THE CATHERINE CREEK REACH ASSESSMENT
GRANDE RONDE RIVER BASIN
Tributary Habitat Program, Oregon

U.S. Department of the Interior
Bureau of Reclamation
Pacific Northwest Region
Boise, Idaho

December 2012

U.S. DEPARTMENT OF THE INTERIOR

Protecting America's Great Outdoors and Powering Our Future

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Cover Photograph: View of Catherine Creek.

Bureau of Reclamation photograph – Catherine Creek Reach Assessment-Grande Ronde River Basin-Tributary Habitat Program, Oregon – July 2012.

RECLAMATION
Managing Water in the West

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Acronyms and Abbreviations

BPA	Bonneville Power Administration
CCACF	Catherine Creek Adult Collection Facility
cfs	cubic feet per second
DEM	digital elevation model
ELJ	Engineered logjams
ESA	Endangered Species Act
FCRPS	Federal Columbia River Power System
GRMW	Grande Ronde Model Watershed
HCMZ	Historic channel migration zone
HEC-RAS	Hydraulic Engineering Center's River Analysis System
LiDAR	light distance and ranging
LWM	large woody material
NOAA Fisheries	NOAA's National Marine Fisheries Service
NPCC	Northwest Power and Conservation Council
NRCS	Natural Resources Conservation Service
ODFW	Oregon Department of Fish and Wildlife
Reclamation	U.S. Bureau of Reclamation
RM	river mile
RPA	Reasonable and prudent alternative
Tributary Assessment	Catherine Creek Tributary Assessment
USACE	U.S. Army Corps of Engineers
VSP	Viable salmonids populations
WACCIA	Washington Climate Change Impacts Assessment

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Introduction

The Bureau of Reclamation (Reclamation) and Bonneville Power Administration (BPA) contribute to the implementation of salmonid habitat improvement projects in the Upper Columbia Basin to help meet commitments contained in the 2010 Supplemental Federal Columbia River Power System (FCRPS) Biological Opinion (BiOp) (NOAA Fisheries 2010). This BiOp includes a Reasonable and Prudent Alternative (RPA), or a suite of actions, to protect salmon and steelhead listed under the Endangered Species Act (ESA) across their life cycles. Habitat improvement projects in various Columbia River tributaries are one aspect of this RPA. Reclamation provides technical assistance to states, tribes, federal agencies, and other local partners for identification, design, and construction of stream habitat improvement projects that primarily address streamflow, access, entrainment, and channel complexity limiting factors. Reclamation's contributions to habitat improvement are intended to be within the framework of the FCRPS RPA or related commitments. The assessments described in this document provide scientific information on geomorphology and physical processes that can be used to help identify, prioritize, and implement sustainable fish habitat improvement projects and to help focus those projects on addressing key limiting factors to protect and improve survival of salmon and steelhead listed under the ESA.

Tributary and reach assessments are early steps in a process aimed at focusing habitat improvement efforts toward the most beneficial actions in the most appropriate locations (Figure 1). Several project areas may be selected based on the assessments and feedback from local project partners and stakeholders. Each project area may undergo an alternatives evaluation to conceptually identify the project that best improves habitat while addressing local stakeholder needs. The preferred conceptual alternative is typically then advanced through a design process that incorporates feedback from several technical reviews provided by local and regional review teams and permitting agencies. With landowner and funding entity approval and permits in place, the final design is advanced for construction. Following construction, Reclamation and other groups monitor the physical and biological performance of the project. Performance deficiencies may be remedied through adaptive management.

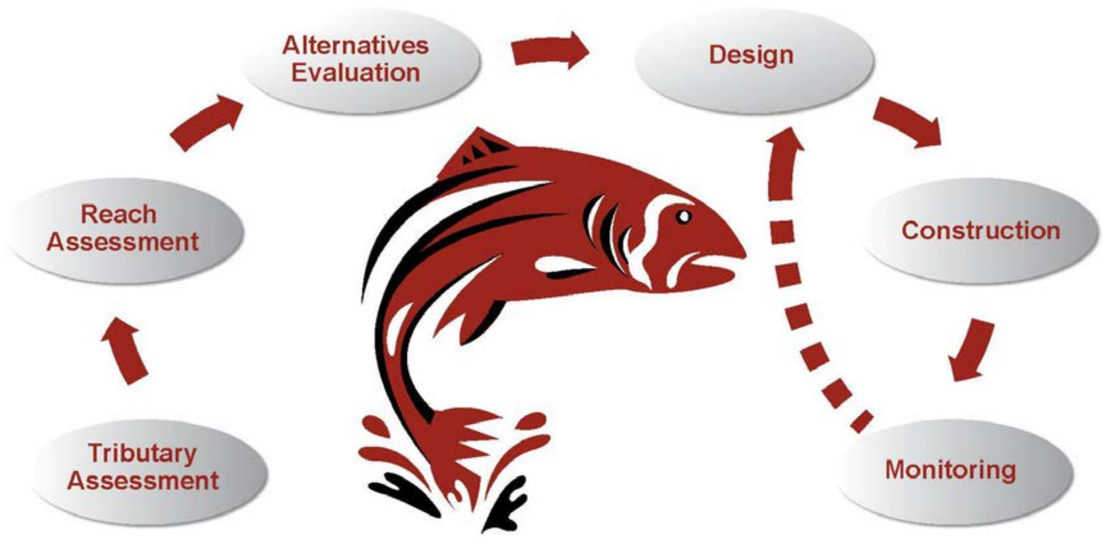

Figure 1. Flow chart illustrating typical steps in the approach to habitat improvement.

Purpose of this Reach Assessment

This Reach Assessment is a compilation report providing a range of scientific information relevant to habitat improvements for salmon and steelhead over a spatial scale fine enough to identify specific habitat improvement actions and coarse enough to support continuity between those actions. The purpose of this Reach Assessment is to assess and document reach-scale characteristics and the changes over time for identifying suitable habitat improvement actions that address known limiting factors within the reach. The completed Reach Assessment can be used to guide future habitat rehabilitation, ensuring that specific projects are developed and advanced in a manner suitable to the geomorphic character and trends prevalent throughout the reach. In this way, a reach-scale approach to habitat improvement can be facilitated.

Reach Assessment Philosophy

This Reach Assessment represents a reach-scale refinement of data and analyses presented in existing watershed-scale reports such as the Catherine Creek Tributary Assessment (Tributary Assessment) (Reclamation 2012a). Information in the Reach Assessment is not intended to duplicate previous efforts, rather it is intended to provide a summary of pertinent larger-scale background information and expand upon that information at the reach scale. The Reach Assessment area was prioritized from the Tributary Assessment in which Catherine Creek was divided into unique valley segments and reaches based on changes in geomorphic character along the length of the channel and its floodplain. Three separate valley segments were identified along Catherine Creek based on channel gradient, geologic controls, and channel morphology. This Reach Assessment covers two reaches, reach 3 and reach 4 that were delineated in the Tributary Assessment. Reach 4 is part of the upper valley group (valley segment) and reach 3 is the sole reach in the Alluvial Fan valley segment. Together these two reaches include about 8.7 river miles (RM) of Catherine Creek.

Although essentially all of Catherine Creek has been identified as a priority for some type of habitat improvement, various strategies for habitat improvement may or may not be appropriate for specific reaches. The Tributary Assessment identified a potential habitat improvement implementation strategy following a hierarchical philosophy adapted from Roni et al. (2002). Following is an outline of the implementation strategy developed in the Tributary Assessment as it pertains to the assessment area:

1. Habitat Protection: Habitat protection is suitable for reaches that have little or no impacts to physical processes and habitat. None of the reaches within the assessment area were identified as a high priority for protection in the Tributary Assessment, due to anthropogenic impacts that could be addressed.
2. Reconnect Isolated Habitat: Reconnect main channel to wetted off channel areas where appropriate. Connection to the floodplain and off-channel habitat was identified in the Tributary Assessment for areas within reach 4 and reach 3, although this assessment indicates that the lack of habitat connectivity is largely a natural constraint within sections of reaches 3 and 4.
3. Re-establish Processes (long term): Re-establishing natural channel process is necessary in order to improve and maintain habitat over the long term. Changes and impacts to channel process will be addressed in the Existing Conditions section of this report.
4. Re-establish Habitat (short term): The Tributary Assessment documented and confirmed previous assessments and studies that identified the need for more habitat complexity in Catherine Creek, including pools, large woody material (LWM), spawning gravel, and improved riparian function.

Reach Assessment Goals

There are two primary goals for this Reach Assessment:

1. Document past (historic), existing (baseline), and potential target physical conditions within the assessment area.

2. Identify potential actions to improve processes and thereby habitat and classify each action's ability to address the limiting factors and attain the target physical conditions.

Using this Document

This report is intended for use by interdisciplinary scientists, engineers, biologists, and planners focusing on fish habitat improvement and rehabilitation. Conclusions from this Reach Assessment are intended to guide future project development as one tool among many others. The primary use of the Reach Assessment should be to guide habitat improvement actions toward those options that are most geomorphically sustainable for a given reach, while providing a means to begin prioritizing a variety of actions based on potential benefit to habitat. This document should not be used exclusively as the basis for habitat design. Detailed, site-specific analyses should be conducted to identify the most appropriate suite of actions, refine conceptual plans, and develop detailed designs for implementation.

This Reach Assessment was prepared by physical scientists and engineers at Reclamation, with assistance and feedback from an interdisciplinary team of local and regional scientists and practitioners familiar with Catherine Creek. This document was prepared following a review of available background information, significant remote analysis using a Geographic Information System (GIS), and multiple site visits during high- and low-flow conditions. Focus was placed on reach-scale data since larger-scaled data were already documented in the Tributary Assessment. Finer-scaled data will likely be necessary for each project proposed in the future.

Information documented in this report is focused around physical processes and physical changes occurring in Catherine Creek. Species such as steelhead, Chinook salmon, and other key species evolved with the physical environment of Catherine Creek over thousands of years. Efforts to re-establish natural and appropriate physical conditions represent an improvement to habitat for these species.

Background Information

The North and South Forks of Catherine Creek come together and flow for 55 miles through the southwestern edge of the Wallowa Mountains before joining the Grande Ronde River on the Grande Ronde Valley floor at RM 140 (NOAA Fisheries 2008) (Figure 2). The assessment area consists of a portion of Catherine Creek from RM 45.8 downstream to RM 37.2 that includes geomorphic reaches 4 and 3 (Figure 3).

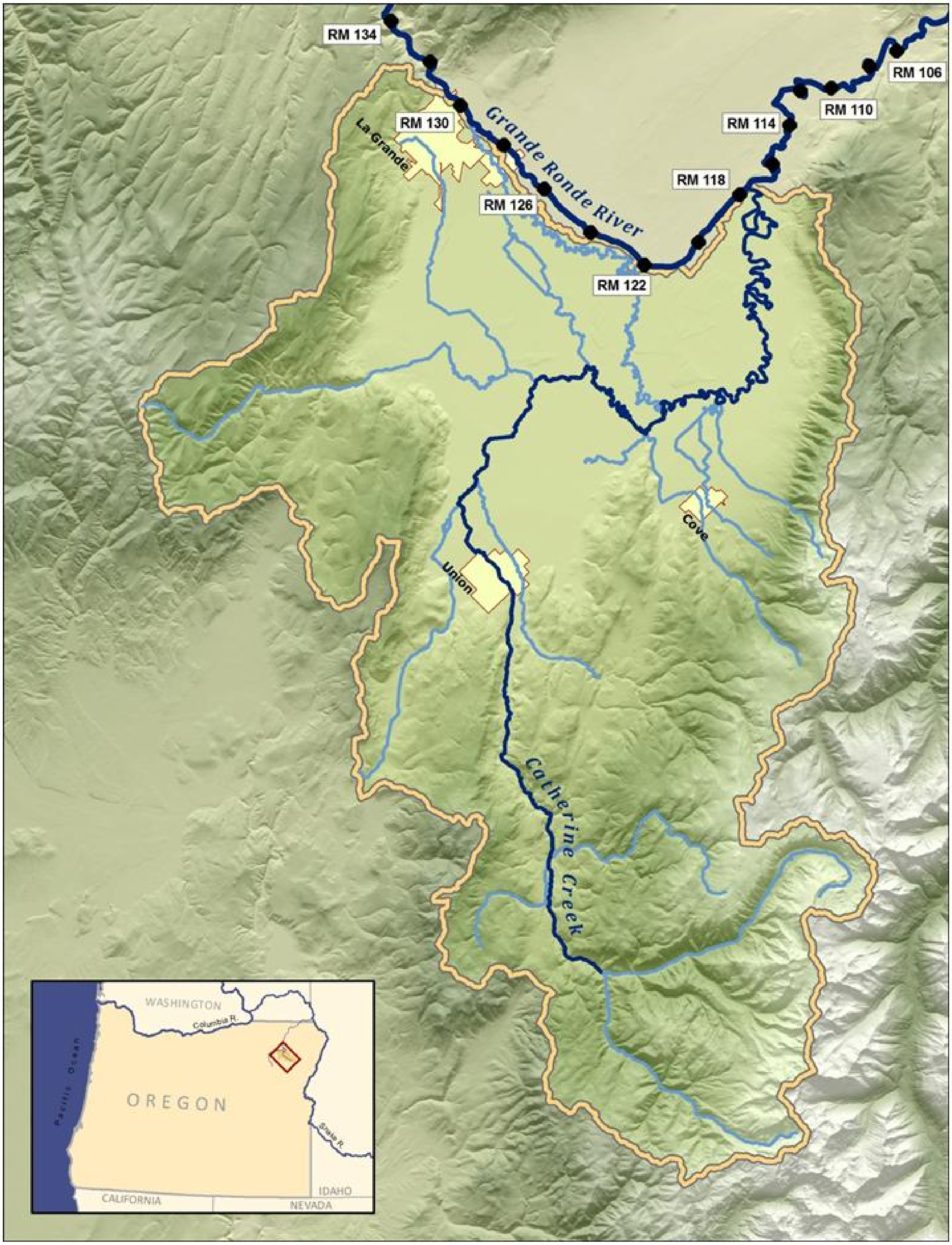

Figure 2. Catherine Creek vicinity map.

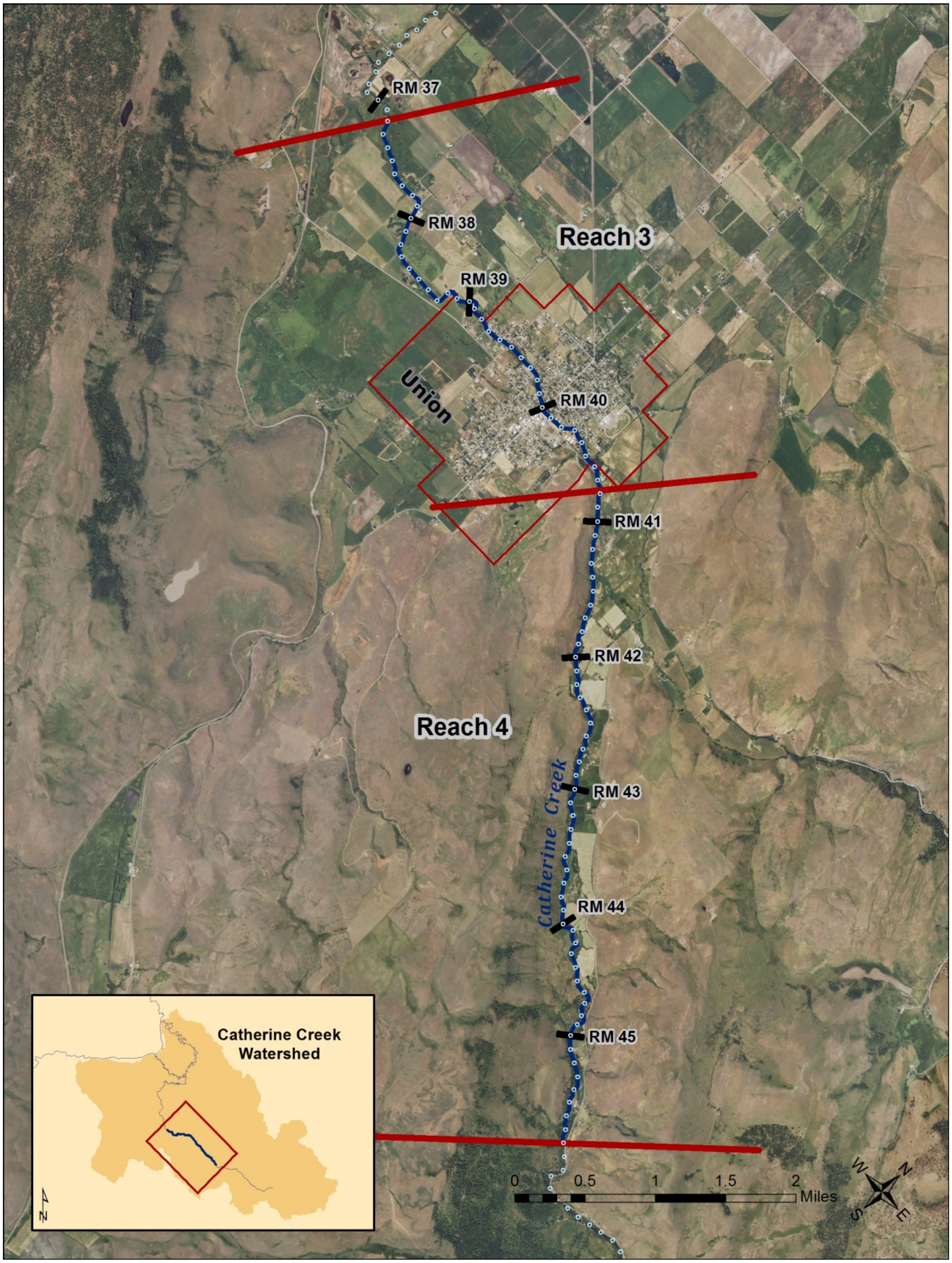

Figure 3. Aerial image of the assessment area, reach breaks, and the city of Union, Oregon on Catherine Creek.

