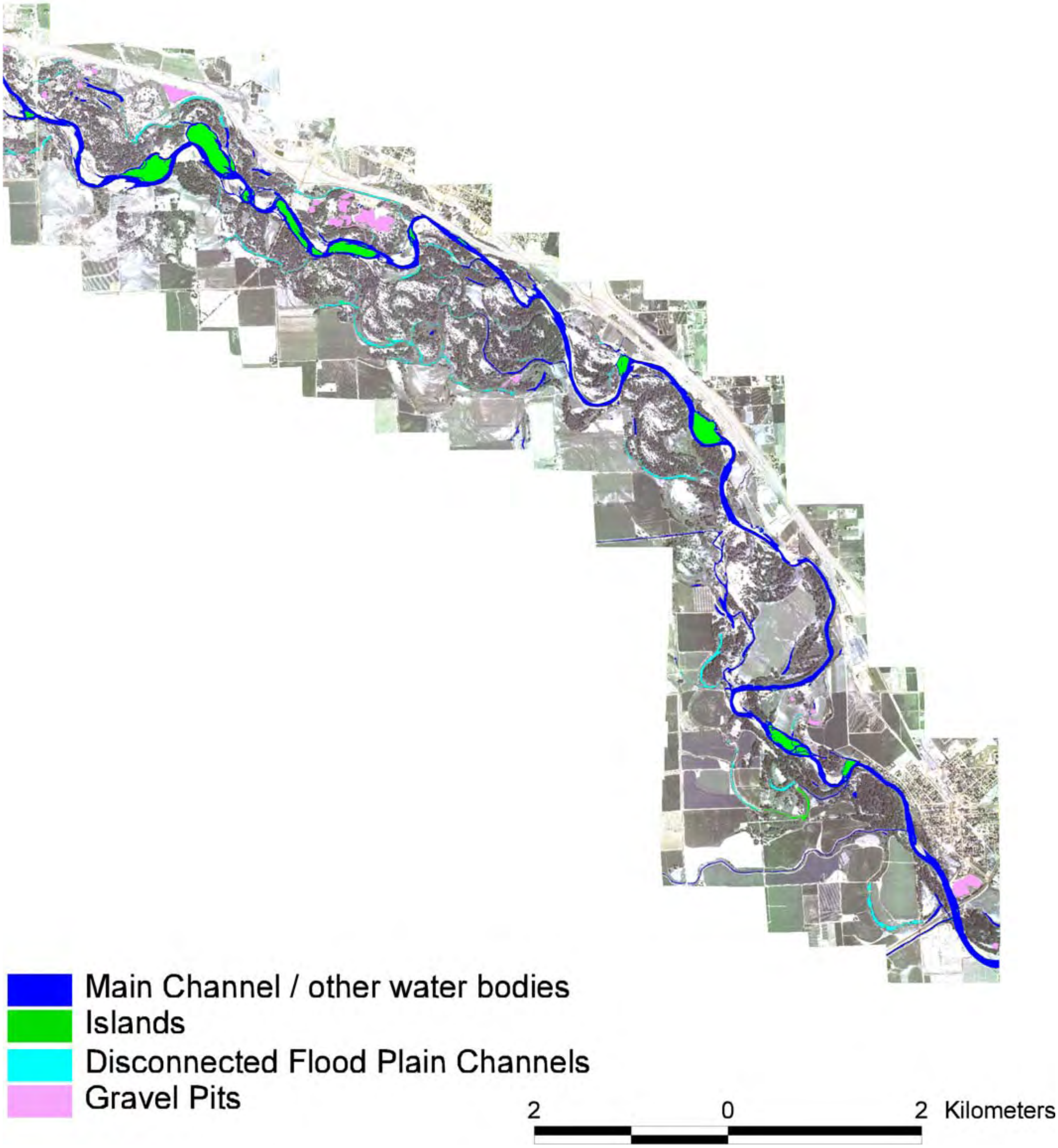


Figure 11b. Channel and water body types for the Wapato (south) reach.

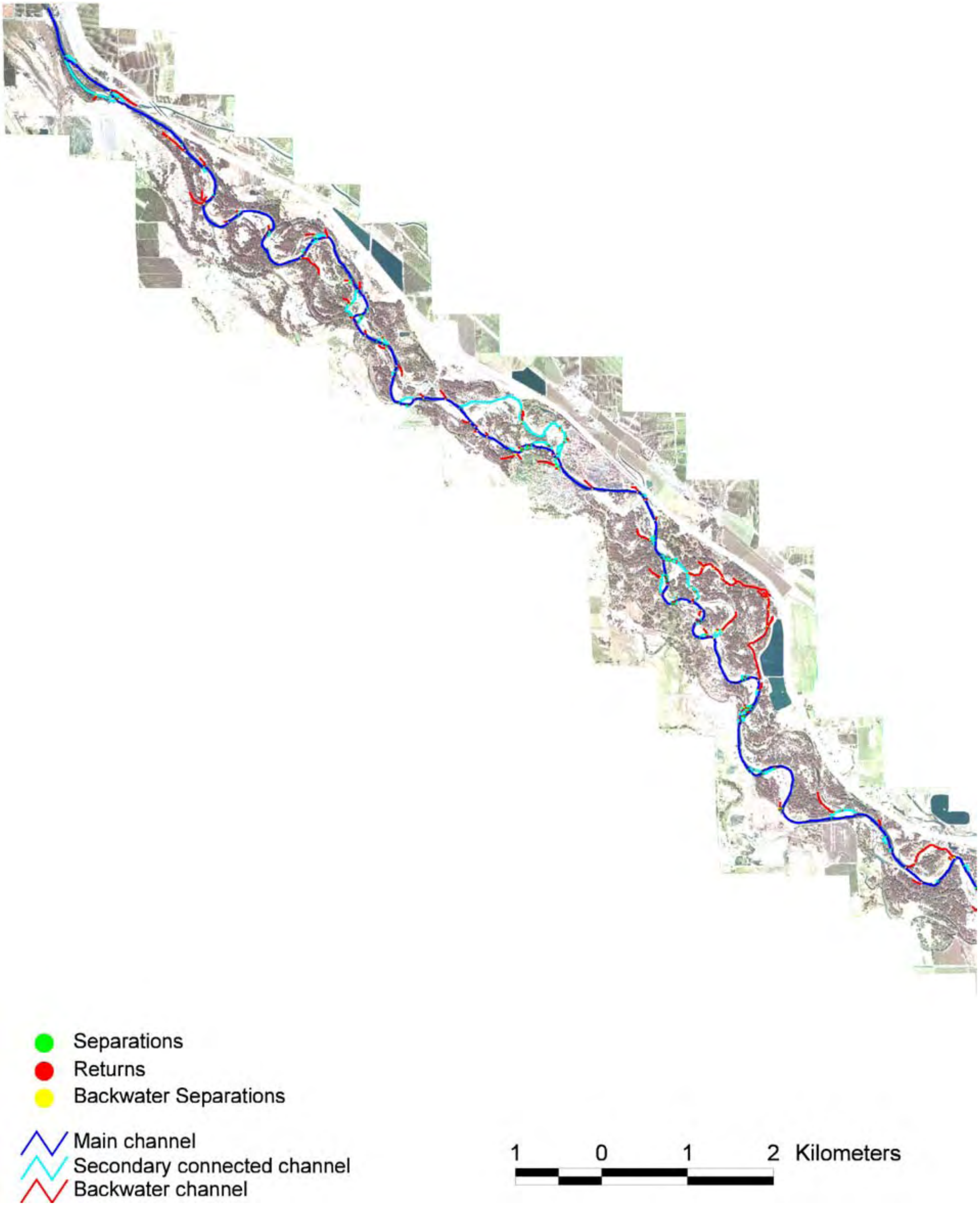


Figure 11c. Channel complexity measures for the Wapato (north) reach.

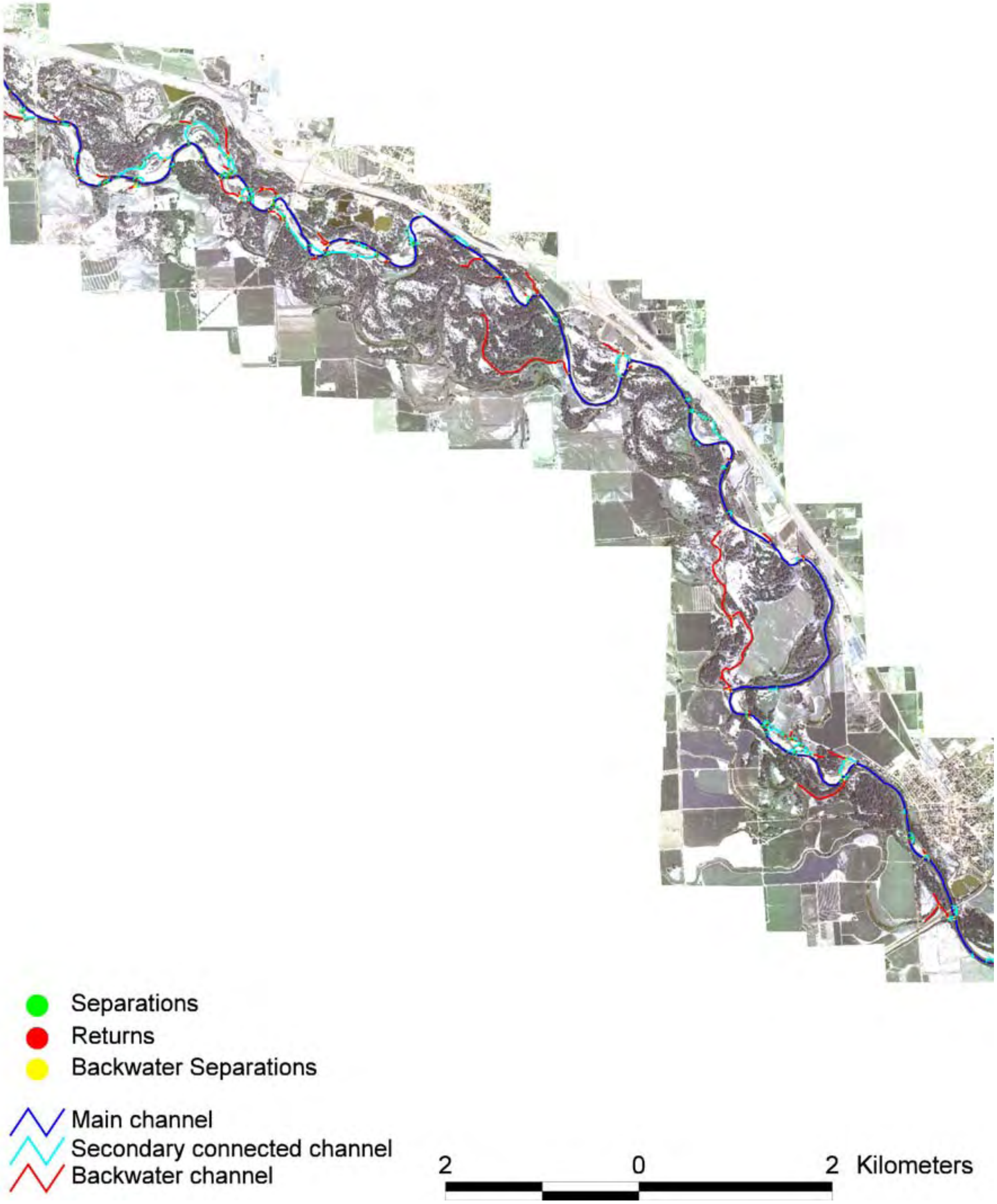


Figure 11d. Channel complexity measures for the Wapato (south) reach..

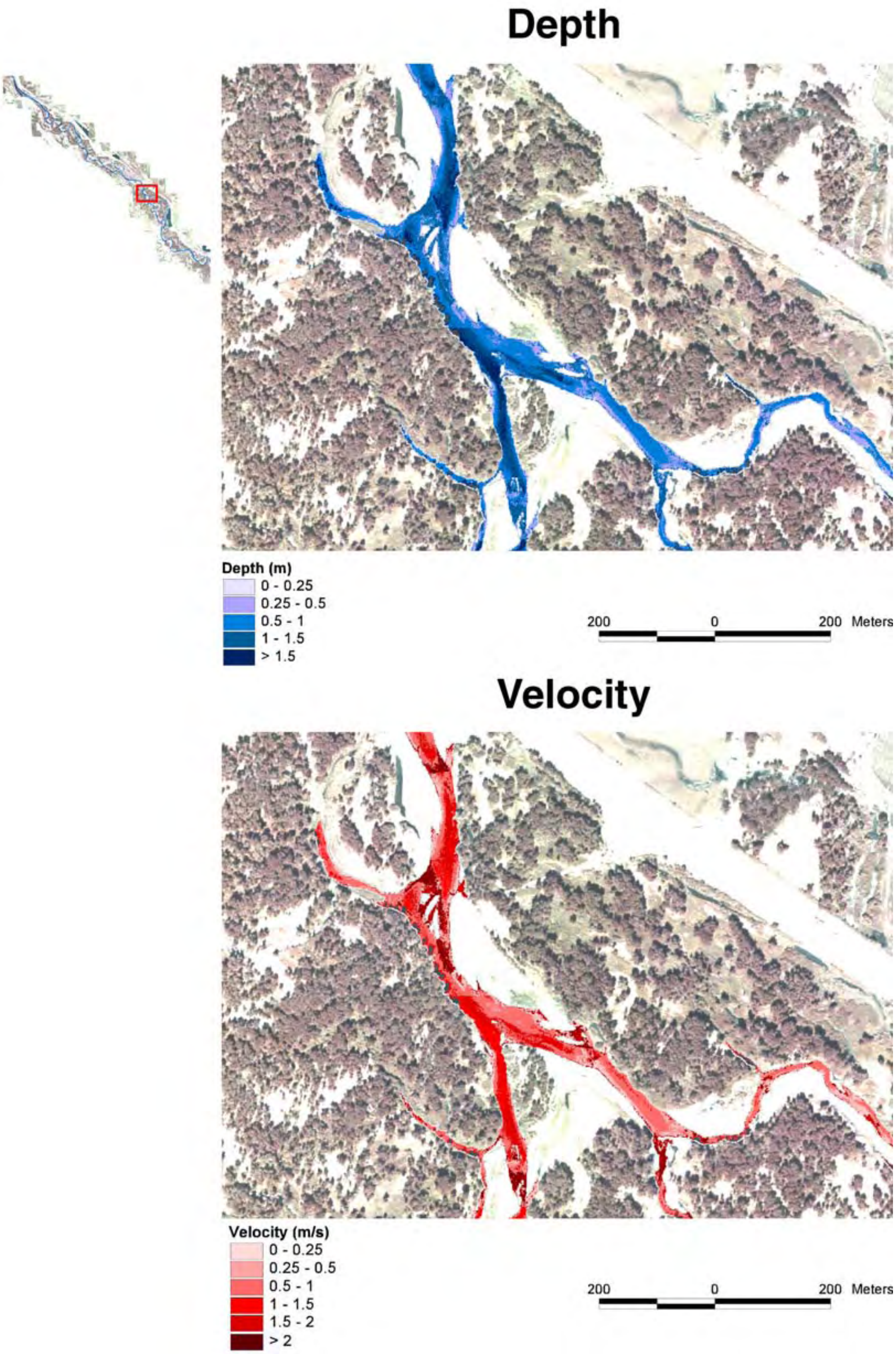


Figure 11e. Example of depth and velocity classifications.

Summary For All Reaches

Tables 7 and 8 provide a summary of water and channel types and channel complexity measures across all reaches.

Table 7. Summary of water and channel types for all reaches. Date of image acquisition and flow are also noted.

	Cle Elum			Selah		
Date of Image		8/26/99			8/26/99	
Flow (m^{3}s$^{-1)}$		92.1			52.3	
Water body type	**Number**	**Area (ha)**	**% of all water**	**Number**	**Area (ha)**	**% of all water**
Main Channel	1	56.44	66	1	41.61	35
Islands within main channel	38	32.49		12	2.77	
Floodplain ponds	2	0.04	< 1	1	0.00	0
Connected off-channel habitat	12	1.61	2	10	1.23	1
Disconnected off-channel habitat	24	1.47	2	17	0.43	<1
Gravel ponds	7	24.80	29	26	72.37	62
Islands within ponds/back channels	2	0.01		31	1.73	
Other open water	7	0.71	1	35	1.63	1

	Kittitas			Naches		
Date of Image		8/26/99			8/26/99	
Flow (m^{3}s$^{-1)}$		104.12			14.1	
Water body type	**Number**	**Area (ha)**	**% of all water**	**Number**	**Area (ha)**	**% of all water**
Main Channel	1	48.16	44	11	48.52	75
Islands within main channel	69	14.34		76	26.91	
Floodplain ponds	6	0.02	< 1	1	0.00	0
Connected off-channel habitat	24	4.55	4	19	5.72	9
Disconnected off-channel habitat	128	9.21	8	28	4.39	7
Gravel ponds	26	45.45	42	4	4.57	7
Islands within ponds/back channels	11	0.47		8	1.28	2
Other open water	13	1.04	1			

	Wapato		
Date of Image		8/12/00	
Flow (m^{3}s$^{-1)}$		15	
Water body type	**Number**	**Area (ha)**	**% of all water**
Main Channel	1	214.96	61
Islands within main channel	320	98.69	
Floodplain ponds	134	4.03	1
Connected off-channel habitat	49	14.84	4
Disconnected off-channel habitat	429	28.84	8
Gravel ponds	32	71.26	20
Islands within ponds/back channels	51	1.31	
Other open water	103	11.90	3
Canals	18	6.27	2

Table 8. Channel length and complexity measures for all reaches. Date of image acquisition and flow are also noted.

	Cle Elum	**Selah**	**Kittitas**	**Naches**	**Union Gap**	**Wapato**
Date of Image	8/26/99	8/26/99	8/26/99	8/26/99	8/24/99	8/12/00
Flow (m^{3}s$^{-1)}$	92.1	52.3	104.12	14.1	74.3	15
Chanel Type, length (km)						
Main Channel	11.24	8.66	8.51	11.91	9.65	41.44
Secondary Connected Channels	6.11	1.56	7.63	11.68	10.63	27.68
Back Channels	2.02	1.80	4.16	7.56	6.19	20.00
Channel complexity, number						
Separations	38	12	75	65	49	275
Returns	37	12	66	65	46	271
Backwater separation	13	19	22	59	58	143
# of separations per river km	3.38	1.39	8.81	5.46	5.08	6.64
# of returns per river km	3.29	1.39	7.76	5.46	4.77	6.54
# of b. separations per river km	1.16	2.19	2.59	4.96	6.01	3.45

CONCLUSIONS

An integrated system of airborne remote sensing, ground truth collection and ADP survey information offers the potential for relatively accurate, consistent and efficient regional assessments of habitat characteristics within large, dynamic river systems. Our results indicate that airborne multispectral imagery, coupled with appropriate ground truth data, is a viable method for regional mapping of extensive channel habitats in large river systems. The addition of the ADP surveys proved crucial as it provided detailed information on depth and velocity measurements over large areas in a relatively short time frame. In the future, simultaneous collection of ADP surveys and airborne imagery and improvements in image mosaiking (illumination errors) will further enhance the capability and accuracy of riverine habitat classification.

Although discharge varied greatly through the six floodplain reaches (min of 14 m^{3} s^{-1} in the Naches reach to a max of 104 m^{3} s^{-1} in the Kittitas reach), some general conclusions can be made. In all reaches, gravel ponds occupied a large portion of the floodplain water (average of 33%). For example in the Selah reach, 62% of the surface water within the flood plain was contained in gravel ponds. Floodplain encroachments such as gravel ponds, revetments and riprap stabilize the flood plain and reduce the ability of the river to avulse and create new habitats, thus decreasing the habitat complexity within the riverine environment (Brookes 1989, Ward et al. 2002). Although our research did not quantify revetments or riprap within the reaches, our results suggest that flood plains with the lowest proportion of gravel ponds had the highest level of channel complexity (high number of separations per river km.).

The Wapato and Naches reaches had relatively high levels of complexities (> 5.4 separations per river km) even with the lowest discharges (15 and 14 m^{3} s^{-1} for the Wapato and Naches, respectively) of all reaches. The Naches and Wapato also had the lowest proportion of the floodplain water occupied by gravel ponds (7 and 20%, respectively). In contrast, the Selah reach had the highest proportion of the floodplain water occupied by gravel ponds (62%) and also had the lowest channel complexity (average of 1.29 separations per river km).

Similarly, the Naches and Wapato have a relatively large area of off-channel habitat (16 and 12%, respectively), while the Selah reach had the lowest amount (< 2%). The high percentage of off-channel habitat in the Naches and Wapato suggest these flood plains provide suitable habitat for juvenile salmonids (Pearsons et al., 1994). Off-channel habitats such as backwater channels, spring brooks and floodplain pools are considered critical to the survival of juvenile salmonid populations (Pearsons et al. 1994; Morgan and Hinojosa 1996).

The Union Gap and Kittitas reach also had a relatively high percentage of off-channel habitat (12% for both reaches). In contrast, the Cle Elum reach had a very low percentage (4) of off-channel habitat.

The Kittitas reach had the highest complexity (averaged 8.81 separations per river km), although this number is probably higher than the other reaches because the Kittitas reach had the highest discharge (104 $m^3 s^{-1}$). In a similar study in the lower Yakima River, Whited et al. (in press) showed that channel complexity decreased as flow was reduced.

SUMMARY

An integrated system of airborne remote sensing and ADP survey information offers the potential for relatively accurate, consistent and efficient regional assessments of habitat characteristics within large, dynamic river systems. The imagery was very successful in identifying and quantifying channel and water body types as well as channel complexity measures. Our results suggest that all six reaches exhibit a range of habits and varying degrees of complexity. Gravel ponds were a major element in all of the reaches, but the reaches that had the smallest area occupied by gravel ponds were also more complex (i.e., high channel complexity and a high percentage of off-channel habitats), regardless of discharge.

Although classification problems arose due to illumination errors in image mosaiking and the ADP runs did not coincide with image acquisition dates, we were still able to reasonably estimate depth and velocity throughout the reaches. This study provides base line data on the complexity of these reaches (for a given discharge) and will be invaluable for future studies within the Yakima Basin.

ACKNOWLEDGEMENTS

This study was funded by the US Bureau of Reclamation, Yakima District (Yakima, Washington, USA). Image mosaics were acquired and processed by Positive Systems, Inc., Whitefish, Montana, USA. The authors also thank Eric Snyder, Mary Harner, Steve Croci, Jake Chaffin, Graeme Aggett, Jennifer Johnson, Clay Arango, Doug Eitemiller and Kelly Clark for their assistance in collecting ADP and ground truth data.

REFERENCES

Brookes, A. 1989. Channelized Rivers – Perspectives For Environmental Management. John Wiley & Sons, New York, New York, USA

Morgan, A., and F. Hinojosa. 1996. Literature review and monitoring recommendations for salmonid winter habitat. Timber-Fish-Wildlife Ambient Monitoring Program. Report No. TFW-AM 9-96-004. Northwest Indian Fisheries Commission, Olympia, Washington, USA.

Pearsons, T. N., G. A. McMichael, S. W. Martin, E. L. Bartrand, M. Fisher, and S. A. Leider. 1994. Yakima species interactions studies. Annual Report FY 1993. Bonneville Power Administration DOE/BP-99852-2.

Tou, J. T., and Gonzalez, R. C. 1977. Pattern Recognition Principles. Addison-Wesley, Reading, Massachusetts, USA.

Ward, J. V., K. Tockner, D. B. Arscott, and C. Claret. *In press*. Riverine landscape diversity. Freshwater Biology.

Whited, D. C., J. A. Stanford, and J. Kimball. *In press*. Application of airborne multispectral digital imagery to quantify riverine habitats at different base flows. River Research and Applications.

PART D: DERIVATION OF NORMATIVE FLOWS FOR A DAMAGED FLOODPLAIN RIVER ECOSYSTEM

by

Eric B. Snyder
snydeeri@gvsu.edu

Jack A. Stanford
stanford@selway.umt.edu

and

Jake L. Chaffin
jchaffin@vt.edu

Flathead Lake Biological Station
The University of Montana
311 Bio Station Lane
Polson, MT 59860-9659
406-982-3301
www.umt.edu/biology/flbs

INTRODUCTION

Tockner and Stanford (in press) state that the high biodiversity and bioproduction associated with floodplain ecosystems is a direct function of a complex habitat templet (sensu Southwood 1977). This complexity is maintained by the physical process of cut and fill alluviation—a natural disturbance process (sensu Lake 2000) that occurs as the channel migrates across the flood plain. This disturbance maintains a shifting habitat mosaic (SHM) that creates a suite of available niches used by a variety of organisms at various life history stages (Ward 1999). Contemporary stream ecological theory holds that flood plains act as regional organizers of biota in the sense that energy is concentrated here and the complex habitat templet or SHM provides the resources necessary for a suite of organisms to complete various life history stages.

The flood plains of the Yakima River provide excellent examples of this phenomenon. For example, the Yakima was once host to the largest overwintering population of ducks and geese in the entire Columbia Basin (Oliver 1983), an observation attributed to the historically diverse flood plain and fringing wetland habitat mosaic, especially in the lower basin.

In addition, the ethnographic and archeological evidence suggests that Native Americans used these same flood plains extensively. The largest communities were centered on the flood plains in the Selah and Union Gap areas (Uebelacker 1986). Uebelacker (1986) states that flood plains were utilized by Native Americans because they were centers of biological organization and provided a diverse array of food and habitat components necessary for survival. Not only were the rivers conduits of energy-rich anadromous salmon, but the nearby flood plains and terraces provided essential building material, such as tule reeds (*Scirpus spp.*), and food, such as camas roots (*Camassia quamash)*. In addition, large game animals (e.g., elk, deer and bighorn sheep) would migrate seasonally between the uplands and the flood plains.

Colonization by Euro-American people occurred in 1848 when missionaries arrived in the Yakima Valley. The first documented non-Indian irrigation ditch was constructed in 1864. By 1902, 121,000 acres were irrigated and diversions exceeded unregulated flow during low flow years. Thus in 1905, the United States authorized the investigation and eventual construction of the five major storage reservoirs in the basin by the Bureau of Reclamation.

The ever-increasing demand placed on the water resources of the basin for agricultural and urban uses, coupled will the increase in human population and floodplain encroachment has contributed to the local decline in the number of returning anadromous fish. For example, salmon and steelhead runs have declined from an estimated number of 800,000 individuals to less than 5% of this number (Tuck 1995, Embrey and Watson 1992, USBR 1999), and summer chinook (*Oncorhynchus tshawytsha*) and sockeye (*O. nerka*) are now considered to be locally extinct along with wild runs of coho (*O. kisutch*). Bull trout (*Salvelinus confluentus*) and steelhead (*O. mykiss*) have been listed as threatened (ESA 1973). The status of each of these stocks has been described elsewhere (Snyder and Stanford 2001, NWPPC 2001). This is not to say that other factors, such as ocean conditions and mortality associated with migration along the mainstem of the lower Columbia, have also contributed to the decline. However, we firmly believe that at least a partial restoration of salmon runs in the Yakima Basin can be accomplished via two main pathways.

Firstly, the flow regime in the system must be regulated in such a way as to emulate the historic discharge regime. In large part, a major objective of this study was to provide baseline data that would assist in the establishment of this flow regime, which we refer to as “normative”. In this context, normative means river flows that provide enough habitat to sustain or expand populations of anadromous salmonid fisheries in all life history stages (Independent Scientific Group 1999). Subsequently, we document the incremental advantages in terms of floodplain connectivity that are derived by increasing discharge based on several criteria including (a) connectivity estimated at unregulated flows, (b) estimated connectivity gained by improving irrigation efficiency and (c) estimated connectivity with Roza and Sunnyside diversions filled directly from Columbia River pump exchange. At the outset, this approach assumes that measures of floodplain connectivity are surrogate for habitat complexity (shifting habitat mosaic). Indeed, the establishment of a normative flow regime serves as the catalyst that improves the complexity of the habitat by initiating the process of cut and fill alluviation on a more wide-spread level than that which has occurred since the existence of the six storage reservoirs in the upper basin.

Secondly, this approach assumes that there is floodplain habitat that can be potentially connected to the river as this process of cut and fill alluviation takes place. Establishment of a normative flow regime accomplishes very little if the river is severely constrained, as has been documented on the major flood plains of the basin by Eitemiller et al. (2001). Thus, the second component of the restoration scheme in the Yakima involves (a) purchasing floodplain land outright, (b) establishing environmental easements when purchase is economically or politically unfeasible and (c) moving and reworking flood control levies, roads, railroad revetments, etc., in areas considered to be vital to salmonid production. Indeed, this process has been initiated on the Union Gap reach (USBR and YN land acquisition).

Throughout this report, we focus on salmonid restoration. However, we consider the fish to simply be indicators of a healthy and intact floodplain-riverine ecosystem. Indeed, given that the process described above can move forward, it is likely that other indicators will respond more quickly. These include but are not limited to benthic macroinvertebrates, physical measures of habitat complexity (e.g., large woody debris (LWD), substrate variability, number of connected spring brooks, channel morphology, etc.,) and riparian stand structure, number of exotic species present (both plant and animal, the number of fish species present in off-channel habitat and the relative abundance of indicator species, such as juvenile salmon and steelhead.

PROBLEM STATEMENT

This project was initiated because of key uncertainties regarding the potential bottlenecks for the instream completion of salmon life histories. Our research demonstrates that all flood plains examined are hydrologically connected, but the degree of this connectivity is variable. The presence of amphibitic stoneflies in the upper two reaches (Cle Elum and Kittitas) indicates that biophysical connection exists. In other words, these indicator organisms would not be present unless substantial subsurface connectivity was present. In addition, this study documented significant use of off-channel habitat by juvenile salmonids in all study reaches. It is well documented that the maintenance of these off-channel habitats is directly related to the flood-mediated shifting habitat mosaic (Heiler et al. 1995, Ward and Stanford 1995, Bansak

1998, Stanford 1998, Harner 2001); and subsequently to the completion of the juvenile life-history stages of salmonids and other species (Tockner and Stanford in press).

Stanford et al. (1996) state that large river basins represent ecosystems in which natural and cultural processes interact. This interaction of biota, material and energy occurs in four dimensions: upstream to downstream, laterally across the flood plain, vertically between the river and shallow alluvial aquifer, and all of which interact dynamically through time (see Snyder and Stanford (2001) for a review of the scientific concepts that underpin stream ecology). Cultural processes involving river regulation tend to result in channel simplification, reduction in natural ecological dynamics and isolation and fragmentation of the river-floodplain ecosystem (Ward and Stanford 1998). The reduction in formerly abundant salmonid runs in the Yakima Basin is at least in part derived from these basin-wide changes. For example, Humphreis et al. (2002) found that changes in fish composition in a regulated river were derived more from poor recruitment over several decades, rather than a failure to spawn. The process of salmonid recovery described in this report implicitly incorporates and recognizes that the Yakima River provides essential goods and services to the Basin. We strongly feel that restoration of anadromous fish runs can be accomplished with minimal impact to the agricultural community and with a net increase in the “value” (both aesthetic and monetary) of the riverine-floodplain ecosystems of the Yakima Basin.

