THE EFFECTS OF ANTHROPOGENIC ALTERATIONS TO LATERAL CONNECTIVITY ON SEVEN SELECT ALLUVIAL FLOODPLAINS WITHIN THE YAKIMA RIVER BASIN, WASHINGTON

By

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ABSTRACT: Human impacts to riverine ecosystems have severed the physical connectivity of the river to the riverine environment. During the past 120 years an extensive and complex assemblage of anthropogenic features has been integrated into the disturbance regime template of all floodplains directly associated with the Yakima River. Dams and storage reservoirs regulate and supplement in-stream flow for irrigated agriculture. Railroads and roads, which act as levees when in close proximity to the mainstem river, dissect the riverine landscape. Wetlands and riparian forests are cleared for utilization by agriculture, industry, recreation, and development, and a system of levees that protect and maintain these land use activities has emerged. To assist in identifying how these cultural features alter the fluvial geomorphic patterns and ecological processes of riverine ecosystems an in-depth study focused on mapping their emergence across seven alluvial floodplains within the Yakima basin was recently undertaken. The final analysis shows a reduction in riverine habitat once inundated by small, frequent, flood events across all seven floodplains. The real contribution of this study is the creation of an ecological baseline that will help managers implement changes directed at preserving and promoting riverine ecosystem health.

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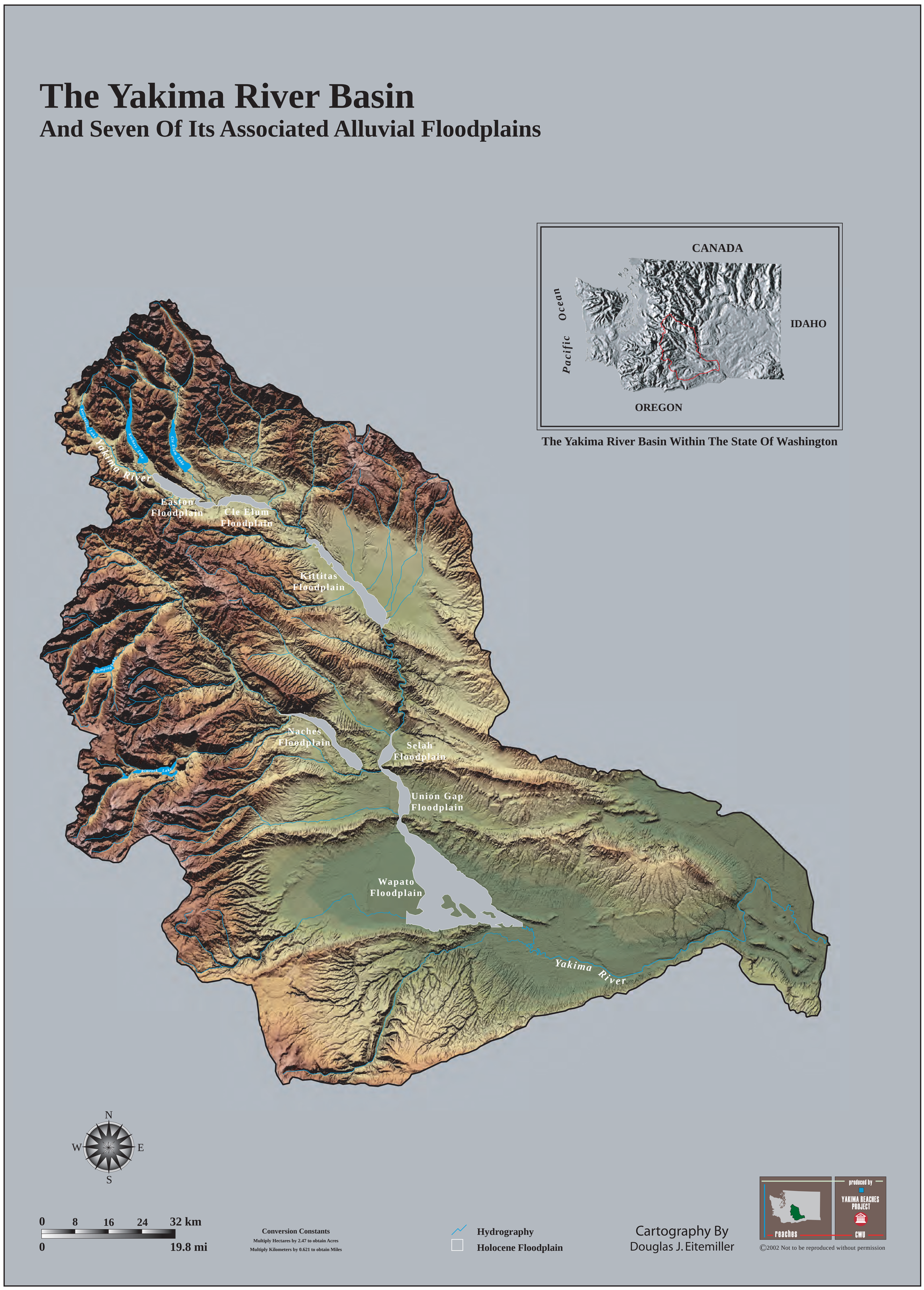

Plate I. Map of the Yakima River basin and seven of its associated alluvial floodplains.

INTRODUCTION

By

Morris L. Uebelacker and Douglas J. Eitemiller

Normative is the functional norm which ensures that we provide the essential ecological conditions and processes necessary to maintain diverse and productive salmonid populations (Independent Scientific Group 1996).

The long term genetic variability of Pacific Northwest anadromous fish is directly linked to the ecological variability expressed in the river basins they occupy (Montgomery 2000). Given this relationship, it is critical for the survival of these and other species that the fluvial geomorphic processes which create and maintain the ecological structure and function of riverine habitats be clearly identified and sustained (Independent Scientific Group 1996). In the Yakima River basin many of these processes have been altered or in some cases eliminated (Snyder and Stanford 2000). For example, human-induced changes have reduced habitat diversity and significantly reduced the extent of habitat available on all large alluvial floodplains within the basin (Eitemiller et al. 2000). Additionally, the construction and operation of dams and storage reservoirs have eliminated all four glacially-formed lakes as essential habitat components, eliminated habitat upstream of the reservoirs, and altered the hydrograph of nearly all downstream reaches.

Knowing the effects of human interactions on the physical and ecological processes that create and maintain biodiversity is imperative in almost every management action regarding anadromous fish. Therefore, a detailed model of the historic habitat conditions for the Yakima River basin is essential to the template from which measurements of change in habitat diversity are made. Significant progress towards understanding historic habitat conditions within the major alluvial floodplains in the basin has been made, and this information will be a first step in prioritizing land acquisition and restoration efforts.

Fluvial ecologists have traditionally emphasized the effects of regulated flow on the longitudinal dimension of riverine ecosystems (Serial Discontinuity Concept) Ward and Stanford 1983). The tenets of contemporary ecosystem ecology required the development of a new paradigm. Accordingly, ecologists now focus on a multidimensional fluvial model that emphasizes three spatial scales (longitudinal, lateral, and vertical) enveloped by a fourth, temporal scale (Amoros et al. 1987; Ward 1989; Ward 1997). Rivers and their associated floodplains are dynamic ecosystems controlled largely by disturbance events across these three spatial dimensions through time. Seasonal floods and associated channel movement maintain, alter, and therefore determine the fluvial geomorphic patterns and ecological processes of these ecosystems (Pautou and Decamps 1985). To what level emergent ecological properties such as biodiversity and bioproduction occur is, in part, a consequence of this disturbance regime. This study assesses the degree of anthropogenic alterations to lateral connectivity on seven select alluvial floodplains within the Yakima River basin, Washington. Starting in the upper basin, they include the Easton, Cle Elum, Kittitas, Selah, Naches, Union Gap, and Wapato floodplains (plate I).

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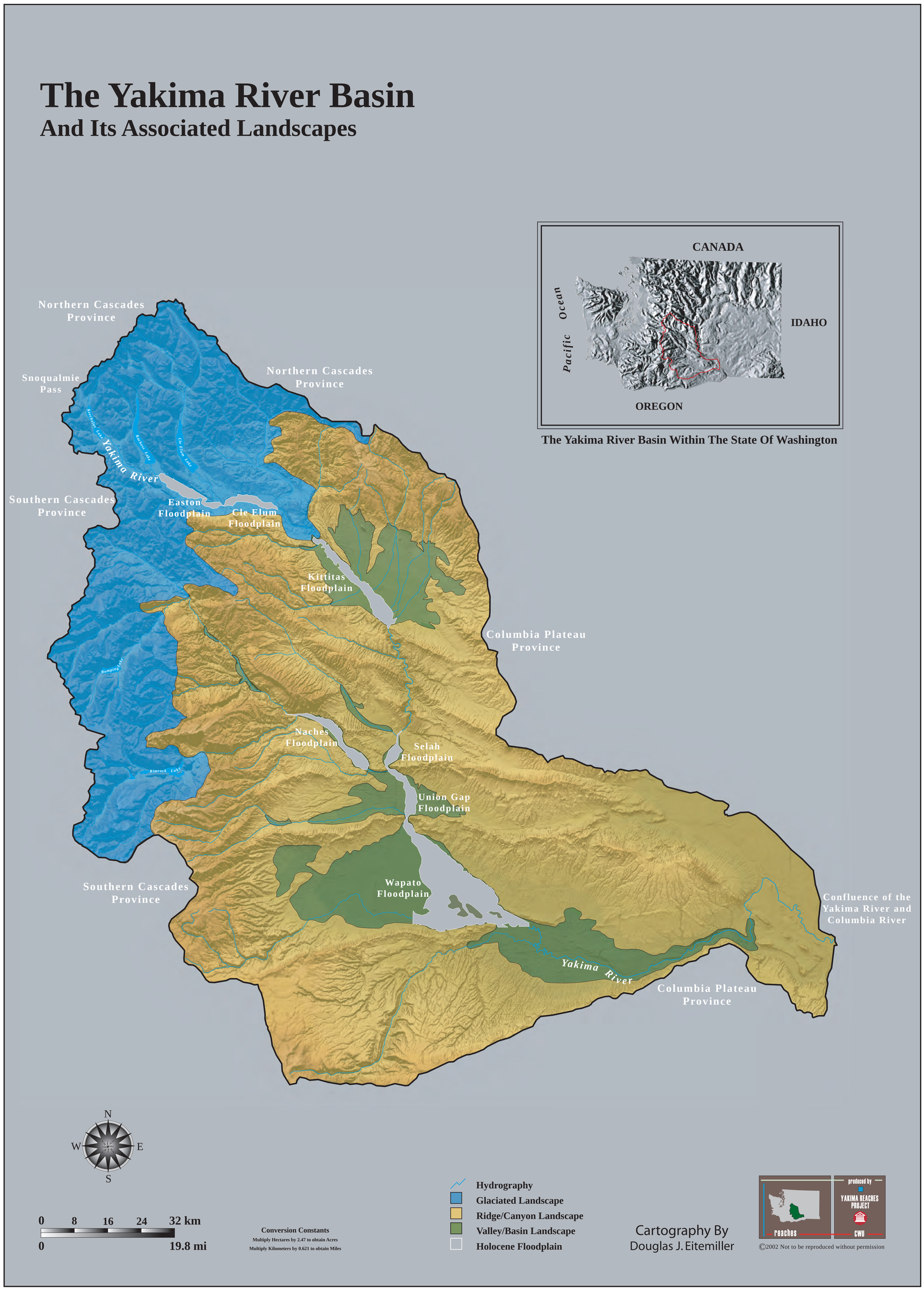
The Yakima River Basin
And Its Associated Landscapes



The Yakima River Basin Within The State Of Washington

Physical Setting

By

Morris L. Uebelacker and Douglas J. Eitemiller

Overall, it is the geologic and climatic conditions of a drainage basin that determines its hydrologic character (Leopold, Wolman, and Miller 1964).