Limiting Factors

Limiting factors are defined as the physical, biological, or chemical conditions and associated ecological processes and interactions (e.g., population size, habitat connectivity, water quality, water quantity, etc.) experienced by fish that may limit the viable salmonid population (VSP) parameters (i.e., abundance, productivity, spatial structure, and diversity). This report focuses exclusively on physical conditions for Upper Grande Ronde steelhead (*Oncorhynchus mykiss*) and Catherine Creek Chinook salmon (*O. tshawytscha*), both of which are listed under the ESA. The draft *Conservation and Recovery Plan for Oregon Spring/Summer Chinook Salmon and Steelhead Populations in the Snake River Chinook Salmon Evolutionary Significant Unit and Snake River Steelhead Population Segment* (NOAA Fisheries 2008) and supporting reports (Huntington 1994; GRMW 1995; NPCC 2004) have documented the limiting factors for spring Chinook in Catherine Creek as (not in a ranked order):

1. Water quality (high summer water temperatures).
2. Water quantity (low summer flow).
3. Excess fine sediment.
4. Poor habitat quantity and diversity.
5. Poor riparian conditions.

In addition, primary threats to the Catherine Creek population of spring Chinook are water withdrawals, roads, livestock grazing, and timber harvest.

The listed limiting factors for steelhead in Catherine Creek are similar, but also include low dissolved oxygen levels (water quality), lack of pools (habitat diversity), poor fish passage, and predation.

Summary of Existing Reports

Some previous reports have suggested that Catherine Creek has been severely impacted by anthropogenic alterations, resulting in the degradation of fish habitat. The severity of the anthropogenic impacts, while somewhat subjective, may have been poorly understood and likely overestimated by not fully evaluating the likely condition of the river before Euro-American settlement or by relying on historical accounts without independent substantiation of their descriptions. This assessment indicates that alterations to Catherine Creek have impacted the instream habitat complexity, channel pattern, and pools, and to a lesser degree, channel geometry and migration rates, though not to the extent suggested by some previous estimates.

Pertinent reach-scale information has been extracted from past work and used in this Reach Assessment. Specific broad-scale background information from existing reports and analyses has been summarized to help develop a better perspective regarding the reach-scale information to follow.

Regional Scale

Catherine Creek flows out of the Eagle Cap Wilderness of the Wallowa Mountains and onto the Grande Ronde valley floor within the Blue Mountain physiographic province in northeast Oregon. The modern Grande Ronde Valley is a large structural basin situated along the east flank of the Blue Mountain uplift, bordered by the Blue Mountains to the northwest with peaks as high as 7,700 feet in elevation, the Wallowa Mountains to the east with peaks of nearly 10,000 feet elevation, and the Elkhorn Mountains to the south with peaks over 9,000 feet in elevation (Carson 2001). The valley is filled with up to 1,550 feet of sandy silt interbedded with thin seams of gravel and sand derived from glaciers and alluvial processes (Van Tassell 2001; Ferns et al. 2002). Deposition during the Pleistocene resulted from three episodes of alpine glaciation in the highlands of the Elkhorn and Wallowa mountains when the Grande Ronde River and Catherine Creek carried glacial outwash into the valley (Ferns et al. 2002). The sediments developed into terraces and alluvial fan-delta deposits. Lacustrine sediments on the valley bottom are indicative of a very low energy environment and hints that intermittent damming of the outflow of the basin may have occurred or large floods resulted in substantial backwater affects that resulted in long-term inundation of the valley bottom (Reclamation 2012a).

Watershed Scale

Catherine Creek and nearby creeks and rivers are dominated by spring snowmelt. Most of the annual precipitation in the Blue and Wallowa mountains occurs during the winter in the form of snow. Peak flows can occur from April through June but generally occur in May, with the Catherine Creek near Union gage showing an average peak date of May 13. Late fall, winter, and early spring rain-on-snow events can develop into substantial peak flow events that approach the magnitude of the annual snowmelt peak. Winter freeze-thaw events are common in the region and can contain large quantities of ice that cause locally damaging floods and promote scour and bank erosion (Reclamation 2012a).

The two principal species of concern in Catherine Creek are Upper Grand Ronde steelhead, listed as threatened under the ESA and Catherine Creek Chinook salmon, listed as endangered under the ESA. Steelhead adults tend to spawn between March and mid-June upstream of the town of Union, Oregon (Reclamation 2012a). Steelhead fry emerge from May to July. Steelhead may remain in Catherine Creek for up to 4 years before leaving the subbasin for their migration downstream to the ocean. The average ocean-going smolt age is 2 years (Reclamation 2012a). Chinook salmon adults are typically holding in the Grande Ronde subbasin near spawning tributaries by June or July, with spawning usually occurring in August and September (NPCC 2004) predominantly upstream of the town of Union, Oregon. The Chinook generally spawn in the section of Catherine Creek upstream of Union and the fry emerge generally between March and early May (Reclamation 2012a).

Valley Segment Scale

Reach 4 is the downstream reach of the upper valley group that encompasses from RM 54.9 at the top downstream to RM 40.78 at the downstream end of reach 4 (Figure 4) (Reclamation 2012a). Within the reach, the stream is relatively straight with bed material consisting of gravel and cobble with sand and boulders. The banks are comprised of similar material, but are also overlain by a layer of silty fine sand with clay that varies in thickness from 0.5 feet up to 2 feet. Within reach 4, sediment is supplied by upstream sources locally within the reach, particularly the upper section of the reach. Overall, the reach is a sediment supply limited transport regime with more capacity to transport sediment than the amount of sediment supplied.

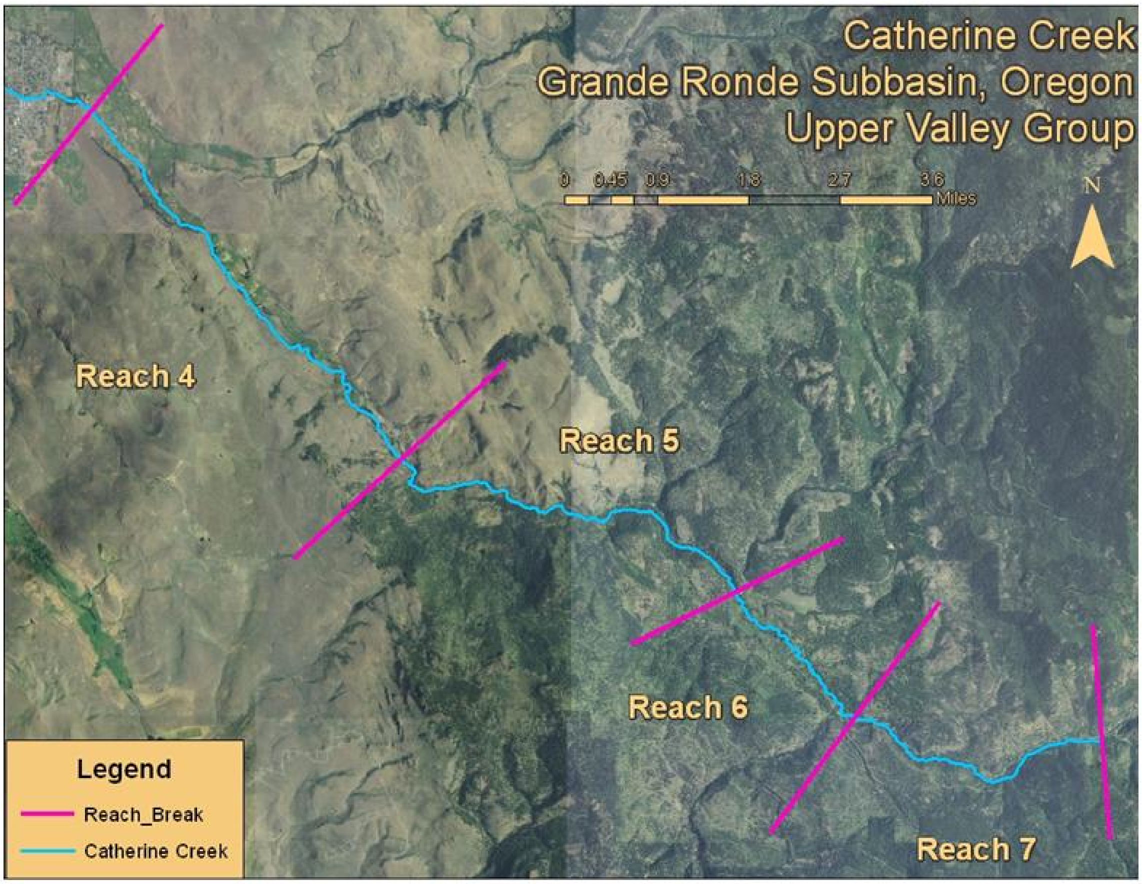

Figure 4. Location of reach 4 within the upper valley group on Catherine Creek. Reach 7 runs from RM 54.9 to 52.0. Reach 6 runs from RM 52.0 to 50.11. Reach 5 runs from RM 50.11 to 45.8. Reach 4 runs from RM 45.8 to 40.78.

Reach 3 encompasses a historical alluvial fan and transitions into fluvial plain in the downstream end (Figure 5). Typical morphological features of a fan include the apex or head where channel incision is common but may not be present, the medial or upper section and the distal, or downstream end. Channel incision, when present, commonly terminates in the medial sections at what is called the intersection point, but can also persist all the way to the distal margin (Blair and McPherson 1994). Incision can also work upstream from the distal end in the form of a head cut. The channel may be a single thread trunk stream or spilt into multiple distributary channels (Blair and McPherson 1994).

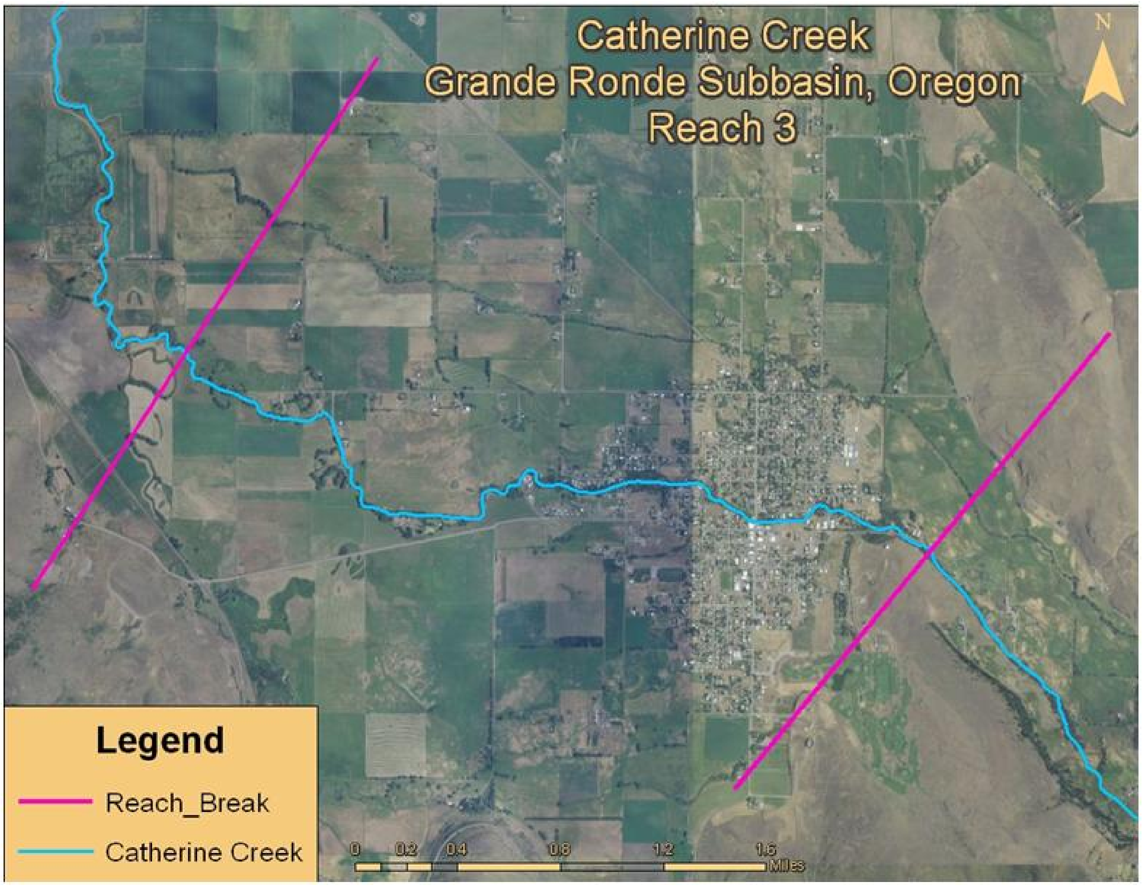

Figure 5. Location of reach 3 from RM 40.7 downstream to RM 37.2 on Catherine Creek.

The upper section of reach 3 is similar to reach 4 in bed and bank material. The banks grade into finer material in the lower section of the reach as the alluvial fan structure grades into fluvial plain and lacustrine sediments. Sediment supply is derived primarily from upstream sources, but local sediment incorporation through bank erosion does occur locally within the reach. Overall, the upstream section is supply limited sediment transport regime and the downstream is a transport-limited regime.

Sections of bare bank are common in both reaches, however, accelerated bank erosion is limited to a local section of reach 4, and overall bank erosion does not significantly contribute to the supply of sediment in the river within the two reaches.

Historical Timeline

Prior to the arrival of Euro-American settlers in the mid 1800s, Native American tribes used established camping and fishing sites on Catherine Creek and the Grande Ronde Valley floor to raise horses and collect Camas root. Recorded manipulations to the channel form, flow, and floodplain of Catherine Creek began upon the arrival of Euro-

American settlers. Table 1 is from Tributary Assessment (Reclamation 2012a) and is a brief summary of historic events on Catherine Creek in the areas of reaches 4 and 3. A more detailed time line for the Grande Ronde Valley can be found in the Tributary Assessment (Reclamation 2012a).

Table 1. Historic events within the assessment area on Catherine Creek.