Through this research effort, we conclude that recovery of salmonid runs in the Yakima is dependent on (1) the provision of normative flows, which we outline, and (2) the protection and enhancement of floodplain habitat. At the outset, we stressed that the ultimate success or failure of the recovery options we are suggesting was not within the scope of this project. We are stating that the data collected thus far indicates substantial hydrologic connectivity yet exists within the flood plains studied and subsequent investment in restoration will likely go very far toward salmonid stock recovery. However, the ultimate success or failure will take considerable time to be manifest (on the order of 10’s of years). As such, we see implementation of the management suggestions outlined in this report being evaluated at a significant level throughout the next several years, and that a process of adaptive management be employed. Thus the results of management decisions can be evaluated in an ongoing fashion and can be adapted to changing environmental and political conditions.

Specifically, our objectives were as follows:

1. Determine the floodplain reaches and extent of human encroachment (Uebelacker et al. 2002).
2. Determine the seasonal biophysical connectivity in three dimensions for each reach.
3. Establish a process by which normative flows can be determined for the five reaches in context of the hyporheic corridor concept (headwaters to mouth) (Stanford and Ward 1993, also see Snyder and Stanford (2001) for a review of this and related concepts) and provide an example in one reach.
4. In light of the above results and conclusions, and Yakima River Basin Water Enhancement Program mandates, determine the restoration options per flood plain that would increase ecological connectivity (e.g., floodplain expansion by revetment removal) and prioritize reaches for connectivity improvement.

SITE DESCRIPTION (OVERVIEW)

Climate is variable, ranging from maritime in the Cascades ecoregion to arid in the Columbia Basin, where annual precipitation ranges from 350 to less than 25 cm, respectively (Rinella et al. 1992). Although the Cascade and Eastern Cascade ecoregions represent 60% of the drainage basin area, they supply 85% of the estimated annual unregulated flow (USBR 1999). Subsequently, most of the water available for irrigation is derived from the Cascade ecoregion (Fig. 1).

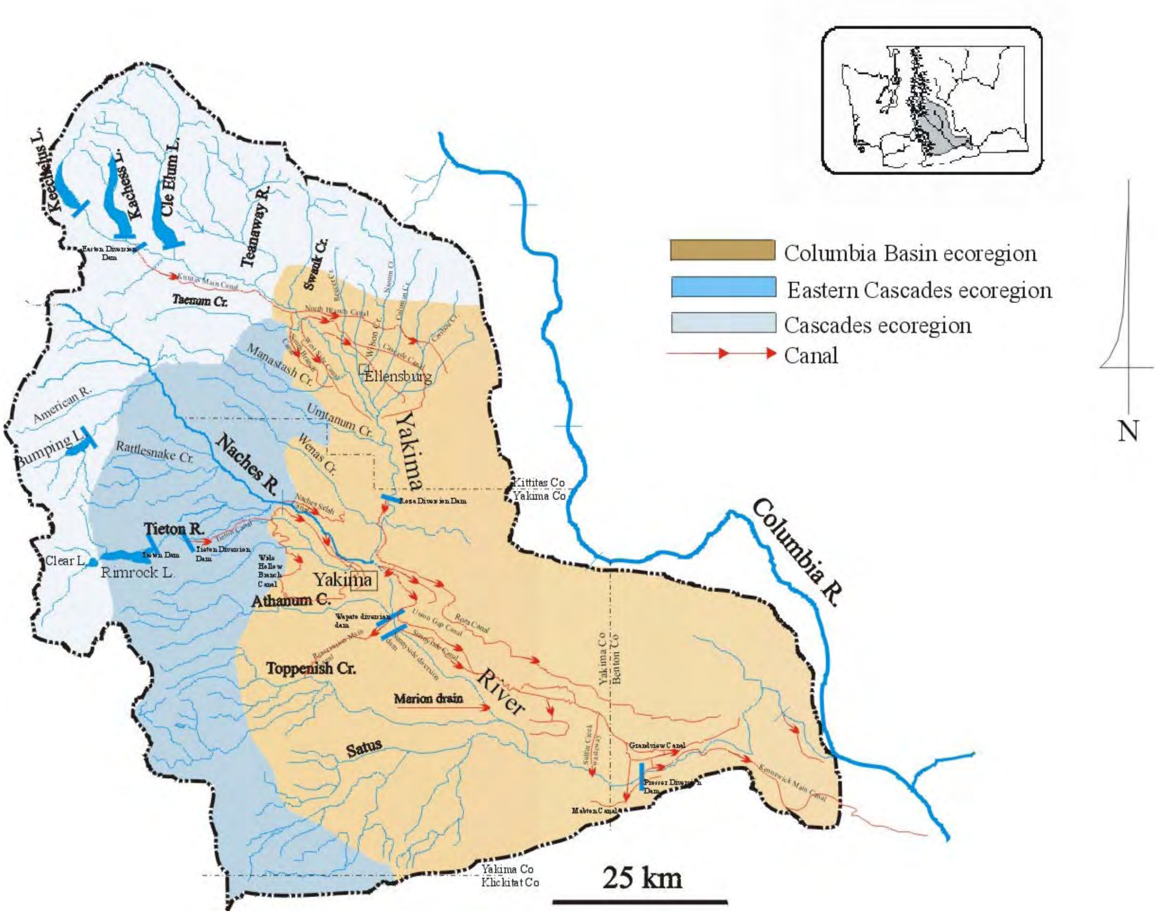


Figure 1. Base map of the Yakima Basin showing various ecoregions and some of the irrigation canals.

Elevation ranges from about 2,500 m in the Cascades to 98 m at the Columbia River confluence. The higher areas, which receive the most precipitation, are thickly covered with fir, pine and larch. On lower slopes with less precipitation, sparse stands of ponderosa pine are found. The arid Columbia River ecoregion is dominated by sage and various species of grass. Historically, this geographic templet generated a river hydrograph in which peak runoff in the lower basin was estimated to occur from April through June, derived from snowmelt in the Cascade Range (Parker and Storey 1916). However, due to the arid nature of the lower basin, fall floods of short duration and high peak discharge generated by rain events also frequently occur in the discharge records (Ring and Watson 1999).

Geologically, the basin consists of two major formations—the Cascade region, which corresponds to the Cascade ecoregion, and the Columbia Plateau, which encompasses both the Eastern Cascades and Columbia Basin ecoregions (Kinnison and Sceva 1963). The Cascade region, lying within the Cascade Mountains, consists of continental formations of Eocene-age sandstone, shale and some coal layers and pre-Miocene volcanic, intrusive and metamorphic formations. The Columbia Plateau is dominated by numerous lava flows consisting of tertiary age Columbia River basalt, which topographically masked preexisting formations. The plateau was deformed into a series of southeast-trending anticlinal ridges and synclinal valleys, through which the Yakima River cut, creating the Yakima Canyon and Selah and Union Gaps (Kinnison and Sceva 1963).

The Columbia River basalts, located within the Columbia Plateau, represent a locally important aquifer system characterized by interbeds and overlying sediments. These alluvial aquifers are highly permeable and are heterogeneous and anisotropic, due to their location within the fluvial environment where the processes of cut and fill alluviation via the Yakima River and tributaries occurred. The Cascade ecoregion stores and transmits little water via aquifer systems and the majority of runoff occurs as overland flow.

In both Cascade and Columbia Plateau regions, recent glacial activity and the network of tributary and main channel flow deposited large amounts of lacustrine and fluvial material in the valleys. This geologic templet produced a series of groundwater basins separated by natural knick points (Selah and Union Gaps) and longer canyons (e.g., Yakima Canyon) (Kinnison and Sceva 1963). The Yakima River cuts through four large subbasins (Rosyln, Kittitas, Upper Yakima and Lower Yakima) (Figs. 2 and 3). This geological setting influences the hydrologic cycle.

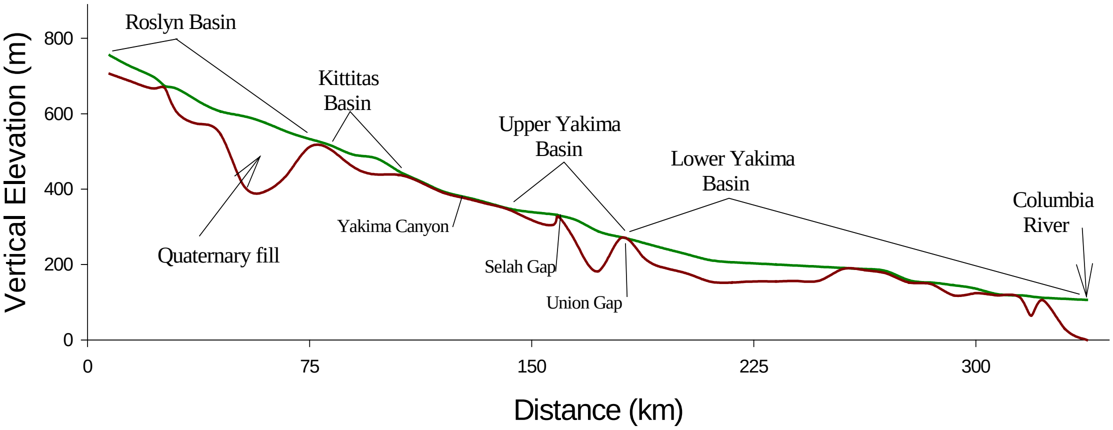


Figure 2. Cross-sectional profile showing depth of alluvial (Quaternary fill) gravel/cobble deposits. Labels and data taken from Kinnison and Sceva (1963).

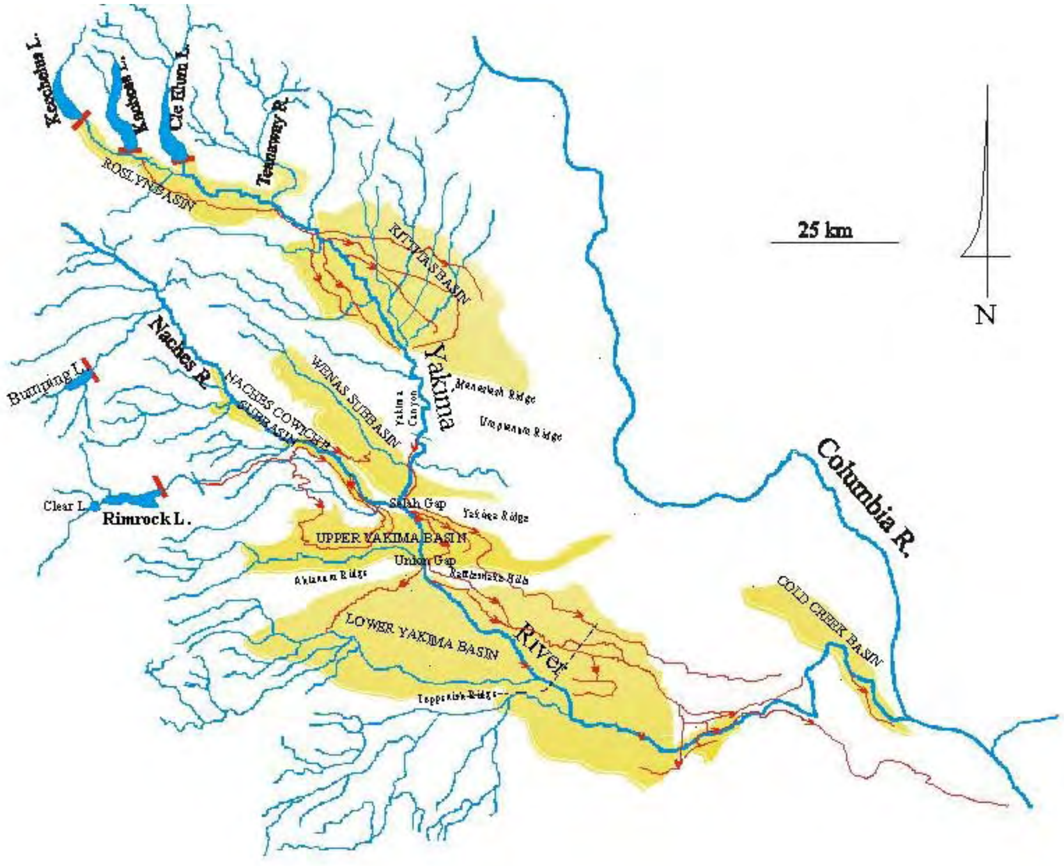


Figure 3. Location of groundwater subbasins separated by natural knick points and longer canyons. Yellow highlights represent the distribution of recent (Quaternary) sedimentary deposits plus the older Ellensburg formations. Basin and subbasin identification from Kinnison and Sceva (1963). Not all basins or subbasins are identified. Red lines with arrows indicate withdrawals, canals and returns (from Snyder and Stanford 2001).

Historically, the hydrologic cycle in each basin was likely characterized by extensive exchange between the surface, hyporheic and groundwater zones (Kinnison and Sceva 1963; Ring and Watson 1999). This exchange would have occurred mainly in the vast alluvial valleys and flood plains, which would have functioned as hydrologic buffers, distributing the energy of peak flows and moving cool, spring melt water out onto the flood plains. This inundation would annually recharge the shallow, surficial aquifers; a process that would occur potentially well into summer due to extensive and long-lasting snow pack in the Cascades (Ring and Watson 1999). As Parker and Storey (1916) point out, base flow during mid to late summer is derived and sustained almost wholly from ground water and natural lake storage. Based on fundamental hydrologic principles, there is no question that groundwater recharge of this nature would not only have maintained base flows, but would have provided areas of cooler thermal refugia as summer progressed and air temperatures increased, as well as maintaining warmer winter temperatures, preventing or reducing the risk of anchor ice (Kinnison and Sceva 1963). Bansak (1998) quantified this process in a similar alluvial valley of the unregulated Middle Fork Flathead River, Montana. How irrigation return flows emulate this natural process is less certain. For example, although abstraction starts in mid to late March, the nature of this potential recharge is quite different from natural processes in which historic spring flooding likely spread water out over large portions of the alluvial valleys versus irrigation diversions that transport water, often in lined canals or pipes, to specific locations often far removed from the active flood plain. The interaction between irrigation activities and the surficial aquifer is currently being studied by the U.S.G.S (John Vaccarro, U.S.G.S., pers. comm.).

On a large spatial scale, each of the Yakima subbasins is conceptualized as being downwelling, or losing surface water to the hyporheic and groundwater systems at the upstream end and upwelling, or gaining surface water from the ground water and hyporheic systems at the downstream end as described for other rivers (e.g., Stanford and Ward 1988 and Tockner and Schiemer 1997). This upwelling is driven by the decreasing size of the sedimentary aquifers causing ground water to move back into the river, tributaries and irrigation drains. Annual inundation and recharge also maintained the connectivity and flow of backwater or spring brook habitats. These habitats are critical for successful completion of the life-history cycles of numerous fish species and other biota (e.g., Morgan and Hinojosa 1996; Tockner and Schiemer 1997).

Historic maps and photographs indicate that these types of habitats were much more abundant prior to anthropogenic alteration of the flood plain (archive, USBR Yakima Office; Morris Uebelacker, CWU, pers. comm.) (see historic survey below).

A portion of the Wapato Reach (the lower Yakima River is the northern boundary of the survey data in this figure) and distributary channels between the towns of Wapato and Toppenish. Survey data was collected by the USBR in 1909. Note the abundance of distributary channels that run from the middle of the figure through the Northern Pacific Rail Road and south of Toppenish.

GEOMORPHIC TEMPLET

Although we found no papers that discuss channel form in the Yakima, five distinct channel provinces are very apparent along the altitudinal gradient from source to mouth; 1) high gradient, largely constrained headwaters, 2) expansive anastomosed or braided alluvial flood plains, 3) constrained canyons, 4) meandering with expansive flood plains containing oxbows and 5) deltaic flood plain at the confluence with the Columbia River.

Six storage reservoirs have been constructed in the Yakima Basin, including impoundment of the natural glacial lakes in the headwaters: Keechelus Lake (157,800 acre-feet); Kachess Lake (239,000 acre-feet); Cle Elum Lake (436,900 acre-feet); Rimrock Lake (198,000 acre-feet); Clear Lake (5,300 acre-feet); and Bumping Lake (33,700 acre-feet) (Fig. 1). All except Rimrock Reservoir were natural lakes prior to impoundment. Together they capture approximately one third of the annual basin-wide runoff. Storage volume equals 1.07 million acre-feet, which leaves an average of 2.79 million acre-feet of unregulated runoff annually (USBR 1983, 1999). A key point is that storage is insufficient to control all flooding, a fact that in part explains the presence of existing complex habitat (e.g., the lower ends of the major floodplain reaches). Flood stage discharge at Umtanum is estimated to occur on about a five-year return interval (Chris Lynch, pers. comm.) (Fig. 5).

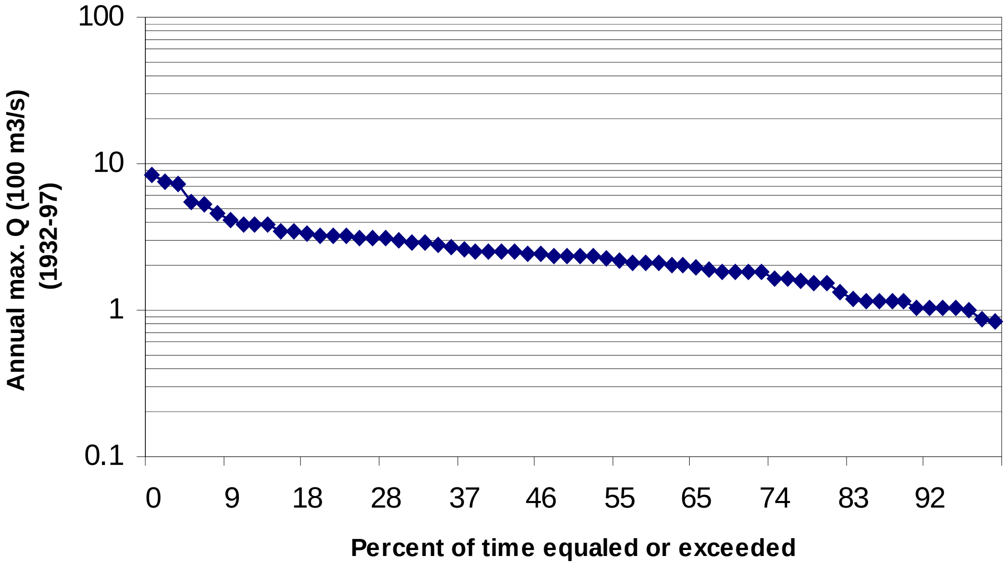


Figure 5. Annual maximum discharge (x 100 m^3/s) from 1932 to 1997 at Umtanum gage (USGS). The period of record is 66 years, thus a change of 10% (x-axis) is equivalent to 6.6 years. Bank-full discharge at Umtanum was estimated to be 232.5 m^3/s (based on a USGS gage located at Ellensburg; rkm 250.8) while flood stage was estimated to be at 436.1 m^3/s. Using these estimates for the Umtanum gage, flood-stage was equaled or exceeded c.a. 8% of the time; or every 5.3 years. Thus, the post-reservoir reoccurrence interval for significant floodplain inundation and cut and fill avulsion would occur twice a decade.

All of the storage reservoirs are located in the headwaters of the upper basin, within the Cascades and Eastern Cascades ecoregions. As such, the majority of the water sustaining the agricultural industry is transported to the lower basin during periods of the summer and early fall when the river would otherwise be approaching baseflow. Seven low-head diversion dams are located on the main stem of the Yakima, including Easton at river kilometer (rkm) 235.8, Town Ditch at Thorp (rkm 258.4), Roza (rkm 205.8), Wapato (rkm 171.5), Sunnyside (rkm 167), Prosser (rkm 75.8) and Horn Rapids (rkm 5.8). The Naches River, the largest tributary to the Yakima River, has two large diversion dams; Wapatox (rkm 27.5) and Naches Cowiche (rkm 5.8) (Fig. 2). Each of these diversion dams maintains screening structures installed to prevent entrainment of migratory and resident fish. In addition, there are literally hundreds of additional diversion structures that do not span the entire river located on both the mainstem and tributaries (River Mile Index 1964).

Groundwater recharge occurs via precipitation and from the application of irrigation water, the latter of which increases recharge over pre-irrigation times by about a factor of 10 at the height of the irrigation season (Tom Ring, pers. comm.). Kinnison and Sceva (1963) noted that water table elevations rose substantially during the onset of irrigation in the first half of the century. Because of this, drains often were cut to reduce high water tables and prevent the development of alkaline soils. Thus, the pattern of groundwater recharge has been substantially altered with post-irrigation recharge following the seasonal patterns of irrigation. Historically, recharge would have occurred mainly in the winter and spring when evapotranspiration was low and precipitation was high. The result has been a reduction in the frequency, magnitude and duration of floodplain inundation because of reservoir storage. As such, recharge of cold spring melt water into the aquifer systems has been replaced by recharge of warmer water derived from irrigation later in the spring and summer.

Over 500,000 acres of irrigated cropland occur, ranking the Yakima Basin among the leading agricultural areas in the United States. For example, Yakima County ranked fifth in the United States in total agricultural production. Perennial crops, such as fruit trees, grapes, hops, mint and asparagus occur on more than 45% of the irrigated area (USBR 1999).

The diversions at Sunnyside and Wapato typically divert one half of the entire river flow during the irrigation season, from May to October, while Prosser diverts 40 m^3/s most of the year, both for irrigation and power production. Because of regulation and withdrawals for irrigation, the Yakima River experiences periods of both dewatering and elevated flows relative to the historic discharge regime (Parker and Storey 1916; Vaccaro 1986a; Conservation Advisory Group 1997; SOAC 1999; USBR 1999). For example, at Union Gap and Parker, regulation has reduced annual discharge (mean based on data from 1926-77) from 134 m^3/s to 108 m^3/s at Union Gap and 65 m^3/s at Parker (Vaccaro 1986a). Declines of this magnitude would significantly effect the processes of cut and fill alluviation that historically maintained habitat heterogeneity. Furthermore, the average annual seven-day minimum mean discharge at Parker for the same time period was 3.7 m^3/s (Vaccaro 1986a). Vaccaro (1986a) estimated that composite error of historic discharge estimates was 12% relative to the 21% change in discharge by regulation at Union Gap and the 52% change at Parker. Thus, potential error in historical discharge estimates was less than the magnitude of change caused by regulation.

Because of the substantial declines in flow during the irrigation season, target flows below Prosser and Sunnyside diversions were established under the authority of Federal Congressional legislation (Title XII; Public Law 103-434). At present, the legislation calls for flows below Sunnyside and Prosser that range from 8.5 to 17 m^3/s, depending on the estimated water supply for a given period of time. These target flows are based on the estimated supply of water. Recommendations believed necessary to establish *biologically* based flows (e.g., discharge regimes necessary to restore and maintain normative river structure and function) are called for in YRBWEP and mentored[2] by the Systems Operations Advisory Committee (SOAC 1999).

FLOODPLAIN DESCRIPTIONS

Eitemiller et al. (2002) provide detailed ethnographic, historical and physical descriptions for each of the flood plains studied in this research effort (Cle Elum, Kittitas, Union Gap, Wapato and Naches) as well as descriptions of the Easton, Upper Naches and Selah flood plains. Therefore, we only report data relevant to identification of particular features, such as monitoring well locations and descriptions of spring brooks, etc., in this report. We encourage concurrent reading of this report and the analysis assembled by Eitemiller et al. (2002).

Cle Elum Reach

Two series of wells were installed within the Cle Elum reach. The first series focused on the confluence of the Teanaway and Yakima Rivers, with wells being installed on both sides of the Teanaway (Fig. 5). At the outset, we suspected that the wetland complex located up-gradient (due North East) from the Teanaway wells would strongly influence groundwater-surfacewater interactions on the West bank of the river. Historically, we know that the East side of the river and adjacent floodplain historically had a side channel present that was used in the earlier part of the century to float logs down to a lumber processing site located on the premises (M. Uebelacker and D. Eitemiller, pers. comm.). Two of the wells (t1 and t2) were placed on this now disconnected side channel. Disconnection was directly a result of levee construction and bridge installation that occurred earlier in the century. Within the last few years, housing developments have been constructed behind these levees.

The second series of wells were installed upstream from the Teanaway confluence and on either side of the Yakima River. Some of these wells were located in areas believed to be strongly influenced by the wetland complex described above (uy3), while others were situated at varying distances from the main channel (uy1 and 2, and uy4-6). Wells on the south side of the Yakima River (uy4-6) were located along a fringing wetland complex out of which multiple spring brooks emerged. Instream sampling focused on the confluence of these spring brooks with a side channel of the main river.

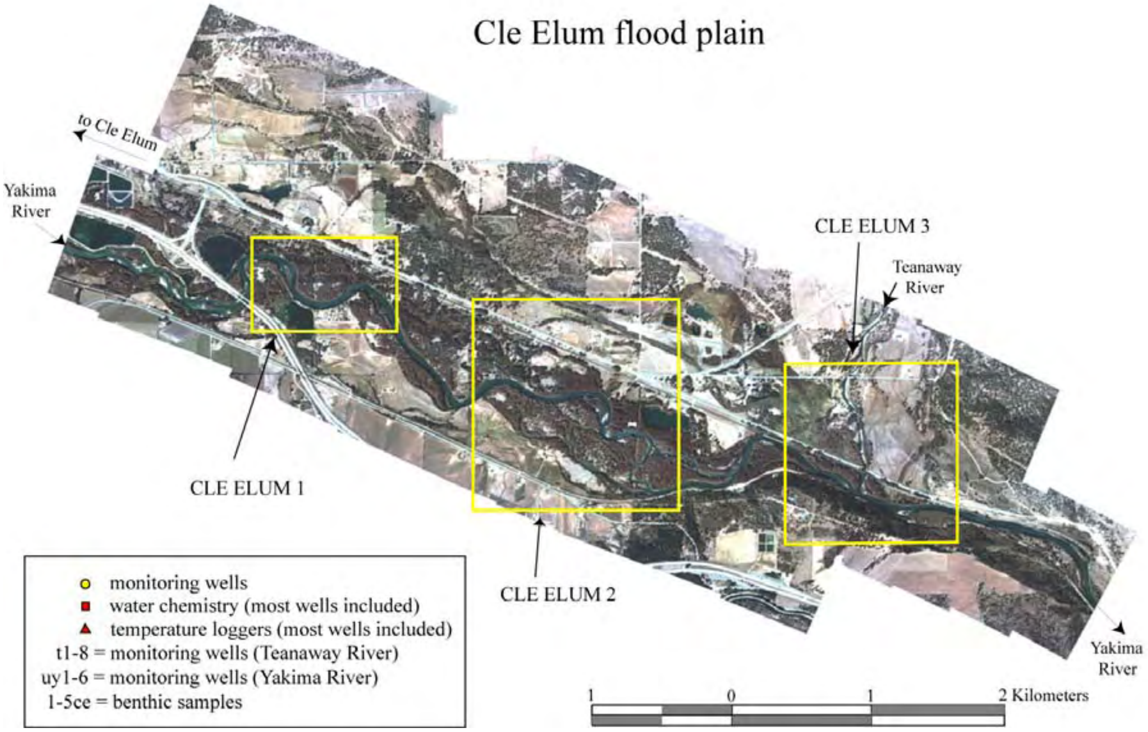


Figure 5. Base map of the Cle Elum reach. Insets are shown in the following figures.

At various times throughout the two years of study, beavers reworked multiple portions of the spring brook complex, thus our sampling regime changed accordingly. Generally, we sampled directly below beaver dams in areas where there was at least minimal water velocity. This was particularly important for sampling benthic macroinvertebrates as our sample device (surber net) required flowing water. This particular property (Cle Elum 2) is ideal for floodplain protection because it maintains high habitat complexity in the form of multiple spring brooks, extensive beaver activity and numerous side channels.

Instream samples (benthic macroinvertebrates, algae, water chemistry) were collected at various points throughout the reach including the mainstem Teanaway and Yakima (1ce and 2ce) and several side channels and spring brooks (3-5ce). In addition, water depth was recorded continuously in some wells (t2, t7, uy7), while temperature was recorded continuously in most wells and in various surface water habitats (see base map for this reach, triangular symbols). In addition, temperature loggers were installed at the upstream and downstream end of each reach, including the Teanaway River.

CLE ELUM 1

CLE ELUM 2

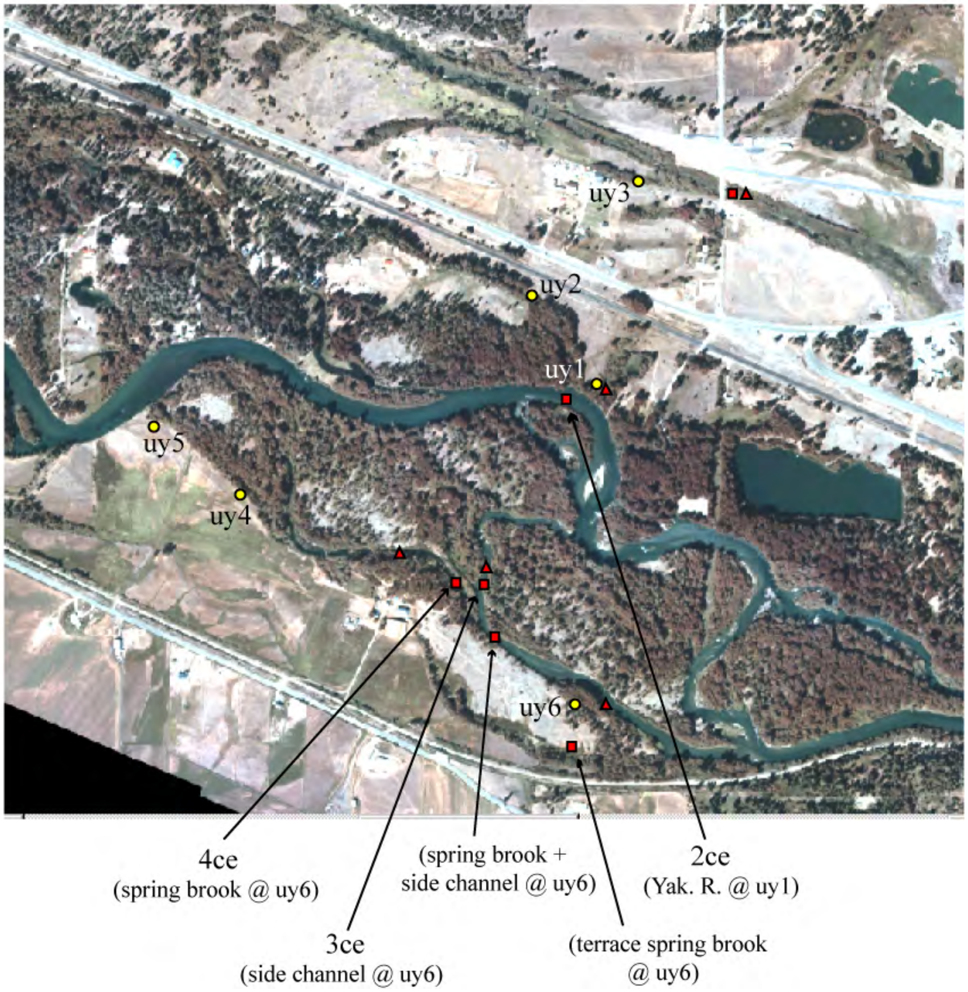


Figure 5 cont.