Located in the south-central region of Washington state, the Yakima River basin drains an area of approximately 15,941 square kilometers (inset map). This equates to 8.9% of Washington state's total land area and is greater than twice the size of any other river basin found wholly within the state's political boundary (Parker and Storey 1916). From its headwaters near Snoqualmie Pass, the Yakima River flows in a southeasterly direction for 344 kilometers to its confluence with the Columbia River. Along its course, the river flows through three distinct physiographic provinces. Formed from an assortment of volcanic, metamorphic, and sedimentary rocks, the Northern and Southern Cascade Mountain provinces demarcate the northern, western, and southwestern boundaries of the drainage basin. The Columbia Plateau province consists of basalt that blankets the older Cascade rocks and envelops the drainage basin on its eastern and southern margins (plate II).

The Yakima River basin itself is comprised of three broad landscapes:

(1) Glaciated: The present-day landforms of the upper Yakima and Naches River basins were shaped by flowing ice and water over millions of years. It is within these high elevations that most of the basin's water is first captured, stored, and released. Climatic, geologic, and biophysical processes operating here determine the character of all downstream reaches. The glacial valley bottoms are core areas of fluvial-hyporheic connectivity in this landscape. Deep accumulations of snow during winter and rain-on-snow events typify the patterns of water storage and movement critical to the ecological integrity of the entire river basin.

(2) Ridge and Canyon: The Yakima Folds landscape is dominated by anticlinal ridges, synclinal valleys, and hydraulically cut canyons. Layered with Columbia River flow basalts, this landscape is characterized by arid conditions along its eastern margins. The western margin is a complex interplay of Columbia River flow basalts, Cascade volcanics, sedimentary, and metamorphic material shaped by tectonic, glacial out-wash, and periglacial processes. Tectonics, mass wasting, and hydraulic erosion continue to actively define the physiographic character of the folded landscape. A substantial snow-pack accumulates above 765 meters in elevation during most winters throughout the Yakima Folds' western boundary. It is a landscape of powerful winds and is subject to repeated episodes of snowfall and snowmelt from late fall through early spring. Occasional yet intense thunderstorms can produce flash-floods during late spring and early summer. Mainstem rivers produce hydraulically cut canyons through anticlinal ridges, linking the Valley Basin landscapes from the delta through the headwater reaches. Tributaries also show substantial canyon development and most contain smaller alluvial floodplains nested in the canyon bottoms (Gellenbeck 1999). The headwater basins of tributary streams exhibit a low gradient that promotes the capture, storage, and release of water more slowly than in areas exhibiting high relief, thereby contributing to the control of base flow (King 1997). Water is stored in a substantial number of basin aquifers and in countless small aquifers located within basalt interstices. Emerging springs along common contour intervals reveal their sub-surface location. These basalt aquifers determine base flow in small perennial and intermittent stream segments throughout the Ridge and Canyon landscape. Stream flow patterns across this landscape are extremely variable, and numerous small-to-medium sized watersheds add critical habitat diversity (Sullivan 1994).

(3) Valley Basins: Primary structural basins containing deep alluvial fill and wide canyons with substantial alluvial development are the zones of maximum ecological connectivity and serve as a biophysical processor of upstream inputs and downstream outputs. Although imbedded within all three broad landscapes of the Yakima River basin, alluvial floodplain development becomes most evident in the Valley Basin landscape. Water delivered by the Glacial, and Ridge and Canyon landscapes directy shapes the three dimensions of these large mainstem alluvial floodplains. Numerous tributary streams join the mainstem Yakima River here. These tributary-mainstem connections have developed alluvial fans, floodplains, and canyons as distinct habitat components. Each of these components plays a critical role in determining the structural and functional biophysical processes that create and maintain a higher order of biodiversity.

These three landscapes are connected through the interaction of complex geologic, climatic, geomorphic, edaphic, and biotic processes operating at multiple spatial and temporal scales. Ultimately, these interactive processes have prescribed the template for the diversity of life history strategies exhibited by historic and contemporary populations of all organisms inhabiting each landscape.

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Plate II. Map of the Yakima River basin and its associated landscapes.

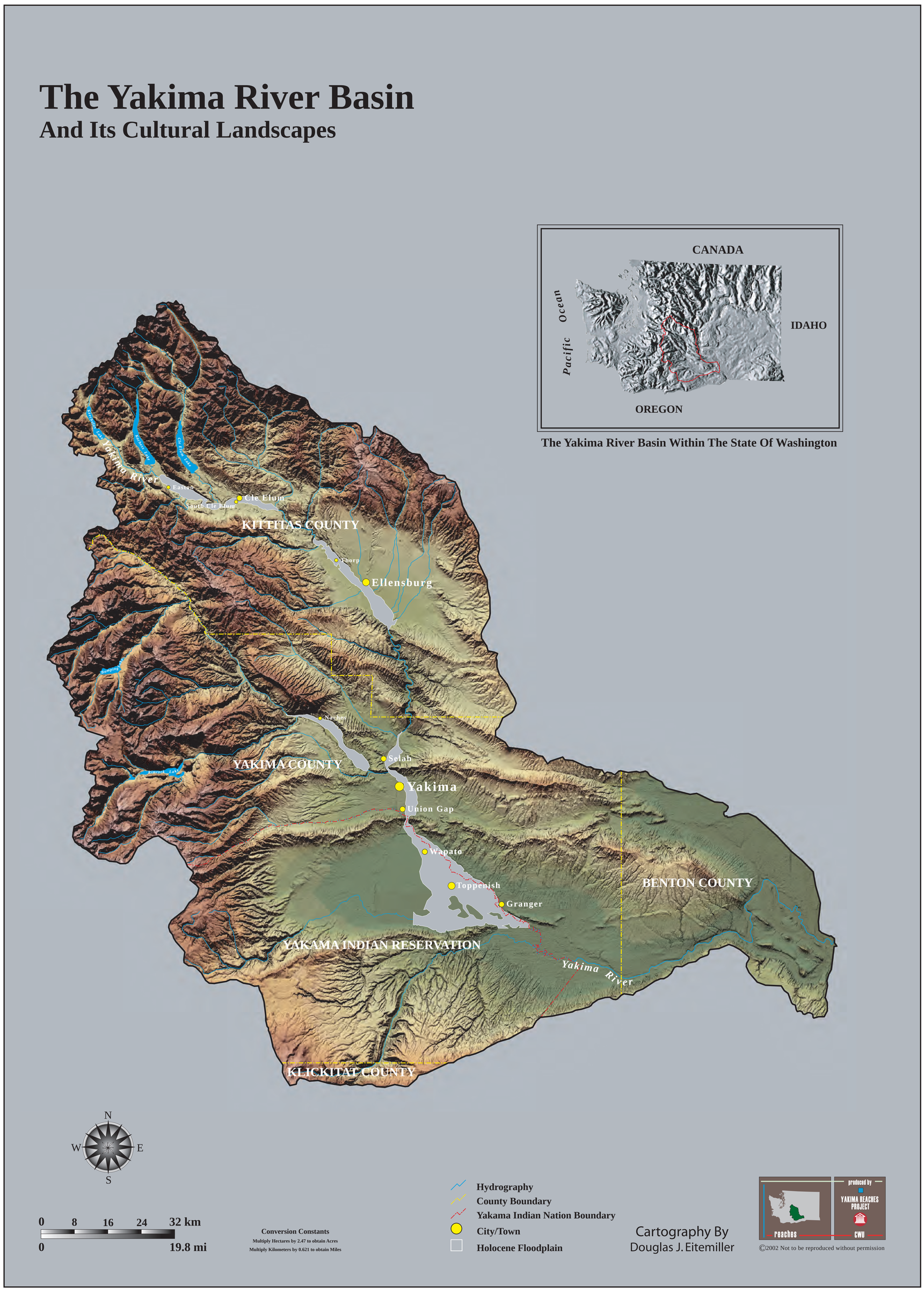

Plate III. Map of the Yakima River basin and its cultural landscapes.

Cultural Setting

By

Morris L. Uebelacker and Douglas J. Eitemiller

Most contemporary ecological systems can only be understood within the context of the cultural systems influencing them (Uebelacker 2000).

At least seven major political entities occupy lands within the Yakima River basin. These include federal and state lands, all of Kittitas and Yakima counties and portions of Klickitat and Benton counties, and a large part of the Yakama Indian Nation. The federal government owns and manages ~37% of this land base. Native American lands account for ~15% while state, county, and city governments own and manage roughly 8%. Private landowners control 688,000 hectares, or just over 40% of all lands within the basin.

The waters of the Yakima River have shaped the cultural face of the basin as much as they have determined its physical character. In turn, these cultures have transformed the riverine landscape. In brief overview, the fluvial-hyporheic systems in the Yakima River basin were essentially unaltered at the signing of the Treaty of 1855 with the Yakama Nation. This assumption is made with the acknowledgement that thousands of horses were present within the basin (Ross 1855) and that beaver populations had been substantially reduced (Glauert and Kunz 1972). The addition of horses to the basin is known to have had localized effects on vegetation, and it is anticipated that in places this modification may have altered ecological dynamics (Uebelacker 1984). Furthermore, the removal of almost all beaver by trappers no doubt modified ground water-surface water interactions of most tributary streams, mainstem and side channel habitats, and riparian biophysical succession. To date, the nature of these alterations remains largely undocumented at the site, landscape, and regional scales.