Year	Historic Event
1861	Conrad Miller was the first to claim pioneer residence on Catherine Creek.
1862	Union was founded by E.H. Lewis, Fred Nodine, and Samuel Hannah.
1863	First irrigation noted on Catherine Creek
1864	First sawmill and hydro-powered dam in Union established on Catherine Creek near present day library. Another sawmill and dam was built 6 miles upstream on Catherine Creek.
1865	Water-powered flourmill built on Catherine Creek on the east edge of Union.
1881	Spring flood floated bridge in Union
1891	July thunderstorm hit valley and up Catherine Creek. Large boulders and logs scattered along all of drainage.
1948	Catherine Creek peak flow during the spring is 1,740 cubic feet per second (cfs). Five blocks of business and residential area underwater in Union
1964	July 31 flash flood on Catherine Creek. Heavy salmon mortality around State Park
1983-84	Ice jams on Catherine Creek in February

Historical Conditions

For this report, the historical conditions are defined as the unaltered or natural conditions representative of the assessment area prior to large-scale human influences (i.e., Euro-American settlement). Although it is not the goal of habitat improvement to restore those exact historic conditions, it is those natural historical conditions in which the species of concern evolved and will likely thrive in the future. As such, the historical conditions and the physical processes that created them can be used as a guide for developing the target conditions for the reach. To reduce redundancy, conditions will be described collectively for each reach within the assessment area because the majority of their reach characteristics are similar. Characteristics specific to a given reach or area will be identified as such.

Historical Form

Forms represent physical conditions on the landscape and in the river. Large-scale forms include the geometry, gradient, and composition of the valley and channel, which largely define the overall character of the channel. Smaller-scale forms include instream structures, bedforms, and channel shapes that provide complexity and diversity to the channel, often representing habitat for fish.

Historical Valley and Channel Forms

Reach 4

The assessment area of Catherine Creek was shaped by three episodes of alpine glaciation in the adjacent highlands of the Wallowa Mountains and the Elkhorn Mountains during the late Pleistocene and early Quaternary (as recently as 10,000 years ago) (Ferns et al. 2002). During post-glacial melting, increased water volume, sediment supply, and transport capacity in Catherine Creek carried glacial outwash downstream to fill the valley floor in reach 4, and out to build an alluvial fan in reach 3 before flowing on to the flat valley floor. Along the valley walls alluvium and colluvium was supplied by presumably intermittent streams and debris flows.

Following the period of increased sediment and discharge associated with the post-glaciations in the Pleistocene, the climate in the Grand Ronde subbasin became warmer and drier. Both discharge and sediment yield decreased following the disappearance of the glaciers, resulting in Catherine Creek becoming an underfit stream, generally defined as a relatively small stream flowing through a valley that was filled in with sediment deposited by a larger river. The channel would have likely been somewhat sediment supply limited, resulting in the overall depletion of smaller sediment to leave behind an armor layer of cobble and boulder substrate that is the dominant substrate observed today throughout the majority of the reach. Given the relatively constant width and planform of the channel over the observable period of 66 years, the channel likely did not have a sinuosity much higher than now and also did not migrate across the entire valley floor, but remained within a preferred location within the historic channel migration zone (HCMZ). The overall narrow width of the HCMZ and low sinuosity are influenced by the structural geology and subsequent surface topography within sections of reach 4 on Catherine Creek. In the downstream end of reach 4, Catherine Creek flows along a major fault scarp that bounds the southwest side of the valley, which has as much as 210 meters (693 feet) of down and to the east displacement (Ferns et al. 2002; 2010). The location of the fault and eastward displacement lends to a surface topography that slopes to the west, toward the left side of the valley, which provides some natural control on the location, and planform of the river. Local geology in the form of bedrock outcrops also provides lateral and vertical control.

Bank stability was likely high as a result of the underfit stream conditions, combined with a mature, forested riparian corridor likely consisting of willow, alder, and hawthorn, and a dense overstory of cottonwood (Gildemeister 1998). The banks and adjacent floodplain consisted of gravel and cobble with sand and boulders overlain by silt and clay.

Planform

Reach 4

Within reach 4, the historical Catherine Creek was predominantly a single thread channel with a relatively straight channel pattern (sinuosity of less than 1.5 [Beechie et al. 2005]); moderate to low gradient, with coarse alluvium and colluvium comprising the bed and banks. There were local sections of limited floodplain and off-channel habitat areas in the form of side or overflow channels. The majority of complexity and habitat in the lower river was provided by instream rock and/or accumulations of woody material, beaver dams, and riparian cover along channel margins.

In reach 4, channel pattern and sinuosity was largely a product of physical process including hydraulic discharge and sediment transport regime, coarse bed and bank material including bedrock, and dense mature riparian vegetation. Catherine Creek slowly cut its path through those areas of least resistance, resulting in an overall fairly straight channel pattern with meanders forced by obstructions due to bedrock, sediment and/or debris accumulations, and occasional beaver dams. In the downstream end of the reach, the structural geology and surface topography would have also reduced the rates of bank erosion and meander bend formation, reinforcing the generally straight channel pattern. Using GIS to build a hypothetical historical channel planform based on current meander wavelength and amplitude, well-defined channel scars and recently disconnected meander bends, a reasonable estimate of the historical average sinuosity for reach 4 is 1.09 to 1.1.

Reach 3

Downstream of the present day site of the town of Union, Oregon, Catherine Creek built an alluvial fan structure in reach 3. The floodplain function associated with an alluvial fan structure is different from that of a typical fluvial floodplain. The section of the reach located on the alluvial fan was pre-historically dynamic with multiple high-flow channels. Flooding would have spread out across the sloping fan surface as sheet and distributary flow rather than in a discreet floodplain, and fine sediment would have been dispersed without building a typical depositional floodplain surface. The channel may have been single-threaded following seasonal high flows or sediment transport events, and the channel location may have switched back and forth between multiple channels across the fan surface. At the toe of the fan in the lower third of the reach, the channel exhibited a developed floodplain due to a lower gradient and the ability of the finer grained sediment to spread out on the relatively flat surface of the valley floor

(Reclamation 2012a). Once on the valley floor, the channel would have meandered through beaver pond lakes and wet meadows.

Historically, sinuosity in reach 3 was higher than currently observed due channel straightening efforts that include channel shortening through the cutting off of meander bends and relocating sections of the main channel. In the upstream section of the reach, nearly all of the major anthropogenic modifications to the channel planform that have occurred in this reach were complete by 1937. Some local changes are observed to have occurred after that time. Estimates for the average sinuosity in reach 3 based on the channel centerline in the 1937 aerial photography is 1.5. Based on this and the modifications that had already occurred at this time, a reasonable historical average sinuosity for reach 3 is 1.5 to 1.7, with the downstream end of the reach having a higher historic average sinuosity than the upstream end.

Historical Instream Structure Form

Reach 4

Historically, the predominant bed form within reach 4 likely ranged from pool riffle to plane bed (Montgomery and Buffington 1997). Bedrock, large boulders, beaver dams, and wood likely provided historic instream structure and form in reach 4 of Catherine Creek. Bedrock and large boulders would have been most prevalent along the left valley wall, where boulders were supplied by historic alluvial fan and debris flow complexes along the hill front (Ferns et al. 2002). Bedrock crops out in the downstream end of the reach along the left valley wall and locally comprises the left bank and channel bottom. In-channel obstructions, including wood and sediment accumulations or beaver dams would have triggered local channel avulsion or migration and the development of local scour pools due to flow convergence, as well as sediment storage.

A 1934 to 1942 U.S. Bureau of Fisheries summary stream habitat survey for sections that include reach 4 reported an average of 20 resting pools per mile (McIntosh et al. 1990). Six pool classifications were presented based on area and depth criterion, and in both reaches, the dominant pool type was defined as 25 to 50 square yards ($yd^{2)}$, and 3 to 6 feet deep (McIntosh et al. 1990), but it is not known at what flow the surveys were conducted. The Bureau of Fisheries section that contains reach 4 extends upstream of the reach 4 boundary to contain all of reach 5.

In addition, small pools and pockets of hydraulic diversity included areas of slower water. Historically, slower-water habitat existed along roughened channel margins near the banks, in the affected area of beaver dams, and on the downstream side of the occasional large instream structure. With very little historical channel migration in the majority of the reach, point bars and other low-lying floodplain areas would have been few in number; therefore, very few primary or instream side channels likely developed under historical conditions. Secondary or floodplain side channels would have been prevalent in areas where beaver were active.

Reach 3

Reach 3 is an alluvial fan in the upstream section from RM 40.78 to 39.12 that grades into a fluvial plain in the downstream section from RM 39.12 to 37.2 (Ferns et al. 2002). The processes that formed it are remnant from the post-Pleistocene runoff and wetter climates (Reclamation 2012a). With the onset of underfit stream conditions in post glacial times, the stream would have remained in a predominantly fixed position, with possible incision in the upper (medial) section, and extending the intersection point (the point where the incised stream meets the surface of the fan) downstream, potentially all the way to the downstream (distal) toe (Blair and McPherson 1994). Incision may also have occurred from the downstream end and migrated upstream as a head cut.

Historic instream structure and form in reach 3 of Catherine Creek was likely provided by coarser alluvial material and woody debris that would have produced a wide range of bedforms. In the upstream section of the reach, the predominant bedform would have been plane bed possibly grading into riffle bar and/or riffle pool. In the downstream section, the predominant bedform would have been pool-riffle. The downstream section would have also had a more developed floodplain due to less confinement of the main channel and active floodplain process of deposition of finer material beyond the banks. In-channel obstructions, such as large wood accumulations would have occurred on an infrequent basis, but would have induced local scour and/or avulsion. Avulsion and channel switching because of sediment deposition in the active channel would have been common during the period of increased discharge and sediment during the early postglacial period, but becoming much more infrequent as the climate warmed and dried.

The 1934 to 1942 survey summary reported an average of 27 pools per mile, with the dominant pool type the same as described for reach 4 (McIntosh et al. 1990). In the upstream section of the channel, the confined, straight, and steep plane-bed form would indicate few pools. If the channel became less confined and developed a floodplain, there may have been a greater number of pools, but it was still likely overall lower than stated.

Historical Process

In an alluvial system, channel processes maintain a relatively stable condition by adjusting numerous variables, which are mutually interdependent, and include hydrology, sediment transport, channel migration, large wood recruitment, and riparian conditions. In order to maintain a state of quasi-dynamic equilibrium, one or more variables respond to change in the others. The response time for adjustment depends on the degree of change and the inherent condition of the river system. During historic post glacial conditions, reach 4 and 3 of Catherine Creek were underfit and the channel form was a relic of hydrologic and sediment transport processes that were generated during the melting of the glaciers. The historic channel lacked the hydrology and sediment transport processes to significantly alter its form and historic channel processes were superimposed onto a remnant channel form. Under these historic conditions, the time required for natural processes to adjust the channel form due to changes in the variables would have been generally longer than in an unconfined actively forming alluvial channel.

Hydrology

The valley that contains reach 4 of Catherine Creek was filled with coarse glacial sediment during the Pleistocene Epoch under conditions of higher flow discharge and sediment supply. After the glacial period, the climate became warmer and drier. There have also been additional measurable changes of the hydrology within the last 60 years associated with climate change. Peak spring discharges are occurring earlier in the year by as many as 11 days and the average annual water yields have decreased over the same period by 13 percent in Catherine Creek (Reclamation 2012a). The reduction of overall discharge during the postglacial period and the overall reduction in water yields noted in the last 60 years indicate that Catherine Creek historically was an underfit stream.

Sediment Transport

Sediment transport consists of two parameters: competency and capacity. Competency refers to the maximum grain size a stream is capable of transporting. Sediment capacity refers to the volume of sediment transported by a stream and is dependent on the channel competency and sediment supply.

Stream competency was higher during the beginning of the Pleistocene post-glacial time due to increased flow volume associated with the melting of the glaciers. During this time, high volumes of water may have enabled Catherine Creek to move boulder sized material. Sediment capacity was also higher due to the sediment production of the glaciers.

Within reach 4, boulders with a diameter of approximately 2 feet that are present are subangular to subrounded and were likely supplied from the adjacent hillslope along the left bank. Rounded material observed within the channel and comprising the banks that measured up 1.5 feet in diameter was likely supplied by glacial-melt water. Following the last glacial episode, the climate warmed/dried, the peak hydrology, and the stream capacity diminished resulting in underfit stream conditions. As a result, the stream was only capable of transporting up to smaller cobble and gravel sized material, which was both transported into and through from upstream, as well as mobilized out of the bed and banks, and transported downstream within the reach.

Within reach 3, Catherine Creek would have also been less dynamic further into the postglacial period compared to the early stages. Channel avulsion and switching, and deposition of coarse material would have decreased as a result of decreased flow volume and sediment load.

Channel Migration

Lateral channel migration within reach 4 on Catherine Creek was historically low. Natural controls contributing to low lateral migration rates include structural geology (valley wall faulting) and associated surface topography, local geology (bedrock), and dense riparian vegetation. Additional controls on rates of lateral migration are overall channel planform and width, which are results of the geomorphic processes including hydrology and the sediment transport regime. Work by Beechie et al. (2006) shows that return intervals for the erosion of the floodplain through lateral migration processes for unconfined straight channels, which are defined as streams with a sinuosity of less than 1.5 is approximately 89 years. This means that, on average, it would require 89 years for this type of channel to migrate laterally the distance of one full channel width. Furthermore, streams with bankfull widths of approximately 50 feet or less typically do not have the competency to migrate across their floodplain.

Episodic occurrences of deposition of large amounts of sediment or woody material transported in from upstream may have caused the channel to avulse around the obstruction, but the new position of the channel would have remained within the HCMZ, and the re-routing of the channel likely would have been temporary.

Within reach 3, historic lateral channel migration rates would also have been low. During the increased runoff and sediment transport during the postglacial runoff, channel migration on the alluvial fan surface typically occurred as channel avulsion and switching between channels rather than through lateral bank erosion, bar formation and floodplain building. The slope of the fan surface, especially near the apex (upstream end), coarse sediment size, and volume of bed load transported onto the fan contributed to processes where episodic bed load transport events filled and plugged the channel in the upstream part of the reach, causing the stream to avulse or completely abandon its channel and either form a new channel or occupy a former channel (channel switching). As the flow volume and sediment load decreased, the channel switching decreased and the current channel location became the main channel. This continued reduction of flow volume resulted in underfit conditions, allowing the channel to become confined and function like an incised stream.

Large Wood Recruitment and Retention

Under conditions that vary from across individual river systems, that can include degree of deformable bed and/or banks, range of channel slopes, and size range of substrate, LWM has the potential to significantly influence channel form and process at multiple scales. At the reach scale, large wood can effectively increase pool frequency, increase hydraulic roughness and channel competence, and alter sediment transport by reducing bed-surface grain size (Montgomery et al. 2003). At the channel unit scale, wood can affect the size and type of pools, bars, and steps in coarse-grained channels (Montgomery et al. 2003). Wood can also affect channel geometry and plan form by localized redirection of flow (Naimen et al. 2002; Montgomery et al. 2003). Processes of wood delivery to streams range from those that provide predictable inputs over long periods, to rare episodic events that generate large amounts of wood in a short period of time (Naimen et al. 2002).

Within reach 4, large wood would have been supplied from two sources with two different mechanisms; transported into the reach from upstream by fluvial processes, and from local inputs within the reach including wind throw and mortality of trees along the bank related to stand development and succession (Naimen et al. 2002). Large wood incorporation through channel migration and/or bank erosion would have occurred, but was likely low due to the low rates of lateral channel migration. Beaver were likely another source of wood material.

Once incorporated into the system, retention of large wood likely occurred at locations such as the apex of instream bars where flow is split at high to moderate flows, against boulder-sized colluvium where wood would lodge as flows decrease, and to a lesser degree on the outside of bends where fallen trees could rack (collect) additional woody material and on the inside of meander bends where wood may lodge on the lateral bar as high flows recede. The moderate transport competency of the river would have served to mobilize most large wood within the channel, suggesting that what LWM was present would have been found mainly in island apex and lateral point bar jams. Occasionally single trees or small collections of woody material would have lodged against bank vegetation or on bars. These wood accumulations may have been long-lived or transient depending on the structure, and would have provided valuable cover habitat and provided a local hydraulic effect. Residence time of large wood in a system varies greatly and depends on numerous factors including species (coniferous vs. hardwood), processes including submergence, burial and wetting and drying and overall decay rates (Naimen et al. 2002). On average, a coniferous piece of large wood will reside on the surface for 84 years and hardwood for less than 50 years. Even with potential low rates of large wood incorporation from lateral channel migration within the assessment area, given the average residence times, overall amounts of large wood in reaches 4 and 3 were likely higher historically than what is observed today.

Riparian Disturbance and Succession

Riparian disturbance occurred infrequently and over relatively small areas as a result of low rates of channel migration. Riparian vegetation would have been varied in composition and well developed with mature to decadent overstory in most locations. The root mass within the banks of the undisturbed riparian vegetation would have contributed to low rates of channel migration.