Figure 5 cont.

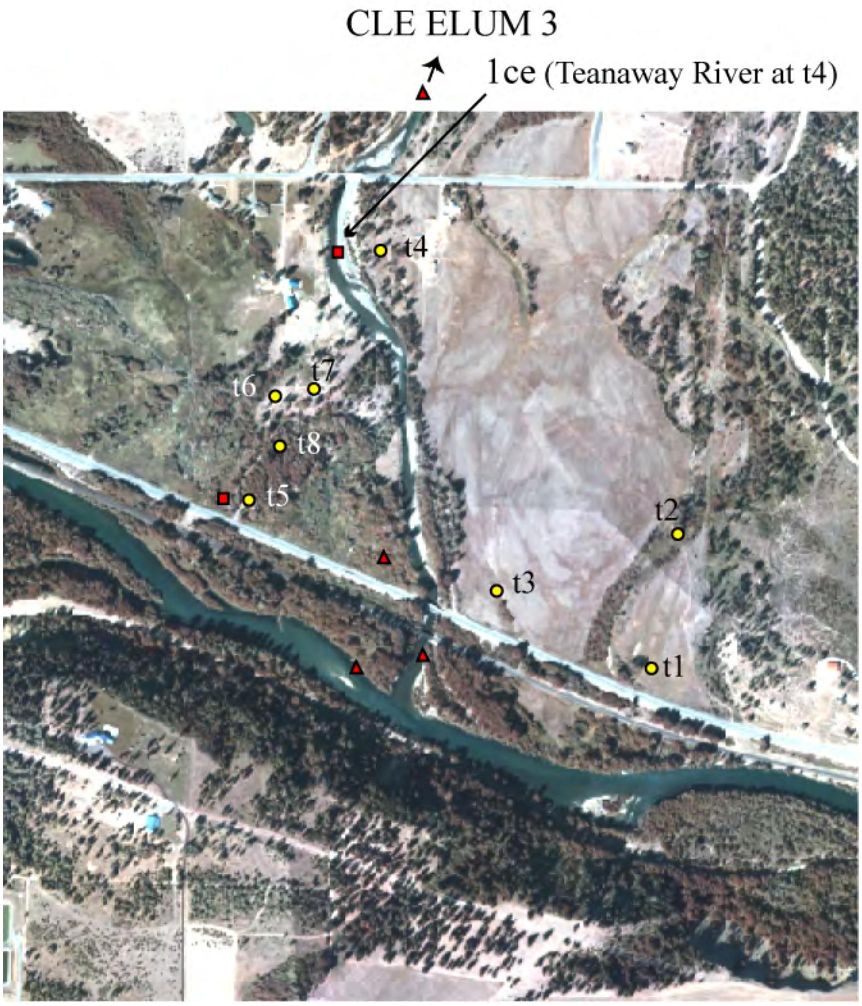


Figure 5 cont.

On at least five dates (see below section on fish monitoring for specifics), fish were quantitatively sampled in near-shore and off-channel habitats. These sites corresponded to the areas where surface water grab samples for water chemistry were collected (1-5ce).

Kittitas Reach

Difficulty in finding access to the active flood plain limited the placement of monitoring wells in the Kittitas reach. Thus all wells were concentrated near the southern end of the reach, where the river enters the Yakima Canyon (Fig. 6). One well was used to continuously monitor depth (eb6) and, as in the Cle Elum reach, most additional wells were outfitted with continuous recorders for temperature. Benthic samples were collected (1-3k) at the same time that water chemistry and algae were sampled, and as in the Cle Elum reach, fish were sampled at least five times. Two spring brook systems were sampled via raft in this reach, both located near the lower end of the reach and on property owned by the Bureau of Land Management.

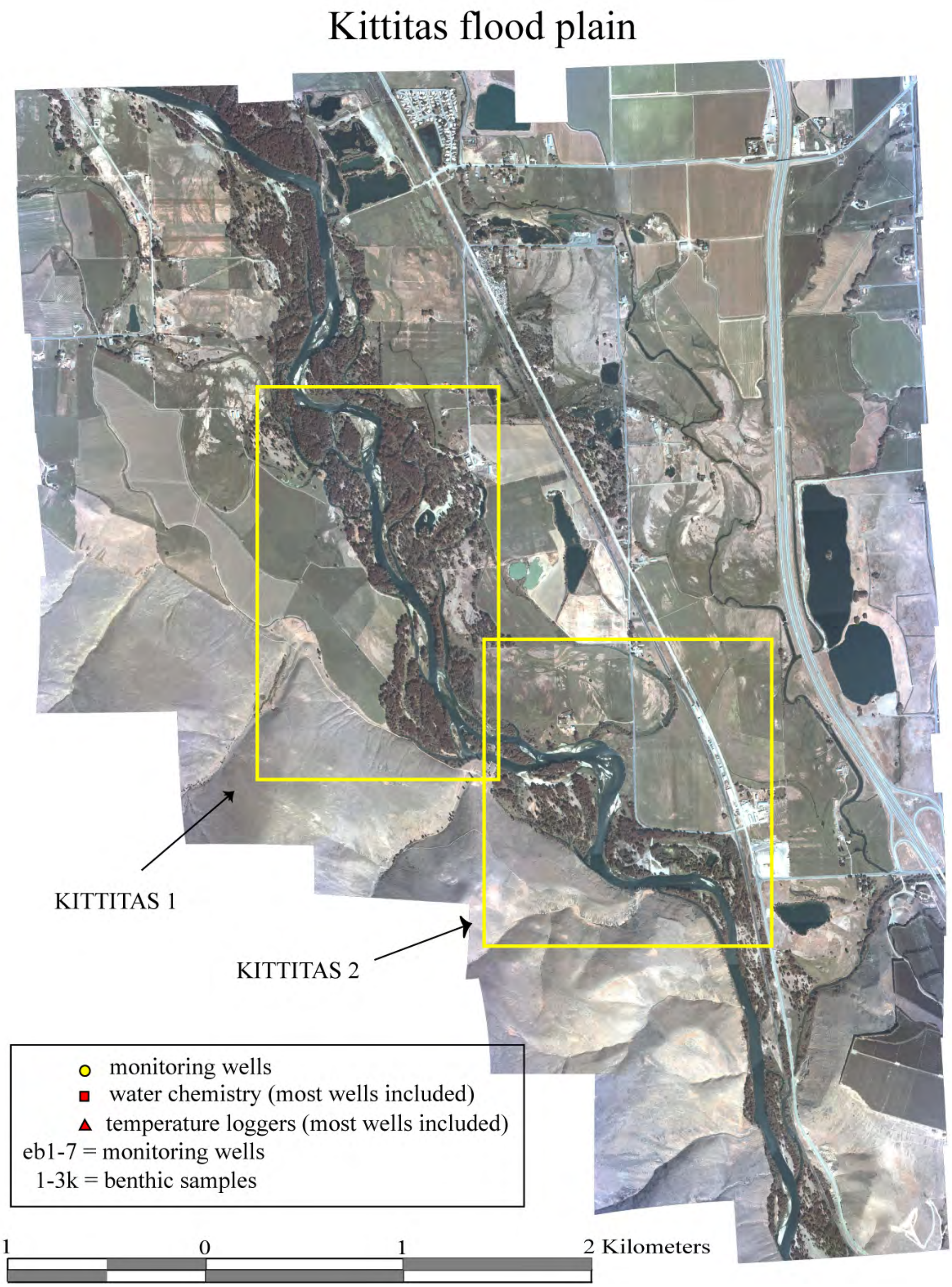


Figure 6. Base map of the Kittitas reach. Insets are shown in the following two figures.

Figure 6 cont.

Plecoptera (stoneflies) were found regularly in well eb7 and occasionally in well eb6. The former well was periodically used for elementary and teacher training workshops and aptly demonstrated the interstitial connectivity that exists in this reach. In addition, the USGS has established a network of three shallow monitoring wells near eb7 (John Vaccarro, pers. comm.). Wells located near water bodies (all, except eb2 and eb5) were surveyed to establish stage-discharge relationships.

KITTITAS 2

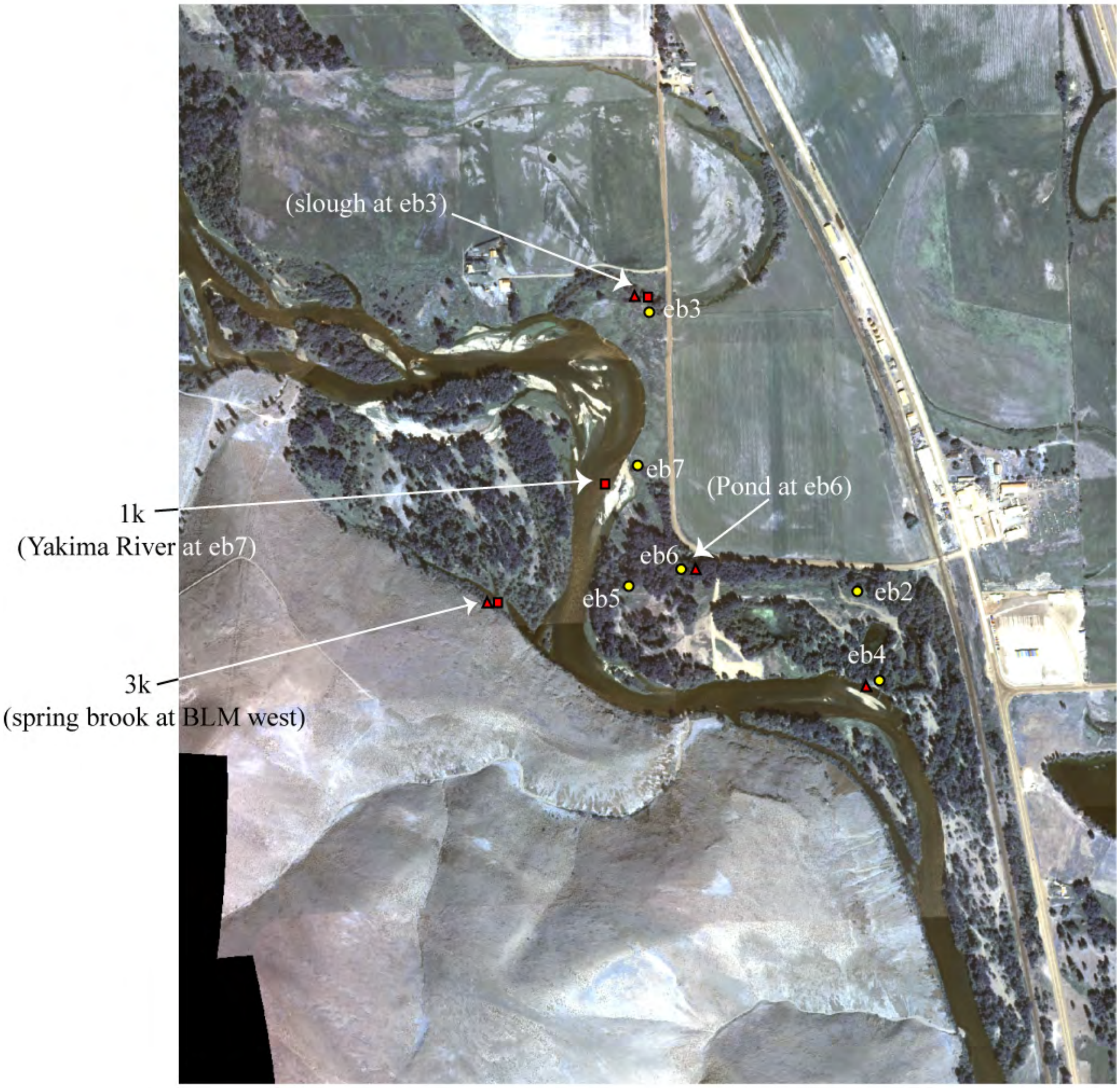


Figure 6 cont.

Union Gap Reach

In the Union Gap reach, two sets of wells were installed (Fig. 7). The first was located near the lower end of the reach and spanned from the first major terrace to the mainstem of the river. The second set of wells was located in the middle section of the reach and all wells (yc10-12) were placed on the opposite side of a large flood control levy located just north of Highway 24 within the boundaries of the Sportsmen State Park. Sites were selected based on proximity to spring brooks and irrigation return flows. Continuous depth recorders were installed in two wells (yc2 and yc12) and, as described previously, most additional wells were outfitted with temperature data recorders. Several surface water habitats were sampled throughout the study period including three spring brooks (3, 6 and 7ug), two backwater sloughs (1 and 2ug), one irrigation slough (1ug) and two mainstem samples (4 and 5ug). Fish were sampled from multiple sites (3 through 7ug).

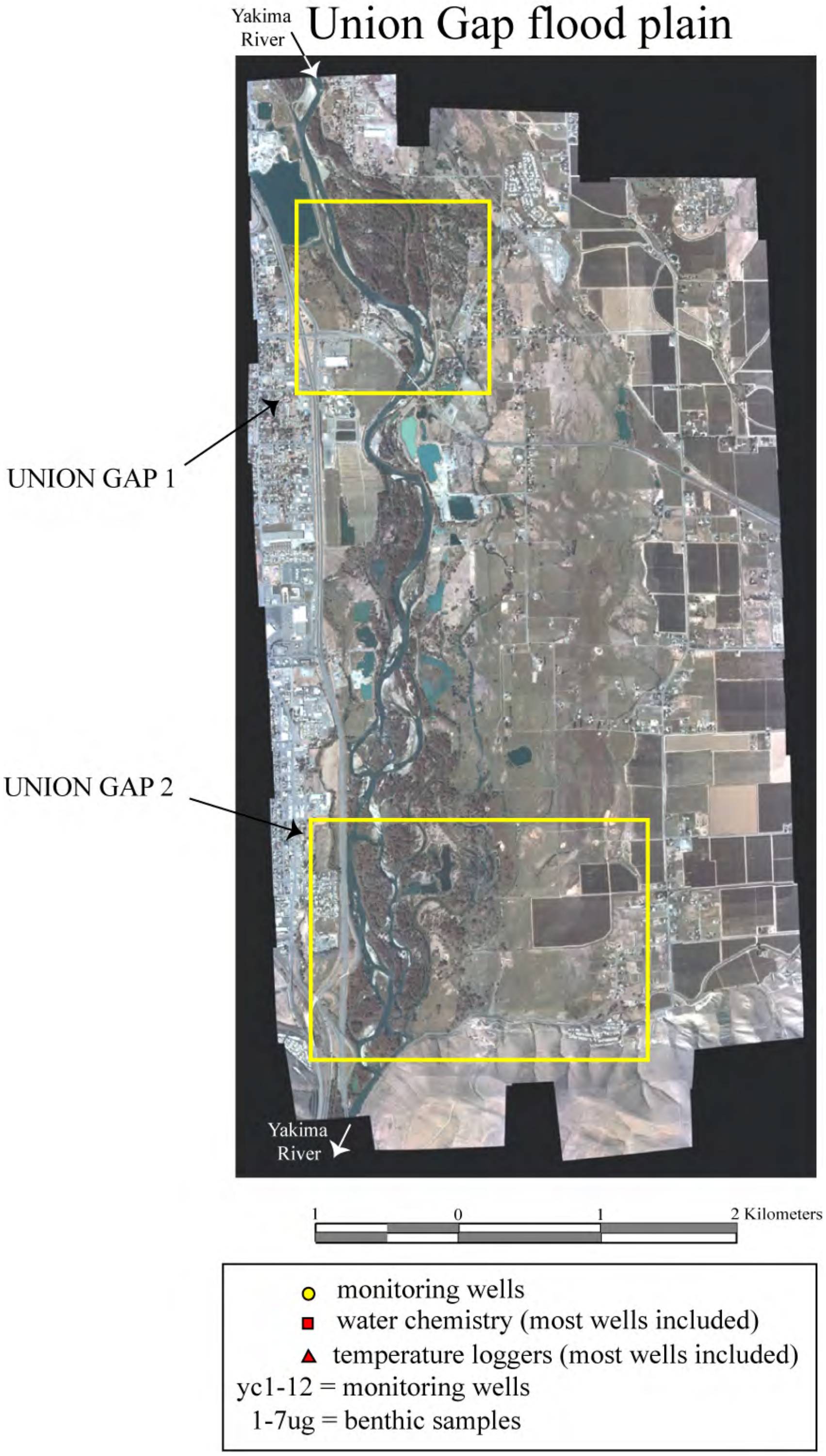


Figure 7. Base map of the Union Gap reach. Insets (Union Gap 1 and 2) are shown in the following two figures.

UNION GAP 1

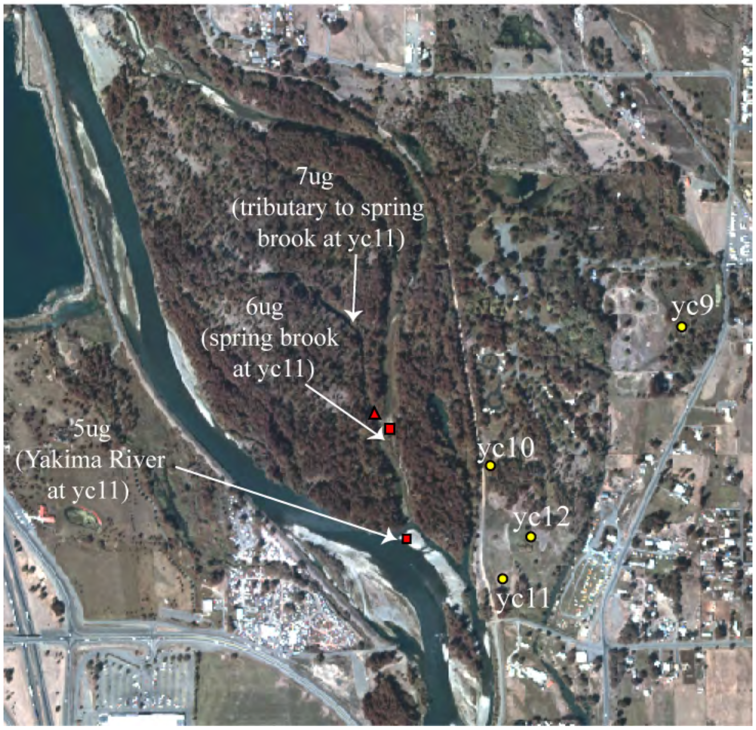
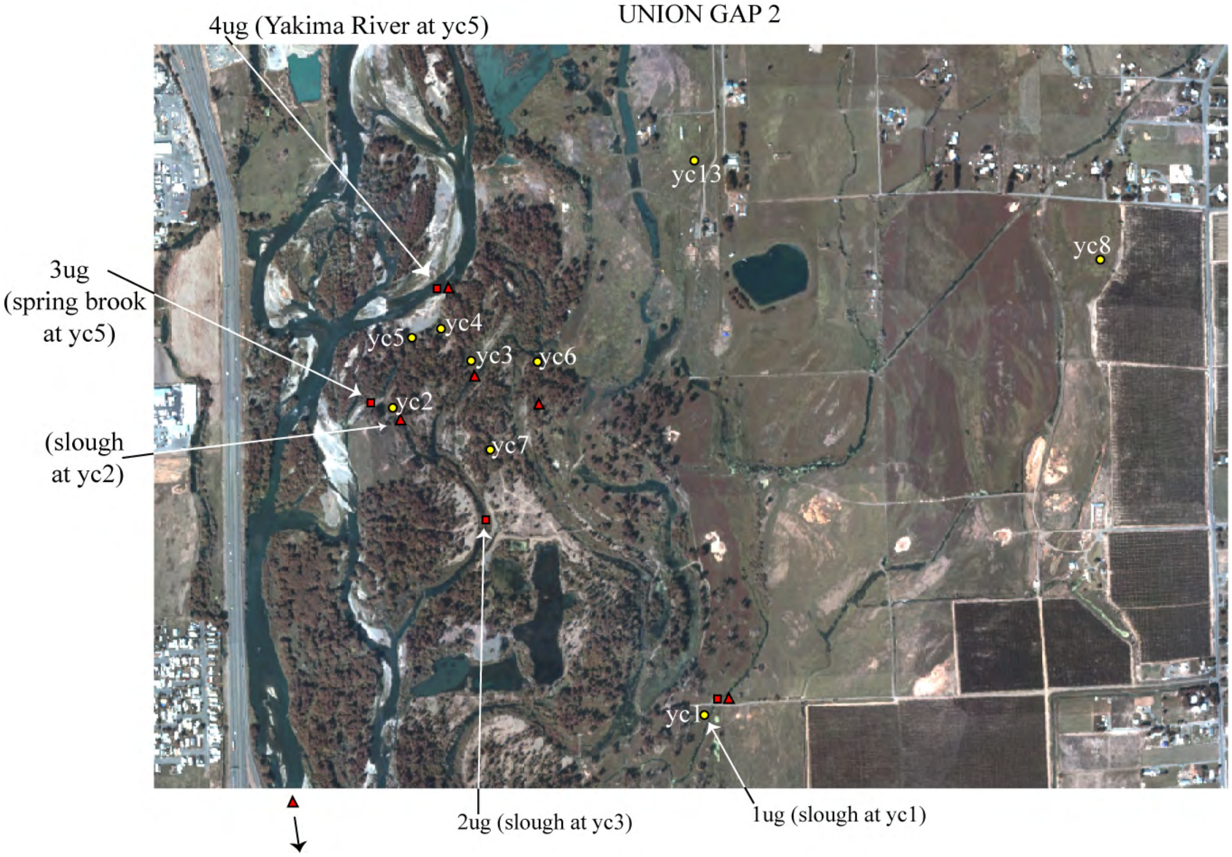


Figure 7 cont.

UNION GAP 2



Wapato Reach

A total of 16 wells were drilled within the Wapato reach, the larger number corresponding to the size of this reach relative to the others (Fig. 8). The first set of wells (w1-10) were concentrated on the Wapato Wildlife Area (WWA), a parcel of floodplain land managed by the YN. These wells spanned a distance from up to 1 km to within 50 m of the Yakima River mainstem. Further downstream, the second set of wells (three total, w12-14) was located on the Buena Wildlife Area, which also is managed by the YN. The final set of wells was located at the West Zillah Boat Ramp, which is managed by the Washington State Department of Fish and Wildlife. Two wells were installed here.

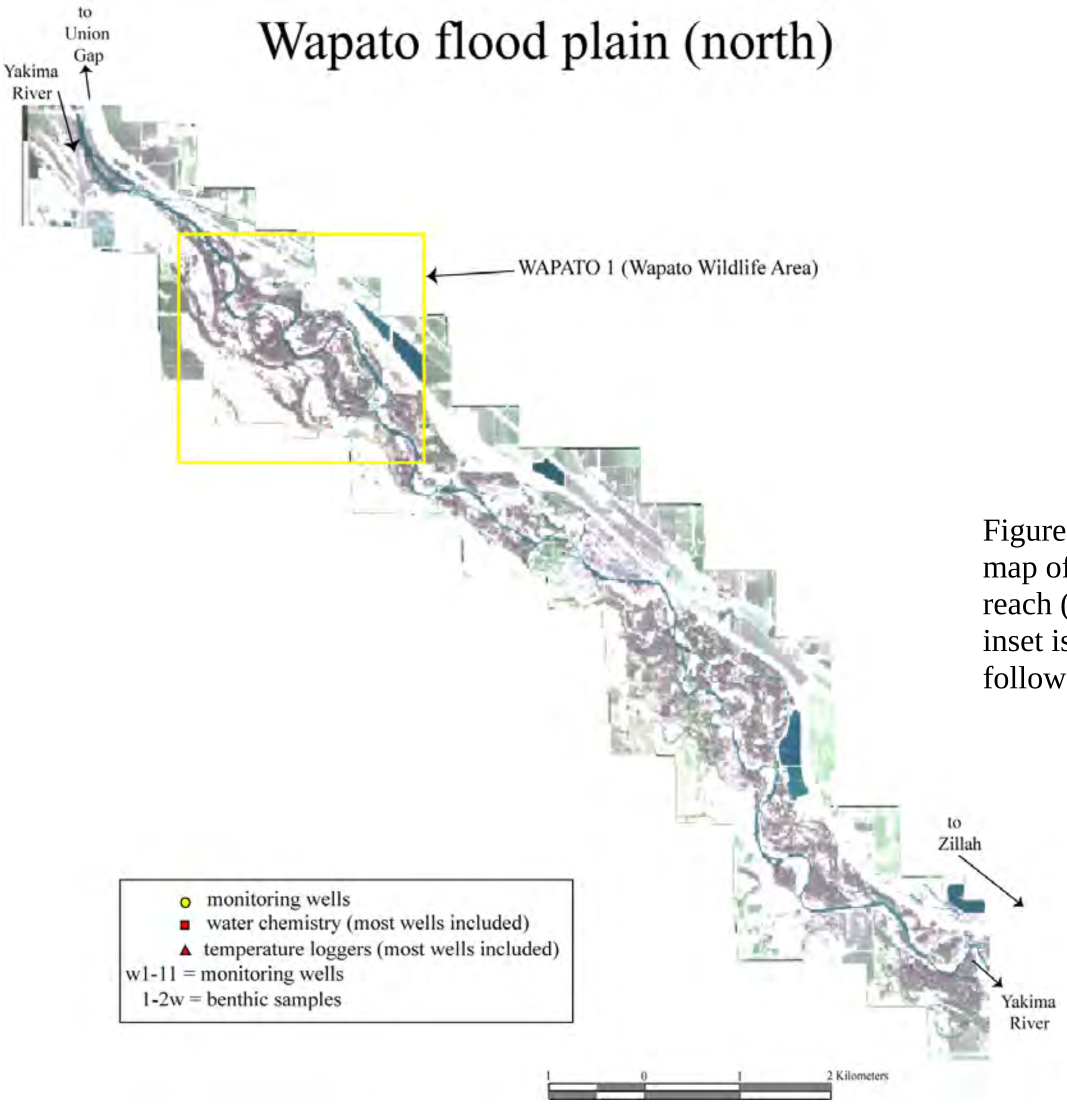


Figure 8. Base map of Wapato reach (north). The inset is shown in a following figure.

WAPATO 1

Figure 8 cont.

A total of three depth recorders were installed in this reach (w2, 5 and 12) and multiple temperature loggers were placed into various habitat types, including beaver ponds, spring brooks, side channels and the mainstem Yakima River. Fish were sampled at the same sites that surface water chemistry, benthic macroinvertebrate and algal samples were collected (1-5w).

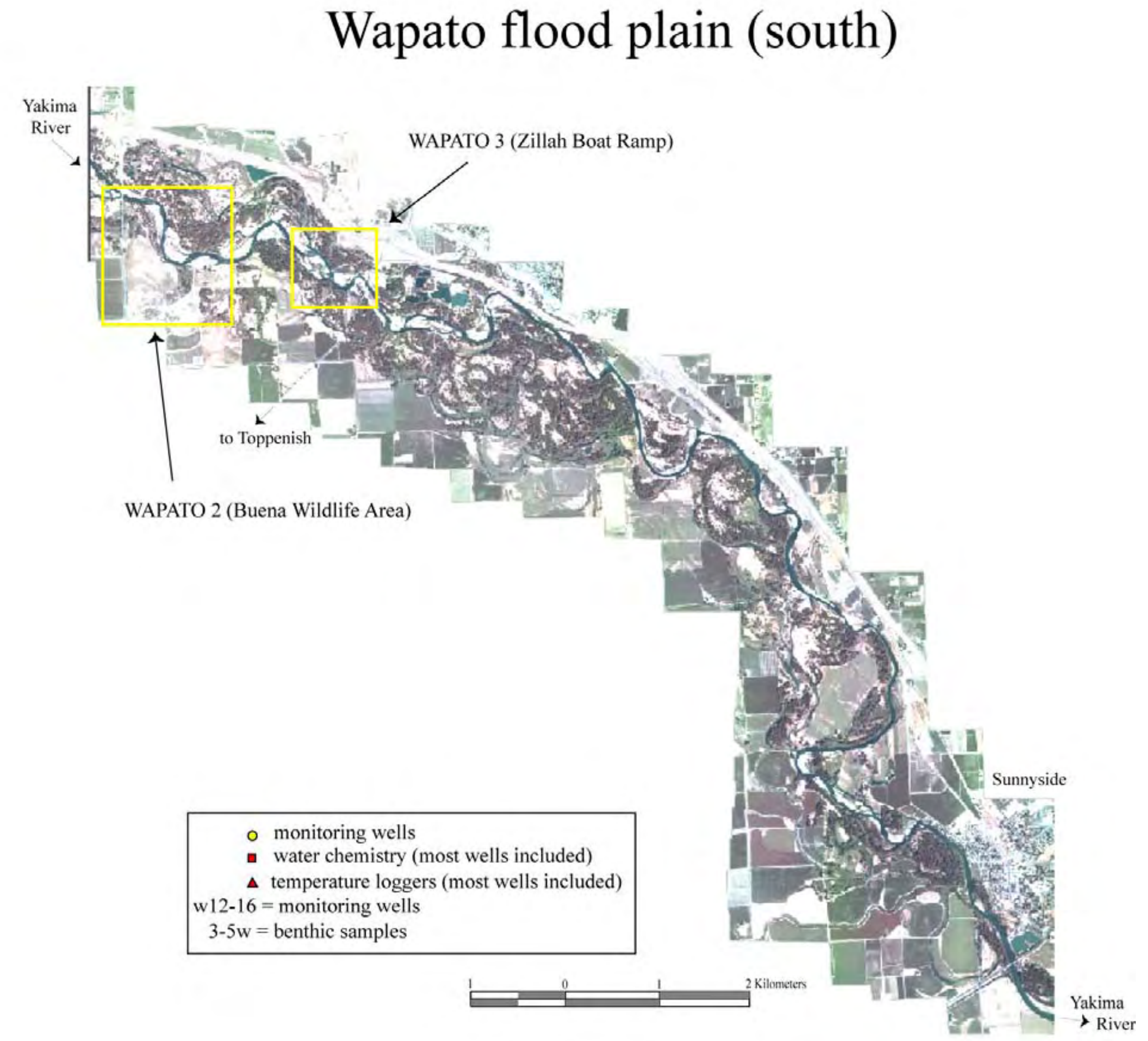
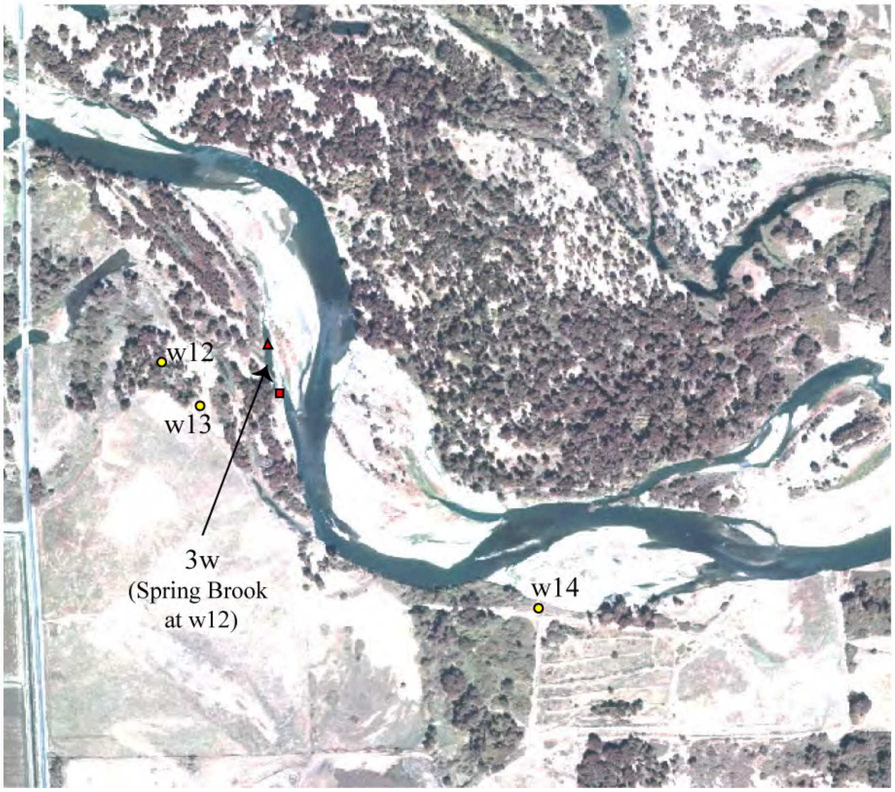


Figure 8 cont.