These modifications were closely followed by the introduction of cattle (1860) and then sheep (1880) (Sullivan 2000). In combination with substantial numbers of horses, these two domesticates transformed the native shrub-steppe, forest, meadow, and riparian communities from the delta of the Yakima River to the high cirque basins and ridges of the Cascade Range. These transformations have caused increased soil erosion and compaction, stream siltation, and in many areas have initiated stream entrenchment. Early researchers noted the severity of these structural changes in vegetative-edaphic communities, which mark the first major alteration of the fluvial-hyporheic system (Plummer 1900; Cotton 1904).

Settlement of the Yakima River basin by non-native people was sporadic and restricted to a few important locations before 1860. Immigration and settlement by Euroamericans was underway by 1880 and focused on water resources in the Valley Basin landscape (Tuck 1995). By the middle 1880s, the effects of the Township and Range survey system and subsequent private land use strategies were creating a new ecological template (Anderson 1996). Settlement patterns were intimately linked to the perceived allotment of water within the basin and restricted to lower elevations where temperature and moisture allowed for reasonable attempts at both dry land and irrigated agriculture. Floodplain farming and private canal building that delivered water to lands above the floodplain are hallmarks of fluvial-hyporheic alterations during this period. Furthermore, timber harvests were focused on the forest-edge and in mainstem valleys, while domestic animal herders followed an ancient pattern of transhumance (Plummer 1900). Timber harvested along the mainstem Yakima and tributary streams was floated down to the newly emerging industrial centers in Yakima and Ellensburg at high water. These log drives were the first cultural practice that worked to create a single-thread river across the floodplains of the mainstem Yakima River and its tributaries and mark a threshold in channel modification.

By the mid 1880s, the Northern Pacific Railroad (NPRR) had laid track and built bridges up the mainstem valleys of the Yakima River basin (Campbell et al. 1916). This single act cut off and redirected alluvial floodplain processes on most major floodplains of the mainstem river and established confined points of entry at many of the tributary-mainstem confluences. The railroad gave focus to the emerging patterns of settlement and land use in the basin and connected human-induced modifications across a much wider region (Meinig 1968). Unlike most roads at this time, the railroad severed critical links between floodplain processes that created and maintained biotic diversity and set the stage for the growth of towns from the delta to the glacial valleys. Subsequent trunk lines further degraded ecological connectivity. After 1906, the Chicago, Milwaukee, St. Paul and Pacific Railroad (CMSP&PRR) mirrored the Northern Pacific's route in the upper reaches of the basin.

The growth of towns within the basin and opportunistic commercial and industrial development from outside areas promoted capitalization of the landscape at large. This encouraged privately funded irrigation efforts that eventually led to federally subsidized projects on a monumental scale. In the early 1900s, the federal government joined in the full-scale industrial development of the Yakima River basin (Buckley 1936; Tuck 1995; Anderson 1996). The fluvial-hyporheic systems were intentionally, yet unknowingly, altered from the formation and management of the Forest Reserves to the construction of dams and irrigation canals. Continued domestic stock grazing had profound impacts not only on riparian systems, but also on public and private forests and rangelands (Cooperative Western Range Survey 1936). This transformation was so complete that its signature has been indelibly imprinted on most forest and range plant communities. When combined with the effects of fire suppression, only vestiges of the endemic system remain (Rummel 1954).

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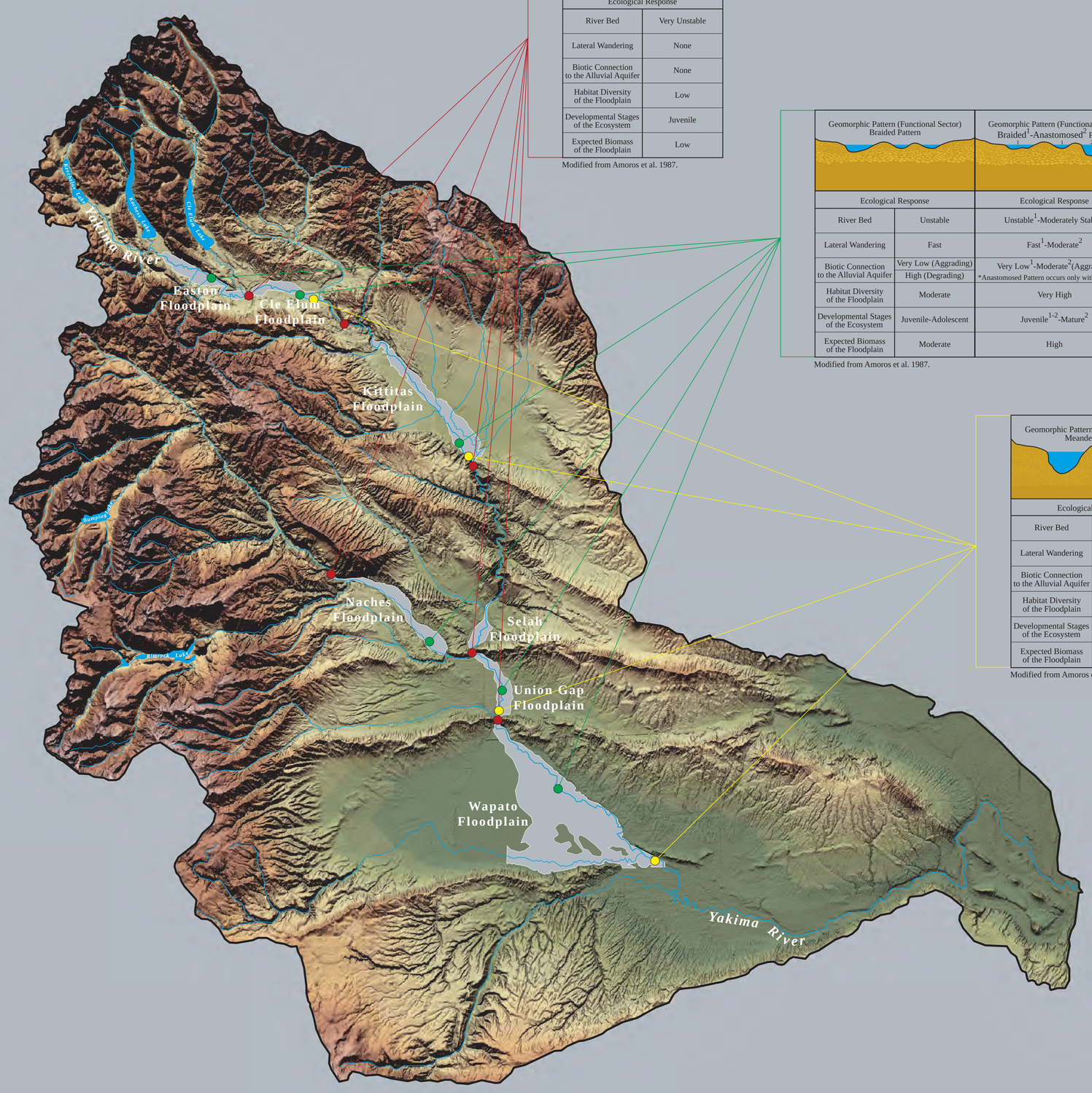
The Processes And Patterns Of Alluvial Floodplains

A Characterization Of River Reaches As Applied To The Yakima River Basin



Geomorphic Pattern (Functional Sector)
Gorge Pattern

Ecological Response	
River Bed	Very Unstable
Lateral Wandering	None
Biotic Connection to the Alluvial Aquifer	None
Habitat Diversity of the Floodplain	Low
Developmental Stages of the Ecosystem	Juvenile
Expected Biomass of the Floodplain	Low

Modified from Amoros et al. 1987.

	Geomorphic Pattern (Functional Sector) Braided Pattern	Geomorphic Pattern (Functional Sector) Braided[1]-Anastomosed[2] Pattern
Ecological Response		
River Bed	Unstable	Unstable[1]-Moderately Stable[2]
Lateral Wandering	Fast	Fast[1]-Moderate[2]
Biotic Connection to the Alluvial Aquifer	Very Low (Aggrading) High (Degrading)	Very Low[1]-Moderate[2](Aggrading) *Anastomosed Pattern occurs only with aggradation
Habitat Diversity of the Floodplain	Moderate	Very High
Developmental Stages of the Ecosystem	Juvenile-Adolescent	Juvenile[1-2]-Mature[2]
Expected Biomass of the Floodplain	Moderate	High

Modified from Amoros et al. 1987.

Geomorphic Pattern (Functional Sector)
Meander Pattern

Ecological Response	
River Bed	Moderately Stable
Lateral Wandering	Slow
Biotic Connection to the Alluvial Aquifer	Moderate (Aggrading) High (Degrading)
Habitat Diversity of the Floodplain	High
Developmental Stages of the Ecosystem	Juvenile-Mature
Expected Biomass of the Floodplain	High

Modified from Amoros et al. 1987.

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Conversion Constants
Multiply Hectares by 2.47 to obtain Acres
Multiply Kilometers by 0.621 to obtain Miles

Hydrography
Holocene Floodplain

Cartography By
Douglas J. Eitemiller

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The Processes and Patterns of Alluvial Floodplains: A Characterization of River Reaches as Applied to the Yakima River Basin

By
Douglas J. Eitemiller and Clay P. Arango

A river reach is a portion of the stream with similar morphological and / or gradient characteristics, typically several tens or hundreds of channel widths in length (Hugenberger et al. 1998).

Until humans began modifying the Yakima Basin, the hydrologic character of the landscape was determined by the changing geologic and climatic conditions of the past eight million years. Present alluvial floodplains were formed along river reaches within the large synclinal valleys during the Holocene epoch (8,000 YBP). Seven major alluvial floodplain reaches have been identified within the Yakima River basin (plate I).

Amoros et al. (1987) describes four major fluvial geomorphic patterns along the longitudinal dimension of a river. Collectively, these patterns are called "functional sectors," and can be considered analogous to a "river reach" as defined above. They include the gorge, braided, braided-anastomosed, and meander patterns. This plate depicts where examples of each type of functional sector are found within the Yakima River basin today. The associated tables describe the geomorphic patterns and expected ecological response for each sector.

Gorge patterns predominate where hydraulic action has cut through anticlinal ridges along the course of the mainstem Yakima River. Here, the surrounding bedrock confines the river to a single, deep channel with high velocity flows. Consequently, the bedload of the river is less stable than in other functional sectors. In addition, confinement negates the river's potential for lateral movement, thereby inhibiting extensive floodplain development. Taken together, these two factors limit the number and degree of possible biotic connections as compared to all other geomorphic patterns. The result is that gorge sectors exhibit juvenile stages of ecological development characterized by low habitat diversity, and therefore, lower indices of biodiversity and bioproductivity.