Existing Conditions

Existing conditions describe the processes and resulting forms that currently exist within reaches 4 and 3. The reach scale existing conditions were assessed during the fall of 2011. To document the extent of change in channel position over time, data in the form of historical aerial photos from as far back as 1956 were used for reach 4 and 1937 for reach 3. Data collected to assess existing conditions also included light detecting and ranging (LiDAR) topography, sediment size data, cross sectional survey data, field observation from multiple flow conditions and information from the Tributary Assessment (Reclamation 2012a). These data were also used to refine a previously generated (2011) existing condition one-dimensional (1D) hydraulic model for flows with recurrence intervals of 1.05, 1.5, 2, 10, 25 and 100 years.

For this report, each reach was further divided into subreaches based on differences in geologic and geomorphic controls, fluvial processes, and planform, which will be discussed later in the report (Table 2; Figure 6 and Figure 7).

Table 2. Locations of subreaches within reach 4 and 3 on Catherine Creek.

Reach	Subreach	Location (RM)
4	4a	45.8 – 44.95
	4b	44.95 – 43.9
	4c	43.9 – 42.72
	4d	42.72 – 40.78
3	3a	40.78 – 39.12
	3b	39.12 – 37.2

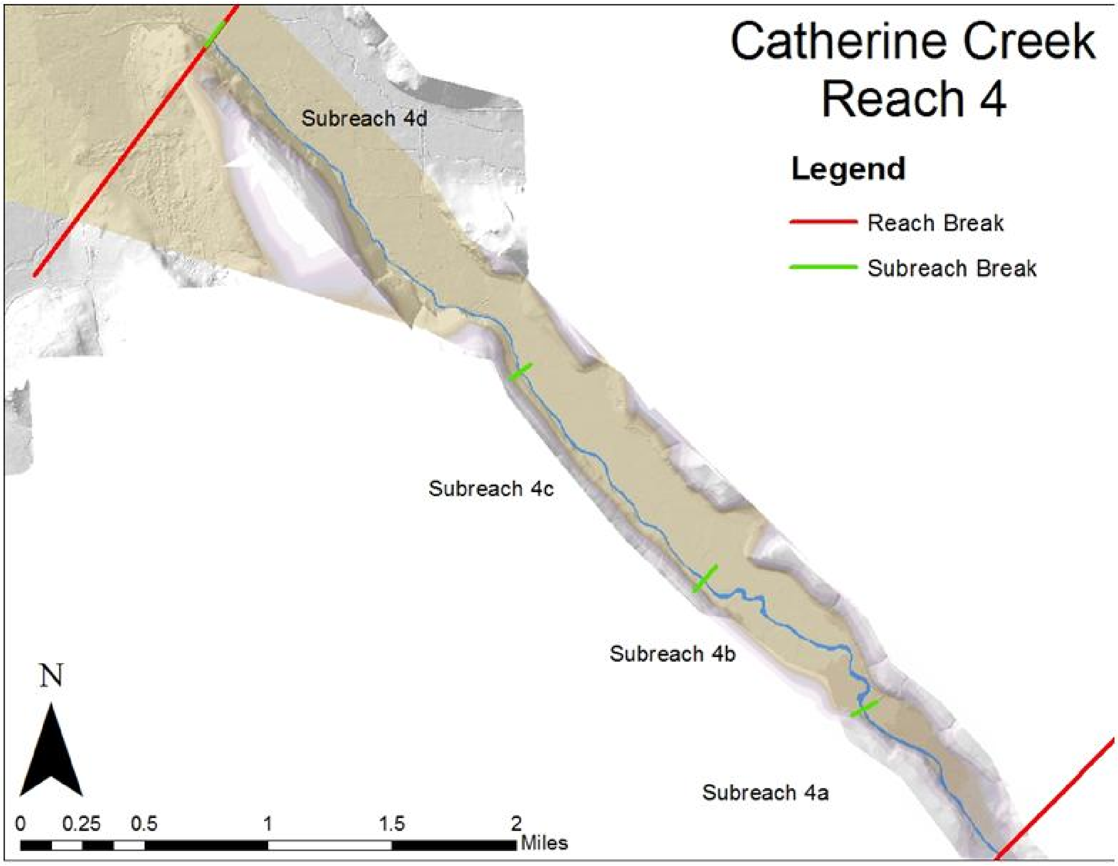

Figure 6. LiDAR and shaded digital elevation model (DEM) image showing reach and subreach boundaries within reach 4 on Catherine Creek.

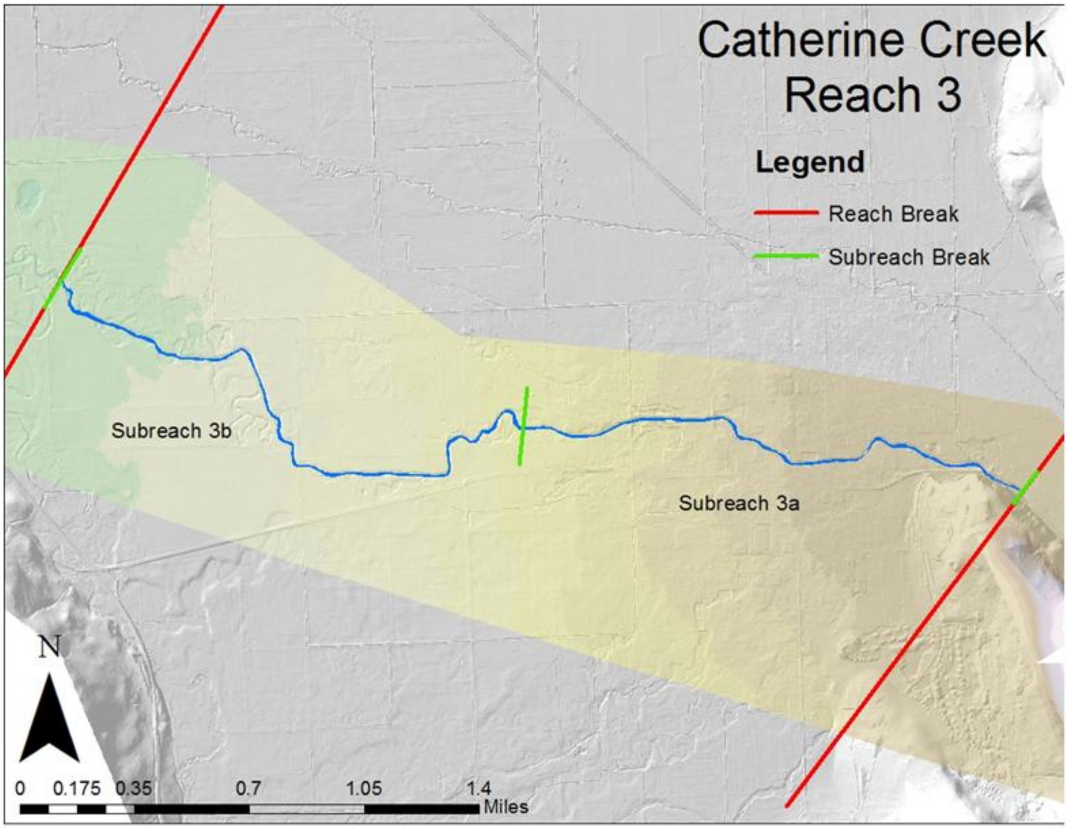

Figure 7. LiDAR and shaded DEM image showing reach and subreach boundaries within reach 3 on Catherine Creek.

Existing Form

Forms are physical conditions on the landscape and in the river. Physical conditions also represent habitat for fish and other species that have evolved along with the landscape and channel form. Changes to the channel form have the potential to impact aquatic species' habitat. The primary defining characteristic forms are described collectively for each reach in the assessment area, along with the important individual characteristics of each reach.

Channel Dimensions

Reach 4

Channel width varies throughout the reach spatially on the 2009 and 2011 aerial photographs. Similar variance of channel width is visible temporally, over the observable record of 53 to 55 years. Remote channel width measurements using the most recent aerial photos available were performed at channel crossover locations (where the thalweg crosses from one side of the channel width to the other, usually at a riffle) within the reach (Table 3).

Table 3. Channel widths in reach 4, Catherine Creek based on 2009 and 2011 aerial photographs.

Subreach	Channel width Maximum (feet)	Channel Width Minimum (feet)	Channel Width Average (feet)
4a	67	34	48
4b	119	61	79
4c	62	26	43
4d	50	35	43

Average bankfull width was compared to the recent (100-year) floodplain to estimate degree of confinement. The results ranged from unconfined to moderately confined to confined within each subreach; however, the overall confinement classification of the channel within reach 4 is unconfined. Table 4 provides definitions for confinement classifications.

Table 4. Confinement classification based on the Oregon Watershed Assessment Manual (Oregon Watershed Enhancement Board 1999).

Condition	Floodplain Width
Unconfined	Greater than 4 times the bankfull width
Moderately Confined	Greater than 2 times but less than 4 times the bankfull width
Confined	Less than 2 times the bankfull width

Within reach 4, depth at lower flow also varies slightly throughout the reach. Within subreach 4a, the depth averaged 1 to 2 feet with a few pools greater than 2 feet in residual depth. In subreach 4b, the average depth was also around 1 foot; however, the thalweg was better developed and with a greater abundance of deeper pools. In subreach 4c, the average depth was about 2 feet, with a poorly developed thalweg and very few pools. The depth in subreach 4d was also around 2 feet deep with a few pools and moderately defined thalweg, although, it was less defined in the lower section of the subreach where Highway 203 confines the channel. At local sections within the reach, flow volume with a 2-year recurrence interval is contained within the banks resulting in relatively fast deep water. However, the water does overtop sections of the banks locally in all subreaches during a 2-year event.

Reach 3

Within reach 4, depths at low flow also vary between the two subreaches. Within subreach 3a, depths at low flow are generally less than 1 foot, and near dry conditions were noted downstream of the Haily-Hutchinson Diversion due to water withdrawals during 2011 field investigations. Within subreach 3b, depths at low flow varied from less than a foot in the plane bed sections from RM 38.7 downstream to RM 38.3, and RM 38.05 downstream to RM 37.85 where the thalweg is poorly developed. Within the pool riffle sections of the reach, depths ranged from 1 to 2 feet with some pools over 2 feet in residual depth.

Table 5. Channel widths in reach 3 of Catherine Creek based on 2009 aerial photographs.

Subreach	Channel width Maximum (feet)	Channel Width Minimum (feet)	Channel Width Average (feet)
3a	63	52	56
3b	67	38	52

The channel is confined underfit, and confined to the relic Pleistocene outwash alluvial fan channel. Confinement would not typically apply to the majority of the reach because floodplain width does not apply to an alluvial fan surface. However, under current conditions that include underfit stream conditions, the channel is confined to the relic Pleistocene outwash alluvial fan channel. At the bottom of subreach 3b where the geomorphology transitions into alluvial plain, there is some floodplain and the channel is unconfined.

Planform

Reach 4 is predominantly single thread, with a straight planform (sinuosity less than 1.5) at bankfull conditions with the exception of subreach 4b. At low-flow conditions, observed occurrences of split flow around gravel bars exist in subreach 4b. The average sinuosity of the subreaches in reach 4 range from 1.03 to 1.25, and the average sinuosity for the reach 4 is 1.08 (Table 6). The average meander amplitude is much the same now as in the earliest aerial photographs and ranges between 140 feet and 325 feet, with an average of 232 feet in subreaches 4a, 4c, and 4d. Similarly, wavelengths of the meanders range from 630 feet to 1,500 feet and average about 1,100 feet. Within subreach 4b, the amplitude and wavelengths are smaller.

Table 6. Sinuosity within reach 4 on Catherine Creek based on 2009 and 2011 aerial photographs.

Subreach	Sinuosity
4a	1.03
4b	1.25
4c	1.04
4d	1.04

Reach 3 is also predominantly single thread, with a straight planform at bankfull conditions. At low-flow conditions, observed occurrences of split flow around gravel bars are in the downstream half of the reach in subreach 3b. The average sinuosity for reach 3 is 1.2, with a higher sinuosity existing in subreach 3b (Table 7).

Table 7. Sinuosity within reach 3 on Catherine Creek based on 2009 aerial photographs.

Subreach	Sinuosity
3a	1.07
3b	1.32

Channel Migration Zone

Channel migration is defined as a change in the location of a stream or river channel due to bank erosion or avulsion (Rapp and Abbey 2003). Lateral bank erosion on the outside of meander bends is typically accompanied by bar deposition on the inside of the bends as the channel migrates across the floodplain while maintaining a relatively constant channel cross section. The HCMZ is the collective area the channel has occupied in the historical record (53 to 55 years in reaches 4 and 3 of Catherine Creek) (Rapp and Abbey 2003). Typically, rates of channel migration are calculated by measuring the maximum distance between locations of the same bank and dividing by the number of years of the historic record to determine an average distance per year of migration. Migration often moves outward and downstream up to a point when the channel cuts-off, meanders, and “resets” the migration pattern or reaches a resistant section and migrates a different direction. For this report, channel migration does not imply typical lateral channel movement as previously described. Rather, it describes the overall average width of the preferred channel locations over the observed record of time. The HCMZ in reaches 4 and 3 was delineated from aerial photographs taken between 1937 and 2011 that were ortho-rectified as part of the Tributary Assessment (Reclamation 2012a) and other efforts.

The width of the HCMZ varies throughout both reaches. The variance of HCMZ width is due to both natural controls such as bedrock, structural geology (faulting), surface topography, geomorphology (valley and stream gradient, substrate and channel form) and vegetation (dense root-mass in the banks), as well as artificial controls including altered vegetation, hardened banks and channel relocation and/or channelization (Table 8; Figure 8).

Table 8. The HCMZ widths in reach 4, Catherine Creek.

Subreach	HCMZ Maximum (feet)	HCMZ Minimum (feet)
4a	81	45
4b	101	179
4c	84	59
4d	74	45

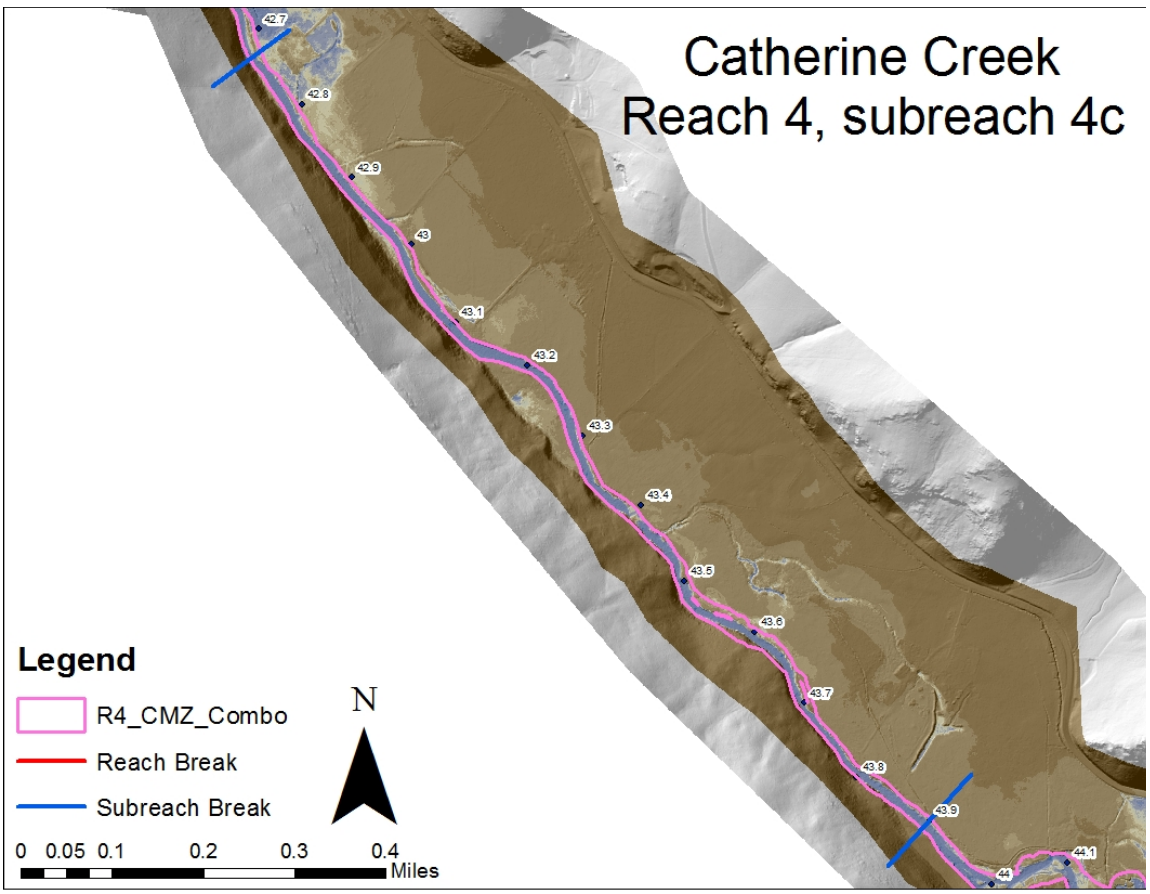

Figure 8. Historic channel migration boundary in subreach 4c with approximate average 2-year recurrence interval.