WAPATO 2



WAPATO 3

Figure 8
cont.

Naches Reach

Eleven monitoring wells were installed on the lower Naches River flood plain (Fig. 9) of which 4 were located within the boundary of Eschbach County Park (N1-4) where additional samples for benthic macroinvertebrates, algae and fish were collected (1n). Other surface water samples collected from the south side of the river included a combination of spring brooks and side channels located along the southeastern boundary of the park (2 through 4n). Much beaver activity was observed within each of these off-channel systems. The second set of wells on the south side of the river was located further downstream (N5 and 6) where an additional spring brook sample was collected (7n).

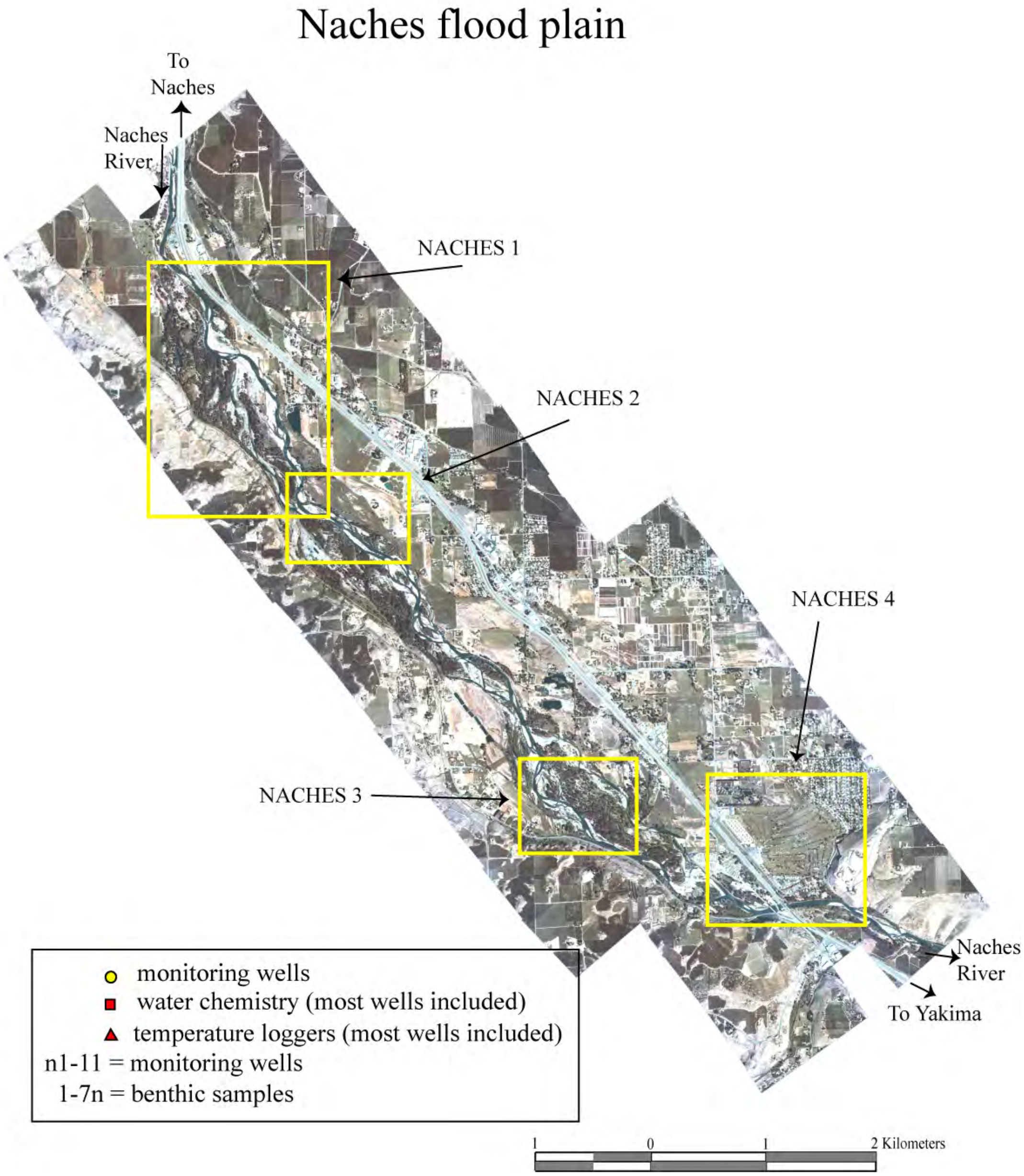


Figure 9. Base map of the Naches reach. Insets are shown in proceeding figures.

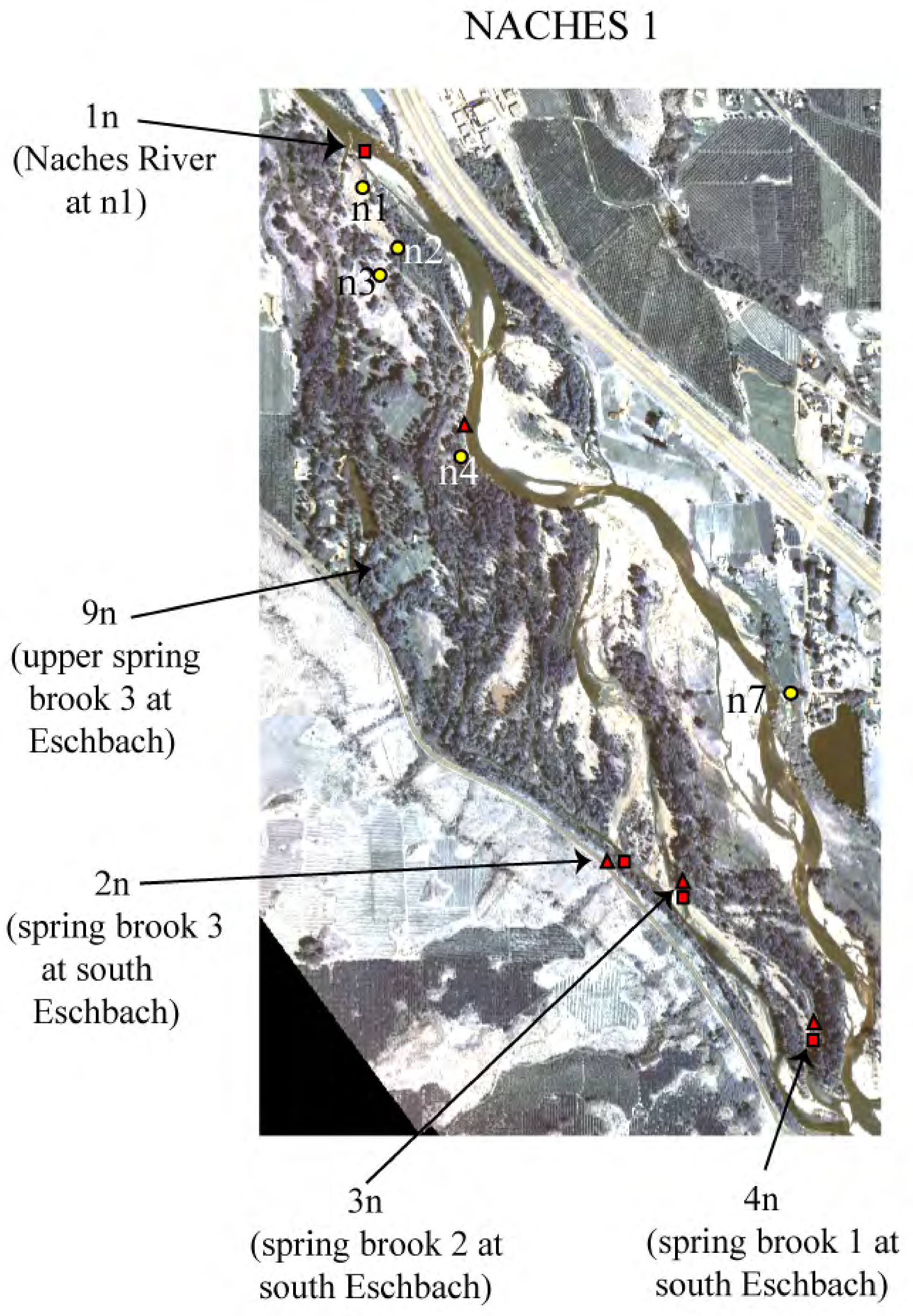
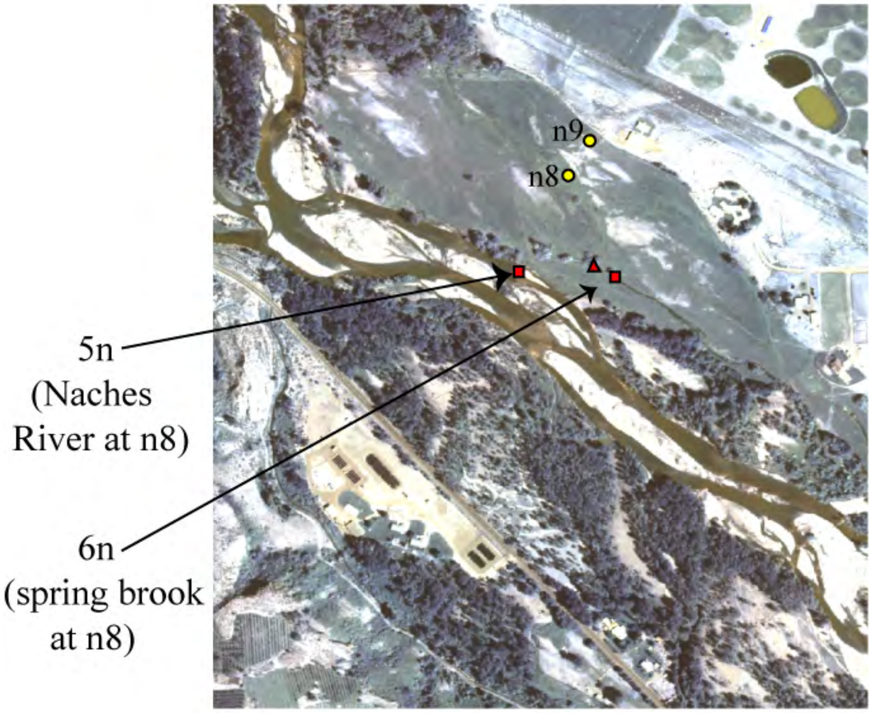


Figure 9 cont.

An additional five wells were located on the north side of river (N7-11) where multiple surface water samples were collected (6 and 8n). With the exception of sites 6, 7 and 8n, all sites from which surface benthic samples were collected were also sampled for fish.

NACHES 2



NACHES 3

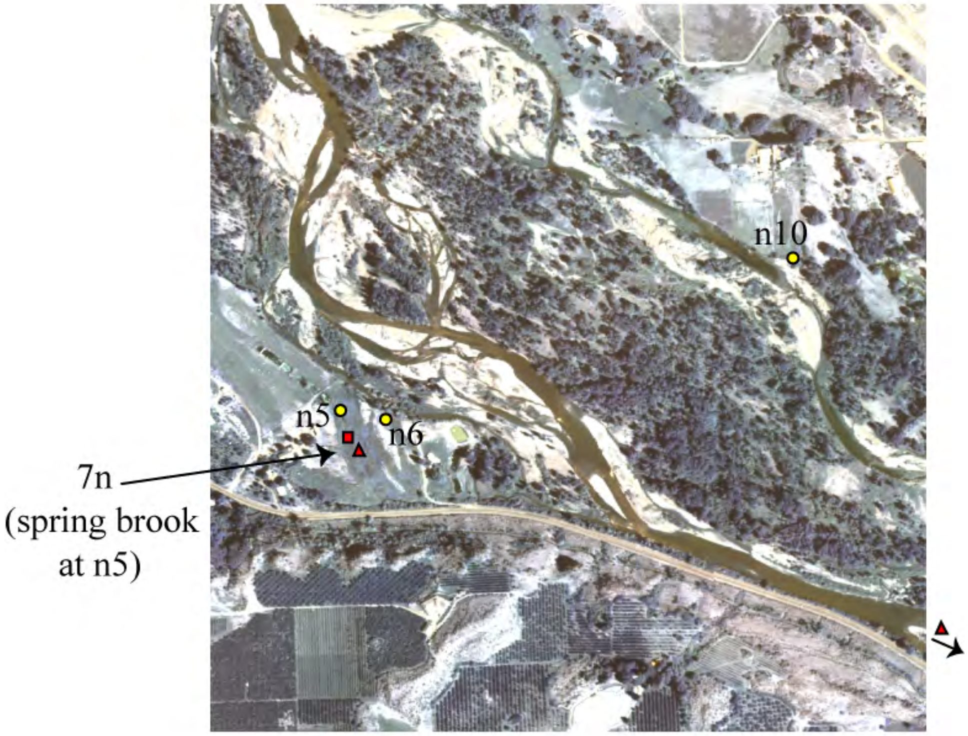


Figure 9 cont.

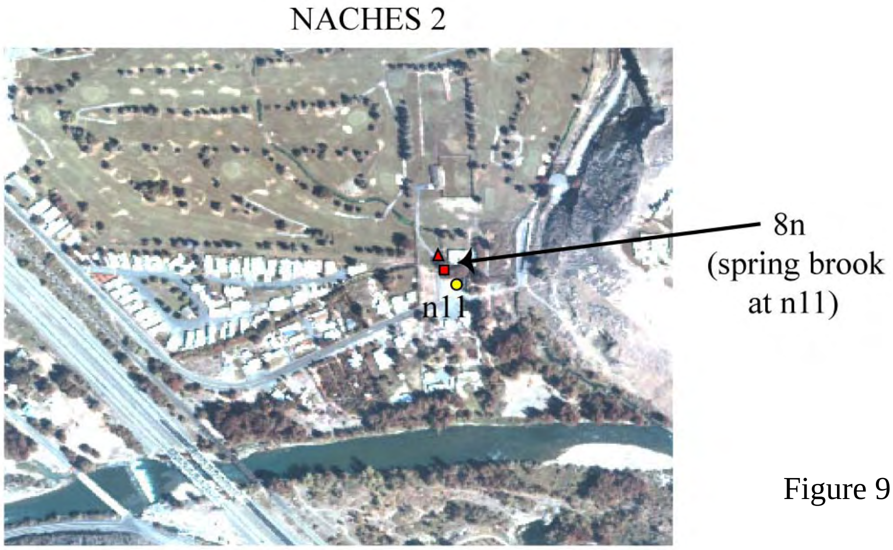


Figure 9 cont.

METHODS

Field Work Conducted Within Each Designated Reach

A series of transects consisting of seven to fifteen monitoring wells (2" PVC slotted pipe) were drilled with a hollow auger drilling rig in influent (downwelling) and effluent (upwelling) zones of each reach described above. These wells were located strategically to allow interpretation of groundwater flow paths to areas of the flood plain where ground water is upwelling to the surface and flowing into the channel via springbrooks and other surficial features.

Each well and surrounding topography (including river channels) was surveyed using a combination of standard (e.g., with a laser theodolite total station) and GPS surveyor's tools. The same survey tools were used to locate the various shallow water habitats on each flood plain. Habitat maps were prepared, including current condition, likely historical condition (as near as can be determined from historical surveys and air photos) and potential condition after restoration.

Within each reach, at least several sites, including springbrooks, side channels or floodplain ponds and the main channel, were designated for time-series sampling of a suite of biophysical variables. The same variables were measured in the monitoring wells to provide evidence of connectivity between the river, the alluvial aquifer and shallow-water habitats on each flood plain. Variables included temperature (continuous recorders and spot measures), water table or surface water elevation (some continuous recorders; spot measures), specific conductance (spot measures), conservative ion concentration (grab samples for carbonate, bicarbonate, calcium and magnesium) and food web structure (abundance per taxon per unit volume of water pumped from wells or per unit area of surface habitat sampled). Our strategy was to relate time trends and spatial patterns in the channel to those in the aquifers and floodplain habitats using multivariate statistics. This allowed prediction of flow (stage) – habitat functions that are the basis of restoration strategies.

Detailed biophysical sampling of wells, flood plain and river sites was conducted on at least six dates per reach. In addition, vertical hydraulic gradient was measured synoptically at four or more transect sites throughout each reach using piezometers and discharge measures (i.e., this determined whether the reach is gaining or losing water to the alluvial aquifers, but we did not do a complete water mass balance for the river and its alluvial aquifers).

On every sampling date, the following data were collected:

- data downloaded from all loggers;
- river stage surveyed relative to elevation of at least two wells;
- temperature and specific conductance surveyed for entire reach;
- discharge measured in springbrooks and side channels;
- monitoring wells sampled (water table elevation, temperature, dissolved oxygen and specific conductance profiles, conservative ion samples and groundwater macrobiota);
- river and springbrooks sampled for conservative ions;
- two 0.5 m kick samples of macrobenthos were collected at major instream sampling sites and
- three samples for determination of algal productivity (as chlorophyll-*a*) and biomass; (same sites as conservative ions).

These field protocols were developed and documented in a manner that should allow long-term use as a monitoring mechanism for salmon habitat in riparian zones of the river and in the context of the long-term need to evaluate the effectiveness of habitat restoration via flow augmentation/reregulation or by physical construction of connecting channels.

Laboratory Work

- A subsample of all well and river macrobiota were sorted by taxa groups and entered into a data spreadsheet. A reference collection was archived and is being kept at FLBS. All samples collected were not identified; indeed, we feel that this is a serious data gap, but lacked the time and personnel to complete all of our samples. We strongly recommend that funding be made available to complete these samples. As it stands, samples were divided into 5 groups, based on the date of collection. We have completed the early spring samples only (group 1).
- Conservative ions in samples were measured and entered into a data spreadsheet.
- The potential for the primary producers to support higher trophic levels was examined via assessment of chlorophyll-*a* in each of the habitat types from which benthic macroinvertebrates samples were collected.
- The relationship between river discharge and stage relative to water table elevations and stage-discharge in springbrooks and other off-channel habitats (or potential habitats) was determined.
- Data were analyzed by: 1) using various spatial and multivariate statistics to correlate likely flow paths with the time-series biophysical data, 2) using graphical output to show quality and quantity of salmon habitat in the riparian environment of each reach and 3) synthesizing all biophysical data in spatially explicit maps showing current and potential conditions.

Analysis of Fish Community Ecology

The abundance and distribution of fish species and life-history stage using various habitat types (main channel, side channel and spring brook) was determined at the same time monitoring wells were sampled. Electrofishing (Smith-Root Model 12-B POW backpack unit), used to survey various habitat types in the five reaches (Table 1), was conducted using the National Marine Fisheries Service's (NMFS 1998) guidelines. Five surveys were conducted bimonthly in each reach beginning in May 2000 and continuing through July 2001. A bimonthly survey was missed in early 2001 due to difficulties renewing the State collecting permit and surveys on the Wapato reach did not begin until September 2000, three months later than the other reaches. Therefore, the Season 1 survey for the Wapato reach is actually one year later than the other reaches. All reaches were generally surveyed within a few weeks time.

Specific sites sampled in each reach included spring brooks, side channels or mainstem margins. Generally, two sampling events occurred at each site during the bimonthly survey and each event lasted approximately 200 seconds, the actual number of seconds fished was recorded. Captured fish were anaesthetized with MS-222, identified to species (suckers, lamprey, sculpin and sunfish were only identified to genus) and counted. Generally no more than ten of each species were measured (mm). Relative abundance (present, common, abundant) of each species was determined for each reach. For each reach, average length for each anadromous species was compared between seasons to determine growth rate.

For each sampling event, the catch per unit effort (CPUE, number of anadromous salmonids captured per minutes fished) was calculated. The anadromous salmonid species captured included *Oncorhynchus tshawytscha* (chinook), *O. kisutch* (coho) and *O. mykiss* (steelhead/rainbow trout). No attempt was made to distinguish between the two life-history types of *O. mykiss*. The average CPUE was determined for like sampling events (same reach, season and site). Average CPUEs were associated with their respective sampling event. This was done to account for unequal sample sizes.

Geomorphic Analysis

The sediment transport project conducted by Lorang et al. (Part B) provides a detailed reach by reach assessment of the capacity of the river to avulse and to transport sediment. We refer back to the conclusions derived from this assessment in our discussions.

Integration and Systems Analysis

The primary analysis tool employed in this project was the relationship between river stage throughout the year and the volume and status of the shallow water habitat and condition of food webs, including salmon and steelhead. A river stage – water flux relation was developed for the various habitats mapped on each flood plain. Statistical correlation was used to relate the hydrology, including flow fluctuations, to the food web response variables. This analysis included consideration of existing and potential water diversion scenarios, such as subordination of the Wapatox Power Plant in the lower Naches reach and the potential to pump-exchange Roza and Sunnyside with Columbia River water.

RESULTS AND DISCUSSION

Measures of Connectivity

Temperature:

The thermal pattern in all reaches indicated that areas more strongly influenced by ground water (e.g., upwelling) were moderated from the thermal regime recorded in the main channel. For example, in a spring brook in the Wapato reach (spring brook at w12), midday temperature in late May was 14.3 C while the adjacent main stem was 19 C. Similarly, temperatures in a Union Gap spring brook (spring brook at yc5) were moderated from main stem temperatures (Fig. 10). In addition, proximity to the main channel and existence of an intact riparian forest appeared to moderate the rate of increase in groundwater temperatures in the Union Gap reach (Fig. 11). This same pattern held true for all other reaches as well, although the data are not presented herein. Bansak (1998) quantified a similar pattern in the North Fork of the Flathead River where he found significant thermal moderation in areas determined to be upwelling. In addition, Harner (2001) noted that riparian trees responded to these same patterns in upwelling and downwelling, possessing more rapid growth and earlier leaf-out in upwelling zones.

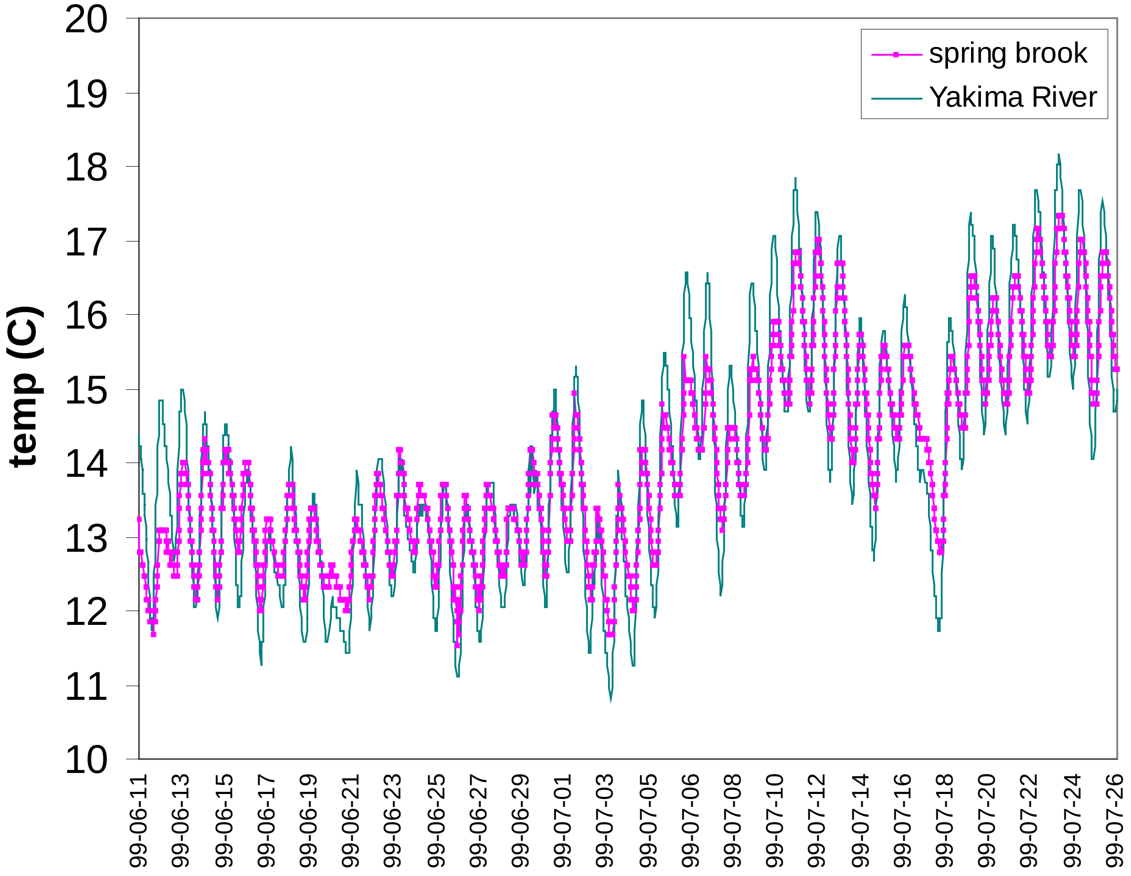


Figure 10. Temperature patterns in a spring brook (at yc5) vs. the main stem (at yc5). Note that the thermal regime in the spring brook is buffered from that observed in the main channel. The flow path connecting this spring brook to the main channel was ca. 20 m long.

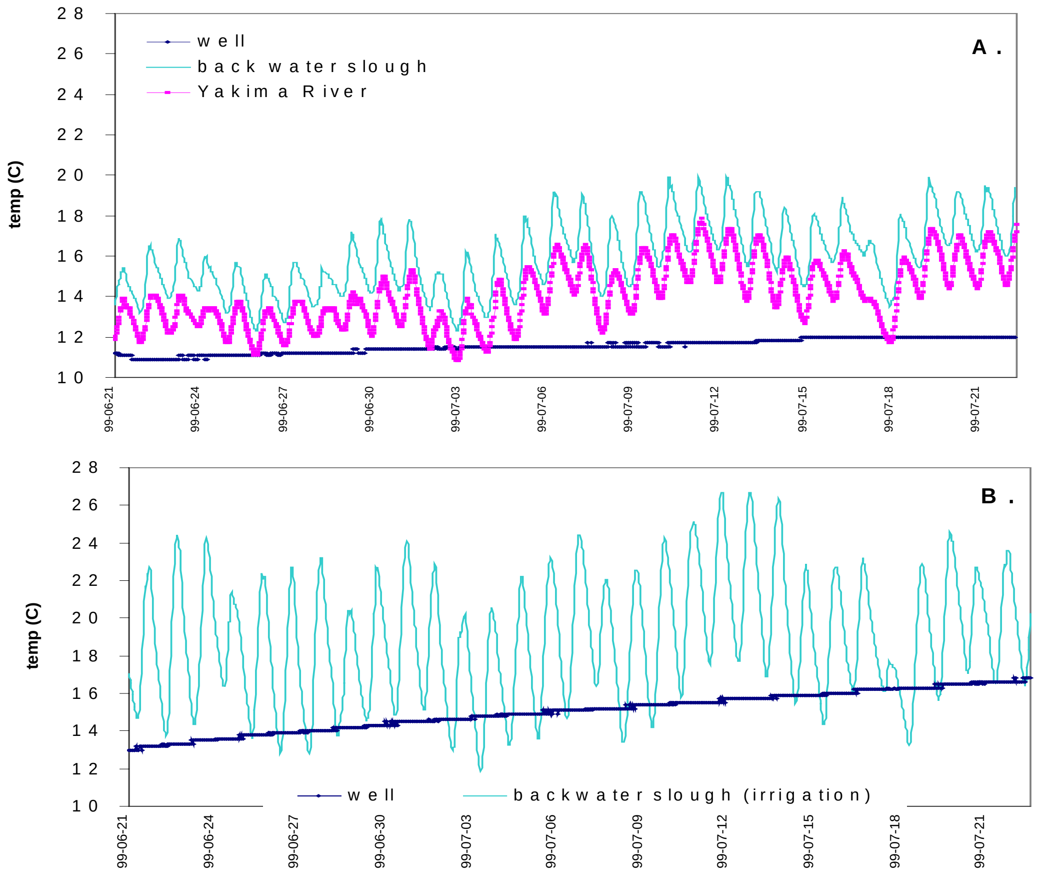


Figure 11. Temperature patterns in a monitoring wells located (A) relatively close to the main channel (ca. 600 m) and in an area of complex riparian vegetation (yc6 and slough at yc6), vs. (B) further from the main channel (ca. 1000 m) in an area lacking in riparian overstory and influenced by irrigation return flows (yc1 and slough at yc1). The rate of increase in groundwater temperatures (dark blue line) is much more rapid in the lower figure (B). This data suggests that groundwater temperatures in the shallow alluvial aquifer are influenced by the degree and extent of riparian vegetation and the influence of and proximity to irrigation return flows.