Examples of braided and braided-anastomosed patterns become manifest on the large alluvial floodplains of the mainstem Yakima River and the floodplains of its larger tributary rivers. Flow velocities range from high (braided) to low (anastomosed) and the movement of bed material promotes an unstable (braided) to moderately stable (anastomosed) riverbed. Lateral movement of a braided reach is fast and promotes high biotic connectivity where the braided channels are degrading and very low biotic connectivity where they are aggrading. Accordingly, ecosystems within a braided reach display a juvenile to adolescent stage of development. Habitat diversity and expected biomass of braided floodplains are moderate when compared to other geomorphic patterns. Lateral movement within a braided-anastomosed reach deviates from fast (braided) to moderate (anastomosed). Biotic connectivity is very low within the braided channels, yet moderate within the anastomosed channel. Developmental stages of ecosystems found within the braided-anastomosed functional sector range from juvenile (braided) to mature (anastomosed). These ecosystems exhibit a very high diversity of habitat types that promote high levels of biomass when compared to other geomorphic patterns.

The mainstem river is typically confined to a single, sinuous, deep channel within the meander functional sector. Flow velocities are low, and the riverbed is considered moderately stable. Lateral wandering, while it does occur, is slow. Still, biotic connectivity can be moderate (aggrading) to high (degrading) in comparison to other geomorphic patterns. Ecosystems within the meander functional sector will range from juvenile to mature stages of development and result in high levels of habitat diversity and biomass production.

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Plate IV. The processes and patterns of alluvial floodplains, a charactrization of river reaches as applied to the Yakima River basin.

The Structure And Function Of Alluvial Floodplains
And Riverine Landscape Connectivity

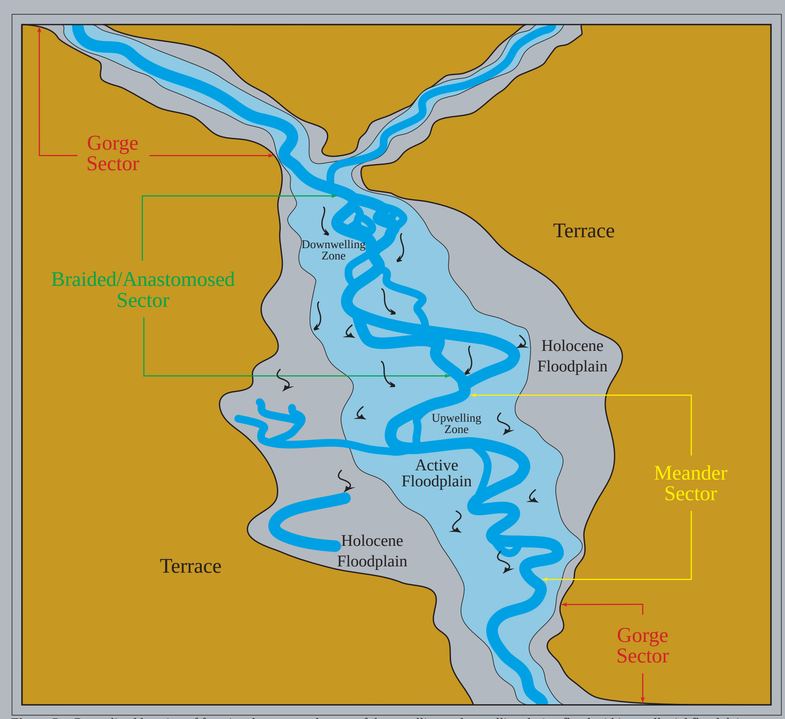

Figure 5a. Generalized location of functional sectors and zones of downwelling and upwelling during flood within an alluvial floodplain (Modified from Ward 1997).

Figure 5b. Types of functional sets associated with each functional sector within an alluvial floodplain (Modified from Ward 1997).

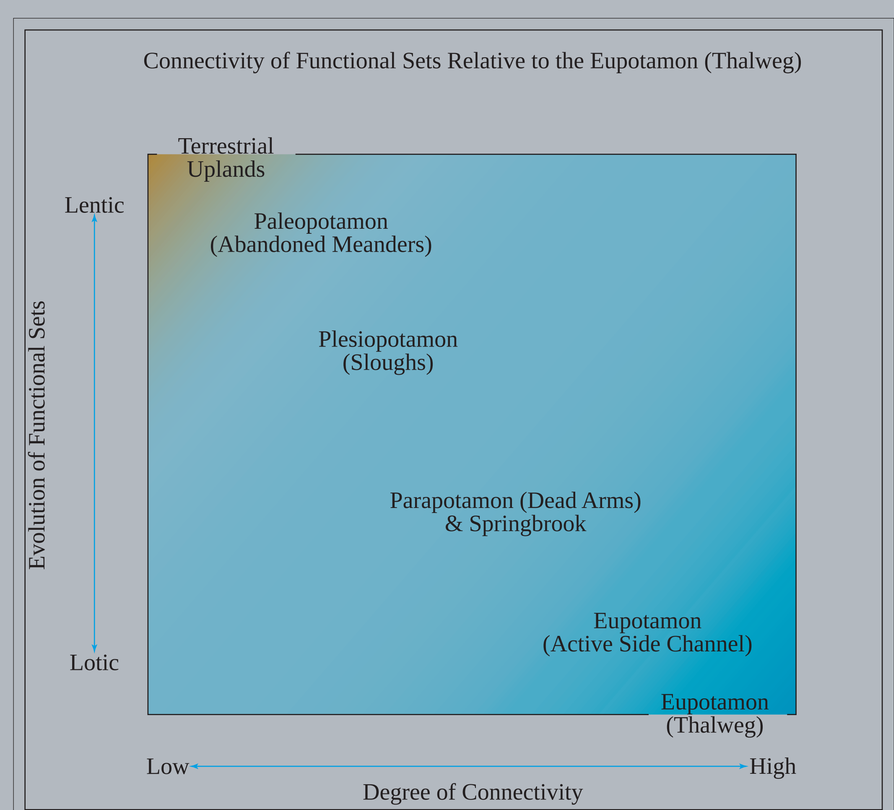

Figure 5c. Functional sets arrayed relative to their degree of connectivity with the mainstem channel and aquatic evolution (Modified from Ward and Stanford 1995).

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The Structure and Function of Alluvial Floodplains and Riverine Landscape Connectivity

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Ecological integrity in floodplain rivers is based in part on a diversity of water bodies with differing degrees of connectivity with the main river channel. Collectively, these water bodies occupy a wide range of successional stages, thereby forming a mosaic of habitat patches across the floodplain. This diversity is maintained by a balance between the trend toward terrestrialization and flow disturbances that renew connectivity and reset successional sequences (Ward and Stanford 1995).

All of the functional sectors described on plate IV occur at various spatial scales within the Yakima River basin. Figure 5a represents a generalized, hypothetical illustration in which each type of functional sector may occur in association within an unregulated alluvial floodplain. To consider the hydrologic characteristics of an unregulated cut and fill alluvial floodplain within the context of the Yakima Basin during flood helps to clarify the fluvial geomorphic processes at work and their consequent patterns. As the flood pulse exits a gorge sector, water begins to spread laterally across the floodplain, decreasing in velocity. No longer competent to carry its entrained load, the river begins to aggrade by depositing alluvium both within its channels and along its active margins. Large woody debris (LWD) accumulates within the mainstem river and its side channels and is deposited on the surface of the active floodplain. In-channel debris jams expedite the excavation of material directly upstream and redeposits this material directly downstream of their positions, facilitating the development of mid-channel bars and islands, point bars, and back-bar channels (Abbe and Montgomery 1996). Conversely, floodwaters also work to cut new channels through the process of avulsion and to reconnect extant side channels to the thalweg. These are just several of the many fluvial geomorphic processes that create the braided-anastomosed river pattern. In addition, some of the water moving across the floodplain in this sector downwells through the highly porous alluvium, and works to sustain a diverse assemblage of hyporheic habitats (Kinnison and Sceva 1963; Stanford and Ward 1993). Further downstream, overland flow coalesces with the thalweg. Having deposited much of its load, the mainstem river regains a higher level of competence and may assume a quasi-meandering pattern as the next gorge sector is approached. This is also the zone where groundwater traveling through preferential flow paths begins to upwell as a result of pooling behind the next sequence of anticlinal ridges. Upwelling groundwater may be delivered directly to an existing channel or emerge as a floodplain springbrook (Stanford and Ward 1993). These processes help create and maintain a diversity of channel forms within the three dimensional floodplain system through time.

As floodwaters recede, a diverse assemblage of channel types begins to emerge along the longitudinal scale and across the lateral scale of the floodplain. Examining each river sector at an intermediate scale of resolution, Amoros et al. (1987) identified varying forms of lotic, semi-lotic, and lentic water bodies within a given floodplain. They have grouped these features into "functional sets" (figure 5b). The "eupotamal," or true river, includes the main channel and its active side arms. Side channels connected to the eupotamon only at their downstream end are called "parapotamal," or near river channels. "Plesiopotamal," or recent river, describes formerly braided and braided-anastomosed channels entirely disconnected from the eupotamon. Also disconnected at both ends from the eupotamon, the "paleopotamal," or ancient river, describes abandoned meanders and oxbow lakes. Stanford and Ward (1993) have added a fifth functional set they call "springbrook."

Functional sets can also be classified sequentially by their degree of lotic-lentic evolution and their degree of connectivity to the mainstem channel (Ward and Stanford 1995) (figure 5c). For example, paleopotamon channels terrestrialize slowly because they typically occur far from the mainstem channel behind flood bars and; except for the eupotamon itself, exhibit a greater overall width and depth than any other functional set. In contrast, plesiopotamon channels terrestrialize rapidly because they are narrow, shallow, and occur close to the mainstem channel. These two channel types are essentially lentic in character because they remain disconnected from the mainstem channel except during high flow events. Parapotamon, springbrooks, and eupotamon side channels remain connected to the mainstem channel except during low flows and therefore are more lotic in character than either paleopotamon or plesiopotamon channel types. The presence of all these channel forms is directly attributable to the dynamic flood and flow pulse of the hydrosystem (Junk, Bayley, and Sparks 1989; Tockner, Malard, and Ward 2000).

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Plate V. The structure and function of alluvial floodplains and riverine landscape connectivity.