Within reach 3, HZCM does not apply to the upper section of the reach, and therefore, the channel would not have migrated, but rather avulsed to reoccupy former channel paths historically. On the distal end of the fan structure, the channel likely had a historic migration zone (Table 9). The wide measurement of the HZMC is due to anthropogenic channel relocation, rather than photographic evidence of the channel migrating through natural processes.

Table 9. The HCMZ widths in reach 3, Catherine Creek.

Subreach	HCMZ Maximum (feet)	HCMZ Minimum (feet)
3b	181	67

Bed Condition

Reach 4

The bed of a river is described by its overall gradient and on a finer-scale, by its grain-size distribution, armoring, and representative bed forms. In reach 4, the average channel gradient is 0.83 percent (Table 10).

Table 10. Average channel gradients in reach 4.

Subreach	Gradient (percent)
4a	0.86
4b	0.84
4c	0.83
4d	0.83

Bed material in reach 4 was generally observed to be predominantly cobble with gravel, sand, and boulders. Data from pebble counts show that the average D50 (mean grain size) of the reach was 56 mm (coarse gravel). It should be noted that pebble counts were conducted at locations with a riffle cross over. No substrate measurements were taken in sections with plane bed features and cobble and boulder substrate. Bed forms within the reach were predominantly riffle bar (defined as an intermediate bedform between plane bed and pool riffle (Montgomery and Buffington 1997), with the exception of subreach 4b, which has a pool/riffle bed form (Figure 9).

Figure 9. Pool riffle bedform in subreach 4b, reach 4, Catherine Creek. Note the LWM accumulation.

The departure from the reach scale predominant riffle bar bedform to pool riffle bedform in subreach 4b is due to several factors. The area is a natural depositional zone coming from the confined canyon section upstream, so material is transported in from upstream, including LWM and is deposited in the subreach. Bedrock and coarse alluvium do not provide lateral control to the stream in this subreach due to the stream being located predominantly in the center of the valley. In addition, the altered or removed vegetation along sections of both banks within the reach increases the potential for channel widening and lateral migration due to the lack of root mass within bank. Once sediment from upstream is deposited and/or incorporated locally within the subreach, it is reworked to form the pool riffle bedform currently observed.

The 2011 Habitat Survey noted an average number of pools per mile to be 29.8 within the top of the reach (4a) and bottom (4d, part of 4c) of the reach, with the upstream section having slightly more than the downstream. However, the average number of deep pools, defined as greater than 1 meter depth (ODFW 2011) in the same areas is 3.9 per mile. The average pool frequency for all pools is 1 pool per 14.6 channel widths or approximately 7 pools per mile (ODFW 2011). Although the habitat reach extends beyond the upstream boundary of geomorphic reach 4 to the confluence of Catherine

Creek and Brinkler Creek, the middle section of the reach (4b) was not surveyed, and contains a relatively high number of pools per mile.

Reach 3

In reach 3, the average channel gradient is 0.57 percent, with average channel gradients of 0.8 percent and 0.4 percent in subreaches 3a and 3b, respectively. Bed material was generally gravel and cobble with sand, but some clay and/or ash material was observed in the banks and bed at the downstream end of the reach. Data from pebble counts indicate the overall D50 (mean grain size) was 46 mm. It should be noted that pebble counts were conducted at locations with a riffle cross over. No substrate measurements were taken in sections of plane bed features where coarser material was noted. Bed forms include plane bed and forced-step in subreach 3a, to alternating plane-bed and pool riffle in subreach 3b. The average number of pools per mile surveyed during the Oregon Department of Fish and Wildlife (ODFW) habitat survey (2011) was 7.5, with 5.6 large pools per mile. More pools exist in the downstream end where the pool frequency for all pools was 1 pool per 5.7 channel widths, or approximately 17.8 pools per mile (ODFW 2011). Very little, if any, scour was noted at bridge constrictions, other than at the Highway 203 Bridge upstream of Swackhammer Diversion.

Bank Condition

Reach 4

Banks within reach 4 range from gently sloping to vertical, and when comprised of alluvial material, generally consist of subrounded to rounded sand, gravel, and cobble with small boulders, overlain by a layer of silt and silty clay up to 2 feet thick. In instances where colluvial material is present, bank material is subangular to subrounded boulders supplied by the hillslope that comprises the left bank throughout much of the reach. Bedrock also occurs in the channel banks along the left valley wall (and channel bottom) and was observed cropping out from the hillslope along the left bank in subreach 4d (Figure 10).

Figure 10. Bedrock outcropping along the left bank in the vicinity of RM 41.9 in subreach 4d on Catherine Creek.

Although sections of bare bank are common throughout the reach, bank erosion is generally occurring at low rates in the majority of the reach (Reclamation 2012a). The overall low erosion through lateral migration can be attributed to geomorphic characteristics (overall width and planform of the stream, the underfit conditions) local and basin scale geology that includes bedrock and coarse alluvial and colluvial material that act as natural vertical and lateral migration controls and faulting (Reclamation 2012a). Locally dense root mass along the banks also help to increase the bank stability. In subreach 4b from approximately RM 44.95 downstream to RM 43.9, active erosion is occurring with the most recent occurrence during the spring high flow of June 2010 (Dyke 2010, 2011). The active erosion is due to altered or removed riparian vegetation.

Within subreaches 4a, 4c, and 4d, the right banks are comprised of the alluvial material described above. The left bank is a mix of the alluvial material with some colluvial material supplied by the hillslope that forms the left bank in the majority of the subreaches. In subreach 4b, the stream is centered in the valley fill and the banks are comprised of the alluvial material.

Reach 3

Banks within reach 3 range from gently sloping to vertical, and are comprised of alluvial material of mixed grain sizes that include subrounded to rounded sand, gravel, and cobble with local limonite (hydrated undifferentiated iron oxide) cementing, overlain by silt and clay. The silt and clay material thickens in the downstream direction to a thickness of up to 8 feet at the downstream end of the reach in subreach 3b (Figure 11).

Figure 11. Tall vertical banks comprised of cohesive fine-grained material near RM 38.1 in subreach 3b of Catherine Creek. Note the lack of riparian vegetation on top of the bank.

Although sections of bare bank are common throughout the reach, bank erosion is generally occurring at low rates in the majority of the reach, especially in subreach 3a (Reclamation 2012a). The overall low erosion rate can be attributed to a combination of underfit stream conditions, consolidated or cemented alluvial material, anthropogenic bank armoring with riprap, and concrete, and locally dense root masses that act as lateral migration controls (Reclamation 2012a). Subreach 3b does have local instances where accelerated bank erosion is occurring (Dyke 2010, 2011; Schellsmidt 2010, 2011). The accelerated rate is due to lack of or altered riparian vegetation.

Forcing Agents

Reach 4

Forcing agents are flow obstructions such as large wood accumulations or bedrock outcroppings that can concentrate the flow to force the formation of a local instream morphology that would not otherwise occur (Bisson, Montgomery, and Buffington 2006). For example, introducing wood into a plane bed system may create local scour and sediment retention forcing a pool riffle morphology (Bisson, Montgomery, and Buffington 2006). Within reach 4, there are very few occurrences of forcing agents such as large wood, constrictions, or anthropogenic features that can force the flow to converge, potentially altering the processes, and form of the river locally or at the reach scale. An exception would be channel spanning concrete diversion dams and push-up dams that can alter the local hydrology and sediment transport. The diversion dams act as artificial grade control creating a local forced step morphology on the riverbed. The Fish Habitat Assessment conducted by ODFW (2011) counted 1.2 pieces of large wood (defined as at least 9.8 feet of length and 6 inch diameter) per mile in the upstream section of the reach and less than 1 piece per mile in the downstream end (ODFW 2011). The habitat reach that contains the upstream half of geomorphic subreach 4c and nearly all of 4b was not surveyed during the ODFW effort. Nearly all of the pieces of wood that were observed within the bankfull width during data collection efforts by Reclamation were found to be within subreach 4b. A list of anthropogenic features within the reach is contained in the Tributary Assessment and includes roads, bridges, levees, riprap, and other bank armoring techniques, and channel spanning diversion dams, as well as push-up type diversions (Reclamation 2012a). Generally, the anthropogenic features listed do not cause flow convergence to a degree that would change the form of the river, but can affect the processes to varying degrees at a local scale, particularly lateral and vertical scour. The bridges and riprap or concrete armored banks can effectively force convergence resulting in a local increase in transport competency and capacity. In the downstream end of subreach 4d, the stream is confined between Highway 203 along the right bank and the bedrock hillslope that comprises the left bank. In this instance, the increase in transport capacity caused by the confinement has created a locally armored bed in this section. Channel spanning concrete diversion dams act as local grade control resulting in a local forced step-pool bedforms in subreach 4d.

Reach 3

Within reach 3, there are multiple forcing agents in the form of channel spanning concrete diversion dams and constructed in-channel rock features. Types include constructed ‘A,’ ‘V,’ and ‘W’ weirs, grade control structures, and rock spurs. The constructed weirs are associated with Swackhammer Diversion located at RM 40.6 and Townley-Dobbin Diversion located at RM 39.9. The weirs are intended to force the flow into the center of the channel and develop enough flow convergence to force a scour pool just downstream of the apex. The weirs, particularly at the Townley-Dobbin site have not provided enough convergence to scour the bed significantly (Figure 12).

Figure 12. Constructed weirs downstream of the Townley-Dobbin Diversion. Note the lack of scour downstream of the apex.

In order for the structures to provide scour to create and maintain pools, the construction would need to be higher on the sides with the low point located in the middle of the apex of the structure. It appears that instead, there has been local deposition of coarse bed load due to the current spacing between the boulders and lack of a well-defined low-flow notch on the apex. If scour is achieved under high flow conditions, it is likely filled with bed load on the descending limb of the hydrograph. The other structures (grade control and rock spurs) seem to have little effect of the processes and form of the channel within the reach.

Off-channel Features

Reach 4

Overall, there are very few off-channel features on Catherine Creek within reach 4. Within subreach 4b, there are split flow conditions around un-vegetated gravel bars. One-Dimensional (1-D) HEC-RAS hydraulic model results indicate that at a flow with a

2-year recurrence interval there are areas of shallow floodplain inundation in local sections of all of the subreaches. However, limited field observation of flows near the 2-year recurrence interval showed more localized inundation from elevated subsurface water tables than from overland flow.

Reach 3

Within reach 3, the upper section (subreach 3a) has very few off-channel features. The 1D HEC-RAS model results show floodplain areas beyond the banks that are inundated to shallow depths during flows of a 2-year recurrence interval, but very few are associated with historic channel locations and function as over flow channels. In the mid and lower end of subreach 3b, there are some off-channel features that are associated with historic channel locations that are disconnected by levees or plugs. The levees or plugs are generally not overtopped during flows with a 2-year recurrence interval. Aside from localized sections in the downstream end of the reach in subreach 3b, field observations during flows near the 2-year recurrence interval noted no overtopping of levees or plugs.

Floodplain and Riparian Conditions

The active floodplain in both reaches is defined in this assessment as that area of the valley bottom inundated with surface flow during a 2-year recurrence interval flood as delineated by the 1D HEC-RAS hydraulic model results and verified by limited field observation during a discharge of approximately a 2-year event. Due to underfit stream conditions resulting from postglacial changes in stream dynamics including flow volume and sediment, supply to Catherine Creek in these two reaches is entrenched. This entrenchment is exacerbated by local anthropogenic effects and results in little active floodplain in either reach. Localized areas of active floodplain connection with Catherine Creek exist depending on the local channel characteristics.

Within reach 4, modeling results indicate that discharges at and more frequent than the 2-year event are mostly contained within the channel, and the 10-, 25-, and 100-year discharges overtop 1, 3.7, and 9.2 percent of all model cross sections, respectively (Appendix A). This means that the channel has the capacity to contain even large flood events and there is very little connected floodplain in either reach. Although flows with a recurrence interval of 2 years and less are contained within the channel, this is likely due to increased local entrenchment combined with local anthropogenic manipulations, including levees. Water elevation data output from the HEC-RAS hydraulic model suggest that there is potential to access the floodplain at flows with a recurrence interval of 2 years with the removal or breaching of existing levees (Figure 13).

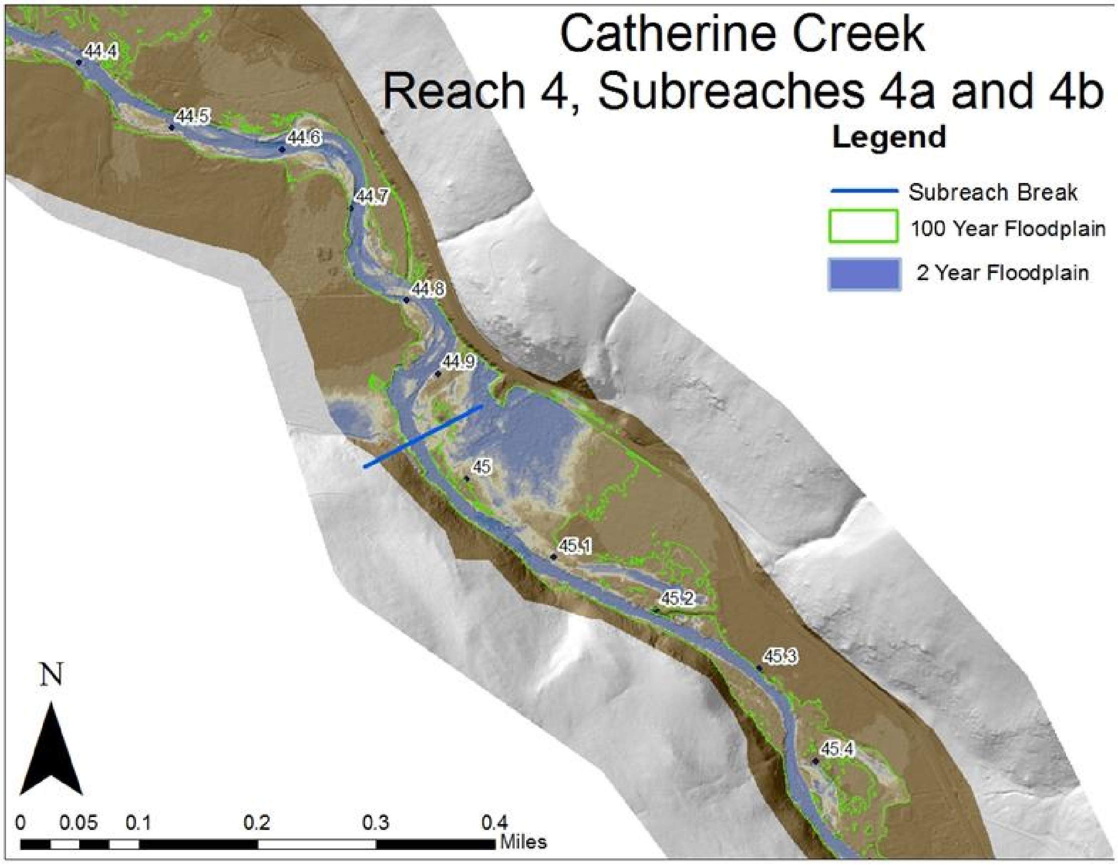

Figure 13. LiDAR image showing the active (2-year) and recent (100-year) floodplains in reach 4 on Catherine Creek.