Water table elevation:

All reaches exhibited some degree of connectivity with the main channel; with the water table fluctuating dynamically with river stage. However, this interaction appeared to be strongly influenced by local geomorphic conditions. For example in the Teanaway reach, the river appeared to fluctuate between gaining and losing ground water, based on monitoring conducted in a well located close to the river on the east bank (t4) (Fig. 12). Whereas on the west side, ground water was continuously moving into the river (gaining reach) (Fig. 12). This data suggests that the Istvan property (west side of the Teanaway River) is strongly influenced by ground water moving into the reach from the upgradient wetland complex. However, there is definitive evidence of hyporheic linkage between the Istvan property and the Teanaway River as hyporheic stoneflies (*Paraperla*) were found multiple times in a monitoring well (t7).

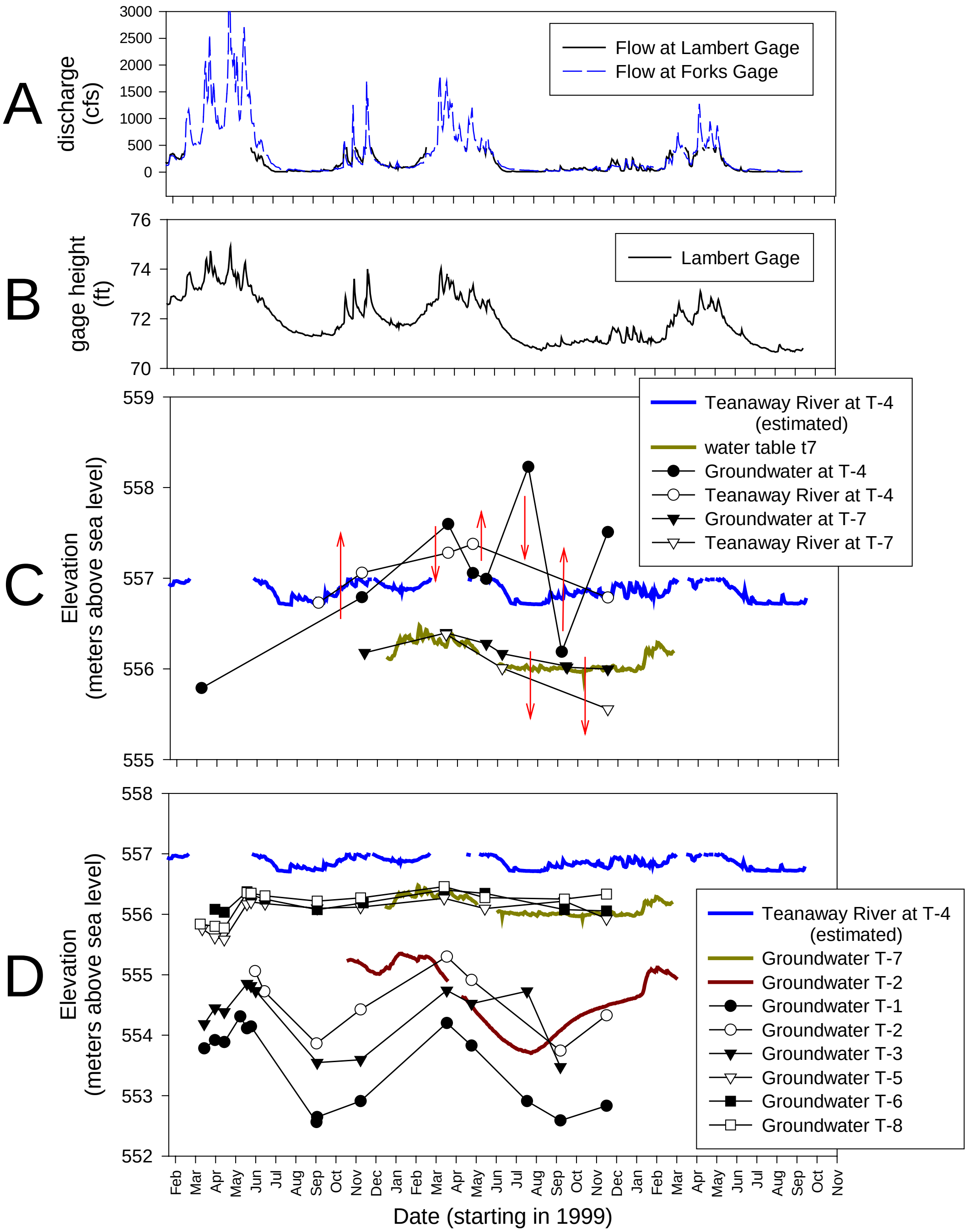


Figure 12. Comparison of groundwater elevations (m) relative to river stage (m) in the Teanaway River (C & D). Note that the elevation of river at t4 was estimated based on the stage/discharge relationship between the Lambert Road gage (A & B) and river at t4. Groundwater elevation was measured both by continuous data recorders (solid lines in C and D; organized from top to bottom as in legends) and by surveys conducted when wells were being sampled (symbols). Red arrows indicate the direction of water movement. Results indicate that river flipped repeatedly between gaining and loosing, whereas the west side (fed by a wetland complex) was strictly gaining.

Water table elevation in the Wapato reach fluctuated according to river stage (Fig. 13a) as well as showing patterns of gaining and losing (Figs. 13b). The Wapato Wildlife Area presented an excellent example of the later, where river water was moving into the groundwater system at the up-gradient transect, and then moving back into the river at a lower transect.

All additional reaches displayed similar patterns in water table elevation—in some cases showing a dynamic relationship with river stage, and in others showing a more random pattern that suggests a complex, shifting relationship between upwelling and downwelling. We believe this strongly contributes to the shifting habitat mosaic and enhances the ecosystem-level processes that occur throughout this ecotone, as described previously for nutrient dynamics.

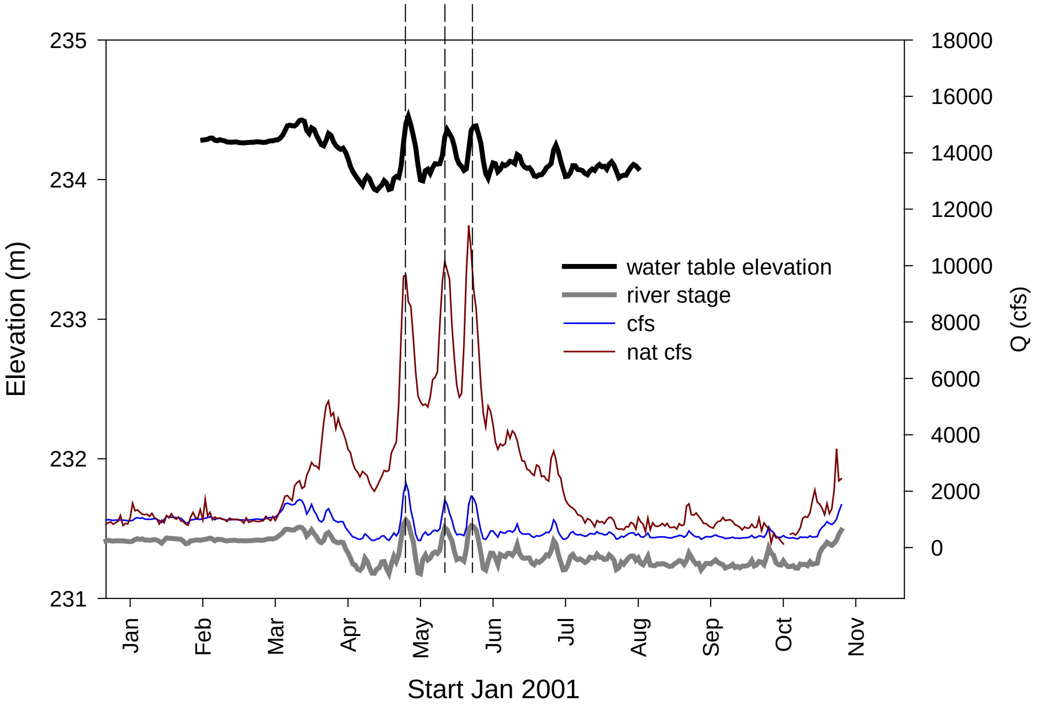


Figure 13a. Water table elevation in the Buena Wildlife Area (Wapato reach, well w12, solid black line) vs. river stage (solid grey line) at the same located estimated from the USGS gage at Parker. Observed discharge (blue line) and natural estimated unregulated discharge (red line) are also included. Note that the three peaks in discharge are mirrored in water table elevation. Thus, the groundwater system is responding in a dynamic fashion to variation in river discharge. The monitoring well (w12) was more than 100m from the main channel. At this point in the flood plain, the river appears to be gaining ground water.

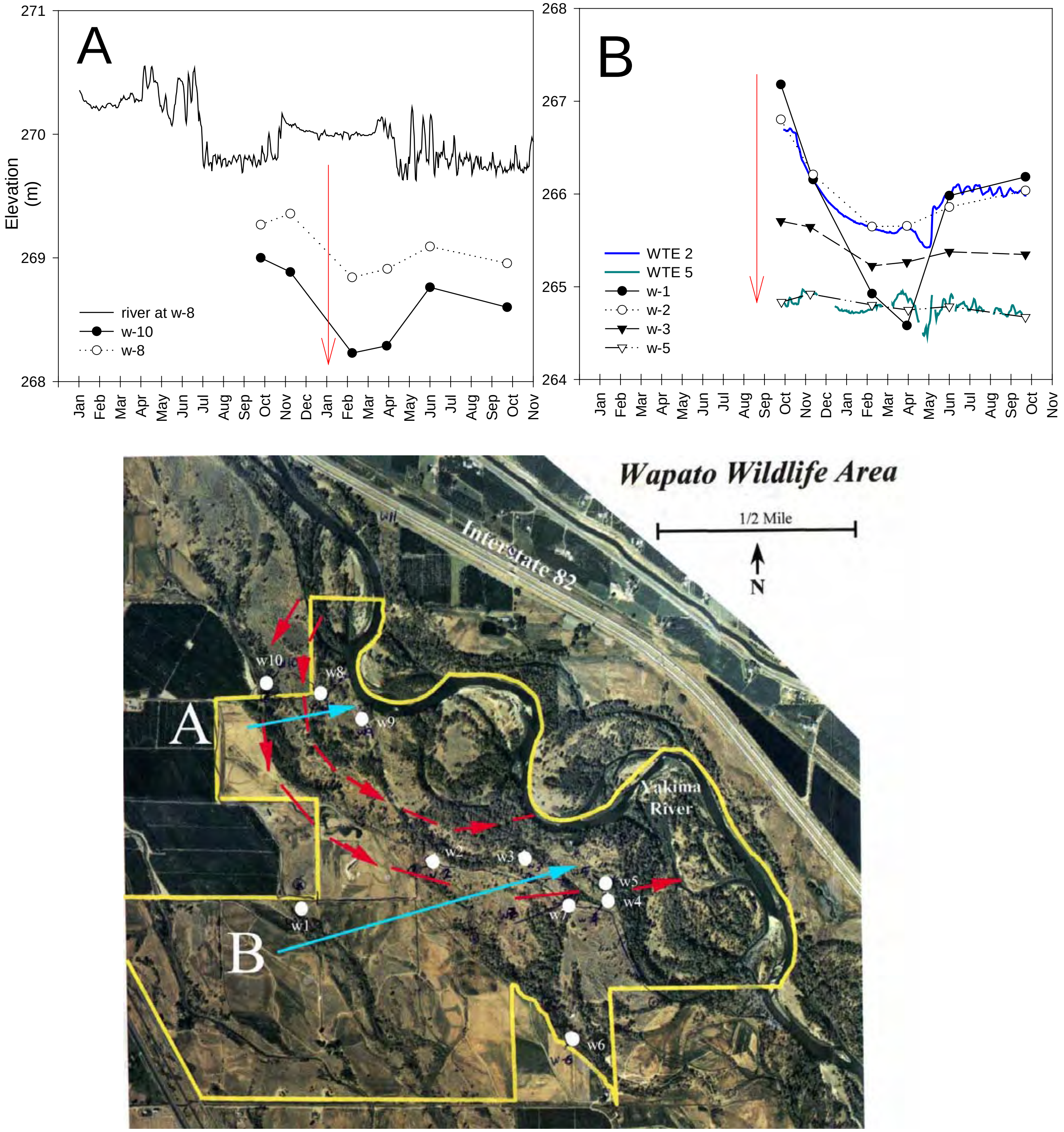


Figure 13b. Water table elevations relative to the main channel in the Wapato Wildlife Area. Figure "A" represents the up-gradient transect with the solid line representing river stage at well w8. Wells w8 and w10 progress from the river, out onto the flood plain with w10 being ca 350 m from the main channel. In figure "B", which is a transect of monitoring wells down-gradient from "A", water table elevation is higher further from the river (w1) and then decreases towards the river (w2, 3 and 5). The pattern in water table elevation (WTE) suggests that the upper transect is a loosing reach vs. the lower transect, which is gaining. In addition, the influence of the irrigation season is shown dramatically in w1. During the winter, WTE declines rapidly; whereas during the irrigation season, WTE rises.

Hyporheic macroinvertebrates:

From upstream to downstream there was a significant (p=0.01; ANOVA) decline in invertebrate abundance in the monitoring wells (Fig. 14, Table 1) that corresponded to an increase in nitrate plus nitrate (Fig. 15). This longitudinal decline occurred for both the true groundwater invertebrates (hypogean; p=0.05; ANOVA) as well as those species that inhabit both surfacewater and ground water (epigean; p=0.025; ANOVA). These basin-wide patterns in distribution and abundance correspond with the decline in water quality from upstream to downstream (Cuffney et al. 1997).

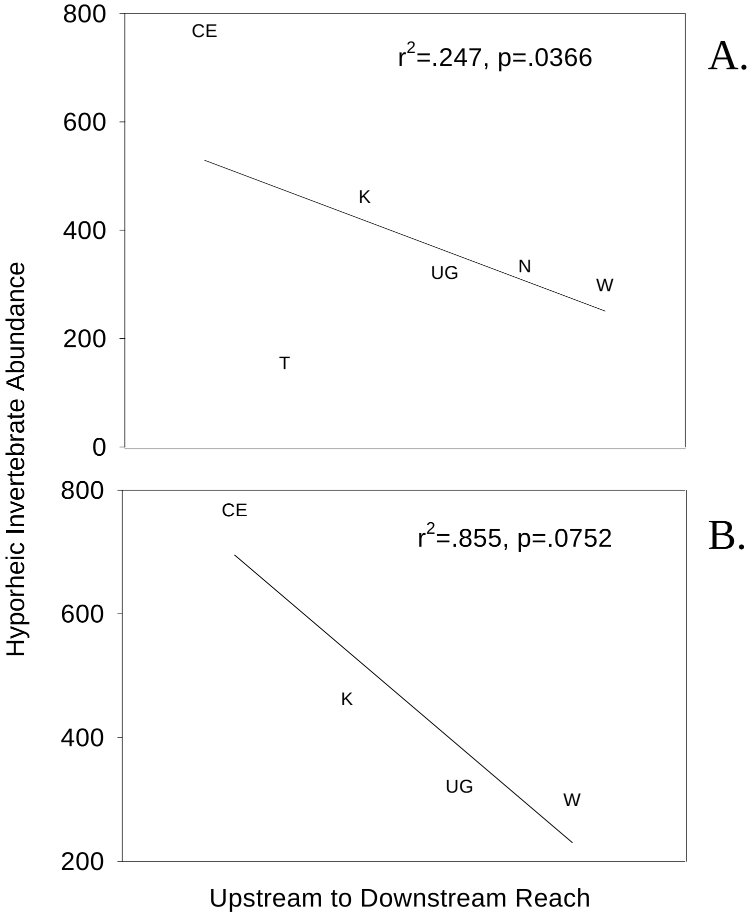


Figure 14. Regression analysis comparing mean invertebrate abundance (monitoring wells) vs. reach. The upper figure ("A") represents all reaches including the two tributaries (Teanaway and Naches), whereas "B" represents only main stem transects. Although the significance (p-value) decreases from "A" to "B", the amount of variation explained by the regression increases substantially. Both results indicate that the abundance of hyporheic invertebrates declines longitudinally in response to declining water quality. Different letters correspond to the various study reaches (CE=Cle Elum, etc.).

Table 1. Summary data for monitoring wells in all reaches. Results indicate the following: (1) the number of wells containing amphibitic stoneflies decreases longitudinally and (2) the abundance of all invertebrates sampled from the monitoring wells follows a similar pattern. As before, this data suggests that decreasing water quality is correlated with the decline in abundance of epigean and hypogean invertebrates found in the monitoring wells. Further, as expected the data suggest higher ecological integrity in the upper reaches.

Characteristic	**Cle Elum**	**Tean-away**	**Kittitas**	**Union Gap**	**Naches**	**Wapato**
Number of wells	6	7	6	13	10	16
Wells with amphibitic stoneflies	3	2	2	0	0	0
Ratio (wells:wells with stoneflies)	0.50	0.29	0.33	0	0	0
Mean invertebrate abundance/well/sample period	768	155	462	321	334	299

The greatest abundance of both epigean and hypogean taxa were concentrated within 350 m of the main channel. However, we did observe representatives of both guilds up to 2 km from the active channel (Fig. 16). In addition, epigean abundance was lower relative to other studies (Table 2); an observation perhaps linked to the lower water quality in the downstream reaches. The presence/absence of amphibitic stoneflies was strongly correlated to patterns in alkalinity, hardness and specific conductance (Fig. 17). These three water quality parameters were low and very similar to river water, relative to ground water, in wells containing stoneflies. In addition, dissolved oxygen was relatively higher in wells containing stoneflies versus those without.

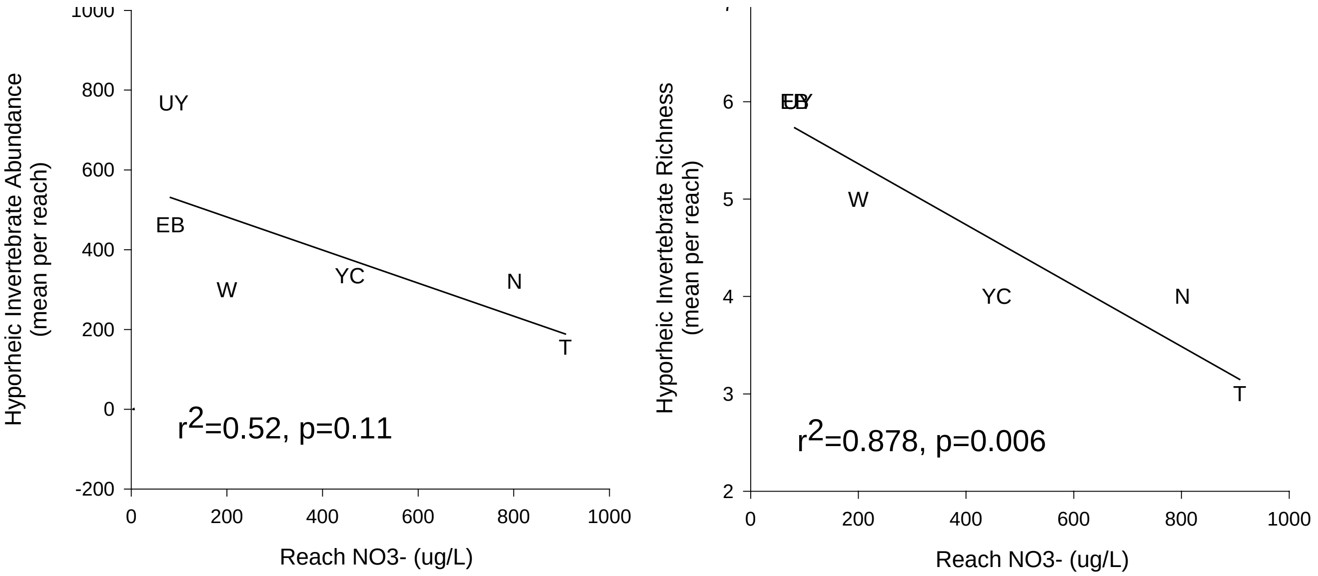


Figure 15. Relationship between abundance (left figure) and richness (right figure) of hyporheic macroinvertebrates and reach-scale patterns in nitrate-N plus nitrite. In both cases, increasing nitrate was correlated to a decline in invertebrates. Indeed, N patterns accounted for 88% of the variation in spp. richness. The increase in N is just one of many indicators of the cumulative decline in water quality.

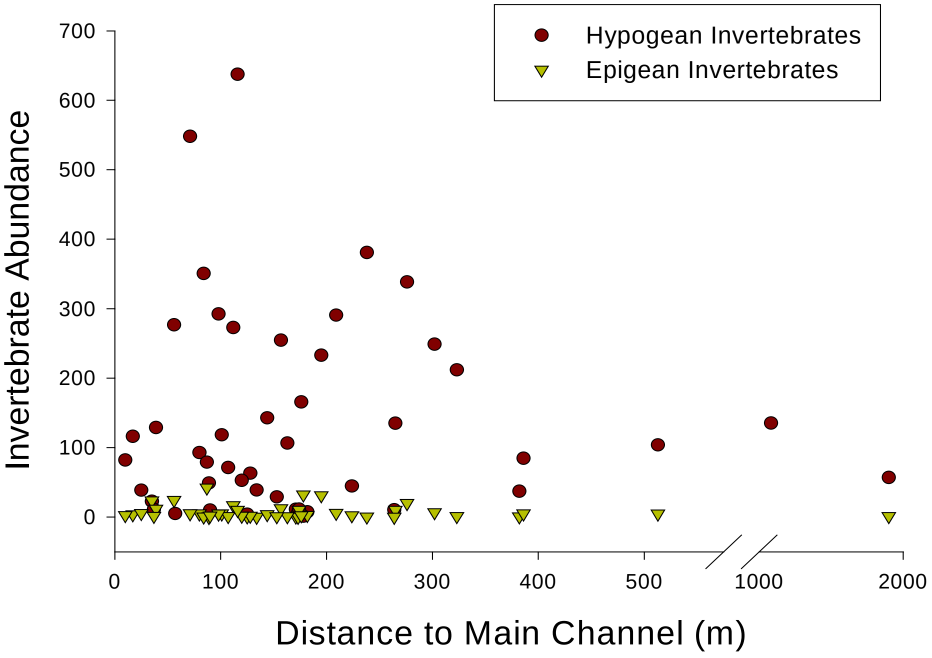
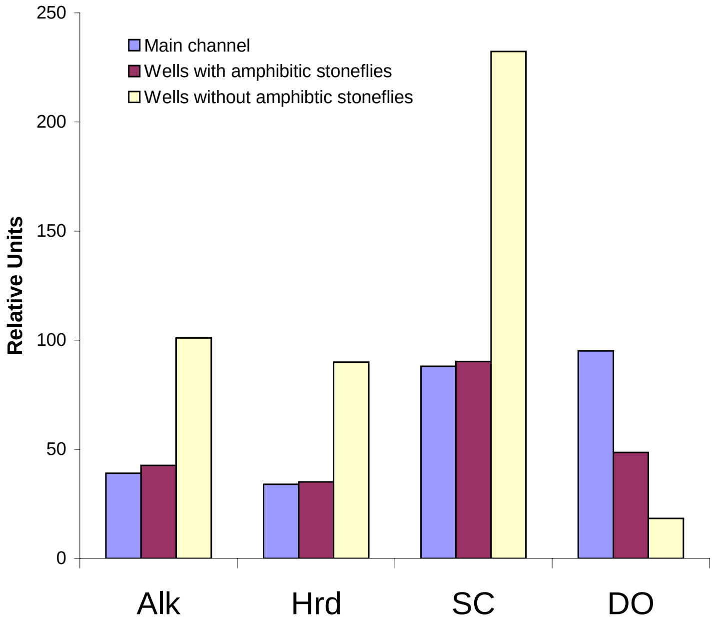


Figure 16. Abundance vs. distance to the main channel of invertebrates sampled from the monitoring wells in all reaches. Hypogean invertebrates (obligate ground water) dominate the community in all reaches and the majority of the subsurface biomass is concentrated within 350 m of the main channel. Epigean invertebrates can be found in either surface or ground water or can migrate between as exemplified by the hyporheic Plecoptera.

Table 2. Comparison of the current study with addition published research. The Yakima Basin appears to maintain very few epigean spp. (such as the Plecoptera *Paraperla* spp.), possibly as a result of anthropogenic constriction of the flood plain and increasingly poor water quality from up to downstream.

Citation	**Distance from the main channel (m)**	**Epigean abundance (mean per sample)**	**Location**
Stanford & Gaufin 1974	150 m	100 (up to several hundred)	Tobacco River, MT
Stanford & Ward 1988	up to 2 km	270	Flathead River, MT
Dole-Olivier 1994	abandoned channel	77	Rhone River, France
Pospisil 1994	up to 100 m	"common"	Danube River, France
current study	10-1900m	6	Yakima River, WA

Figure 17. The presence of amphibitic (hyporheic) stoneflies in individual monitoring wells was strongly related to the degree of similarity between instream and groundwater-water chemistry (alkalinity, hardness, specific conductance and dissolved oxygen). In this case, histograms represent mean values for all reaches combined. From left to right within each water quality category, histograms are as follows; main channel→wells with stoneflies→wells without stoneflies.



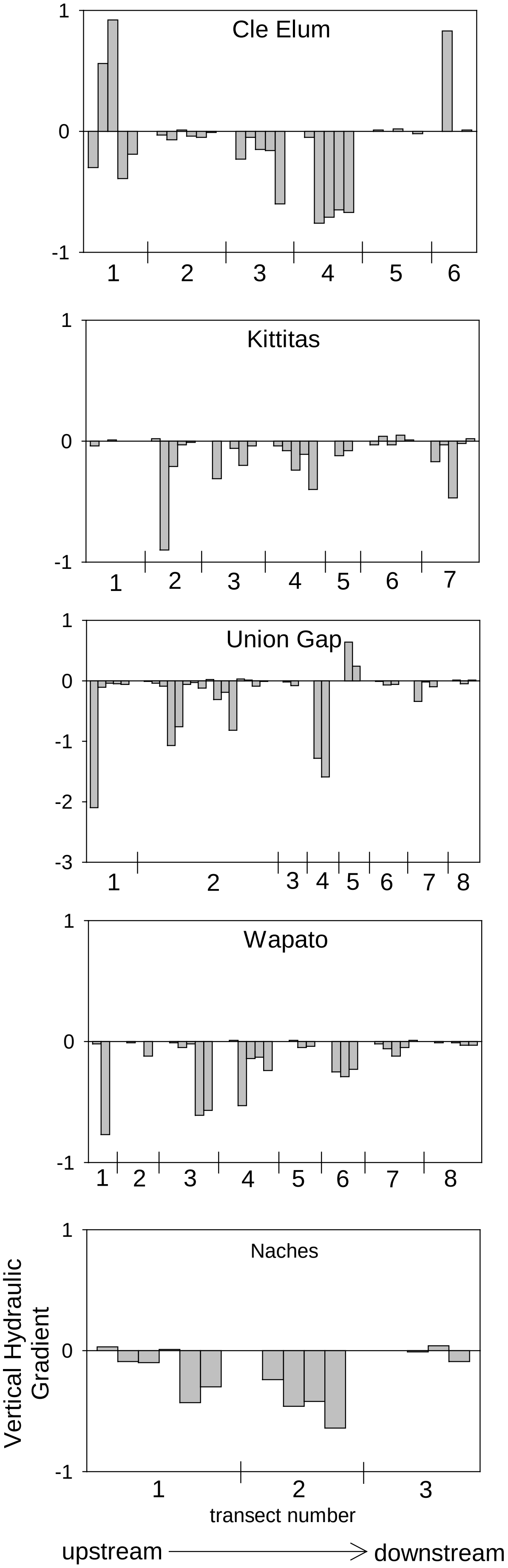


Figure 18. Vertical hydraulic gradient (VHG) for each piezometer. Thus, each histogram represents data from one piezometer. Surveys were conducted from upstream to downstream, with a minimum of two, and a maximum of 6 piezometers installed per transect. Although not presented herein, discharge and velocity were measured at each transect as well. Transect locations correspond to Table 3. Note that the x-axis is organized from upstream to downstream although position of transects along the continuum is relative versus absolute.

Vertical hydraulic gradient:

Piezometers were used to survey all reaches for patterns in upwelling and downwelling (e.g., the direction of exchange between surfacewater and ground water). Vertical hydraulic gradient (VHG) measures the pressure differentials between piezometers installed to different depths (Lee and Cherry 1978). In our analysis, multiple piezometers were installed to the same depths and the difference between water elevation inside the piezometer versus river stage was measured. If the water level inside the piezometer was lower than river stage, the location was classified as downwelling (surface water moving into the hyporheic zone) and vice versa. VHG was determined for multiple transects in all study reaches. The formula used to calculate VHG was as follows:

$$\mathrm{VHG} = \frac{h_s - h_p}{L}$$

; where h_s = distance between piezo. top and river water (cm)
h_p = dist. between piezo. top and inside water (cm)
L = depth of piezo. into the sediment (cm)

Results indicated that in most locations, the reaches were downwelling, or losing water from the river into the hyporheic zone (Fig. 18, Table 3). This pattern changed near the lower end of end of each reach, with VHG become less negative and actually positive in many instances (indicative of upwelling). Although these observations are limited, they do indicate that the hypothesized patterns in water exchange between the surface and subsurface are indeed occurring. Specifically, we postulated that the river would tend to loose water to the shallow alluvial aquifer in upper portions of the reaches and be gaining in the lower portions of the reaches, a process driven by the porous nature of the alluvial fill and the natural nick points that occur at the lower portions of each reach (e.g. Union Gap, Yakima Canyon, etc.) that would force subsurface water back to the surface. In addition to positive VHG, the abundance of spring brooks and increase in channel complexity in the lower portions of the reaches supports this explanation.