Riverine Landscape Connectivity
And The Effects Of Disturbance From Flooding

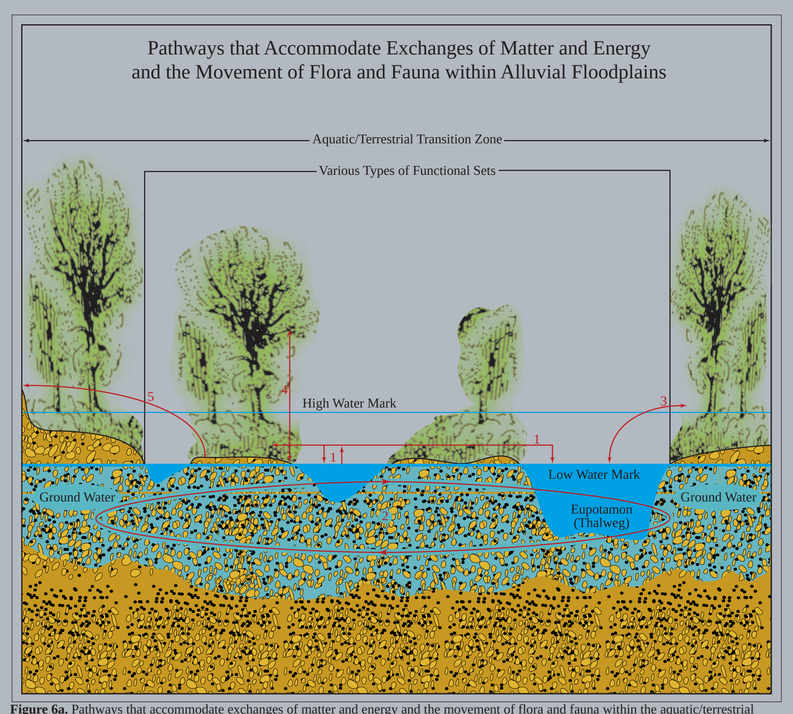

Figure 6a. Pathways that accommodate exchanges of matter and energy and the movement of flora and fauna within the aquatic/terrestrial transition zone (ATTZ) (Modified from Ward 1997).

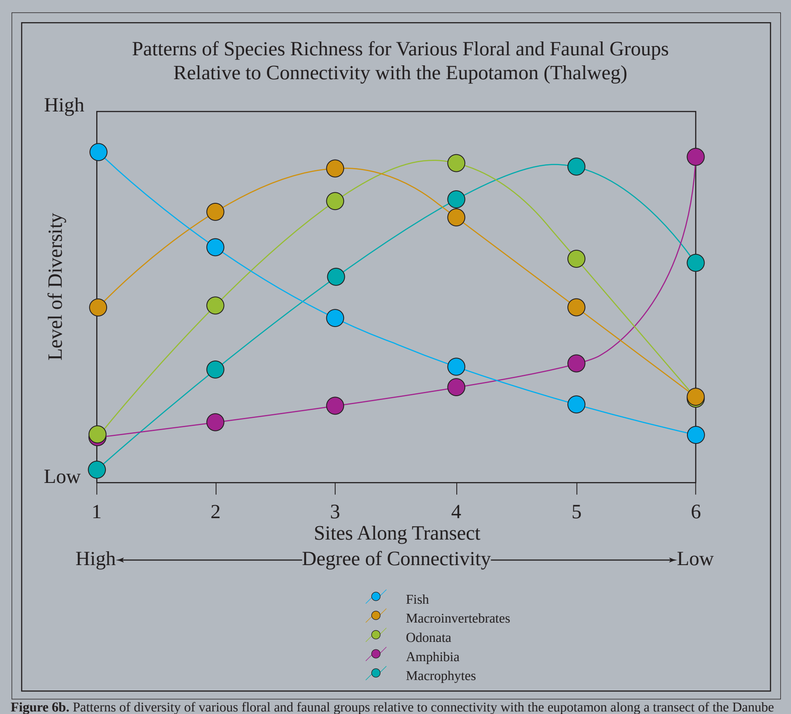

Figure 6b. Patterns of diversity of various floral and faunal groups relative to connectivity with the eupotamon along a transect of the Danube River floodplain (Modified from Ward 1997).

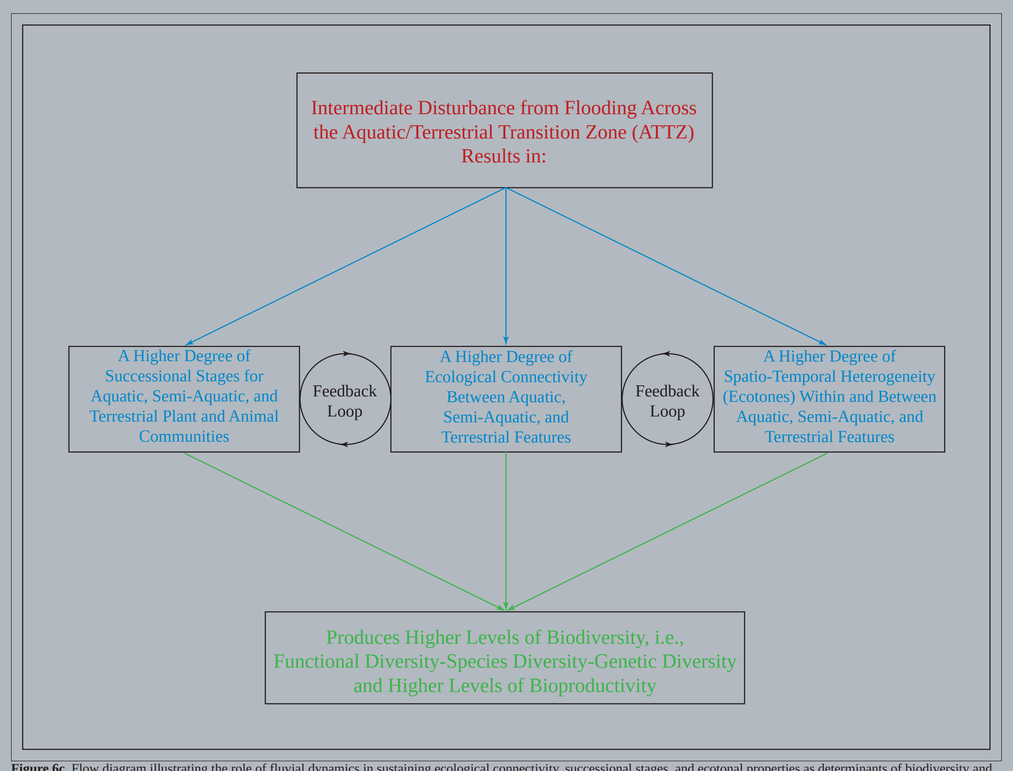

Figure 6c. Flow diagram illustrating the role of fluvial dynamics in sustaining ecological connectivity, successional stages, and ecotonal properties as determinants of biodiversity and bioproductivity (Modified from Ward, Tockner, and Schiemer 1999).

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Douglas J. Eitemiller

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Riverine Landscape Connectivity and the Effects of Disturbance From Flooding

By
Douglas J. Eitemiller and Clay P. Arango

The term "normative ecosystem" is by definition " ... necessarily general and focuses on biological and physical processes and conditions ... " (Independent Scientific Group 1996).

Not only do late winter and early spring floodwaters initiate, shape, and maintain the fluvial geomorphic character of the floodplain, they also influence its structural and functional ecological attributes. For example, terrestrial features in combination with semi-aquatic and aquatic functional sets accommodate exchanges of matter and energy and the movement of flora and fauna along the floodplain's longitudinal dimension, across its lateral dimension, and through its vertical dimension.

Figure 6a highlights some of the known pathways found within alluvial cut and fill floodplains. Pathway number one accommodates the movement of fishes that utilize connected side channels and springbrook systems during their juvenile life stage and then migrate to the eupotamon as adults (Copp 1989; Stanford and Ward 1992). Side channels also serve as sinks for plankton and aquatic invertebrates that are exported to the eupotamon during flood events. Pathway number two promotes the movement of specific species of aquatic insects that utilize the lattice of interstitial flow paths far from the eupotamon during their nymphal life-stage, and then migrate to the main channel to reproduce (Stanford and Ward 1993). Pathway number three highlights the exchange of dissolved inorganic matter and coarse particulate organic matter between the terrestrial, semi-aquatic, and aquatic components of the floodplain (Ward and Stanford 1995). Pathway number four represents the movement of terrestrial species from the floodplain to the riparian canopy during flood events; furthermore, other terrestrial species transmigrate from the floodplain to upland sites in pathway number five (Ward 1997). Collectively, these fluvial geomorphic patterns and associated ecological processes form the aquatic/terrestrial transition zone (ATTZ), a highly dynamic and diverse structural and functional landscape (Junk, Bayley, and Sparks 1989).

Figure 6b depicts patterns of species richness for select floral and faunal groups along a series of transects on the Danube River floodplain relative to the degree of connectivity with the eupotamon (Ward 1997). Fishes exhibited higher species richness within sites closest to the mainstem channel and connected side channels (eupotamon side channels and parapotamon channels). Biodiversity of macroinvertebrates was also higher within these connected side channel systems. The greatest numbers of species within the division odoanata were found in plesiopotamon channel types. Species richness for macrophytes was also higher within plesiopotamon channels. Diversity for the class amphibia was highest in paleopotamon channel types (abandoned meanders and oxbow lakes).

To recapitulate, it is the flood and flow pulses of the hydrosystem that are directly responsible for creating and maintaining the fluvial geomorphic patterns and ecological processes that define the character of the ATTZ. Figure 6c depicts how this disturbance regime determines to what degree ecological connectivity, successional stages, and habitat heterogeneity will occur across the spatio-temporal landscape found within the ATTZ. The interrelation of these three attributes consequently produces higher levels of biodiversity and bioproductivity. Moreover, the frequency of such events determines the degree of biodiversity exhibited within and between similar regions across an array of varied landscape scales. Connell (1978) predicts low species diversity within habitat types subject to both abnormally low and high levels of disturbance. Conversely, diversity is highest in those habitats experiencing an intermediate level of disturbance. Working in both unregulated and regulated lotic systems, Ward and Stanford (1983) have found patterns of diversity consistent with Connell's Intermediate Disturbance Hypothesis.

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Plate VI. Riverine landscape connectivity and the effects of disturbance from flooding.