Within reach 3, underfit stream conditions, local channelization with levees, concrete walls, and anthropogenic channel relocation that potentially included widening and deepening of the channel contribute entrenched conditions that range from moderate to locally severe. HEC-RAS model results indicate that the majority of flood flows with a recurrence interval of 2-years or less are all contained within the channel and levees constructed along Catherine Creek. Flows up to the 2-year event are all contained in-channel, and the 10-, 25-, and 100-year discharges overtop only 4.5, 9, and 15 percent of model cross sections, respectively (Figure 14; Appendix A).

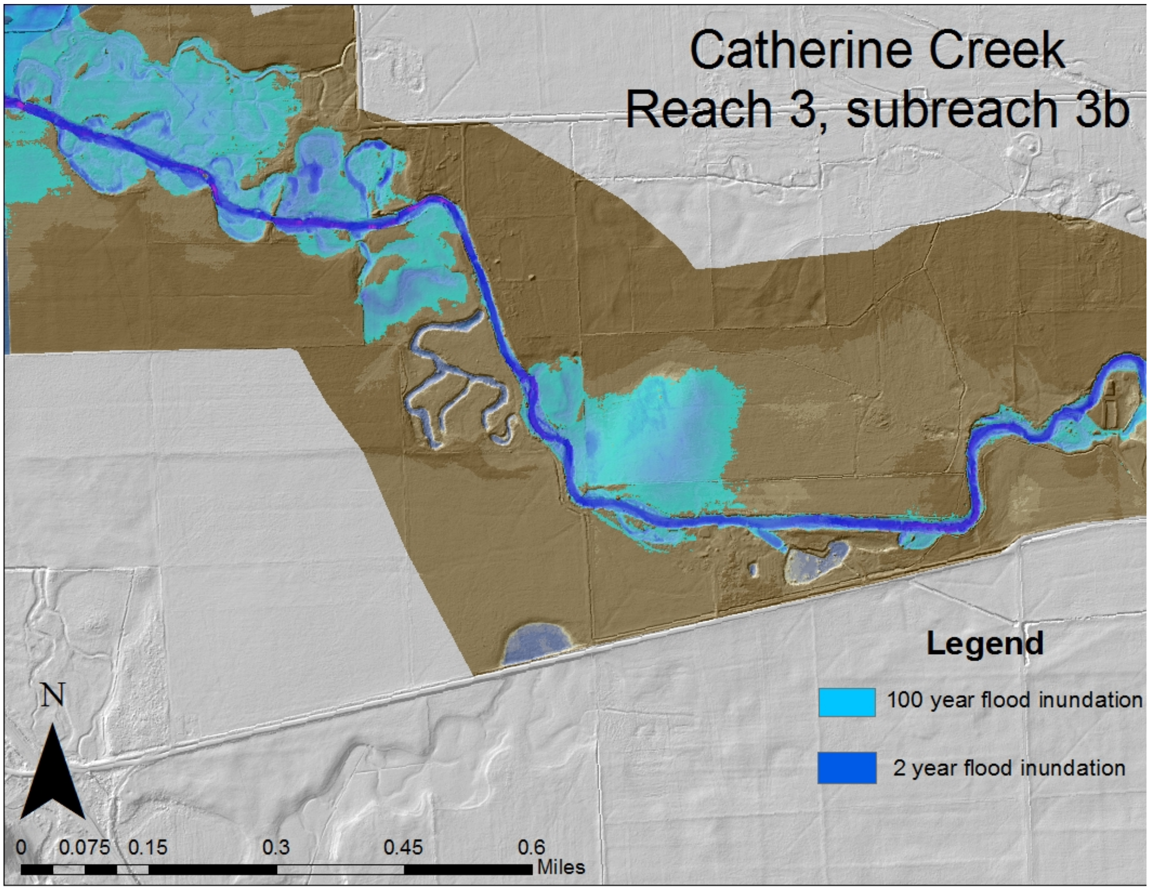

Figure 14. LiDAR image showing the active (2 year) and recent (100-year) floodplains in reach 3 on Catherine Creek.

Existing Physical Processes

Hydrology

Hydrologic inputs on Catherine Creek are predominantly surface runoff generated by melting snow and/or rain on snow events. Reach 4 has a moderate average stream gradient of approximately 0.83 percent. Reach 3 has a lower average stream gradient of 0.57 percent. The average stream gradient upstream is over 1 percent (Reclamation 2012a). Bankfull discharge and channel forming flow for this area has been defined as flow with a recurrence interval of 1.4 to 1.5 years (Castro and Jackson 2001). Analysis using a flow with approximately a 2-year return interval shows that in general, very little of the floodplain is accessed at the 2-year flow. Within reach 3 very little floodplain is inundated at the 2-year flow, except for local sections of the downstream end of the reach. The 1D HEC-RAS model results show that in some instances, the 2-year discharge, and even the 100-year discharge is contained within the banks at most locations within reaches 4 and 3 due to the combination of underfit stream conditions and anthropogenic manipulations.

Irrigation withdrawals within both reaches reduce already low summer flows. Low-flow fish passage has been identified as a limiting factor (NOAA Fisheries 2008). While most, if not all, of the diversions located on the main stem of Catherine Creek in reaches 4 and 3 meet ODFW criteria for fish passage, water withdrawals can reduce instream flow volumes to make the stream non-passable to fish. Warm summer water temperature has also been identified as a limiting factor (NOAA Fisheries 2008). Warm water temperatures can be exacerbated by excessively shallow water in the main channel reduced riparian vegetation along the banks, and warm water irrigation returns (Reclamation 2012a).

Sediment Transport

The sediment transport regime in reaches 4 and 3 likely differs very little from that of postglacial historic conditions. Sediment is still supplied from upstream sources, including episodic large-scale disturbances such as landslides and debris flows. Occasionally, sediment is generated locally because of channel migration or avulsion due to sediment and/or woody material accumulation. Although fine sediment (defined here as fine sand, silt, and clay) is listed as a limiting factor (NOAA Fisheries 2008), observations of depositional bars in both reaches noted little accumulation of fine material. Within reaches 4 and 3, transport competency and capacity varies locally with the channel gradient, geometry, sinuosity, and bed material size. Overall, in the majority of reach 4 and the upstream section of reach 3, sediment transport competency and capacity are both low. However, based on the general observation of the overall coarse bed material and riffle bar bedforms indicates that capacity may be slightly higher. In subreaches 4b and 3b, the general observation of increased local deposition leads to an increase in vertical and lateral scour and the reworking of active bars. This indicates that transport competency is slightly greater than the transport capacity.

Within reach 4, hydraulic model results show that a discharge of 760 cubic feet per second (cfs), has about a 2-year recurrence interval. Coarse gravels from 19 to 75 mm are mobilized and transported through most of the reach and fine gravels (4.75 to 19 millimeters) are mobilized and transported throughout the entire reach at this flow. The maximum size particle that can be mobilized in local areas during this flow is cobble of up to about 113 millimeters.

These results show that throughout reach 4 during a discharge with a 2-year recurrence interval, fine sediment is transported through the reach. Although channel geometry and shear stresses vary greatly throughout reach 4, typically in order for a large sized cobble (up to 300 mm) to be mobilized it would require a discharge with a 10- to 25-year occurrence interval. Even if those conditions were achieved, lateral scour/migration would likely occur before the larger cobble material of the bed was mobilized.

Within reach 3 shear stresses produced by a discharge with a 2-year recurrence interval are similar to that in reach 4. The maximum shear stress produced has the capability to move a particle of around 116 mm, which is close to the median diameter of a cobble-sized particle. The average shear stress produced within the reach at a discharge with a 2-year recurrence interval will move coarse gravel, but subreach 3a will move a much coarser fraction (63.7 mm) than subreach 3b (36.4 mm).

As in reach 4, during discharge with a 2 year recurrence interval, most fine sediment gets flushed through reach 3 and either remains within the channel to form dune ripple bedform downstream of reach 3, or deposited on the floodplain of the valley floor further downstream of the assessment area. Within the sections of subreach 3b that have smaller substrate of coarse gravel with few cobbles (RM 39.1 to 38.7, 38.25 to 38.1 and 38.75 to the downstream end of the reach at 37.2), vertical scour takes place at a 2-year discharge at locations with very little channel constriction from forcing agents. In the plane bed sections of the subreach with coarse gravel and small cobble substrate, the material is scoured at a 2- to 10-year discharge with roughly a 25 to 30 percent channel constriction. Without a channel constriction, it would take a flow with a recurrence interval of 30 to 50 years to mobilize sediment and initiate localized scour due to the lack of hydraulic roughness elements in those sections.

Channel Migration

Lateral channel migration occurs typically at meander bends in an unconfined meandering alluvial channel, and involves erosion of the outside bank of a bend coupled with concurrent deposition of sediment along the inside bank of the same bend. This process results in the lateral movement of the channel, while maintaining a relative consistent channel shape and width. The meandering planform creates helical flow patterns with the result that the area of the most pronounced migration usually occurs where the flow converges against the outer bank near the downstream end of a bend, resulting in simultaneous lateral and downstream migration of the bend. Where laterally migrating meander bends impinge on erosion resistant material such as bedrock, lateral movement ceases and downstream migration of the bend may occur.

Channel migration rates within reaches 4 and 3 of Catherine Creek are overall comparatively low due to primarily the relatively straight channel planform and plane-bed conditions including channel width, erosion resistant materials (i.e., bedrock and coarse alluvium), and local sections of dense root mass within the banks that are present in reach 4. The one exception is subreach 4b, where the channel is unconfined by valley walls or bedrock and removal of riparian vegetation has resulted in little or no rootstrength to resist erosion. The combination of these conditions and the deposition of sediment load from upstream cause the river to actively erode the bank and migrate laterally in this subreach. Anthropogenic manipulations in the form of bank hardening and channel straightening also contribute to low migration rates in the downstream end of reach 4 and upstream end of reach 3. The downstream end of reach 3 also has generally low migration rates due to the cohesive bank material, but there are local sections where bank retreat is occurring. The bank retreat is due to multiple factors including local deposition, more sinuous channel planform creating true helical flow with deposition on inside bends driving erosion on outside bends and vice-versa, especially where vegetation has been altered and erosion resistance has been reduced.

Large Wood Recruitment and Retention

Most streams in the northwest evolved with significant inputs of large wood, which has the ability to force channel response by altering instream hydraulics, sediment routing and storage, channel dynamics and processes and channel morphology of a river across scales ranging from site to watershed (Montgomery et al. 2003). A common trend of streams in the northwest is the reduced availability of large wood in the river over the past century. In addition to whole-scale clearing of LWM that was resident in the stream channel, timber harvests and riparian clearing for development have removed upland and riparian trees, especially large-diameter key members, and significantly reduced or eliminated the source for large wood.

Large wood recruitment in reach 4 on Catherine Creek has been mainly dependent on upstream sources, episodic wind-throw, and dead or dying tree fall-in within the reach. Channel migration and bank erosion are occurring at low rates within the reach, and do not contribute significant amounts of large wood. Recruitment is also limited partially because of a lack of trees large enough to be key members available to enter the river in these reaches. The habitat assessment conducted by ODFW (2011) counted 54.7 total pieces of wood in the downstream end of reach 4 and 116 pieces in the upstream section. Of those pieces surveyed, only 1.6 pieces per mile were key pieces, defined as greater than or equal to 12 meters (37 feet) by 0.6 meters (2 feet) (ODFW 2011). Large wood retention was observed to be most common with subreach 4b at the head or on top of bars, and along the outsides of meander bends. Subreach 4b was not surveyed by ODFW during the 2011 Habitat Assessment. Single pieces of large wood were also observed along the banks in locations where they were caught on living riparian vegetation, or the bank itself throughout the reach. Single logs and small logjams may be transient or long-lived depending on their composition and whether or not they are held in place by stable bank vegetation or boulders. These log structures provide valuable cover habitat and local velocity breaks despite imparting little influence on main stem hydraulics.

Within reach 3, large wood recruitment is predominantly by transport from upstream. Lateral migration and bank erosion is also low in this reach. Total pieces of wood counted per mile during the 2011 Habitat survey were 35.4 in the upstream end and 61.2 in the downstream end (ODFW 2011). There were no key pieces observed in the reach during the Habitat Assessment.

Riparian Disturbance and Succession

Riparian vegetation influences other processes largely based on the type, density, and age of vegetation within the riparian corridor. In reaches 4 and 3, the riparian overstory is largely sporadic and is dominated by mature to decadent cottonwood trees with an understory comprised of willow, alder, and grass. The existing riparian corridor is narrow, typically less than 25 feet wide and very rarely over 100 feet wide, and ranges from patchy or completely removed in reach 4 to mostly continuous in reach 3. In those areas where there is mature overstory, the stream is at least partially shaded and the vegetation provides nutrients and bank stabilization to the river. The roots of mature cottonwood trees were observed growing between and holding together cobbles along the banks of the river, increasing the erosion resistance of those banks.

Riparian species are not generally present on the floodplain further than 25 feet from the edge of the active channel due to alteration or removal. Other than the narrow strip of vegetation along the riverbanks, the majority of the active floodplain capable of sustaining a riparian area has been cleared for agricultural and/or urban development. Recovery of the riparian vegetation is limited due to the maintenance of current land use practices.

Riparian species typically require regular disturbance (overbank flows and flooding) for regeneration. The natural disturbance frequency within the riparian area along reaches 4 and 3 is very low, mainly because of the low occurrence of floodplain interaction, bank erosion, and channel migration. Although common in the uplands in the headwater regions, fire has not burned the riparian area within the assessment area in recent history.

Differences from Historical Conditions

Differences from probable historical conditions vary within reaches 4 and 3 on Catherine Creek. Urbanization, resource consumption, alteration of the channel planform by relocation and/or channelization, the removal of beaver, and the alteration and/or removal of riparian vegetation along the banks and within the floodplain have resulted in the loss of structure and complexity within the channel, along the bank, and in the floodplain. This contributes directly to the limiting factors of loss of habitat quality and quantity, and indirectly relates to other limiting factors such as water quality (increased summer water temperatures), and water quantity. Less dramatic changes include local alteration of the longitudinal profile due to artificial grade control.

Planform

Reach 4

Gildemeister (1998) discusses 'farmland improvement projects' that include channel relocation and the land being leveled and drained in the 'meadow' reaches upstream of Union (reach 4). In addition, a road that existed on the south side of the channel was relocated to the north. No maps were located that show the approximate location of the original road on the south side of the channel, or the subsequent one on the north side. Assuming that the historic road on the north side of the channel is in approximately the same location as Highway 203, the biggest impact within subreach 4d exists where the channel is confined between the road and the hillslope. The extent and location of manipulations is not discussed, but the Gildemeister report suggests that approximately 5 miles of Catherine Creek above Union were altered to some degree. In the downstream end of the reach, Catherine Creek is confined between the valley wall on the left bank and Highway 203 on the right bank. Within the downstream section of reach 4, the general location of Catherine Creek historically would likely have been in the vicinity of the current site near the west valley wall due to cross-valley sloping caused by the Catherine Creek Fault and resulting surface topography along with geomorphic controls. However, in the section of the main channel from RM 43.0 downstream to RM 41.0, the 2009 LiDAR imagery shows channel scars that are evidence that sections of Catherine Creek were at one time located in a position to the east of the current location on the east side of Highway 203. The 1937 aerial imagery shows differences in vegetation that also suggest that the stream could have been located away from the left valley wall in this area prior to the original construction of Highway 203/Medical Springs Highway. Additional sections of altered historic main channel are discernible on the LiDAR in the upstream section of the reach in subreach 4a at RM 45.45. These sections have been occupied by the main channel in recent times (1971), and are disconnected from the current channel by a levee. The cumulative results of these channel relocation efforts are a reduction in the estimated sinuosity in each of the respective subreaches that slightly reduces the estimated sinuosity at the reach scale.

In reach 3, channel planform modification efforts in the form of multiple cut-off oxbow meanders and channel relocation have reduced the overall sinuosity in the reach, although most of the reduction in sinuosity occurs in subreach 4b. The results of sinuosity measurements performed on aerial photographs in GIS indicate that average channel sinuosity decreased from 1.53 in 1937 to 1.2 in 2008. In addition, in the downstream end of subreach 3b, there is approximately 3,637 linear feet of different sections of oxbow channel that appears to be at least partially disconnected due to channel straightening efforts in the 1937 aerial photographs (Reclamation 2012a).