In the Union Gap reach, two of the piezometers that registered positive VHG (transect 5) were located directly in a spring brook system that contained visible upwelling. Water could be directly observed moving up through the sandy substrate into the spring brook. Because of the interest in the reclaimed gravel pit just downstream of the railroad bridge crossing, measurement of VHG was concentrated here. Results indicated that VHG was generally negative, which is perhaps not surprising given generally upstream location within the Union Gap reach overall. In addition, many salmon redds were observed within this particular segment of the Union Gap reach making it a prime location for additional monitoring and study. Also note that in the Kittitas reach, transect 7 was located well within the Yakima Canyon.

All of the transects at which VHG was measured were permanently marked, providing a mechanism by which these measurements could be repeated at a later date.

Table 3. Location (GPS using UTM and latitude/longitude coordinate systems) and sampling date of piezometer transects within the five study reaches of the Yakima Basin. Note that transect numbers correspond to Figure 18.

reach	date	name	GPS UTM & Lat./Lon.		Location description
			easting/lat.	northing/lon.	
Cle Elum	13-Sep-00	transect 1	657972	5227653	Just downstream of Hansen Ponds
		transect 2	658972	5227312	Upstream from interstate bridge (0.5-1.0km)
		transect 3	660122	5227375	Downstream from interstate bridge ca 2km
		transect 4	662146	5226583	Upstream from public access site (monitoring well uy1 & 2)
	02-Oct-00	transect 5	663864	5226164	Just upstream of Teanaway R. confluence
		transect 6	na	na	Within canyon mouth, downstream from Teanaway confl. by 1 rkm
Kittatas	02-Oct-00	transect 1	676852	5216449	Downstream from Thorp bridge 2 rkm (ca)
	14-Sep-00	transect 2	685587	5205498	Downstream from Irene-Rhinehart (0.5 to 1.0 km)
		transect 3	687384	5202956	
		transect 4	688690	5200631	Just upstream from BLM public access (monitoring wells)
		transect 5	na	na	Just upstream from public access site at Ringer Road
	18-Sep-00	transect 6	689407	5199535	Downstream from public access (1-1.5km) at Ringer Rd.
		transect 7	689573	5198806	Just upstream of confluence with Wilson Cr.
Union Gap	14-Nov-00	transect 1	na	na	Yakima River just above reclaimed gravel pit and below RR bridge
		transect 2a	na	na	Reclaimed pit; just downstream of transect 1 in side channel
		transect 2b	na	na	Reclaimed pit; just below mid-isalnd transect
	15-Nov-00	transect 2c	na	na	Reclaimed pit; midway between transect 2 and 3
		transect 2d	na	na	Reclaimed pit; just upstream of confluence between side and main channel
		transect 2e	na	na	Reclaimed pit; just below transect 5
	04-Apr-01	transect 3	46.25.21	120.27.71	Upper point bar of the Sportsmen State Park
		transect 4	46.35.21	120.27.71	Yakima River at monitoring well yc10
		transect 5	46.35.25	120.27.73	Spring Brook at yc10 ca. 25 m upstream from confluence with side channel
		transect 6	46.34.53	120.27.9	Downstream of Moxee Bridge (SR 24) ca. 0.5 km
		transect 7	46.33.55	120.27.96	Yakima River at monitoring wells yc3, 4, and 5
		transect 8	46.32.39	120.27.95	Upstream from Union Gap (0.5 km)
Wapato	24-Oct-00	transect 1	6972560	5151476	Just downstream from monitoring well w9
		transect 2	697573	5151118	Just around bend from transect 1
		transect 3	698910	5150254	At lower end of Wapato Wildlife Area
		transect 4	700176	5148910	Just downstream of Wapato Rd. bridge crossing (1 km)
	07-Nov-00	transect 5	na	na	Located downstream from Zillah boat ramp ca 1 km.
		transect 6	na	na	Located 2 rkm downstream from transect 5
		transect 7	na	na	Located 2 rkm downstream from transect 6
		transect 8	na	na	Located ca 1km upstream of Granger take-out
Naches	28-Jul-00	transect 1	679411	5172660	Naches River at monitoring well n1
		transect 2	680312	5171361	Fish and Wildlife access at monitoring well n7
		transect 3	682578	5168146	Monitoring wells n5 and 6

Floodplain Productivity

Nutrients:

As Dahm et al. (1998) note, the interface between surface water (SW) and ground water (GW) is a critical control point that regulates the longitudinal movement of nutrients between the uplands and river (Triska et al. 1990, Hedin et al. 1998). The network of monitoring wells that we installed and monitored overlapped this ecotone and allowed us to examine nutrient fluxes within this zone. Additional variables known to influence nutrient flux include the topographic location of the interface, the three-dimensional geomorphic structure of the flood plain as determined by its fluvial history, and the temporal variability in the hydrologic regime.

Nutrients and dissolved organic carbon (DOC) tended to increase (statistically significant in many cases) from main stem to spring brook to monitoring well (Fig. 19). Thus in the lateral dimension, nutrients tended to be higher as one moved from the river out onto the flood plain. This is not surprising given that others have found that the SW–GW interface tends to be quite effective at removing nutrients (Dahm et al. 1998). For example, Hill (1996) found that on average, stream riparian zones removed greater than 80% of the incoming nitrate.

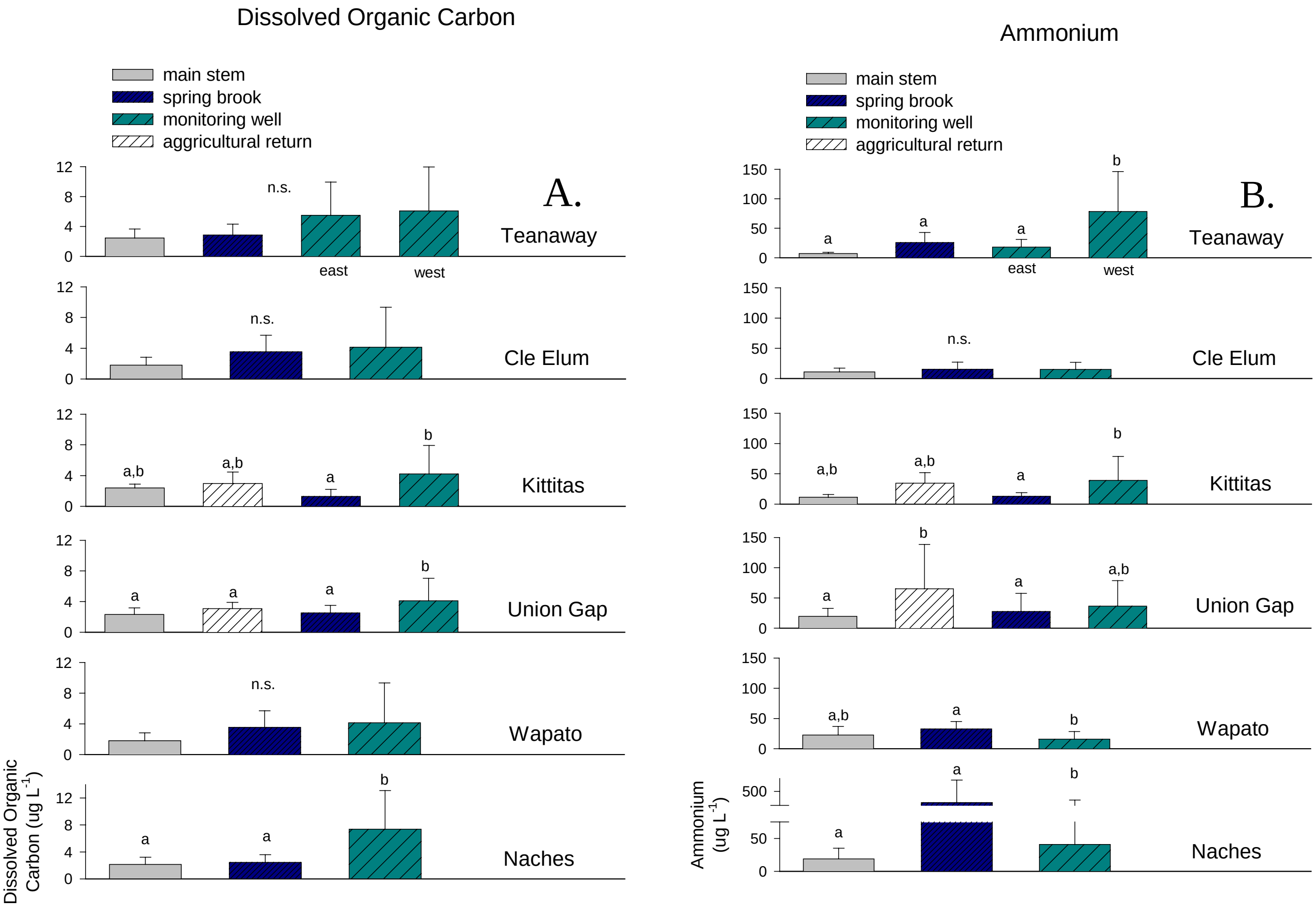
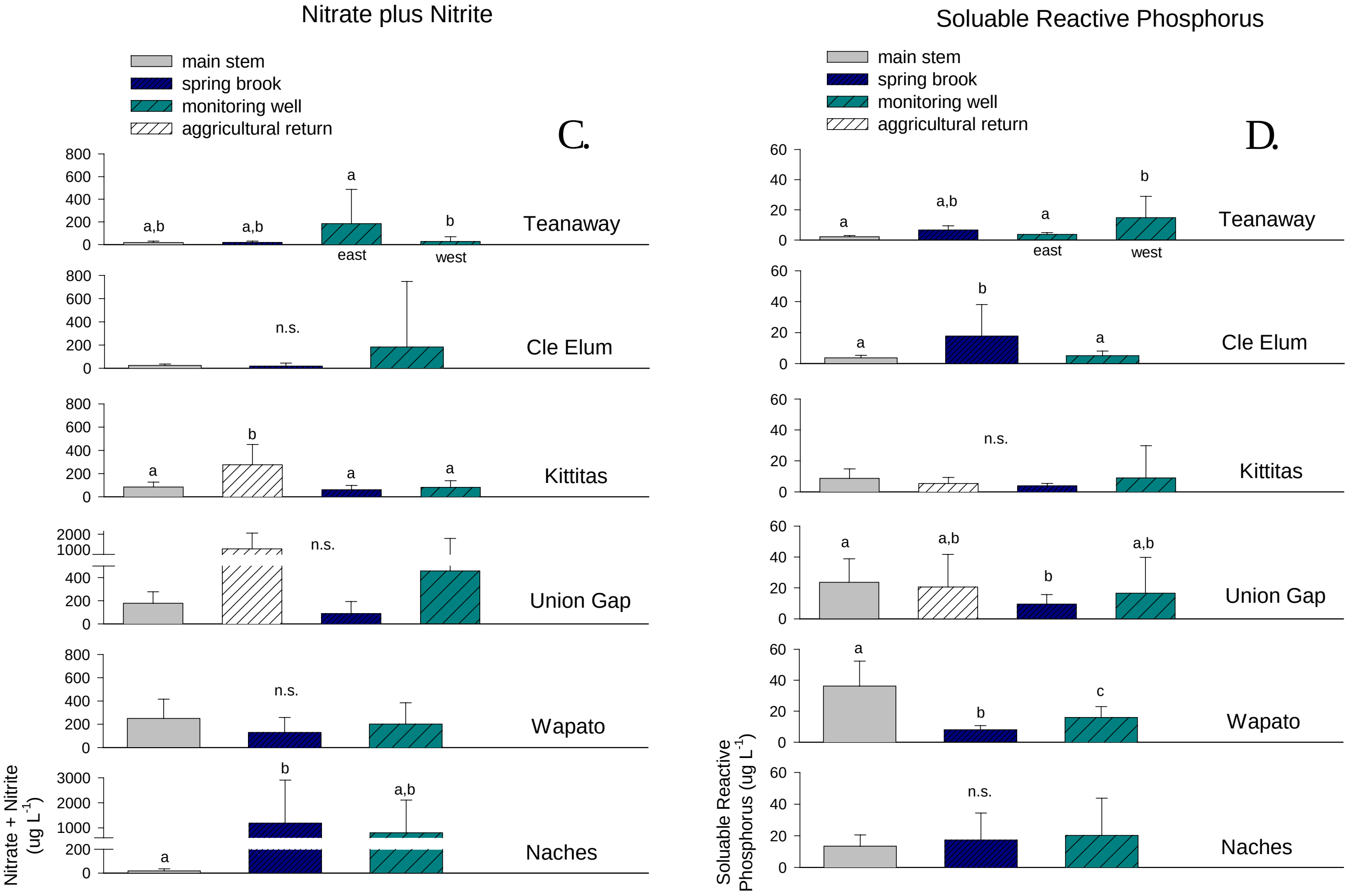


Figure 19. Comparison of (A) dissolved organic carbon (DOC), (B) ammonium (NH_4), (C) nitrate plus nitrite (NO_3+NO_2), (D) soluble reactive phosphorus (SRP), and (E) total phosphorus (TP) (ug L^{-1}) between habitat types in all five study reaches. Different letters above each histogram (+1 standard deviation) indicate significant ($p<0.05$) differences (ANOVA with Tukey's post-hoc multiple comparison test). Results indicate the following: (1) the concentration of nutrients in all habitats tends to increase longitudinally from Teanaway-Cle Elum to Wapato, although this is particularly true for the main-stem; (2) there is a significant increase in nutrients laterally from the river out onto the flood plain, and (3) agricultural returns tended to have high concentrations of nitrogen.



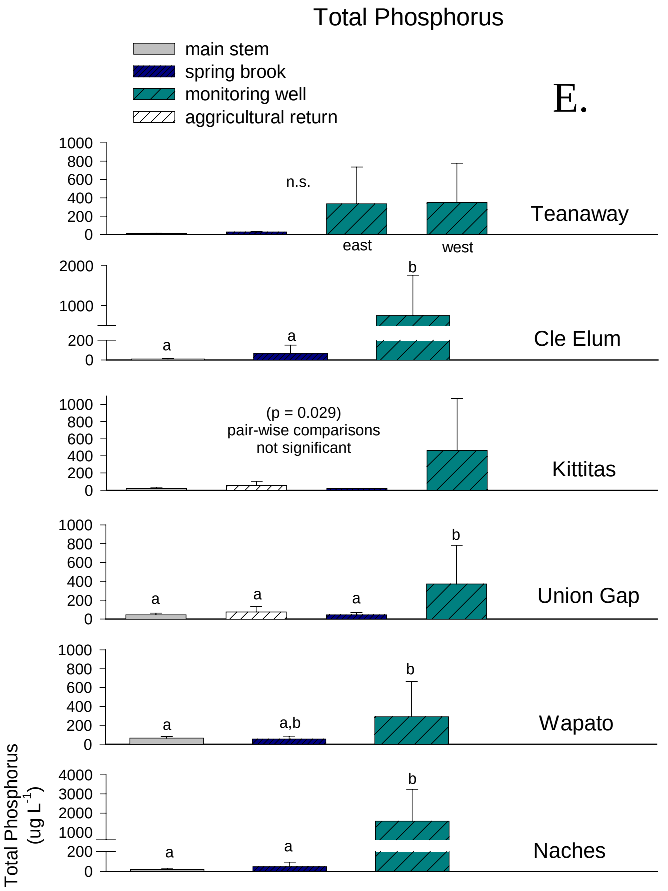


Figure 19. Continued.

In addition, nutrients increased longitudinally, such that the Wapato reach had higher concentrations versus the Cle Elum. Total phosphorus was particularly high in the monitoring wells due mainly to the fact that TP samples were not filtered and were digested during analysis. Usually, well samples contained significant quantities of suspended sediment that would adsorb significant quantities of phosphorus. We utilized a digestion technique that resulted in measurement of this adsorbed phosphorus.

Because of the fluctuating hydrologic regime in the Yakima Basin, we predicted that nutrient concentrations would be quite variable through time, and indeed this was observed (see Fig. 20 for an example). In addition, we expected to see nutrients fluctuate in accordance with application of agricultural fertilizers. This was observed in limited cases; specifically those sites located in close proximity to fields, e.g., see yc-8 and yc-1 in the Union Gap reach (Fig. 21). As the hydrologic regime changes, the chemical nature of the three-dimensional floodplain changes; e.g., we consider it to be a dynamic ecotone or shifting habitat mosaic (SHM). The variation in chemical composition is largely determined by the redox potential, which shifts according to hydraulic connectivity and residence time, and possible biogeochemical pathways such as nitrification/denitrification, iron oxidation/reduction, sulphide oxidation/sulphate reduction, etc., (Dahm et al. 1998).

Figure 20. Example of temporal patterns in nutrient concentrations relative to river discharge in the Kittitas reach. Discharge is indicated in the solid line in the lower figure (Umtanum gage).

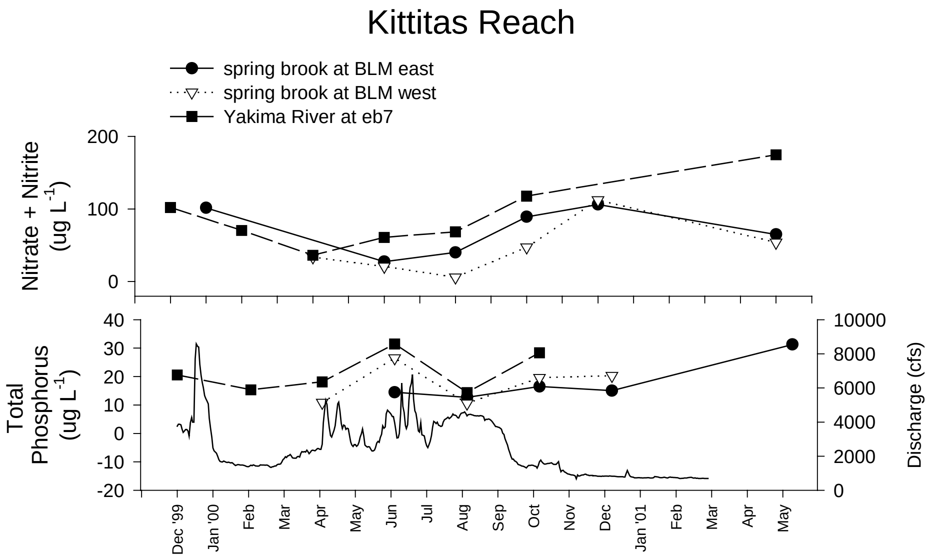
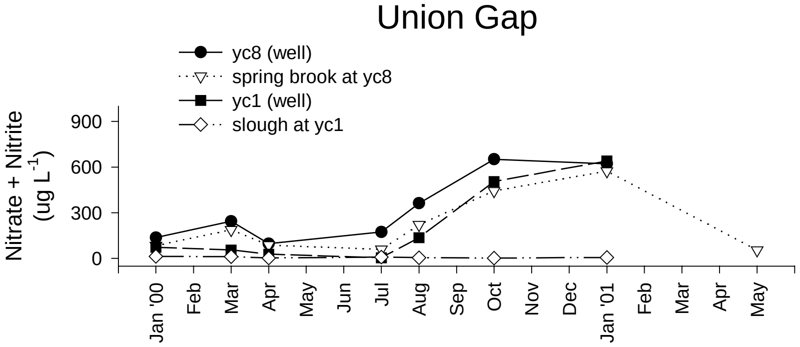


Figure 21. Temporal variation in nitrogen concentration in two wells and adjacent sloughs influenced by local agricultural activities. Note the lag time in response.



As noted in the introduction, we conceptualize the various reaches as a shifting habitat mosaic, the pattern of which is dependent upon (1) the historic fluvial regime and subsequent geomorphic templet, (2) the existing hydrologic regime, (3) the degree of lateral confinement (both natural and anthropogenic) and (4) the substrate being worked upon by channel avulsion. In summary then, we conceptualize that the nutrient regime in each of the reaches is responding to this shifting habitat mosaic and creating substantial temporal biogeochemical heterogeneity. Valett et al. (1997) attributed this type of variation to differences in parent lithology, alluvial composition and channel geomorphology.

Given that lateral interaction can be increased, we predict that the capacity of the flood plain to control anthropogenic nutrification should improve. In other words, the capacity of the flood plain and associated riparian zones to remove nutrients, for example via denitrification, should increase. In addition, increased lateral interaction should increase retention, and therefore transformation of nutrients, e.g., nutrient spiraling distances should decrease. For example, D'Angelo et al. (1993) demonstrated that unconstrained reaches increased SW–GW interaction, while Lamberti et al. (1989) demonstrated that retention of ammonium-nitrogen was improved in unconstrained reaches.

Algae (Chlorophyll-a and Ash-free Dry Mass):

In general, patterns in chlorophyll-*a* and AFDM suggested that off channel habitats such as spring brook–side channel complexes maintained higher algal biomass (Fig. 22) and pigment concentration (Fig. 23) in the Cle Elum, Kittitas and Naches reaches. The remaining reaches exhibited the opposite pattern. Higher algal biomass is likely correlated two variables; (a) higher nutrient concentrations observed in these habitat types and (b) lack of scouring flows. From an energetic standpoint, these data suggest that the potential for algal productivity to sustain higher trophic levels is greater in these areas vs. the main channel, an observation substantiated by the higher number of organisms present in these same habitat types relative to the main channel. However, it is important to note that primary productivity was not measured and we are using pigment concentration as a surrogate for productivity.

In addition, the concentration of chl.-*a* and organic matter in the main-stem habitat increased along the continuum, likely in response to the significant increase in ambient nutrient concentrations documented in the this report and many other places as well (e.g., see Cuffney et al. (1997)).

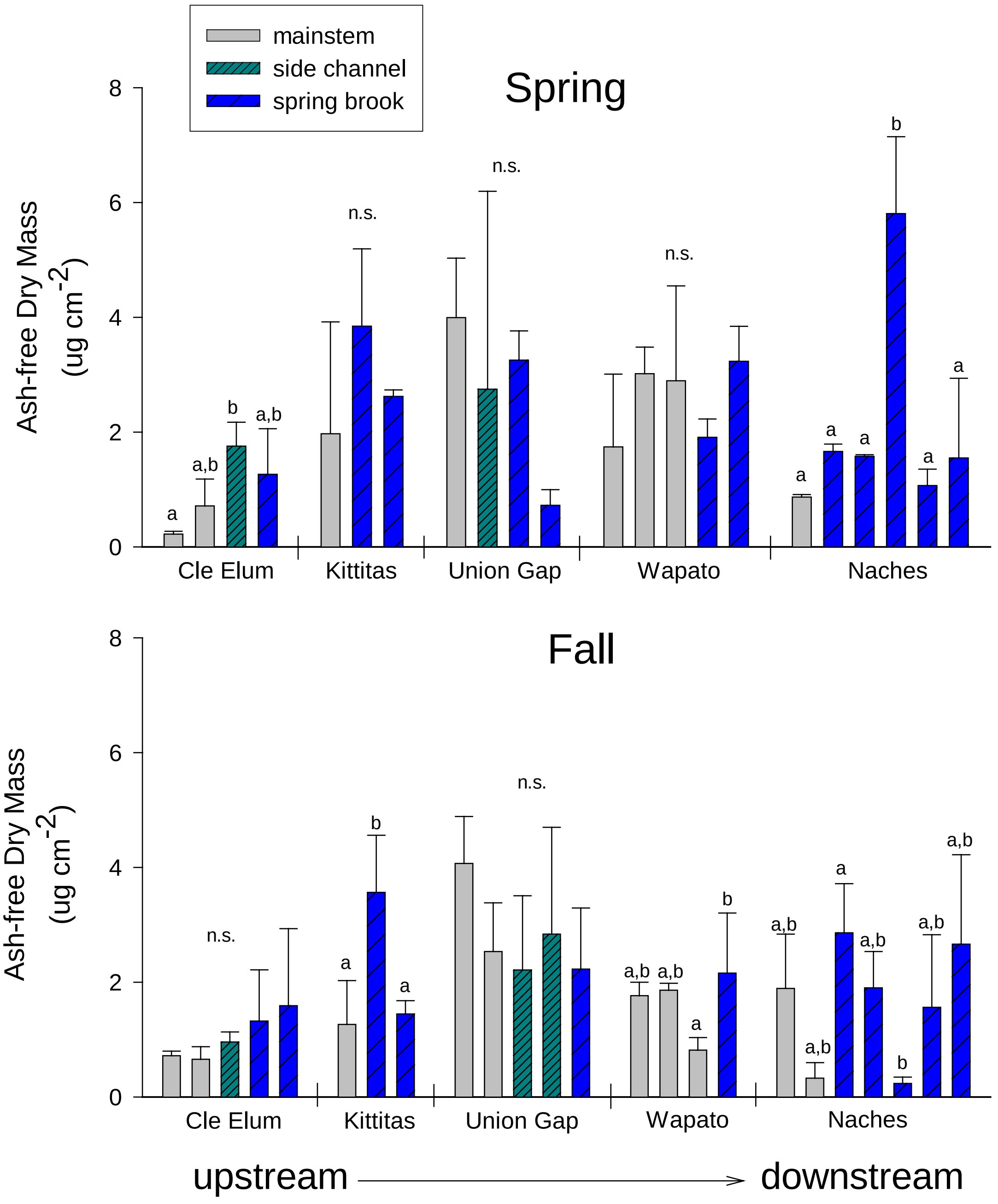


Figure 22. Comparison of seasonal organic matter content (AFDM +1 SD) in the periphyton matrix of the three habitat types in all reaches studied. Results indicate that the overall concentration of organic matter was higher in the spring, as would be expected based on increased algal productivity. Only in the Cle Elum reach were patterns consistent (although only significant in the spring) with organic matter greater in the spring brooks and side channels. Otherwise, results were quite variable. Different letters represent significant differences (ANOVA with Tukey’s post-hoc multiple comparison test; n=3).

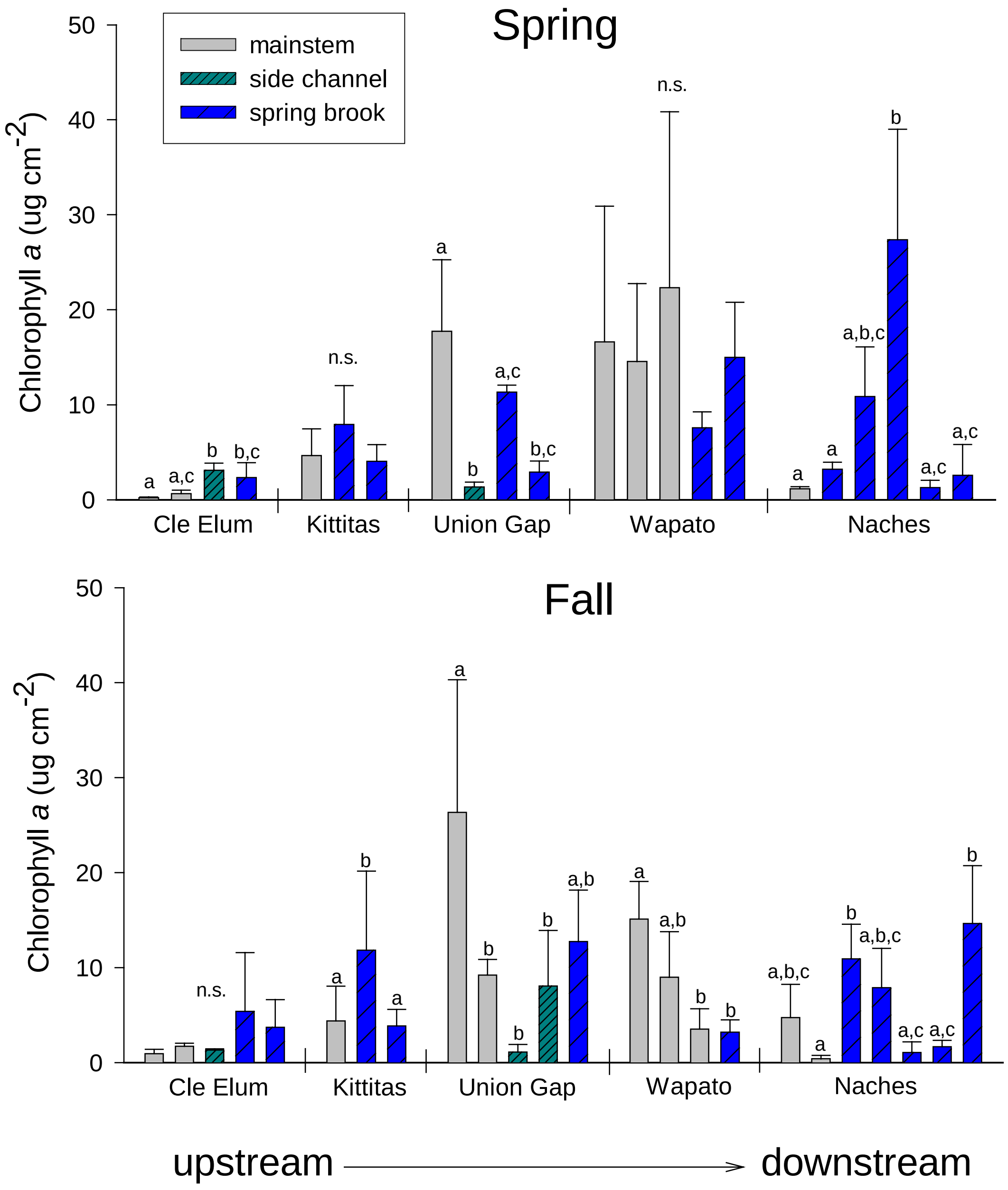


Figure 23. Comparison of seasonal chlorophyll-*a* concentrations in the three habitat types in all study reaches. In spring, the main-stem concentrations increased longitudinally from upstream to downstream in conjunction with increasing ambient nutrient concentrations. In the fall, similar patterns were observed with the exception of the Wapato reach, which had lower concentrations. In addition, the Cle Elum, Kittitas, and Naches reaches had higher chl.-*a* concentrations in spring brooks vs. the main channel (ANOVA; $p<0.05$).

Benthic macroinvertebrates:

In a subset of macroinvertebrate samples identified (fall samples only), there were a total of 50 taxa identified (Table 4). Macroinvertebrate abundance was strikingly similar between habitat types (spring brook vs. mainstem); whereas diversity was slightly lower in the main stem habitats (Fig. 24). This data suggests that food is equally abundant in either habitat type, but is likely easier to garner in the spring brooks. From an energetic standpoint, it is likely that fish would be much more capable of maintaining a positive energy balance in spring brooks given that less energy would be expended maintaining position relative to the main stem (Hall et al. 1992).

Table 4. Summary of benthic macroinvertebrate taxa collected in the various reaches of the Yakima River (see base maps for sample locations). Samples were collected throughout the year, but this data set is representative of only the fall sampling effort.