The Yakima River Basin
And The Effects Of Regulation On Flow Regimes

The Yakima River Basin Within The State Of Washington

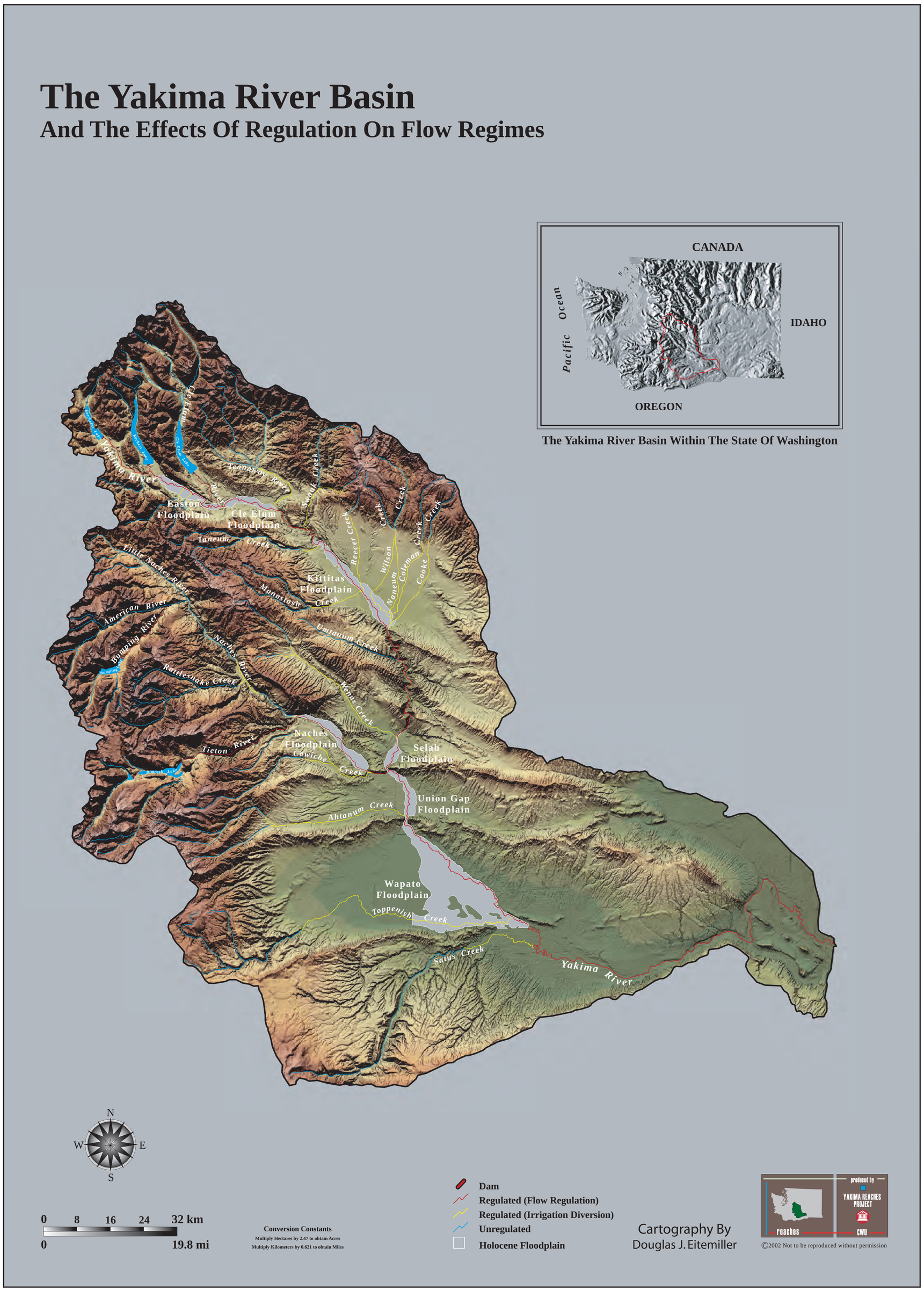

Plate VII. The Yakima River basin and the effects of regulation on flow regimes.

The Yakima River Basin And The Effects Of Regulation On Flow Regimes

By

Douglas J. Eitemiller and Clay P. Arango

The Yakima River basin ... is the largest single river system entirely within the confines of the State. Its waters are the most extensively utilized of all the rivers in Washington (Kinneson and Sceva 1963).

The first person to divert water within the Yakima River basin was a Native American named Kamiakin, who in the 1850s irrigated his small garden from Ahtanum Creek. Euroamerican settlers soon followed suit and began irrigating small plots of ground with water diverted from the Naches River in 1867 (Lyman 1919). Groups of individuals and private irrigation companies constructed the first sizeable diversions of size off many of the Yakima River's larger tributaries from the 1870s through the 1890s (Tuck 1995). By 1900, water right claims exceeded the total available water within the entire basin. During the summer of 1905, 55,442 hectares were under irrigation and "the entire flow of the Yakima River had been diverted" (Tuck 1995).

The promulgation of the 1902 Reclamation Act provided public funds for the first large-scale irrigation projects in the western United States, and in 1906 Congress authorized the building of the Yakima Project (Anderson 1996). The Bureau of Reclamation (BOR) started construction of the first storage reservoir at Bumping Lake in 1908. Completion dates for the six largest dams and their reservoir storage capacities are as follows:

Reservoir	Year	Storage (Acre Feet)
Bumping Lake	*1910*	*33,700*
Kachess Lake	*1912*	*239,000*
Clear Creek	*1914*	*5,300*
Keechelus Lake	*1917*	*157,800*
Rimrock Lake	*1925*	*198,000*
Cle Elum Lake	*1933*	*436,900*

(Bureau of Reclamation, Unpublished).

These federally-funded dams and storage reservoirs supply the regulated flow that sustains the intensive agricultural economy of the Yakima River basin today and have impacted the land and water courses of the Yakima Basin more than all other irrigation systems constructed up to that time (Anderson 1996). Currently, 259,000 hectares (16% of the basin) have been converted to irrigated agriculture. Most of this agricultural activity occurs within the valley-basin landscape of the Yakima River basin (plate II).

Regulation of waters impounded by a dam works to uncouple at least three fundamental ecological principles essential to the proper functioning of riverine systems. Early research on flow regulation focused on dams and the consequent modifications to the timing, quantity, and quality of flow released from their storage reservoirs. Their effects include the following:

1. *Habitat diversity is substantially reduced*
2. *Native biodiversity decreases and non-native species proliferate*
3. *Biophysical conditions reset predictably in relation to influences of tributaries and as distance downstream from the dam increases*

(Stanford et al. 1996).

This plate depicts the results of a Geographic Information System (GIS) analysis for the mainstem Yakima and Naches rivers and their major tributaries.
The designation "Regulated (Flow Regulation)" refers to those reaches primarily influenced by the release of storage flows from reservoirs and mainstem diversions that show marked differences in the timing and quantity of flow when compared to preregulation conditions. The designation "Regulated (Irrigation Diversion)" describes reaches primarily influenced by diversions for irrigated agriculture and rangeland. Data surrounding the effects of irrigation return flows in the Yakima basin suggests that the timing, quantity, and quality of flow in these reaches has diverged from pre-irrigation conditions (Cuffney et al. 1997). River reaches classified as "Unregulated" do not exhibit differences in the timing, quantity, or quality of flow as a direct result of dams or diversions, yet they may nevertheless be deleteriously affected by other land-use activities (plate III).

Results of the GIS analysis show that of the 1,991 kilometers of river corridor examined throughout the basin, 424 kilometers (21% of the total) are subject to the effects of flow regulation by dams and storage reservoirs. This includes the entire mainstem Yakima River from below Keechelus Dam to its confluence with the Columbia River, the Kachess and Cle Elum rivers from below their respective dams to their confluence with the Yakima River, the lower Naches River from where the Tieton River enters to its confluence with the Yakima River, the Tieton River from below Rimrock Dam to its confluence with the Naches River, and the Bumping River from Bumping Lake Dam to its confluence with the American River. Because the influence of regulated flow from the Bumping River is negligible (plate VIII), we do not consider that portion of the Naches River above the Tieton River confluence to be regulated.

Three hundred seventy-five kilometers (19% of the total) of smaller tributary streams within the Yakima basin are influenced by irrigation diversions. Most of these modifications begin at or just below the topographic break between the valley floor and the headwater basins these streams drain. Flow regimes of the Big Creek, Little Creek, Teanaway River, Swauk Creek, Taneum Creek, Reecer Creek, Wilson Creek, Naneum Creek, Coleman Creek, Cooke Creek, Manastash Creek, Wenas Creek, Cowiche Creek, Ahtanum Creek, Toppenish Creek, and Satus Creek have all been severely altered.

The majority of the 1,192 kilometers (60% of the total) of stream corridor within the basin that remain "Unregulated" drain the higher elevation headwater basins and do not exhibit differences that depart from pre-irrigation flows as a result of regulation *per se*.

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The Yakima River Basin

And The Effects Of Regulation On The Bumping, Tieton, and Naches Rivers

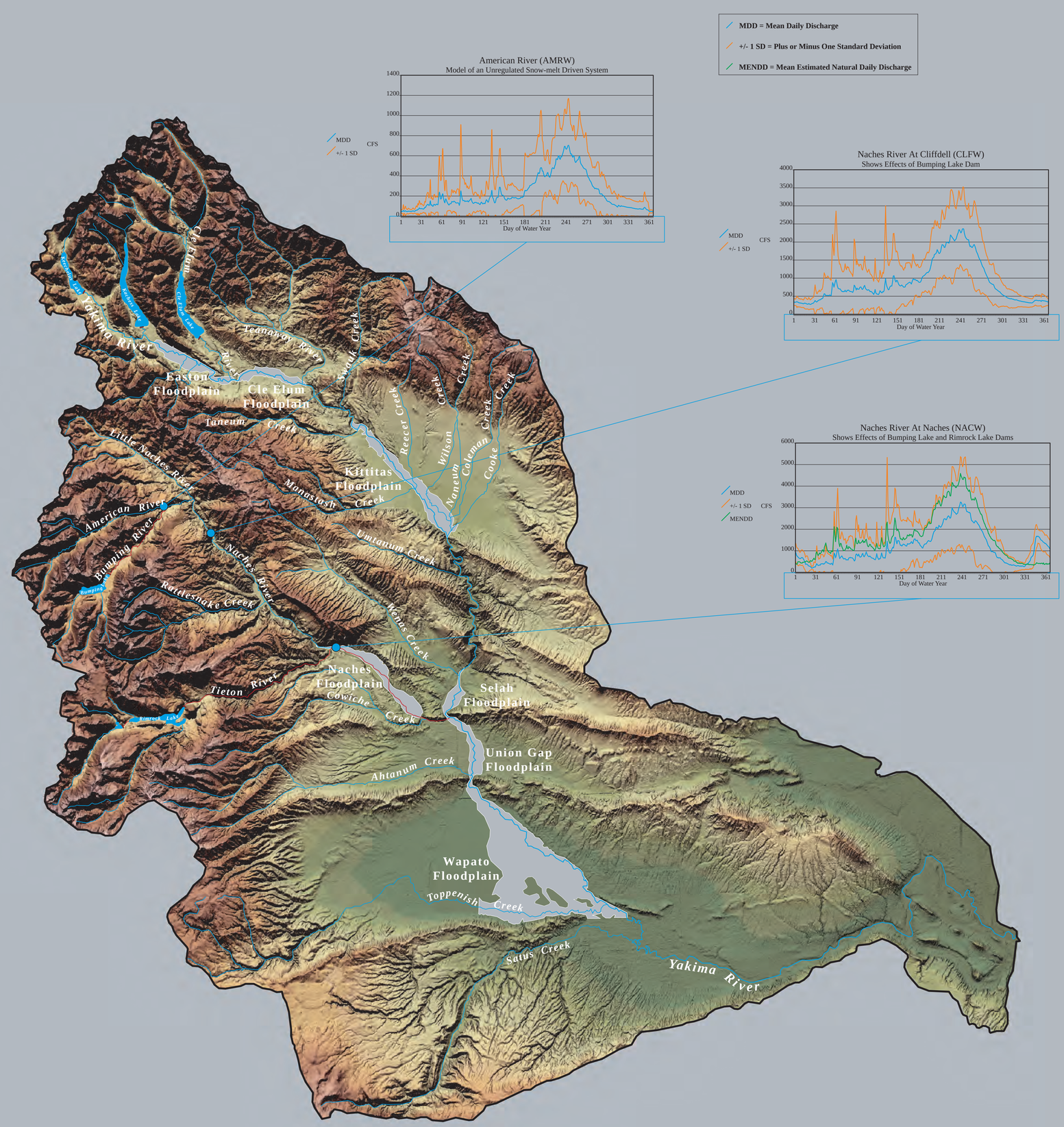

Plate VIII. The Yakima River basin and the effects of regulation on the Bumping, Tieton, and Naches rivers.