Dams

Dams were built within reaches 4 and 3 on Catherine Creek soon after settlement by Anglo-American settlers in the mid-to-late 1800s. Gildemeister (1998) describes a lumber mill dam that was constructed in 1863 approximately 6 miles upstream of Union, near the upstream end of reach 4. Photographic documentation shows that the dam was in place at least as late as 1904, but the removal date is unknown. Another dam existed for log storage purposes in the town of Union during the same time (Gildemeister 1998).

Currently within reach 4, there are 2 channel spanning concrete diversion dams that are equipped with fish ladders for passage (Table 11). The concrete dams act as grade control structures that impose artificial base elevation creating deposition directly upstream. There are also two push-up type diversions structures that span nearly the entire channel within the reach and may be fish barriers at various flows due to height and water velocities.

Table 11. Location, type, and name of dams located in reach 4 on Catherine Creek.

River Mile	Type	Name
44.8	push up	
43.4	push up	
42.5	Concrete dam	Catherine Creek Adult Collection Facility
42.2	Concrete dam	State diversion

Within reach 3, there are 4 channel spanning concrete diversion dams (Table 12). All are equipped with modern ladders for fish passage but impose the same artificial base elevation on the channel.

Table 12. Location and name of channel spanning concrete diversion dams within reach 3 on Catherine Creek.

River Mile	Name
40.6	Swackhammer
39.99	Godley
39.83	Townley-Doblin
39.63	Hempe-Hutchinson

Flood Control

Catherine Creek has a recorded history of major floods. The flood of record for Catherine Creek occurred in 1948 with a discharge of 1,740 cfs, and a large number of flood control measures had already been constructed by 1937 as observed in the aerial photographs.

In reach 4, there are approximately 2,735 feet of riprap, of which 1,300 feet are associated with Highway 203 in subreaches 4b and 4d. There are also approximately 2,033 feet of levee within the reach. The largest levee is associated with the Catherine

Creek Adult Collection Facility (CCACF), but a small levee is located perpendicular to the channel downstream of the CCACF in subreach 4d. Additionally, there is approximately 0.8 mile, or 4,060 feet of Highway 203, that acts as a levee at the downstream end of subreach 4d (Reclamation 2012a). Another small length of levee is located on the right bank in subreach 4a that plugs a channel that was occupied from 1956 through 1971.

The flood control measures within reach 3 are more extensive. Approximately 1,900 feet of levees are located within subreach 3b, generally occurring in the lower portions of the subreach. Bank protection measures that include approximately 6,335 feet of rock and concrete are spread out over the entire reach (Reclamation 2012a). One online document from the U.S. Army Corps of Engineers (USACE) indicate that in addition to woody debris removal performed in the mid 1980s, emergency work was performed in 1949 that is described as raising and revetting the banks of Catherine Creek at critical sections through and in the vicinity of Union, Oregon (USACE 2011a). Another USACE online document states that emergency work was also accomplished in 1950 and 1951, and describes a project that would provide local flood protection through the construction of levees, channel clearing, straightening, enlargement, and realignment along 27.2 miles of Catherine Creek (USACE 2011b). The document does state that funds were expended on the project but does not state specific type of work or the location. A third USACE online document notes that local farmers had in several cases excavated channel cut-offs across narrow reaches of stream meanders, and constructed low earth levees (Reclamation 2012a).

Bank armoring via riprap or other material (i.e., rock/concrete filled drums or car bodies) reduce the natural rates of local lateral channel migration and increases the local levels of shear stress on the channel bed and therefore potentially increases local rates of scour (vertical migration). Lateral channel migration is a product of bank erosion accompanied by bar building on the opposite bank. Erosion of the bank supplies needed sediment and potentially some woody material to the system as well as energy dissipation during flooding and erosion events. Concurrent bar building through deposition provides low floodplain surfaces for colonizing vegetation (such as cottonwoods), hydraulic diversity, and low-energy areas during high flows, and high-flow refuge for fish. Disturbances to the balance between erosion depositions often result in a depletion of one or the other. When that occurs, processes that normally create and maintain diverse habitat types are reduced or eliminated. The result is a decrease of in-channel complexity and habitat diversity, which is identified as a limiting factor (NOAA Fisheries 2008).

Channelization through relocation and/or levees also alters natural processes. Levees inhibit the ability of the river to dissipate energy by confining the high flow, rather than allowing high flow to spread out over the floodplain. This can also increase the local shear stress, which in turn increases the potential for local scour. In areas where floodplain interaction has been reduced through levees or channelization, the fine sediment remains in the river and is transported elsewhere rather than being allowed to deposit on the floodplain or along and within the channel (NOAA Fisheries 2008). Additional effects of reduced floodplain interaction during high flow as a result of levees and/or channelization (combined with other factors such as current land use) are an altered hydrograph and reduced groundwater recharge. These may contribute slightly to the limiting factor of water quantity by reducing the levels of low-flow recharge.

Logging

Past logging practices on nearly 11,000 acres of upland forests in the Catherine Creek watershed have reduced the amount of large wood available from the upland areas. Low numbers of pieces of large wood per mile noted by ODFW contribute directly to the limiting factors of low habitat quality and quantity. In addition to the decrease in large wood available to the stream both upstream and within the assessment area, present-day Catherine Creek may not have the competency to transport large logs that would act as key members to form large wood complexes from upland areas. This is due to the overall reduction in transport competency associated with the reduction in stream discharge associated with end of the glacial period. An increase in fine sediment input from upland logged areas could have an impact on reaches 4 and 3, but fine sediment (silt and fine sand sized particles) were not observed to be a problem throughout all of reach 4, and the majority of reach 3.

Removal of Large Woody Material

The historical number of logjams (pieces of wood) per mile within reaches 4 and 3 on Catherine Creek is unknown. Gildemiester (1998) included a map that was generated by Thompson and Hass during their 1960 environmental survey report, which shows no logjams on the main stem of Catherine Creek from the confluence of the North and South forks, downstream to the CCACF. It should be noted that the main stem of Catherine Creek was only partially surveyed from the CCACF downstream through reach 3. McIntosh et al. (1990) also did not report any logjams in the main stem of Catherine Creek. USACE reports describe the removal of wood from the channel in and through the vicinity of the town of Union in reach 3. No documentation of large wood removal was found for reach 4, although it likely occurred during the ‘farmland improvement’ projects performed in the late 1930s and early 1940s (Gildemiester 1998) and following major flood events.

In rivers where wood has been removed, the effects include lowered overall roughness, reorganized bed topography, and increased bed-load transport rates due to an increase in shear stress and increased transport capacity, and the coarsening of bed material (Montgomery et al. 2003). In channels where wood is forcing the morphology, such as pool riffle, removal of wood can allow the morphology to evolve to plane bed or even bedrock, if present.

Large Pools

The number of large pools within reaches 4 and 3 reportedly decreased from 20 to 3.9 in reach 4, and from 27 to 5.6 in reach 3 between the 1935 U.S. Bureau of Fish counts of resting pools and the modern counts of deep pools (ODFW 2011). In the U.S. Fish Bureau pool count, resting pools were defined as pools greater than 25 square yards and 1 to 2 meters deep. With the modern survey, a deep pool is defined as a pool greater than 1 m (3 feet) deep, with area recorded, but no area criterion defined. The definition of a deep pool in the historic versus the modern habitat survey is similar, but conditions at which historical measurements were taken is unknown (e.g., what the river flows were at the time of measurement; whether the pool depth measurements were taken from the water surface, bankfull surface, or as a comparison of maximum depth to average depth, or residual depth at low flows).

As a result of these unknowns, it is difficult to evaluate the accuracy of the estimated decrease in pools. With the current channel geometry, the most frequent means by which large pools could have been scoured from the coarse bed of Catherine Creek and sustained for more than one season, is by the presence of a large flow obstruction likely caused by bedrock, large boulders, or large wood accumulations. Within reach 4, interactions with bedrock and/or large boulders require the river to be near the valley wall. The formation of large logjams can occur at many locations with a riverscape including along the outsides of meander bends. There are currently about 48 locations in reach 4 where the river is located near the valley wall or where there are meanders that range from gentle to sharp. If a large pool had been scoured at every one of these 48 locations, there would have been an average of roughly 9.3 large pools per mile. It is unlikely that a large logjam capable of scouring a sizable pool would have formed at every meander and bedrock exposure, making roughly 5 to 8 large pools per mile a more reasonable historical estimate. Using the 5 to 8 pools per mile as a reasonable estimate, the percent of pool reduction in reach 4 ranges between 20 percent and 50 percent. The reduction in large pool quantity is likely a consequence of the removal of instream structure such as LWM. Without large instream structures capable of forcing significant flow convergence, the armored bed cannot be scoured and large pools cannot be formed or maintained.

Within reach 3, the reduction in number of pools per mile is likely closer to about 50 percent. In unconfined streams with both pool-riffle and dune-ripple bedforms, pool frequency is typically 1 pool every 5 to 7 channel widths (Bisson, Montgomery, and Buffington 2006). In subreach 3b, remote channel width measurements conducted in GIS indicate the average channel width is 52.4 feet. Multiplying the average channel width by the pool frequencies given by Bisson, Montgomery, and Buffington (2006), then dividing by 5,280 feet gives an estimate of 14.4 to 20.1 pools per mile. Historic conditions likely included unconfined to confined sections with a relatively straight planform. The overall channel width was likely more narrow than present conditions as well. Given the probable historic conditions, a reasonable number for historic pools per mile in subreach 3b would have been 13 to 18.

In both reaches, the reduction in large pool quantity is likely a consequence of the removal of instream structure such as LWM. Without large instream structures capable of forcing significant flow convergence, the armored bed cannot be scoured and large pools cannot be formed or maintained.

Agriculture and Irrigation

Historical stream survey reports annotated in Gildemeister (1998) noted as many as 29 irrigation diversions on Catherine Creek throughout reaches 4 and 3 and beyond in the 1940s, many of which did not have fish screens and were not originally equipped with well functioning fish ladders. Over approximately the past 30 years, all known irrigation diversions have been reconstructed or retrofit with fish ladders to provide passage. Most, if not all, are also equipped with fish screens and fish returns, but often the fish returns are placed at elevations several feet above the water surface and/or may discharge onto a dry gravel or cobble bar at low flows.

Irrigation withdrawals also reduce instream flows, particularly during summer low-flow periods. Decreed water rights can exceed the base flow of Catherine Creek and permitted withdrawals can totally dry the creek in some locations during low-flow conditions. Summer low flows and elevated temperatures have been identified as a limiting factor within reaches 4 and 3 (NOAA Fisheries 2008).

Roads and Development

Hard surfaces associated with roads and development can lead to increased runoff potential, decreased time of concentration of runoff, higher and faster peak flows, and increased sediment production. These results can directly contribute to two of the known limiting factors within reaches 3 and 4. First, the altered timing, magnitude, and concentration of runoff can decrease infiltration, thereby contributing to the limiting factor of seasonal low-flow conditions. Second, the increase in sediment production contributes directly to the limiting factor of excess fine sediment. However, within reach 4, the sediment transport characteristics in subreaches 4a, 4c, and 4d transport most of the fine sediment through at seasonal high flows. Similar transport conditions exist in the top of reach 3 in subreach 3a. Fine sediment was not observed to be an issue in reach 4 or in subreach 3a.

Bridge abutments and approaches may constrict the channel and floodplain altering local hydraulics and sediment dynamics. Bridges may cause both local depositions upstream of the constriction and scour at or directly downstream. In reaches 4 and 3, artificial constriction effects on water surface elevations range from negligible to an increase of 3 feet at the 100-year discharge based on HEC-RAS model results. Local channel velocity and shear stress increase roughly 15 to 20 percent when measured in HEC-RAS by comparing geometries and shear stress estimates upstream of the constriction with those at the constriction

There are three private bridges within reach 4. Two are constructed of old railcar beds and one is a small wood deck bridge with concrete abutments. Observed local bed and bank scour due to increased local channel velocity and shear associated with the abutments ranged from very little to moderate. Hydraulic modeling results show that State Diversion and CCACF diversions and the Highway 203 Bridge No. 1 exert hydraulic control during flood flows, affecting several parameters of flow (Appendix A).

There are six bridges in reach 3, one of which is private in addition to three channel spanning concrete diversions. Hydraulic modeling results indicate that the Pond Slough, 10th Street, and Main Street bridges as well as Hempe-Hutchinson, Townley-Dobbin, and Swackhammer diversions exert hydraulic control during flood flows. The result is an artificial influence on several hydraulic parameters, such as depth, velocity, and shear stress. In general, depth increases while velocity and shear stress decrease upstream of the bridge. Conversely, at and below the structures the flood depth is lower and velocities and shear stresses are higher (Appendix A).

Observed local bed and bank scour due to increased local channel velocity and shear associated with the abutments ranged from very little to moderate. These locations represent the majority of channel constriction and local convergence areas that interact with the coarse bed load sufficiently to alter the bedform of the channel.

Removal of Riparian Vegetation

The alteration or removal of vegetation within the floodplain and riparian zone is prevalent throughout reaches 4 and 3 on Catherine Creek and has affected composition, type, age-class distribution, and density of the existing riparian vegetation. Gildemiester (1998) describes vegetation along waterways in reach 4 as a mix of willow brush, alder, and hawthorn, with a dense overstory of cottonwood trees. Today, the composition consists of predominantly grasses and willow brush, with some alder. There are sections of decadent cottonwood trees but they exist in small remnant stands in the historic floodplain and along small sections of the banks. With the current composition, there is lack of a well-developed succession stage. The majority of the hawthorn, cottonwood, and alder are sapling and pole or younger with little or no mature trees, aside from the decadent stands. In addition, the total area that the riparian vegetation occupies is reduced from historic times due to agricultural land use practices.

Reach 3 would have had a different riparian vegetation composition than that of reach 4. Composition likely included willows and cottonwood trees in a fairly narrow strip along the banks in the upper section of the reach. In the downstream section of the reach where the floodplain was more developed, the vegetation would have been composed of dense mature cottonwood trees with a mixed understory including cottonwood, willow, and grasses. The existing riparian vegetation in reach 3 consists of alder, willow, and grasses. The succession stage is poorly developed with predominately two age classes, 1 − shrub/sapling and pole, and 2 − decadent. The area that the vegetation occupies has also been reduced, especially in the downstream end of the reach where there would have been a more well-developed floodplain to support floodplain vegetation.

Within both reaches the vegetation shows areas of improvement as well as decline in mature to decadent trees along the banks based on comparison of the earliest aerial photographs with present-day conditions. Simple measurements in GIS show that within reaches 4 and 3, 10 percent and 15 percent, respectively, of the vegetation within the 10-meter buffer along both banks has been disturbed by some type of development or land use practice.

The effects of the removal of riparian vegetation include the potential for an increase in local bank erosion due to loss of rootmass in the bank, reduced nutrient input for macro-invertebrates and other aquatic and terrestrial species, and decreased stream shading. The reduction in stream shading allows for greater amounts of solar radiation to be absorbed, which contributes to the limiting factor of water quality (high summer water temperatures) (NOAA Fisheries 2008). Seasonal low-flow conditions can further exacerbate this condition.

Beaver

References to high numbers of beaver and levels of beaver activity are numerous within Gildemeister (1998) and Duncan (1997). The extirpation of beaver took place roughly from 1818 to 1835 by the Hudson Bay Company primarily in an effort to discourage American fur trading companies from crossing the Rocky Mountains (Gildemeister 1998; Duncan 1997). Beaver dams play a vital role in maintaining and diversifying instream and riparian habitat. Beaver dams form large pools, provide increased sediment retention, increase groundwater recharge and retention which may increase in-channel flow at low-flow conditions, and typically provide increased total area of available fish habitat. In addition, beaver dams may contribute to reduced water velocities, attenuated peak flows, and increased area of riparian vegetation (Pollock, Heim, and Werner 2003). Beaver activity can also contribute large wood to the river, as they use mature trees for food and building material (Naimen, Johnston, and Kelly 1988).

The removal of beaver has impacted channel planform and habitat complexity and quantity. Beaver activity would have increased the amount of woody debris in the channel and promoted a network of ponds and/or wetlands connected by single or multiple thread channels, rather than the predominantly single thread channel noted today.