Family	**Genus**	**Family**	**Genus**
Coleoptera (Beetles)		**Plecoptera (Stoneflies)**	
Elmidae	*Heterolimnius*	Chloroperlidae	*Sweltsa*
Elmidae	*Narpus*	Nemouridae	*Zapada*
Elmidae	*Optioservus*	Perlidae	*Claasenia*
Haliplidae	*Haliplus*	Perlidae	*Hesperoperla*
Diptera (True Flies)		Perlodidae	*Skwala*
Chironomidae		**Trichoptera (Caddisflies)**	
Empididae	*Chelifera*	Brachycentridae	*Brachycentrus*
Empididae	*Hemerodromia*	Glossosomatidae	*Glossosoma*
Simuliidae	*Simulium*	Hydropsychidae	*Arctopsyche*
Tipulidae	*Antocha*	Hydropsychidae	*Cheumatopsyche*
Tipulidae	*Tipula*	Hydropsychidae	*Hydropsyche*
Ephemeroptera (Mayflies)		Hydroptilidae	*Hydroptila*
Baetidae	early instar	Hydroptilidae	*Oxyethira*
Baetidae	*Acentrella*	**Miscellaneous (Non -Insects)**	
Baetidae	*Baetis*	Annelida	Oligochaeta
Baetidae	*Diphetor*	Arachnida	Hydracarina
Ephemerellidae	*Drunella*	Coelenterara	Hydrazoa
Ephemerellidae	*Ephemerella*	Crustacea	Amphipoda
Heptageniidae	*Cinygmula*	Crustacea	Cladocera
Heptageniidae	*Epeorus*	Crustacea	Copepoda
Heptageniidae	*Rithrogena*	Crustacea	Isopoda
Heptageniidae	early instar	Crustacea	Ostracoda
Leptophlebiidae	*Paraleptophlebia*	Hirudinea	
Tricorythidae	*Tricorythodes*	Mollusca	Gastropoda
Lepidoptera (Moths)		Mollusca	Sphaeriidae
Pyralidae		Nematoda	
Odonata (Dragon/Damselflies)		Planaria	Turbellaria
Zygoptera		Tardigrada	

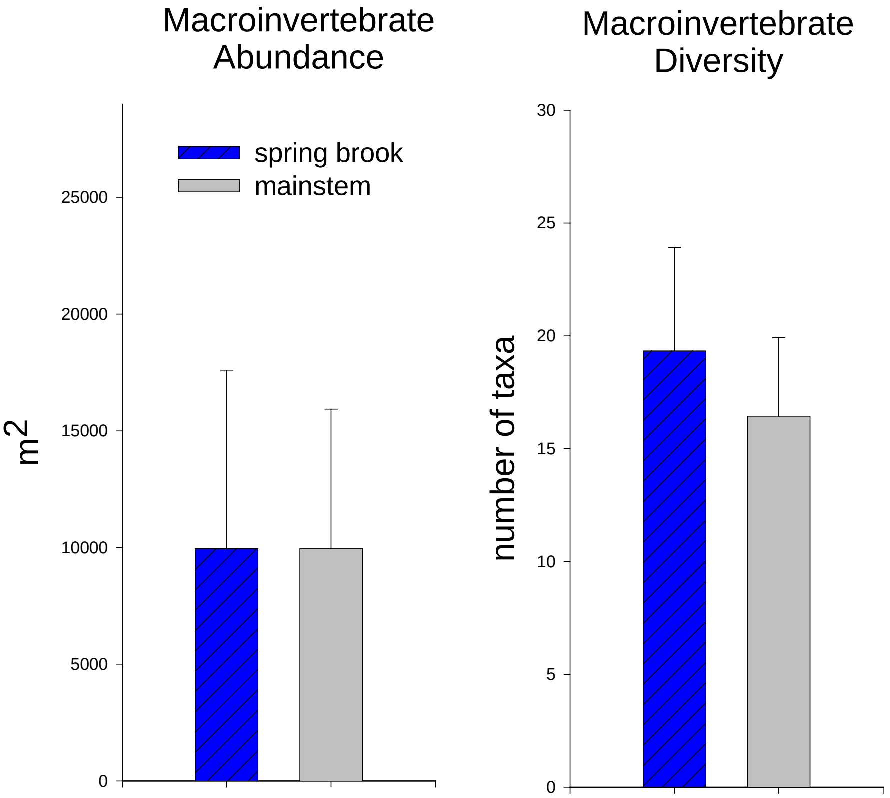
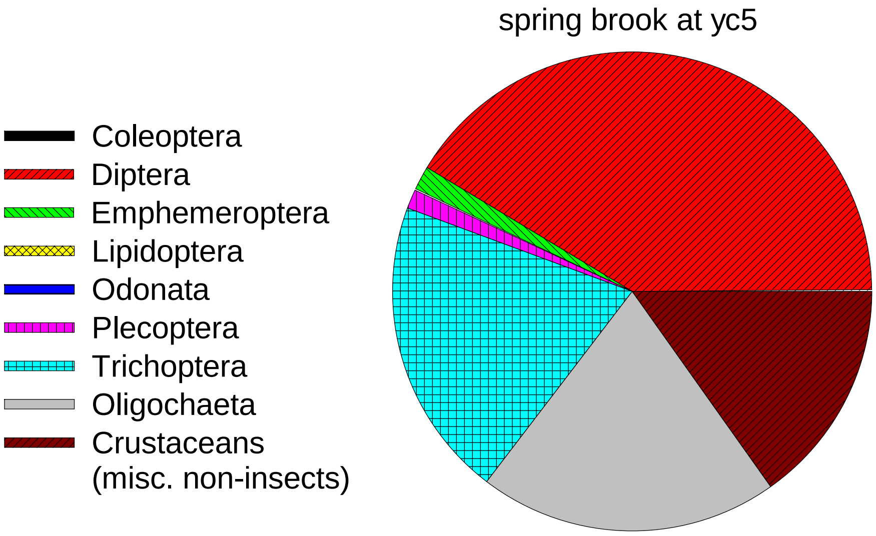


Figure 24. Benthic macroinvertebrate abundance and diversity (subset of sampling dates and sites combined) in spring brooks and main channel habitats. Results indicate that both habitats maintain substantial food resources for fish. From an energetic standpoint, it is likely that off- channel habitat, such as spring brooks, would be preferred by fish. This is substantiated by the distribution of fish (main channel vs. off-channel).

The distribution of taxa at the family level was very similar between a spring brook (spring brook at yc5) and main-stem sample (Yakima River at yc5) in the Union Gap reach (Fig. 25). The major differences occurred in the non-insect category, where the spring brook contained 11 representative taxa vs. the main-stem with only 2 taxa. In addition, the relative abundance of oligochaetes increased whereas Diptera (mainly Chironomidae) decreased in the main-stem relative to the spring brook. Although additional data are not presented, the general trend in taxon distribution was for the spring brooks to contain greater abundance and diversity of crustaceans.

We would like to conduct a more detailed assessment of the samples collected, but did not have enough time or personnel to accomplish this task. However, the samples remain and we strongly advise that these samples be processed and identified, and all samples weighed and organic content (AFDM) determined. This type of assessment would yield very useful information pertaining to energetics and availability of food to higher trophic levels that directly influence the survival of indicator species, such as the salmon.



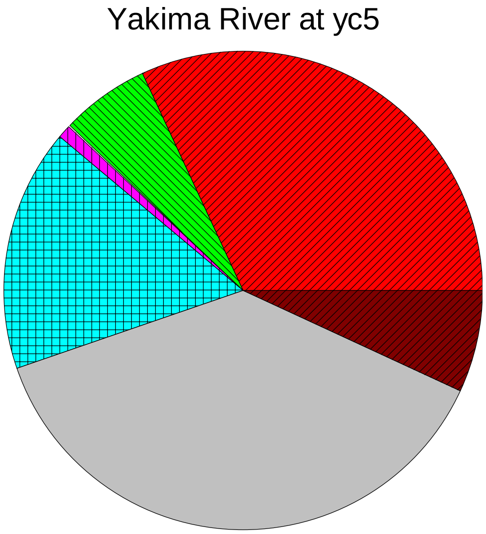


Figure 25. Distribution of taxa between a spring brook and main-stem sample collected on Oct. 25, 2001. Major differences occurred in the Diptera, Oligochaeta, and Crustaceans, the later of which included but were not limited to Amphipoda, Copepoda, Cladocera, Isopoda, and Ostracoda. The number of representative taxa within the Crustaceans was much higher (11) in the spring brook relative to the main-stem sample (2).

Fish assessment:

A total of 4,713 individual fish were counted and measured. Seventeen species were identified (Table 5). Catostomidae (sucker), Cottidae (sclupin) Petromyzontidae (lamprey) and Centrachidae (sunfish) were classified to family. Five of the species were non-native to the Yakima River (Table 5). Speckled dace were the most prevalent species encountered at 24% of measured fish followed by sucker spp., redside shiner, sculpin spp., Chinook and *O. mykiss* were observed in all reaches. Coho were not observed in the Upper Yakima and Ellensberg reaches. Relative abundance of the fishes encountered are displayed in Table 6.

Table 5. Tally of the number of individual species captured and measured in each reach during the duration of the study (May, 2000 to July, 2001). Total number of species captured and measured for each reach and each species are presented. Note: The actual number of fish captured was much higher as we did not measure all fish particularly dace, minnows and sucker species.

Species	Total Number	Cle Elum	Kittitas	Union Gap	Wapato	Naches
Chinook	242	148	46	6	12	29
Coho	171			75	33	62
O. mykiss	279	155	23	12	7	79
Whitefish	32			1	25	6
pike minnow	148		6	10	109	19
Chisslemouth	273		6	47	169	40
Redside shiner	601	13	71	139	255	108
Sculpin	475	167	95	77	25	111
Speckled dace	1135	112	101	231	370	301
Longnose dace	254		34	53	120	47
Stickleback	233		198	34	1	
Sucker	772	19	87	183	313	162
Lamprey	3	1		2		
Yellow perch	2		2			
Bluegill	2	2				
brook trout	79	36	43			
Cutbow	1	1				
Largemouth bass	7		5		2	
Smallmouth bass	2				2	
Sunfish	2		1		1	
SUM	4713	654	718	870	1444	964
Richness	20	10	14	13	15	11

Table 6. Species present and relative abundance for each of the surveyed reaches in the Yakima River, WA. Blanks indicate that species was not observed, present indicates that less than 25 individuals of that species were observed, common indicates 25 to 75 individuals of that species were observed and abundant indicates that greater that 75 individuals of that species were observed. Species in *italic* are non-native to the Yakima River.

Species	Upper Yakima	Ellensburg	Yakima	Wapato	Naches
Chinook	Abundant	Common	Present	Present	Common
Coho			Abundant	Common	Common
O. mykiss	Abundant	Common	Present	Present	Abundant
Whitefish			Present	Common	Present
pike minnow		Present	Present	Abundant	Present
Chisslemouth		Present	Common	Abundant	Common
Redside shiner	Present	Common	Abundant	Abundant	Abundant
Sculpin spp.	Abundant	Abundant	Abundant	Common	Abundant
Speckled dace	Abundant	Abundant	Abundant	Abundant	Abundant
Longnose dace		Common	Common	Abundant	Common
Stickleback		Abundant	Common	Present	
Sucker spp.	Common	Abundant	Abundant	Abundant	Abundant
Lamprey spp.	Present		Present		
Brook trout	Common	Common			
Cutbow	Present				
Largemouth bass		Present		Present	
Smallmouth bass				Present	
Bluegill	Present				
Sunfish		Present		Present	
Yellow perch		Present			

The distribution of salmonids relative to habitat type suggested that catch per unit effort (CPUE) was greater in side channel and spring-brook habitat vs. the mainstem, although this pattern was only significant in the Naches reach (ANOVA; Tuckey's post-hoc multiple comparison test) (Fig. 26). This is similar to results obtained by others (Pearsons et al. 1994) in which bank and off channel habitats were found to be more important to juvenile and age 0+ spring chinook where on average 2.7 more fish were found, relative to the mainstem. In addition, Pearsons et al. (1994) found that rainbow trout in the upper basin maintained higher densities in tributaries and along the banks of the mainstem, relative to the center of the channel. The results presented above suggest that food, in the form of macroinvertebrates, may be more abundant in these off channel habitats due to the combined effects of a moderated flow regime and generally higher nutrient levels.

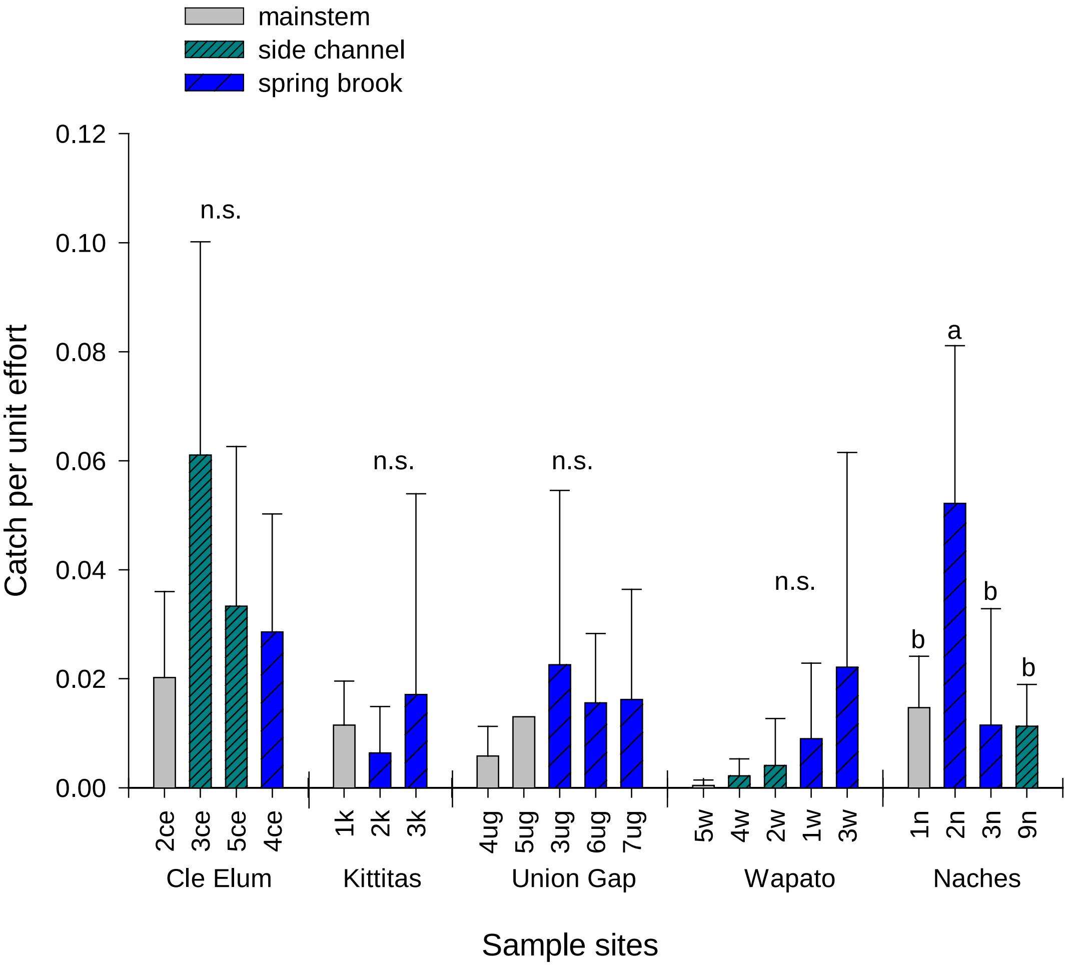


Figure 26. Salmonids associated with various habitat types (mainstem, side channel, spring brook) throughout the five study reaches. Data presented (catch per unit effort; +1 SD) are pooled between collection dates (fish were sampled a minimum of five times throughout the year). Specific sample sites correspond to the base maps. Although significant (ANOVA; p<0.05) differences between sample sites were observed only in the Naches reach, the trend in all reaches without exception was for CPUE to be higher in side channel and spring brook habitats vs. the main channel.

In addition, the number of salmonids captured declined from upstream to downstream (Table 5), which is likely a function of thermal regime, water quality and the life-history strategies of the surviving salmon runs (e.g., Chinook) (Snyder et al. 2001). This is in contrast to the abundance of non-anadromous species, which increases in a downstream direction, for many of the same reasons (Table 5).

Salmonids were represented in all reaches during all sampling efforts. Patterns in temporal distribution suggested that in the upper two reaches and the Wapato reach, CPUE was greater April than at any other time, although this trend was statistically significant only in the Cle Elum reach (Fig. 27). However, in the Union Gap and Naches reaches, salmonid CPUE peaked in August and September; an observation that suggests the salmon (spring chinook in this case) are emerging in early spring in the upper reaches and migrating downstream to the lower reaches later in the summer.

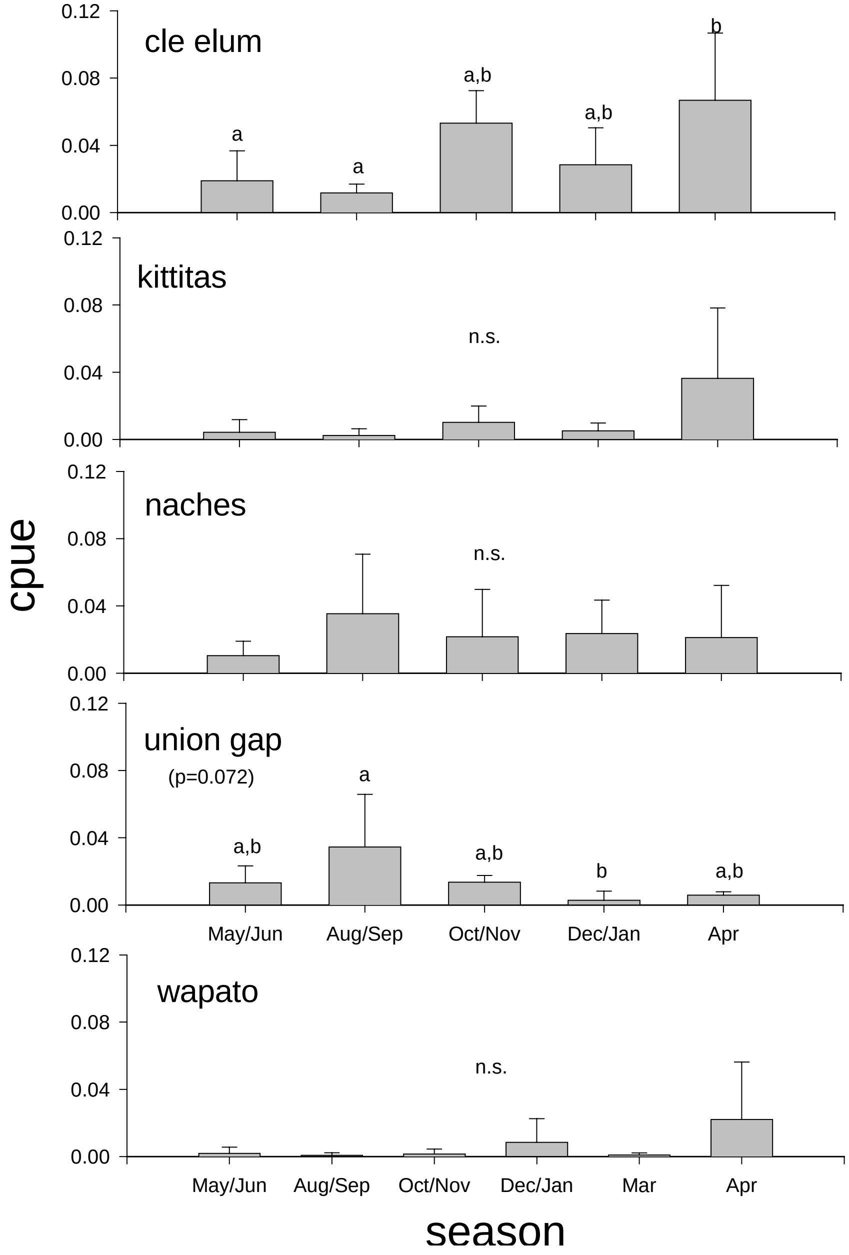


Figure 27. Temporal distribution (pooled habitat types) of salmonids (catch per unit effort); +1 SD) in each reach. Surveys in all reaches except Wapato were conducted in 2000 with the exception of April (2001). Wapato surveys were conducted in 2001. Different letters represent significant ($p<0.05$) differences (ANOVA with Tuckey's post-hoc multiple comparisons).

Reach-scale Assessment

In making an initial attempt to establish restoration priorities, it is important to note reoccurring patterns in the studied reaches. First, it is apparent that habitat heterogeneity increases in the lower portion of each flood plain; those areas considered to be strongly upwelling (Snyder et al. in press) (Fig. 28). For example, the percent of the flood plain containing alluvial spring brooks is significantly higher (ANOVA & Tukey's post-hoc multiple comparison test; p=0.047) in the lower 3rd vs. the upper 3rd of each reach. These portions of the flood plains that remain the least altered by human activities should be placed very high on a restoration priority list because they likely are acting as important refuge areas for native biota (Frissell and Bayles 1996). In addition, channel density significantly declines through time (1927-'42 vs. 1996); an observation that has direct relevance on the potential carrying capacity of each reach (Fig 28). There is no question that a decline in channel density will lead to a decrease in both the abundance and diversity of organisms that inhabit the flood plain. In essence, the habitat templet has become more simplified. This provides at least a partial mechanistic explanation for the decline in indicator species such as the salmon.

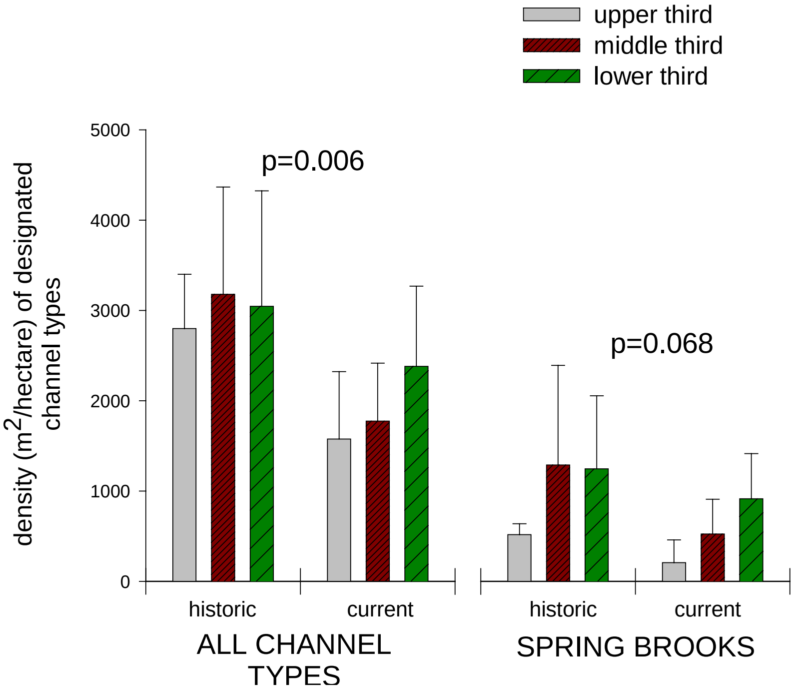


Figure 28. Data derived from aerial photographs (all reaches but Wapato) were used to estimate the following: (1) the change in channel density from historic (1927-'42) to present (1996) (ANOVA; p-values above histograms (+1 SD) represent this comparison, with data between upper, middle, and lower thirds combined); and (2) each reach was divided into thirds to compare channel density. Results indicate that spring brooks densities in particular were higher in the middle and lower third of each reach. In addition, the greatest loss in spring brooks and all channel types has occurred in the middle third of the reaches, where constriction and anthropogenic alteration of the flood plains are relatively high (Eitemiller et al. 2002).

At the outset of this project, we intended to integrate the GIS land-use data compiled by Eitemiller et al. with our ecological and geomorphic assessment. To a limited extent, this was done, but we strongly advise a much more complete integration. As an example, a limited assessment on just four of the reaches was conducted with the goal of (1) examining reach-scale patterns in the physical habitat templet and (2) providing an example of how restoration priorities should be established. Land-use data was compiled by Morris Uebelacker (unpublished data) using aerial photographs and thus, we note the need to ground-truth this data set (Morris Uebelacker, pers. comm.).

The analysis indicated that the distribution of amphibitic stoneflies was greater in the upper reaches versus further down the continuum, suggesting that surficial connectivity is higher in the upper flood plains (Cle Elum and Kittitas) versus the lower two. As previously noted, this is logical given cumulative anthropogenic impacts downstream. However, land use intensity is highest in the Kittitas reach, whereas habitat complexity is highest in the Union Gap reach as indicated for example by channel densities (Table 7). The Union Gap flood plain also is appealing for restoration because of limited floodplain encroachment in the lower half of the reach and the presence of deteriorated revetments that are protecting mainly unused gravel pits.

Table 7. Reach characteristics of four of the seven alluvial flood plains. The first three reaches (Cle Elum, Kittitas and Union Gap) are listed in order from upstream to down; while the Naches reach is located on the largest tributary to the Yakima, with the confluence at the upper end of the Union Gap reach (taken from Snyder et al. in press)**.**

	REACH			
Characteristic	Cle Elum	Kittitas	Union Gap	Naches
number of wells	12	6	13	11
number of wells w/ stoneflies	5	3	1	1
ratio (wells:wells with stoneflies)	0.42	0.50	0.08	0.09
size of holocene floodplains (km2)	17.49	54.2	23.25	33.4
% Holocene floodplain containing channels	19	15	25	21
% Holocene fp with off-channel or side-channel habitat	7.5	4.8	13.5	8
% Holocene fp with spring brook habitat	4	5.5	8.5	6.4
upper 3rd of reach with spring brook habitat (%)	0.7	5.7	0.0	1.9
lower 3rd of reach with spring brook habitat (%)	8.0	7.4	16.3	4.8
% floodplain disconnection (holocene vs. present state)	59	69	61	44
land use intensity (13=pristine; 4=highly degraded)	8.3	6.1	7.9	6.7

Conclusions Based on Monitoring

The acquisition of floodplain habitat in all reaches should be a priority, particularly those areas that yet maintain some degree of habitat complexity. The discussion above notes that the general pattern is for the lower end of each of the various reaches to maintain higher complexity. This is not unexpected given the deposition of gravel derived from this portion of each reach and further upstream via cut and fill alluviation. The nick points at the lower end of each reach (e.g., Yakima Canyon, Union Gap, Selah Gap, etc.) dictate this deposition and subsequent channel migration (see Lorang et al. Part B). In addition, large-scale physical processes of down- and upwelling predict that the lower portions of the study reaches contain a greater percentage of active spring brooks (Snyder and Stanford 2001). Thus human alteration of the flood plains has tended to occur last in these areas (e.g., the lower portions of the flood plains). To preserve high quality habitat that currently exists should be a priority. The pressure placed on remaining undeveloped areas will only increase as the basin-wide human population continues to grow (Snyder and Stanford 2001).

To rank the reaches based on our assessment is a more difficult task. As noted in the discussion, the upper reaches maintain populations of amphibitic stoneflies, whereas no such indicator species appear to exist on the main stem habitat that was sampled in the Naches, Union Gap or Wapato reaches. However, we believe it is extremely important that some of these same indicator species were found on the Toppenish fan—a pattern that suggests that cumulative impacts have perhaps led to the local extinction in these lower reaches, but that populations yet exist in the less disturbed tributaries (personal communication, Kale Gullet; NMFS). We believe that these species, along with many other potential species, could be used as indicators of ecosystem recovery as the process of restoration continues. That hyporheic stoneflies yet exist in the upper reaches indicates that hydrologic connectivity still exists and, subsequently that reconnection of the flood plain and maintenance of existing high quality habitat will likely enhance the productivity of salmonids in these reaches.

Although the lower reaches maintained no such populations, results indicate that some of the processes associated with floodplain connectivity yet exist. For example, water table elevation in monitoring wells in the Wapato, Union Gap and Naches reaches were dynamic with the mainstem. In addition, an analysis of water table elevation strongly suggests a localized pattern of downwelling and upwelling (movement of water from the river out onto the flood plain and then back again to the river). In addition, measurement of vertical hydraulic gradient indicates that the reaches tend to be generally downwelling until the natural nick points, such as Kittitas Canyon or Union Gap, force water in the shallow alluvial aquifers back to the surface where upwelling becomes more evident. These types of interactions are critical for the maintenance of high quality habitat via the following mechanisms. Specifically, hydrologic connectivity between the river and flood plain provides for thermal moderation (winter warm–summer cool conditions), transformation of nutrients from organic to inorganic form (more readily used by biota) and actual removal of anthroprogenically derived nitrogen via denitrification.

In addition to dynamic water table elevations, localized temperature regimes were strongly influenced by patterns in upwelling ground water. In all reaches, spring brooks maintained thermal regimes that were more stable than the main stem habitat.

Importance of off-channel habitat:

The distribution and concentration of algae, macroinvertebrates and fish pointed to the importance of off-channel habitats including overflow channels, spring brooks and disconnected channels. For example, in the Wapato reach, several spring chinook were trapped in a spring brook that became disconnected at the onset of the irrigation season. Several of these fish were recaptured on successive dates and were found exclusively at the upper end of the spring brook, near an upwelling area that maintained cool water temperatures. Although not confirmed, it is likely that these fish managed to survive the summer "drought" within the Wapato reach until the end of the irrigation season when increased discharge reconnected the spring brook system.

The data collected all strongly indicates that maintenance of diverse off-channel habitat is critical for the completion of many species, including juvenile salmonids. This habitat can be *maintained* by (1) protecting existing high-quality habitat via land acquisition, environmental easements, etc., and (2) not increasing water abstraction through construction of additional storage reservoirs. The existing shifting habitat mosaic has been maintained because only one third of the annual basin-wide runoff is stored in reservoirs: to increase storage would only decrease the habitat complexity that currently exists. On the other hand, to actually *enhance* the river ecosystem for indicator species such as salmon, we strongly recommend normalizing the flow regime. This means providing additional flows at times that better mimic the historic discharge regime and thereby provide enough habitat to sustain or expand populations of anadromous fishes in all life history stages (Independent Scientific Group 1999) (see Fig. 30 below). In addition, the flood plains must be reconnected by revetment set-back and removal, and expansion bridges that constrain the flood pulse, thereby allowing the water to interact with the adjacent flood plain.

Normative Condition—Union Gap and Wapato as Examples

Although conservation activities greatly reduce the transfer of pollutants (mainly herbicides and pesticides) to the river system, there likely will be little benefit derived from an increase in instream flows (see above discussion). For example, in the Union Gap reach, our analysis indicates that the improvement in irrigation efficiency would potentially increase instream flows by less than 1% (Fig. 29b vs. 29a, Table 8). This is not ecologically meaningful in terms of enhancing floodplain connectivity. Alternatively, supplying Roza with irrigation water derived from Columbia River pump exchange would increase instream flows by 29% and increase the connection of off-channel habitat by 80% (Table 8). This is meaningful from an ecological standpoint (although see the discussion below for additional considerations). In addition, and perhaps most importantly, this water could then be used to reestablish normative based flows in the Wapato reach.