The Yakima River Basin And The Effects Of Regulation On The Bumping, Tieton, And Naches Rivers

By

Clay P. Arango and Douglas J.Eitemiller

Flow regulation is perhaps the most pervasive change wrought by humans on rivers worldwide (Stanford et al. 1996).

Comparing hydrographs of those rivers within the Yakima Basin affected by dams and storage reservoirs to their previous natural hydrographs elucidates the present existence of serial discontinuities within the fluvial hydrosystem. The data presented here were generated from Bureau of Reclamation gauging stations during the last twenty years (1981-2001).

The hydrograph for the American River yields the best estimation for flow dynamics in an unregulated Yakima system. It is very similar to other snowmelt-driven systems where the mean annual peak flow occurs through water days 215 and 270 (May through June). Because of the seasonal drought experienced by the inland Pacific Northwest, the hydrograph drops smoothly to base flow by late August when only groundwater discharge feeds the river. Fall rains during late October and early November send flow pulses through the system. The spikes of variability seen in the standard deviation bars between water days 31 and 151 (November through February) are indicative of localized rain-on-snow events.

The gauging station for the Naches River at Cliffdell measures the influence of the regulated Bumping River. Nevertheless, its hydrograph is very similar to that of the unregulated American River. It has the same characteristic spring flood peak of a snowmelt-driven system with a drop to base flow by late summer. The only storage facility upstream from this gauging station is Bumping Lake, the smallest of the five main Yakima Project reservoirs. Due to its small size, Bumping reservoir has little regulatory effect on the mainstem upper Naches River. In fact, the only apparent flow augmentation occurs between water days 340 and 15 of the following water year (September through mid-October) when flows increase from 325 cfs to almost 400 cfs. This is Bumping Lake's contribution to the annual flip-flop operation that characterizes the Bureau of Reclamation's Yakima Basin flow management system. The hydrograph for the Cliffdell gauging station shows that the upper Naches River has more in common with the unregulated American River than any other regulated Yakima System hydrograph, despite the influence from Bumping Lake.

The estimated unregulated discharge for the gauging station at the city of Naches displays the same pattern as for the American River. However, unlike the minimal effects of Bumping Lake reservoir, flow management from Rimrock Lake significantly affects mean annual discharge in the Naches River. This is the result of its greater storage capacity and the method in which its captured flow is managed. Tieton Dam reduces the spring mean annual peak runoff to approximately 75% of the estimated unregulated discharge. In fact, estimated unregulated discharge exceeds mean annual discharge for all days of the water year except from days 330 to 15 of the following water year (September through mid-October). This is a direct result of flip-flop, which occurs as a major flow pulse at the end of the irrigation season. At its peak, the mean flow pulse from flip-flop is half the discharge of the mean spring flood peak. Although one may consider the spring snowmelt and drop to base flow in the Naches system normative, the flow pulse from September through October is distinctly non-normative. This late season pulse has no analogue in an unregulated snowmelt system, with the possible exception of a low frequency stochastic event such as a catastrophic glacial melt-water flood. However, in an unregulated system such an event would have a much shorter duration.

Some effects from flip-flop may include the following: (1) excessive export of organic matter (Radford and Hartland-Rowe 1971); (2) altered channel geometry and thus, altered habitat template (Ligon, Dietrich, and Truch 1995); (3) catastrophic aquatic insect drift (Anderson and Lehmkuhl 1968); (4) decreased late season spawning success due to bed scour (Nicolai 2001); and (5) stranding of insects (Corrarino and Brusven 1983; Kroger 1973; Minshall and Winger 1968) and redds (Tuck 1995) because of rapid flow recession at the end of flip-flop. This list is by no means comprehensive. However, because flow regulation in the lower Naches River has lowered flood magnitude and decreased flood frequency, the habitat template has most likely experienced a significant change as compared to its preregulatory status.

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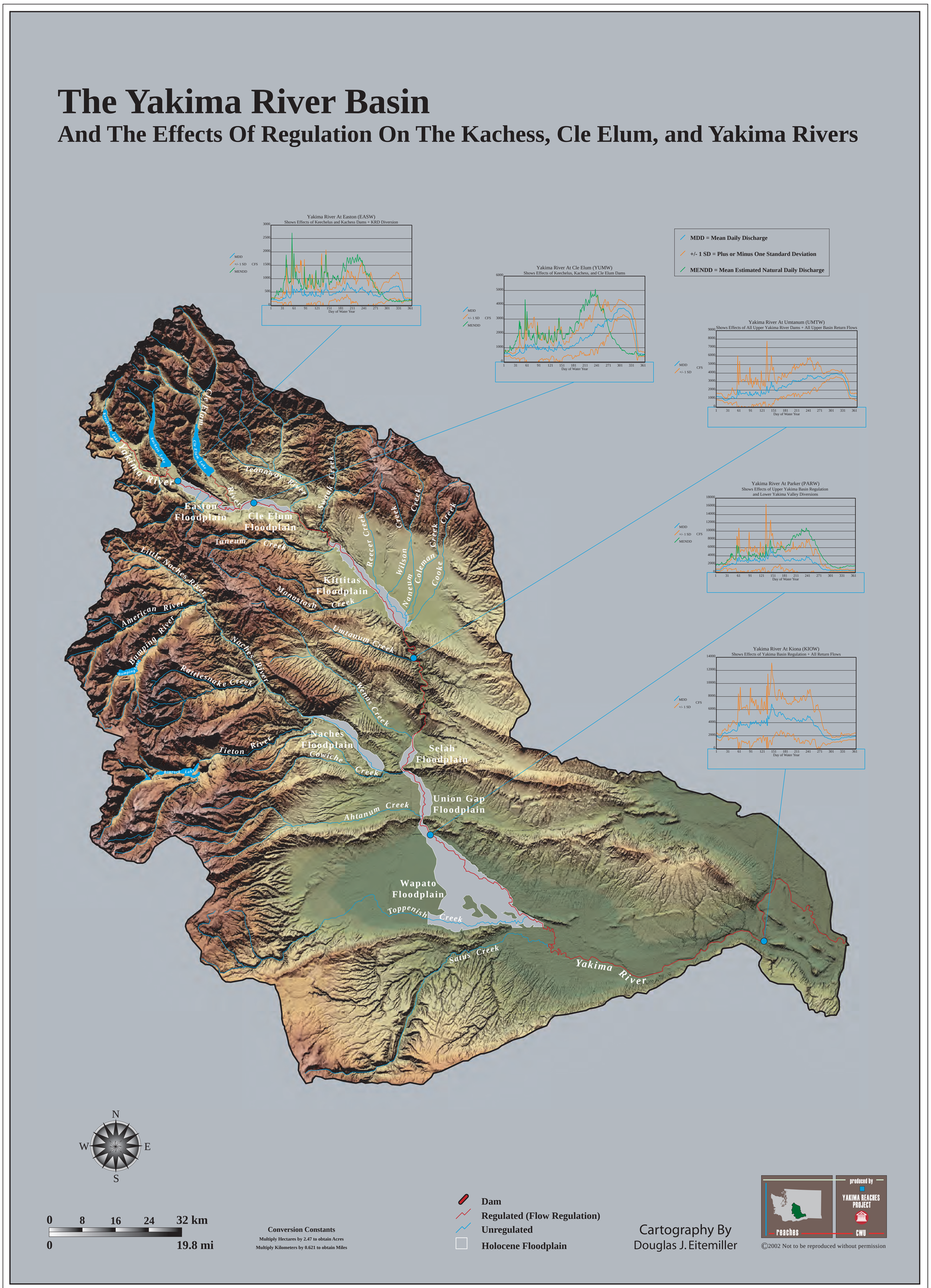

Plate IX. The Yakima River basin and the effects of regulation on the Kachess, Cle Elum, and Yakima rivers.

The Yakima River Basin And The Effects of Regulation On The Kachess, Cle Elum, And Yakima Rivers

Clay P. Arango and Douglas J. Eitemiller

Rivers cannot be seperated in theory or practice from the lands they drain (Hynes 1975).

Lakes Keechelus and Kachess, two of the five storage reservoirs in the Yakima Project, lie upstream from the Kittitas Reclamation District (KRD) diversion at Easton. The hydrograph for the gauging station on the Yakima River from just below this diversion is exemplary of a regulated flow regime. There is no distinct spring peak flow, nor is there a smooth drop to base flow. At the end of the water year in the first weeks of September, flip-flop operation brings discharge to a stable level so spring chinook salmon can spawn without danger of redd stranding. The estimated unregulated discharge data available for this gauging station are suspect. These data suggest that the mean annual flow peak occurs over a very brief window in early December and that this peak exceeds the mean annual spring snowmelt by almost thirty percent.

The hydrograph for the gauging station at Cle Elum defines the full extent of upper Yakima River regulation closest to the source of the largest reservoir in the Yakima Project, the Cle Elum Dam and storage facility. Water from this reservoir supplies lower Yakima Valley irrigation demand and is delivered by using the upper Yakima River system for conveyance. This hydrograph is exemplary of a completely regulated system. By comparing estimated unregulated discharge with mean annual discharge from this point in the river continuum, we see that regulation has effectively shifted the mean annual hydrograph forward by two months. Like the Easton hydrograph, the spring peak flow has been eliminated. The rapid drop to base flow accompanying the initiation of flip-flop has been shown to strand aquatic insects, increase aquatic insect drift density, and reduce benthic insect diversity (Arango 2001). Regulated winter discharge is also lower and less variable than the estimated unregulated discharge.

The Umptanum hydrograph is very similar to the Yakima River at Cle Elum. Its differences result from additional flow inputs by numerous tributary streams and return flows from the KRD irrigation project across the Cle Elum and Kittitas valleys. Winter mean annual discharge mimics the pattern of the Cle Elum hydrograph; however, the comparative variability of peak winter flows between the two graphs reveals the effective differences between rain-on-snow events here and at the Cle Elum station.

The general characteristics of flow regulation in the upper Yakima branch of the basin include the following: (1) peak flow reduction in volume and frequency; (2) elevated summer flows; and (3) a sharp drop in flow as flip-flop commences. Some effects from flow regulation may include the following: (1) increased vegetation recruitment due to less frequent scouring flows, leading to locally increased channel stability (Ligon, Dietrich, and Truch 1995); (2) stranding of sessile insects after flip-flop (Arango 2001); (3) reduced nutrient exchange between the floodplain and river channel due to less frequent overbank flows (Junk, Bayley, and Sparks 1989; Tockner, Malard and Ward 2000); (4) high frequency, small discharge flood events that are central components to maintaining habitat connectivity, occurring less frequently and altering habitat formation processes (Heiler, Heim, and Schiemer 1995); (5) altered thermal dynamics due to the large proportion of flow from reservoirs with hypolimnetic release which leads to fewer degree days available, decreased insect fecundity, less secondary production, and therefore, decreased productivity at higher trophic levels (Ward and Stanford 1979).

The above discussion of flow regulation impacts to the two upper Yakima Basin sub-watersheds characterizes the flow delivery aspect of the system. Most of the flow in the system is bound for the large, lower valley irrigation districts that divert water downstream from Union Gap. Hydrograph characteristics from the next two gauging stations highlight changes that result from a system dominated by flow withdrawal, rather than by flow augmentation.

The Parker gauging station, located downstream from the major lower valley diversions, reveals a flow pattern that completely diverges from the hydrographs for the upper basin. Differences between estimated unregulated discharge and mean annual daily discharge illustrate the effects of reduced flow throughout the year and significantly reduced volumes during summer peak flow. Because headwater reservoirs capture the peak flow that is diverted just upstream from Parker, the snowmelt flow pulse is never fully expressed here. In fact, the highest mean annual peak flow occurs in March rather than in early June, as one would expect under an unregulated snowmelt-driven system. However, stochastic rain-on-snow events at this station have not been significantly affected by storage reservoirs, as evidenced by flow variability between water days 55 and 160 (late November through early March).

The hydrograph for the Kiona gauging station, located near the confluence of the Yakima and Columbia rivers, shows the same pattern as the Parker hydrograph. At this point almost all irrigation return flows have re-entered the river, so this hydrograph captures the net effect of flow regulation on the Yakima system. For example, in all other hydrographs analyzed the spring flood peak has been markedly reduced in volume. It was missing from the Easton hydrograph but re-enters the river (minus loss from evapotranspiration and irrigation) in the Kittitas Valley as the flow diverted at Easton Dam finishes routing through the KRD. In the Cle Elum and Umtanum hydrographs, it is shifted forward. In the Naches system, the flood peak is reduced and a portion of it is put back into the system in the fall. At Parker the flood peak is missing, diverted through the Roza Irrigation District, the Sunnyside Valley Irrigation District, and Wapato Irrigation Project lands. The significance of the hydrograph for Kiona is that the spring flood peak is completely removed from the system, lost to evapotranspiration and irrigation.

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Contemporary research shows that anthropogenic modifications made to alluvial floodplains extend the effects of flow regulation further along a river's longitudinal scale, and across its lateral scale, than would otherwise occur (Bravard, Amoros, and Pautou 1986; Sparks et al. 1990; Stanford and Ward 1992). The construction of railroads, roads, and levees exacerbate the loss of biodiversity, bioproduction, and the proliferation of non-native species that result from flow regulation. The following methodology permits both qualitative and quantitative comparisons of changing fluvial geomorphic processes and patterns and the structural and functional ecological attributes contingent on those processes as a result of anthropogenic alterations through time.

METHODOLOGY

This study demonstrates the application of a GIS-based analysis in assessing the effects of anthropogenic alterations on seven select alluvial floodplains within the Yakima River basin, Washington. The methodology progresses through a sequence of steps that define the following:

- Development of a spatial scale within which the analysis was performed
- Development of a temporal scale within which the analysis was performed
- Analysis of those anthropogenic features that effect lateral connectivity
- Interpretation of aerial photography to define and analyze differences in the extent of active floodplain zones and the length of channel types as a result of anthropogenic features
- Acquisition and processing of digital imagery.

The first step was to define a spatial scale for the analysis. Using the USGS 1:100,000 Geologic Quadrangle series and 1990s color aerial photography as a reference guide, the perimeter of each floodplain was interpreted and transferred to a corresponding USGS 1:24,000 Quadrangle map. This bounding unit was then digitized from each Quadrangle map using the ArcInfo 7.2 GIS. It represents the areal extent of surficial material deposited by the mainstem Yakima River throughout the Holocene period (8,000 YBP-present). As such, this unit demarcates the area in which the mainstem Yakima River and its associated water bodies were present at one time or another during the last 8,000 years. We refer to this unit as the Holocene floodplain, or geomorphic floodplain, throughout this text. The biological and ecological significance of this fluvial geomorphic feature, discussed above, cannot be understated (plates IV, V, VI). The perimeters of all floodplain limits have been field-verified and are considered highly accurate.

After establishing a spatial scale within which all analysis would occur, we developed a temporal scale intended to capture snapshots of anthropogenic features that could affect lateral connectivity across all seven floodplains. Three discrete periods were defined. Time 3 encompasses the period from 1884 through 1915. This period represents the emergence of the railroad and early county road systems throughout the Yakima Basin. Time 2 spans the period from 1916 through 1964 and was dominated by the advent of the state highway system. Time 0 captures the most recent stage of development and is characterized by the interstate highway system, the continued growth of the state and county road network, and flood levees. Railroads and roads were identified using the USGS 1:125,000 Quadrangle map series from 1902, the USGS 1:62,500 Quadrangle map series from 1958, the USGS 1:24,000 Quadrangle map series, and the most recent available orthophotography as reference data. Levees were mapped onto mylar sheets overlaid on color aerial photography while we rafted the mainstem Yakima River through each floodplain reach. All of the features listed above that could potentially prevent small, frequent, flood events from spreading over a portion of the respective floodplain were then digitized for each temporal scale. We acknowledge that larger floods may have had the potential to breach railroad beds, roadbeds, and rudimentary flood revetments in places. However, we assumed that land use activity behind these features would soon revert to the pre-flood environment, effectively precluding riverine successional processes and maintaining lateral disconnection. The lack of a consistent construction record precluded the placement of levees into a known period. Therefore, they were assigned to the most recent period. Although this diminishes the accuracy of area reportedly affected by these features within the temporal analysis on some of the floodplains, the results for floodplain area currently disconnected from the mainstem Yakima River were not affected. The locations of all anthropogenic features that could influence lateral connectivity have been field-verified and are considered highly accurate. Plates XI, XIII, XV, XVII, XIX, XXI, and XXIII represent the results from this GIS-based temporal analysis of anthropogenic alterations and their subsequent effects on lateral connectivity.

Those areas that lie between the center of the mainstem Yakima River and the nearest anthropogenic feature within each period are representative of where the river could potentially accomplish geomorphic work. However, areas of active hydrologic cut and fill alluviation also exist within all floodplain reaches. We define this area as the active floodplain (Huggenberger et al. 1998). Those portions of each floodplain exhibiting riparian vegetation, active channel forms (eupotamon side channels, parapotamon channels, plesiopotamon channels, and springbrooks), and an absence of cultural land use features (e.g. land cleared for pasture or irrigated agriculture) were classified as active floodplain. Analysis of aerial photography for periods two and zero determined the extent of those areas meeting these criteria. Their boundaries were then "heads-up" digitized on the corresponding digital aerial photographs for each floodplain reach. Plates (XII, XIV, XVI, XVIII, XX, XXII, and XXIV) represent the results from this GIS-based temporal analysis of the active floodplain.

An analysis of the effect of anthropogenic features on the lengths of various channel types between the last two periods was also conducted. A protocol that differentiates the various channels defined by Amoros et al. (1987) was implemented to insure a consistent record. The protocol is as follows:

- Eupotamon - the thalweg or active channel (defined as the corridor of the river where vegetative growth does not occur because of frequent scouring flows), and segments of the active channel that split into two channels where neither appears subordinate. They are lotic in character.
- Eupotamon side channel - connected to the eupotamon on both its upstream and downstream end, but tending away from the active channel at the apex of its arc. These channels exhibit unidirectional flow and are significantly smaller than the eupotamon itself. They are lotic in character.
- Parapotamon - connected to the eupotamon or eupotamon side channel only on its downstream end and exhibiting multidirectional flow. They are semi-lotic in character.
- Springbrook - connected to any of the above channel types on its downstream end. However, springbrooks may arise within eupotamon side channels and parapotamon channels during low flows or from areas outside of these channel types but within the Holocene floodplain. They are lotic in character.
- Plesiopotamon - not connected at their top or bottom end but occurring within the hydrologically active floodplain. Depending on flow volumes, these channels may or may not carry water. They are lentic in character.
- Paleopotamon - not connected at their top or bottom end. These channels always carry water and most often occur far from the hydrologically active floodplain. However, in the context of analysis, anthropogenic features may result in this channel type occurring within close proximity to the eupotamon; for example, the disconnection of a meander by a flood revetment. They are lentic in character.
- Outflow channel - a channel known to drain an anthropogenic feature such as a gravel pit pond or waste treatment facility. In the context of this analysis, these do not include springbrook channels that deliver irrigation return flow to the mainstem river.

All of these channel types exist along a gradient of connectivity to the eupotamon itself. Therefore, channel segments were classified by their degree of connectivity. For example, if a springbrook channel flows into a parapotamon channel, the length of the segment from where they merge to the next differing channel segment was recorded as parapotamon. Because these channel types vary at different flow volumes, this classification scheme was highly dependent on the flow recorded by gauging stations through each floodplain reach at the time the aerial photography was made. Therefore, differences in the length of all channel types between the last two periods can only be compared across those floodplain reaches exhibiting similar flows. However, because variable flow volumes do not appreciably affect the length of the mainstem river, differences in its length were comparable across the last two periods. All channel segments were "heads-up" digitized on corresponding digital aerial photographs for each floodplain reach.

The earliest aerial photography available was used for this research. Aerial photographs from 1927, 1942, 1945, and 1947 were scanned into digital files for the time two analysis. They were then rectified and geo-referenced into an appropriate coordinate system, Universal Transverse Mercator (UTM) Zone 10, North American Datum (NAD) 27 using ERDAS Imagine software. Digital orthophotography from 1992, 1993, and 1994 was utilized as a geo-referenced backdrop for the time zero analysis.

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Plate X. Methodology.