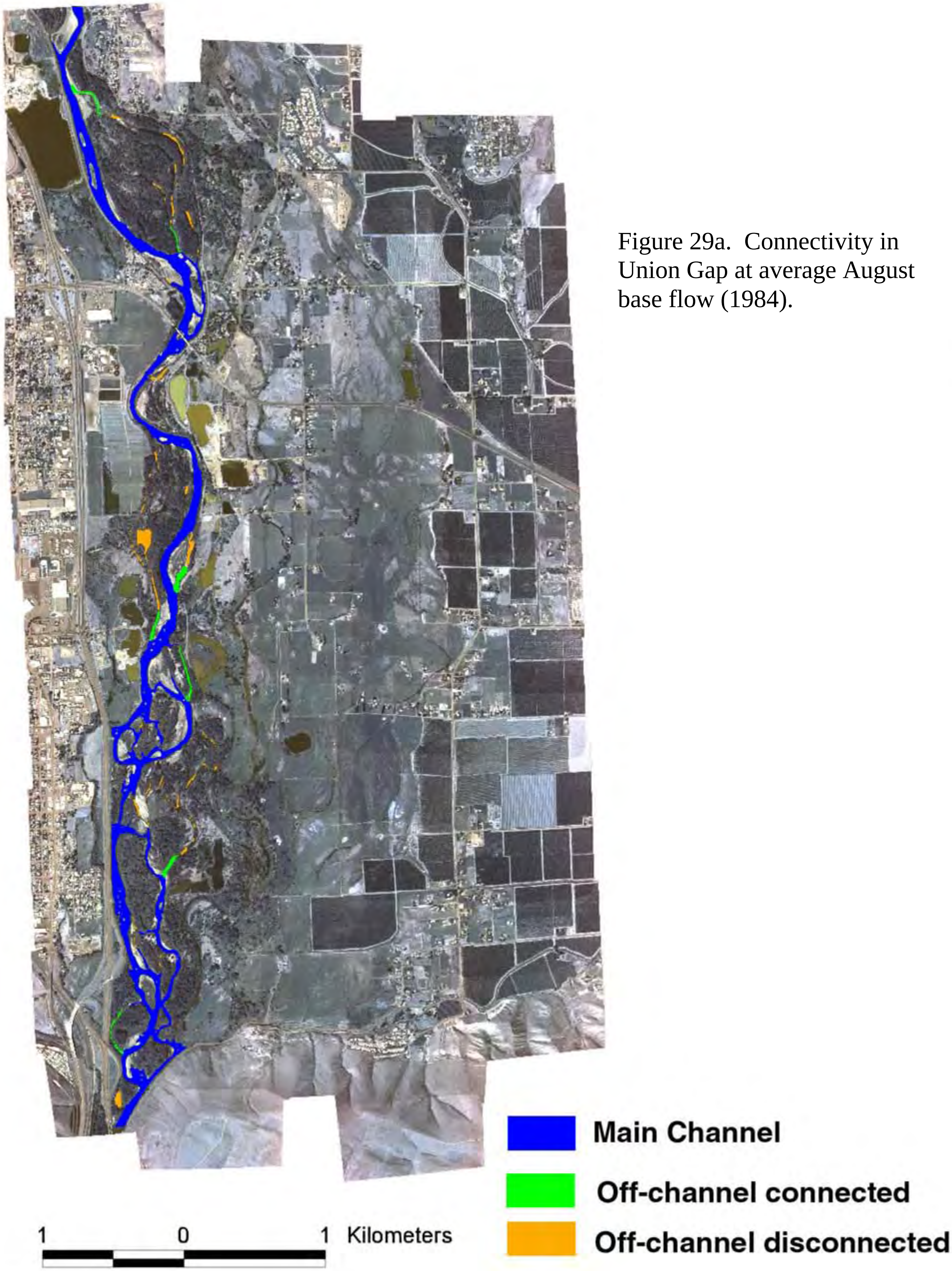


Figure 29a. Connectivity in Union Gap at average August base flow (1984).

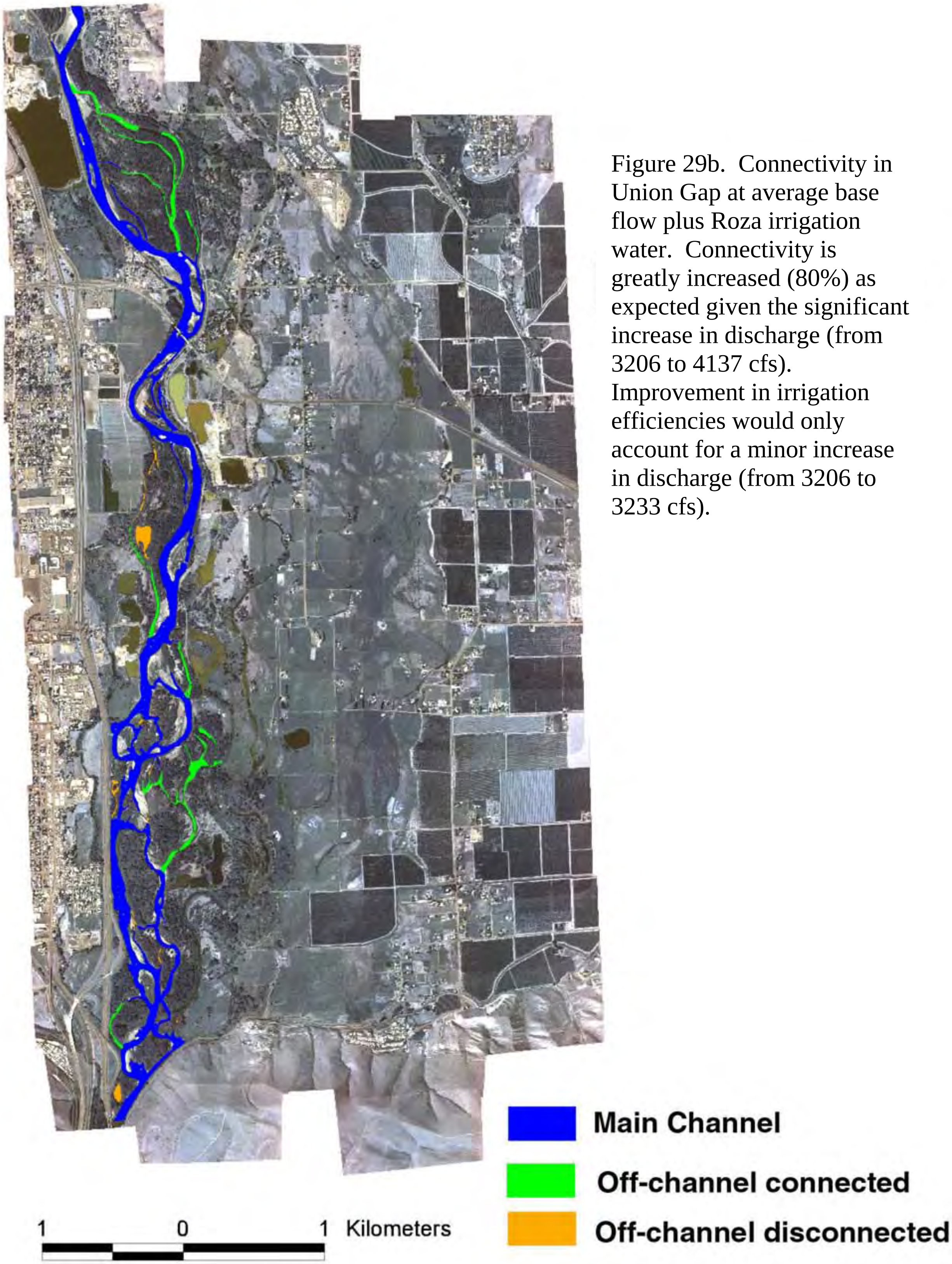


Figure 29b. Connectivity in Union Gap at average base flow plus Roza irrigation water. Connectivity is greatly increased (80%) as expected given the significant increase in discharge (from 3206 to 4137 cfs). Improvement in irrigation efficiencies would only account for a minor increase in discharge (from 3206 to 3233 cfs).

Table 6. Example of the process of deriving of normative flows in the Union Gap reach in August, 1984 (closest to mean base flow from 1981 to 1999). Improvement in irrigation efficiencies, although beneficial for many other reasons, does not enhance discharge in any ecologically meaningful way. Connectivity of off-channel habitat is substantially increased by pump-exchanging Roza irrigation diversion with water derived from the Columbia River. However, we note that this is just an example of how multispectral imagery can be used to determine the potential ecological benefits of altering the flow regime and returning it to a more normative condition. In other words, it is certainly possible to put too much water through the reach at the wrong time of the year.

	Q (cfs)	Water surface area (ha)	Main channel (ha)	Connected off-channel (ha)	Disconnected off-channel (ha)
Average discharge (from 1981-1999)	**3206**	**70**	**62.1**	**2.07**	**4.9**
Average discharge with additional flows derived from agricultural improvements	**3233**				
Average discharge with additional flows derived from Roza pump exchange	**4137**	**87.9**	**74.7**	**10.3**	**2.8**
% change	**+23**	**+20**	**+17**	**+80**	**-43**

The hydrologic connectivity at base flow in the Union Gap is not a significant worry; whereas base flow abstraction in the Wapato reach is of great concern. The Wapato reach maintains the most expansive and ecologically connected flood plain (see Whited et al. Part C). Base flow abstraction is a significant ecological problem that could be solved by the pump exchange scheme described above. Normative base flow conditions can be established by comparing (a) historic discharge records, (b) estimated unregulated discharge from USBR hydromet system, and comparing these two data sets with (c) regulated discharge regime during base flow (Fig. 30). The upper limit to normative flows can be established by using maximum discharge in the Wapato reach, for example during the 1998 flood. The potential for conservation measures to significantly improve connectivity in the Wapato reach is minimal. However, we again stress that instream flows are not the sole objective of conservation measures and there is likely to be great ecological benefit in the form of improved water quality—a variable that has already been identified as potentially constraining ecological integrity (Snyder and Stanford 2001).

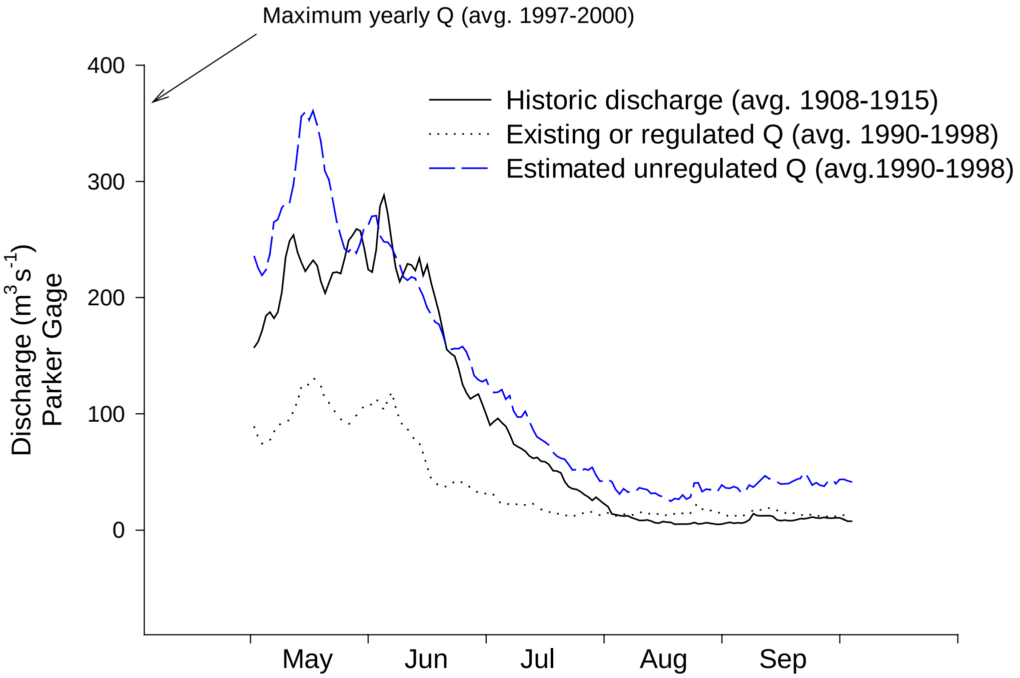


Figure 30. Example of 'normative' flows for the Wapato reach below the Parker USBR gage. The data presented compares average discharge regimes from May to September under the following scenarios: (1) historic discharge from 1908 to1915, (2) observed regulated discharge from 1990 to1998 and (3) estimated unregulated discharge from 1990 to 1998.

It is important to note that water abstractions from 1908 to 1915 were in existence and that these contributed to a reduction in base-flow in August and September. Thus, we cannot use the historic discharge records to answer this question of 'normative', as has been noted elsewhere (Snyder and Stanford 2001). Interestingly, peak floods yet occurred in May and June, likely as a result of minimal storage in the headwaters. This is contrasted with the contemporary regulation flow regime in which base-flow reduction is still occurring, in addition to a reduction in peak flows. A 'normative' flow regime for Wapato would focus in particular on base-flow conditions, with the intent to return base flows in August and September to estimated unregulated discharge. We feel that this parameter (estimated unregulated Q) provides the best representation of discharge necessary to maintain connectivity between the river and adjacent spring brooks and floodplains during base-flow. To put a value on this, the mean estimated unregulated Q from August to September is 36.9 $m^3 s^{-1}$ (1304 cfs) and this provides at least a starting point to establish minimum flows necessary to reach normative condition during base flow in the Wapato reach.

An upper limit to the normative condition would be bank-full discharge. This was estimated by comparing maximum yearly discharge from 1997 to 2000 (the arrow in Fig. 30). Interestingly, this value of 383 $m^3 s^{-1}$ (13,510 cfs) is very similar to maximum estimated unregulated discharge (average from 1990-1998).

In order to meet the criteria outlined above, we are advocating that pump exchange between the Columbia River and Roza and Sunnyside diversions at least be examined. The quantity of water required from the Priest Rapids pool is minimal. For example, Roza and Sunnyside collectivity would use a maximum of 69 $m^3 s^{-1}$ (derived by summing maximum discharge from 1981-2001 in Roza and Sunnyside, USBR Hydromet). The minimum mean monthly discharge (from 1918 to 2000) for September at the USGS gage below Priest Rapids Dam (USGS 12472800) was 1700 $m^3 s^{-1}$ (60,050 cfs). Thus, pump exchange would require approximately 4% of the overall Columbia River discharge at Priest Rapids under severe conditions (maximum withdrawal for Roza and Sunnyside and minimum flow in the Columbia River). Although this analysis is simplistic and we recognize that there are many questions that need to be addressed prior to embarking on this proposed management scenario, we strongly feel that the ability to leave water currently used by Roza and Sunnyside in the river provides the most effective mechanism for restoring normative conditions in the lower reaches.

Restoration potential:

As stated above, all of the reaches, with the exception of Selah, perhaps, maintain significant potential for restoration. However, we believe that the restoration potential is highest in the Union Gap reach, based on many factors including its size, location, current condition, willing sellers and especially, current water availability, being located just below the Naches tributary and not experiencing severe dewatering evident in the Wapato reach. Sediment supply is sufficient to fill shallow pits and thereby potentially provide an excellent example or demonstration of normative condition, whereas deep pits are problematic. Lorang et al. (Part B) notes that there is significant potential for the river to avulse above the Moxee bridge and that this sediment would be adequate to fill the shallow gravel pits located just downstream. In addition, Lorang et al. (Part B) demonstrate that reconnection of shallow abandoned pits produces high quality habitat via the process of cut and fill alluviation and revegetation, although this restoration process would take on the order of 10’s of years. A more normative condition would allow flood events of greater magnitude and frequency to occur within the reach.

In addition to Union Gap, the Wapato and Naches reaches show great potential for restoration, particularly given that dewatering can be minimized in the Wapato. It is structurally very intact (Whited et al. Part C), although flow abstraction accelerates the detrimental effects of high temperatures and pollution and expands the range of non-native species.

Supplying both Sunnyside and Roza irrigation districts with water derived from pump exchange with the Columbia River would substantially increase the ecological integrity of the Wapato reach. At the present, we believe that dewatering during the irrigation season is the major environmental bottleneck that constrains the productivity of the reach. We recognize that there are many questions that must be answered prior to proceeding with this management scenario. The potential impacts to the Columbia River would need to be fully investigated. However, we do know that the benefits in the Yakima Basin would be many-fold, although there are essentially two major benefits. Firstly, instream flows are enhanced, particularly in the Wapato reach and the upper Yakima from Union Gap upstream, and can experience lower base flows (more normative) than currently exist. Secondly, junior water rights holders (such as Roza irrigation district) would receive a more continuous and steady supply of water, even in low water years.

Recommendations:

1. The Yakima flood plains are substantially constrained by human activities, mainly revetments, highway corridors and gravel pits. In the Cle Elum, Kittitas and Naches reaches, in addition to constrainment, the flip-flop flow regime flushes the system abnormally. The Selah reach was not studied, except by remote sensing (Whited et al. Part C), owing to significant gravel mining (>60% of the flood plain was gravel excavation). Within the Wapato reach, the primary ecological issue is de-watering of the base flow. For example, the two spring brooks studied within this reach were significantly dewatered; stranding several juvenile chinook in one and causing beaver to move upstream substantially to even reach water in the other. Anthropogenic constrainment was less an issue here versus the other reaches, with the exception of the Naches, which was also constrained to a lesser degree (Whited et al. Part C, Eitemiller et al. 2002).

2. Nonetheless, the shifting habitat mosaic is relatively complex in many places within the reaches due to flooding. In addition, off-channel habitat is likely essential for fish, including the salmonids, of which steelhead (*O. mykiss*) is listed as threatened per the Endangered Species Act.

3. Longitudinal connectivity is severed by flow abstraction, which accelerates temperature and pollution effects, particularly within the Wapato reach.

4. Normative flows would reconnect the Yakima floodplain ecosystem in all three physical dimensions (laterally, vertically and longitudinally).

5. The normative condition cannot be reached through water conservation. Water leasing, even if highly subsidized (e.g., ‘gold’ fish), likely is not a solution due to the need to fill the irrigation canals with water (e.g., we only have so much basin-wide storage) and the unacceptable economic impacts on junior water rights holders (e.g., Roza Irrigation District). Increasing storage within the basin is not ecologically viable and would send the flow regime in the opposite direction from normative. We strongly recommend that Columbia River flow exchange to Roza and Sunnyside be examined and coupled with the development of a strategic plan for floodplain expansion through revetement removal. We believe this would generate normative conditions within the Yakima Basin and provide the best possible chance for reestablishing a semblance of historic anadromous fish returns.

ACKNOWLEDGEMENTS

We would like to thank the following individuals for extensive assistance in field work and sample processing: Clay Arango, Tim Brown, Kelly Clark, MaryBeth Delucia, Doug Eitemiller, Nick Gayeski, Tracy Hames, Julie Lind, John Merz, Scott Nicholai, Tucker Orvald, Joan Para, Kate Pucket, Kristin Rein, Jill Scheffer, Lester Spencer and Diane Whited. In addition, we thank Steve Croci and Gary Torretta for many hours spent in the field surveying fish communities and analyzing data. Without the help of all of these individuals, this project would not have been possible. Finally, there were many landowners throughout the basin who were willing to allow us access to various portions of the flood plains. We extend our thanks to these all these individuals. This project was funded by the US Bureau of Reclamation as part of the Yakima River Basin Water Enhancement Program and the Yakima Nation.

REFERENCES

Bansak, T. S. 1998 The influence of vertical hydraulic exchange on habitat heterogeneity and surficial primary production on a large alluvial flood plain of the Middle Fork of the Flathead River. Masters Thesis. The University of Montana, Missoula, Montana. USA.

Conservation Advisory Group. 1997. Draft basin conservation plan for the Yakima River Basin water conservation program. Report to Secretary of the Interior.

Cuffney, T. F., M. R. Meador, S. D. Porter, and M. E. Gurtz. 1997. Distribution of fish, benthic invertebrate, and algal communities in relation to physical and chemical conditions, Yakima River Basin, Washington, 1990. Water Resources-Investigations Report 96-4280. U.S. Geological Survey, Raleigh, North Carolina, USA.

Dahm, C. N., N. B. Grimm, P. Marmonier, H. M. Valett, and P. Vervier. 1998. Nutrient dynamics at the interface between surface waters and groundwaters. Freshwater Biology **40**:427-451.

D'Angelo, D. J., J. R. Webster, S. V. Gregory, and J. L. Meyer. 1993. Transient storage in Appalachian and Cascade mountain streams as related to hydraulic characteristics. Journal of the North American Benthological Society **12**:223-235.

Dole-Olivier, M. J., P. Marmonier, M. Creuze des Chatelliers, and D. Martin. 1994. Interstitial fauna associated with the alluvial floodplains of the Rhone River (France).Pages 314-343 *in* J. Gibert, D. L. Danielopol, and J. A. Stanford, editors. Groundwater Ecology. Academic Press, Inc., San Diego, California, USA.

Eitemiller, D. J., C. P. Arango, K. L. Clark, M. L. and Uebelacker. 2002. The effects of anthropogenic alterations to lateral connectivity on seven select alluvial floodplains within the Yakima River basin, Washington. Department of Geography and Land Studies, Central Washington University, Ellensburg, Washington, USA.

Endangered Species Act. 1973. Statutes at Large. Volume 87:884.

Embrey, S. S., and B. D. Watson. 1992. Fish and other aquatic biological communities. *In* J. F. Rinella, S. W. McKenzie and G. J. Fuhrer, editors. Surface-water-quality assessment of the Yakima River Basin, Washington: Analysis of available water-quality data through 1985 water year. U.S. Geological Survey Open-File Report 91-453. Portland, Oregon, USA.

Frissell, C. A., and D. Bayles. 1996. Ecosystem management and the conservation of aquatic biodiversity and ecological integrity. Water. Res. Bulletin **32**: 229-240.

NMFS. 1998. Backpack electrofishing guidelines. National Marine Fisheries Service, National Oceanic and Atmospheric Administration, US Department of Commerce, Portland, Oregon, USA.

Hall, C. A. S., J. A. Stanford, and F.R. Hauer. 1992. The distribution and abundance of organisms as a consequence of energy balances along multiple environmental gradients. Oikos **65**:377-390.

Harner, M. J. 2001. Growth and distribution of Populus trichocarpa on an alluvial flood plain in northwestern Montana. Masters Thesis. The University of Montana. Missoula, Montana, USA.

Hedin, L. O., J. C. von Fisher, N. E. Ostrom, B. P. Kennedy, M. G. Brown, and G. P. Robertson. 1998. Thermodynamic constraints on nitrogen transformations and other biogeochemical processes at soil-stream interfaces. Ecology **79**:684-703.

Heiler, G., T. Hein, F. Shiemer, and G. Bornette. 1995. Hydrologic connectivity and flood pulses as the central aspects for the integrity of a river-floodplain system. Regulated Rivers: Research and Management **11**:351-361.

Hill, A. R. 1996. Nitrate removal in stream riparian zones. Journal of Environmental Quality **25**:743-755.

Humphries, P., L.G. Serafini, A. J. King. 2002. River regulation and fish larvae: variation through space and time. Freshwater Biology **47**:1307-1331.

Independent Scientific Group. 1999. Return to the River: Scientific issues in the restoration of salmonid fishes in the Columbia River. Fisheries Management **24**:10-19.

Kinnison, H. B., and J. E. Sceva. 1963. Effects of Hydraulic and Geologic Factors on Streamflow of the Yakima River Basin Washington. U.S. Government Printing Office, Washington. USA.

Lake, P. S. 2000. Distribution, patchiness and diversity in streams. Journal of the North American Benthological Society **19**:573-592.

Lamberti, G. A., S. V. Gregory, L. R. Ashkenas, R. C. Wildman, and A. D. Steinman. 1989. Influence of channel geomorphology on retention of dissolved and particulate matter in a Cascade Mountain stream. Pages 33-39 *in* D. L. Abell, editor. Proceedings of the California Riparian Systems Conference: Protection, Management, and Restoration for the 1990's. Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Berkeley, California, USA.

Lee, D. R., and J. Cherry. 1978. A field exercise on groundwater flow using seepage meters and mini-piezometers. Journal of Geological Education **27**:6-10.

Morgan, A., and F. Hinojosa. 1996. Literature review and monitoring recommendations for salmonid winter habitat. Timber-Fish-Wildlife Ambient Monitoring Program. Report No. TFW-AM 9-96-004. Northwest Indian Fisheries Commission, Olympia, Washington, USA.

North West Power Planning Council. 2001. Draft Yakima Subbasin Summary. Edited by L. Berg and D. Fast.

Oliver, W. H. 1983. Farm-wildlife history, relationships and problems on the Yakima Indian Reservation. Wildlife Resource Management, Yakama Nation, Toppenish, Washington, USA.

Omernik, J. M. 1987. Ecoregions of the conterminous United States. Annals of the Association of American Geographers **77**:118-125.

Parker, G. L., and F. B. Storey. 1916. Water Powers of the Cascade Range: Part III. Yakima River Basin, Washington. U.S. Geological Survey Water Supply Paper 369.00000.

Pearsons, T. N., G. A. McMichael, S. W. Martin, E. L. Bartrand, M. Fisher, and S. A. Leider. 1994. Yakima species interactions studies. Annual Report FY 1993. Bonneville Power Administration DOE/BP-99852-2.

Pospisil, P. 1994. The groundwater fauna of a Danube aquifer in the "Lobau" wetland in Vienna, Austria. Pages 347-364 *in* J. Gibert, D. L. Danielopol and J. A. Stanford, editors. Groundwater Ecology. Academic Press, San Diego, California, USA.

Rinella, J. F., S.W. McKenzie, and G. J. Fuhrer. 1992. Surface-water-quality assessment of the Yakima River Basin, Washington: analysis of available water-quality data through 1985 water year. Open-File Report 91-453. U.S. Geological Survey, Portland, Oregon, USA.

Ring, T. E., and B. Watson. 1999. Effects of geologic and hydrologic factors and watershed change on aquatic habitat in the Yakima River Basin, Washington. Pages. 191-194. *in* Sakrison, R. and P. Sturtevant, editors. 1999 Watershed Management to Protect Declining Species. TPS-99-4. American Water Resources Association, Middleberg, Virginia, USA.

River Mile Index, Yakima River. 1964. Hydrology Subcommittee, Columbia Basin Inter-Agency Committee.

Snyder, E. B., D. J. Eitemiller, C. P. Arango, M. L. Uebelacker, and J. A. Stanford. *In press*. Floodplain hydrologic connectivity and potential for restoration in the Yakima River Basin, USA. Proceedings of the International Association of Theoretical and Applied Limnology, Vol. 28.

Snyder, E. B., and J. A. Stanford. 2001. Review and synthesis of river ecological studies in the Yakima River, Washington, with emphasis on flow and salmon habitat interactions. Final Report. Bureau of Reclamation, Yakima Office, Washington. USA.

Southwood, T. R. E. 1977. Habitat, the templet for ecological strategies? Journal of Animal Ecology **46**:337-365.

Stanford, J. A., and J. V. Ward. 1988. The hyporheic habitat of river ecosystems. Nature **335**:64-66.

Stanford, J. A., and A. R. Gaufin. 1974. Hyporheic communities of two Montana Rivers. Science **185**: 700-702.

Stanford, J. A., and J. V. Ward. 1988. The hyporheic habitat of river ecosystems. Nature **335**:64-66.

Stanford, J. A. and J. V. Ward. 1993. An ecosystem perspective of alluvial rivers: connectivity and the hyporheic corridor. Journal of the North Amercian Benthological Society **12**:48-60.

Stanford, J. A., J. V. Ward, W. J. Liss, C. A. Frissell, R. N. Williams, J. A. Lichatowich, and C. C. Coutant. 1996. A general protocol for restoration of regulated rivers. Regulated Rivers: Research and Managemen**t** **12**:391-413.

Stanford, J. A. 1998. Rivers in the landscape: introduction to the special issue on riparian and groundwater ecology. Freshwater Biology **40**:402-406.

Systems Operations Advisory Committee (SOAC). 1999. Report on biologically-based flows for the Yakima River Basin. Final Report, Yakima, Washington, USA.

Tockner, K., and F. Schiemer. 1997. Ecological aspects of the restoation strategy for a river-floodplain system on the Danube River in Austria. Global Ecology and Biogeography Letters **6**:321-329.

Tockner, K., and J.A. Stanford. *In press*. Riverine flood plains: present state and future trends. Environmental Conservation.

Triska, F. J., J. H. Duff, and R. J. Avanzino. 1990b. Influence of exchange flow between the channel and hyproheic zone on nitrate production in a small mountain stream. Canadian Journal of Fisheries and Aquatic Sciences **47**:2099-2111.

Tuck, R. L. 1995. Impacts of irrigation development on anadromous fish in the Yakima River Basin, Washington. Masters Thesis. Central Washington University, Ellensburg, Washington, USA.

Uebelacker, M. L. 1986. Geographic exploration in the Southern Cascades of Eastern Washington: Changing land, people and resources. Dissertation. University of Oregon, Eugene, Oregon, USA.

U.S. Bureau of Reclamation. 1983. Yakima Project. Washington: Benton, Franklin, Yakima and Kittitas Counties. Water and Power Resource Service: Project Data, Water Resources Technical Publication. U.S. Government Printing Office, USA.

U.S. Bureau of Reclamation. 1999. Yakima River Basin Water Enhancement Project, Washington. Final Programmatic Environmental Impact Statement. U.S. Dept. of the Interior, Bureau of Reclamation, Pacific Northwest Region, Upper Columbia Area Office, Yakima, Washington, USA.

Vaccaro, J.J. 1986a. Comparison of unregulated and regulated streamflow for the Yakima River at Union Gap and near Parker, Washington. U.S. Geological Survey, Tacoma, Washington, USA.

Valett, H. M., J. A. Morrice, C. N. Dahm, and M. E. Campana. 1996. Parent lithology, groundwater-surface water exchange and nitrate retention in headwater streams. Limnology and Oceanography **41**:333-345.

Ward, J.V., and J.A. Stanford. 1995. Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. Regulated Rivers: Research and Management **11**:105-119.

Ward, J. V., K. Tockner, and F. Schiemer. 1999. Biodiversity of floodplain river ecosystems: ecotones and connectivity. Regulated Rivers: Research and Management **15**:125-139.