Existing Trends

Although current channel dynamics vary greatly within the assessment area, overall it is unlikely that the identified limiting factor conditions within reaches 4 and 3 on Catherine Creek will naturally improve, even after several centuries of evolution at the reach scale. This is due to changes at the watershed scale to drivers such as hydrology working within a remnant channel that was created under much higher hydraulic discharges and sediment loads. However, the potential to induce small-scale changes at a more local scale over shorter periods does exist. For example, channel migration could be increased in areas that are currently armored and “maintained” in which the river can begin to adjust itself. Local bed morphology could also be changed on a shorter time scale with the addition of LWM structures.

Effects of Climate Change Predictions

The effects of regional climate change are extremely variable at the regional scale. In general, regional climate models predict an overall increase in summer and winter air temperatures leading to a decrease in the accumulation of snow during the cool season (i.e., late autumn through early spring) and the availability of snowmelt to sustain runoff during the warm season (i.e., late spring through early autumn). In addition, warming is expected to lead to more rainfall-runoff during the cool season rather than snowpack accumulation (Reclamation 2011).

Projected climate changes are likely to have an array of interrelated and cascading ecosystem impacts. At present, most projected impacts are primarily associated with increases in air and water temperatures and include increased stress on fisheries that are sensitive to a warming aquatic habitat, potentially improved habitat for invasive exotic species such as quagga mussels which bears implications for maintenance of hydraulic structures and impacts to native species, and increased risk of watershed vegetation disturbances due to increased fire potential and agricultural pressure on lands closest to water sources such as floodplains and riparian areas (Reclamation 2011).

Climate change implications specific to salmon fisheries in the Pacific Northwest are addressed by the Washington Climate Change Impacts Assessment (WACCIA), which reports that rising stream temperatures likely will reduce the quality and extent of freshwater salmon habitat. WACCIA also suggests that the duration of periods that cause thermal stress and migration barriers to salmon is projected to at least double and perhaps quadruple by the 2080s for most analyzed streams and lakes; areas of greatest increases in thermal stress include the interior Columbia River Basin (Reclamation 2011).

The potential negative impacts resulting from earlier runoff and greater peak flow are less significant with regard to physical habitat in reaches 4 and 3 on Catherine Creek. Some of the observable dynamic changes that have occurred within the assessment area were the result of sustained flows that were at, or slightly above bankfull discharge. Greater peak flow suggests the potential for more extreme floods, which, although potentially damaging to human infrastructure, health, and safety, may actually induce change and increase channel complexity leading to improved instream habitat within reaches 4 and 3 on Catherine Creek.

The effect of warmer/drier summers with less snowpack that could result in fires and fewer trees in upland areas would not have a direct impact on reaches 4 and 3, but could indirectly affect levels of fine sediment and pieces of woody debris that would be eventually transported in to the reaches. However, the limiting factor of water quantity due to seasonal low flow would be amplified with warmer/drier summers and less snow pack.

Target Conditions

Target conditions represent the most appropriate physical characteristics for a given reach and should guide future habitat improvement projects. The difference between target conditions and historical conditions is that target conditions take into consideration existing conditions, constraints, and future trends. Critical to the identification of target conditions is an understanding of the linkage between the physical characteristics of the channel and the biologic needs of the species of concern. By better understanding this relationship, targeted conditions can be identified which will provide fish with the physical habitat necessary to overcome identified biological limiting factors.

Table 13 outlines the general physical conditions preferred by spring Chinook salmon and steelhead during several different life stages. While this table was prepared for the Entiat River subbasin, the general preferred conditions should be relatively similar for the same species in the Grande Ronde subbasin.

Table 13. Generalized preferred habitat characteristics for steelhead and spring Chinook salmon at various life stages (Reclamation 2012b).

Preferred Habitat	Steelhead	Spring Chinook Salmon
Spawning Habitat		
Depth	1.8 feet (0.54 m);[a] 0.78 feet (less than 24 cm)[b]	1-1.5 feet
Velocity	2.3 feet/second (0.71 m/second)[a] 1.31 to 2.98 feet/second (40 to 91 cm/sec)[b]	1-2 feet/second
Gravel size	1.28 inches (32.5 mm)[a] 0.24 to 4.0 inches (0.6 to 10.2 cm)[b]	0.8 – 104 inches (20-35 mm)
Water temperature	Between 39°F (4°C)[b] and 55°F (13°C)[r]	39°F – 57°F
Other	Prefer protective cover	
Egg incubation to emergence habitat		
Fine sediment (particles less than 1 mm)	Less than 20 percent fine sediment results in increased embryonic survival[c]	Less than 15 percent
Water temperature	5.0° C to 11.0° C[d]	5.0° C to 11.0° C[d]
Dissolved oxygen	At least 50 percent survival of embryos achieved at 5 mg/L to 9 mg/L[e]	1 mg/L after fertilization, 7mg/L prior to hatching
Juvenile rearing habitat		
Groundwater	Groundwater provides cooler temperatures during the summer and warmer temperatures during the winter, resulting in increased juvenile survival.[c]	
Velocity	Less than 1.0 feet/second for holding; proximity of low-velocity water for holding to relatively high velocity water for feeding[p, q] Refugia from extreme high flows and extreme high velocity[q]	
Large woody debris	Large woody debris increases the complexity of stream habitats by creating areas with different depths, velocities, substrate types, and amounts of cover[c,p] more than 20 pieces/mile more than 12-inch diameter, more than 35 feet long;[k,n] and adequate sources of woody debris recruitment in riparian areas	
Pools	As pool density (m^2/km) increases, smolt production increases (i.e., 2,000 [m^2/km] pool area resulted in approximately 1,000 smolts/km and 3,000 pool area [m^2/km] resulted in between 2,000 and 3,000 smolts/km).[f] Where streams are more than 3 m in wetted width at base flow, pools more than 1 m deep (holding pools) with good cover and cool water and a minor reduction of pool volume by fine sediment[l]	
Temperature	10.0° C to 14° C[g]	
Substrate Character and Embeddedness	Substrate is gravel or cobble with clear interstitial spaces; reach embeddedness less than 20 percent[i,j,ln]	
Overhead Cover	Juveniles exhibit preference for habitats with overhead cover[o]	
Adult holding habitat		

Preferred Habitat	Steelhead	Spring Chinook Salmon
Pool Quality	Depth 1.0 to 1.4 m[h]; Deep habitats of intermediate size (200 to 1,200 m^2)[h]; Adults use pools with cover associated with flow (average is 9.3 cm/second). Cover associated with flows less than 3 cm/s are avoided[h]; Low streambed substrate embeddedness (less than 35 percent)[h].	Where streams are more than 3m in wetted width at base flow, pools more than 1 m deep (holding pools) with good cover and cool water, minor reduction of pool volume by fine sediment[n]
Pool Frequency	channel width — # pools/mile[k,n] 5 feet — 184 10 feet — 96 15 feet — 70 20 feet — 56 25 feet — 47 50 feet — 26 75 feet — 23 100 feet — 18	channel width — # pools/mile[k,n] 5 feet — 184 10 feet — 96 15 feet — 70 20 feet — 56 25 feet — 47 50 feet — 26 75 feet — 23 100 feet — 18
Large Woody Debris	more than 20 pieces/mile more than 12-inch diameter, more than 35 feet long[i,n;]and adequate sources of woody debris recruitment in riparian areas	more than 20 pieces/mile more than 12-inch diameter, more than 35 feet long;[i, n] and adequate sources of woody debris recruitment in riparian areas
Temperature	10.0° C to 14° C[g]	10.0° C to 14° C[g]
Channel Condition and Dynamics		
Average Wetted Width/Maximum Depth Ratio in scour pools in a reach	less than or equal to 10[k, m]	
Streambank Condition	More than 80 percent of any stream reach has at least 90 percent stability[l,m]	

Although it is helpful to understand the physical conditions preferred by the species of concern, preferred conditions can vary widely as most species have the ability to adapt to the conditions associated with individual river systems. There can also be considerable variance within the same system. For example, larger fish can build redds in larger substrate, faster, and deeper water than could smaller fish. Based on these local adaptations, generalized conditions shown in the above table may not be completely accurate in reaches 4 and 3 on Catherine Creek. Table 16 summarizes the constraints that could potentially influence the habitat improvement process in reaches 3 and 4 on Catherine Creek.

Table 14. Summary of constraints that are impacting habitat improvement on Catherine Creek.

Constraint	Description
Floodplain development	Buildings, roads, and bridges associated with urban development and agricultural land use practices occupy the floodplain, in some cases restrict the potential for floodplain, and channel rehabilitation due to the risk of damaging valuable infrastructure. Land acquisitions and easements for areas with high habitat potential could be considered to reduce the effect of this constraint over time.
Floodplain clearing	Large portions of the valley bottom and active floodplain have been converted from native vegetation to agriculture, grazing pasture, and urban areas. It is unlikely that all of this land can be reclaimed for native vegetation and floodplain connection, but buffer areas could be developed especially in areas of high habitat potential.
Irrigation	Irrigation withdrawals reduce seasonal low flow during the irrigation season, in some instances, return warm, nutrient loaded water to the channel, and may even dry the channel for short sections. Removal of all irrigation practices is unrealistic in the short term, since irrigation is vital to the local economy, however, locally driven efforts to change irrigation efficiency and associated benefit to streamflows may be achievable.
Infrastructure and risk	Although LWM and other instream structures are natural components of rivers, many people view these as increased risks of both loss of land through bank erosion and property damage due to flooding.
Climate change	Catherine Creek is likely to experience larger peak discharges, lower summer flows, and warmer summer water temperatures in the future because of climate change. Habitat actions should consider conditions that are likely to occur in the future in order to target conditions that will buffer endangered species from the changing conditions enabling them more time to adapt and evolve.
Funding, politics, and time	Habitat rehabilitation is a collaborative process that requires cooperation, time, and money. In particular, landowner participation is a key requirement to move forward with any implementation. Risks and constraints must be identified, assessed, and communicated to all involved (the landowner, design team, project sponsor) in order to minimize them. Failure to do so could result in the inability to implement anything on private land for an indefinite period.

The identified limiting factors affecting fish growth and survival on Catherine Creek are lack of habitat quality and quantity, water quantity and quality (elevated summer temperature), and riparian function.

The limiting factor of habitat quality and quantity is a result of low amounts of instream hydraulic structures and a variety of bedforms. This contributes to lack of sufficient slow-water areas during high flow, such as off channel areas, as well as low-flow habitat, such as deep pools. Instream hydraulic features such as bedrock and other natural forcing agents like instream woody material promote local scour and subsequent deposition. The result can be the creation of varied local bed morphology that include pool riffle and/or riffle bar. The woody material also provides instream cover, further increasing habitat quality.

Increased riparian function would address multiple limiting factors. Increased riparian function could potentially improve water quality by decreasing amounts of solar radiation absorbed by the stream and providing areas for fine sediment to deposit during out of bank flow. Increased riparian vegetation can also filter excess nutrients out of overland flow before entering the stream and provide terrestrial materials to the river, increasing beneficial nutrient loading (leaf packs and vegetation inputs necessary for aquatic macro invertebrates and microbes). A healthy riparian community along the banks would increase local cover associated with overhanging branches and banks supported by root mass, improving habitat quality, and quantity.

The limiting factor of water quantity could be addressed by improving levels of interaction between the river and the floodplain. Increased occurrences of water on the floodplain will increase the absorption of water into the shallow subsurface. The water is returned to the channel at low-flow conditions, increasing the baseflow. Improving efficiencies in local irrigation systems could also improve in-channel water quantities in the late summer months.

Instream Structure

The degree that anthropogenic manipulations impact river process and fish habitat varies between the two reaches in the assessment area. Target conditions include greater variability of instream structure, bedform, and habitat. This could be provided by large wood and boulders, as well as the rehabilitation of riparian and floodplain areas to provide establishment of diverse species and age-class riparian vegetation that will contribute to instream structure. More variability of instream structures will increase habitat quantity by increasing the potential for pool and more defined low-flow thalweg development, with a target condition of roughly 4 to 6 large pools per mile and low flow depths no less than 1 foot. Individual structures will be most effective when placed in series or in areas where they can interact with natural features including bedrock in order to amplify their cumulative effect. Providing more instream structure variability will increase habitat diversity and/or instream complexity, provide instream velocity breaks, and increase available cover, all of which will address the limiting factor of habitat quality.

Riparian Corridor

The LWM component of the instream structures should be maintained by the natural succession of riparian vegetation in a broad, relatively undisturbed riparian easement (corridor). Ideally, the target riparian corridor width would be related to the local width of the recent (100-year) floodplain. Taking constraints into account that include current land use practices and active floodplain width, an appropriate average target for multi-species, age, and structural class vegetation would range between less than 25 and up to 100 feet (30 meters). The maximum of a 100 feet (30 meter) riparian buffer is based on tree height, stream shade, and the potential for large wood recruitment. Naiman et al. (2002) reported that 70 to 90 percent of the large wood from floodplain areas is yielded to the stream channel from within 100 feet (30 m) of the channel edge. The riparian buffer also allows for long-term channel processes associated with local avulsion or rerouting of flow due to accumulations of additional large wood. Beyond 100 feet from the bank or less, LWM recruitment potential is very low given the height of mature trees and the low migration rates. With the low rates of active migration, the buffer along reaches 4 and 3 of Catherine Creek will not likely need to be expanded to account for significant channel migration. Creation of these conditions through natural succession will likely take hundreds of years to achieve due to current levels of floodplain interaction, and overall low migration rates.

Sinuosity

The channel form has been altered by humans within the assessment area directly through mechanical means, including channel shortening by cut-off meanders and oxbows as well as channel relocation.

Within reach 4 target conditions for sinuosity are similar to the estimated historic sinuosity of 1.09 to 1.1. This target range considers current/historic meander wavelength and amplitude, well defined channel scars and recently disconnected sections of main channel.

Within reach 3 target conditions for sinuosity are 1.3 to 1.5.

Bed and Banks

Target conditions for the channel bed include an overall increase in abundance and diversity in bedforms, particularly in those sections that are currently plane bed. Those areas that currently have a pool riffle or riffle bar bedform could be enhanced. Target conditions for the banks include the removal of riprap where possible, and improvement of riparian vegetation.

Within the majority of reach 4, both the bed and banks are naturally armored with coarse material derived from glacial outwash. The combination of coarse material and relatively straight planform of the channel precludes significant channel migration. The greatest benefits will be associated with the removal of existing riprap from those few areas where naturally occurring channel migration is expected over time. In addition, at most locations within the reach where riprap is not associated with a road prism or a concrete diversion structure, it could be replaced with alternative bank protection, such as logs and root masses to increase local habitat and provide local roughness and associated velocity breaks to protect the bank. For example, in subreach 4c, channel migration is expected to follow the pattern of the existing thalweg development, with expansion into the left bank where the thalweg abuts the left bank and expansion into the right bank where the thalweg abuts the right bank. At those locations, removal or replacement of riprap would increase the potential to develop variance with local hydraulics and geomorphic features and habitat.

In reach 3, the channel bed and banks have been more manipulated. In the upstream half of the reach in subreach 3a, preferential mobilization and transport of fines has armored the bed and toe of the bank. Reinforcing the banks with riprap and concrete has also taken place and urban development occupies the area adjacent of the channel essentially to the top of the banks on both sides. A series of channel spanning concrete diversions also forces step morphology in otherwise very flat plane-bed channel between structures, with a moderate change in bed elevation between the upstream and downstream sides of each structure. Although the stream in this section had some variability, target conditions are similar to the conditions of the today in subreach 3a. In subreach 3b, target bed conditions include an increase in abundance and diversity of bed by the addition of LWM structures.

Floodplain Connection

Floodplain connection varies between the 4 subreaches in reach 4 as well as within each subreach. Levee, (or plug) removal will help achieve the target conditions by allowing at least partial access of high flows to the overbank/floodplain areas. Levees may need to be maintained in areas where required to protect infrastructure that cannot be relocated or abandoned. In some instances, it may be possible to partially achieve floodplain connection even within the constraints of the levees, by passing a regulated amount of water through a levee using a culvert, irrigation gate, or some other metering device. Locations where this may be possible would be in subreach 4d in the vicinity of RM 41.3 downstream to RM 41.0, and in subreach 3b at RM 38.65, 38.35 and 38.1 (Figure 15). It should be noted that HEC-RAS model results do not imply that overland flow currently accesses these areas during a flow with a recurrence interval of 2 years. The results indicate that it is potentially possible to activate these areas at a 2-year flow, if the levee or plug is removed or breached based on elevation. Further evaluation is required before moving forward with concepts.

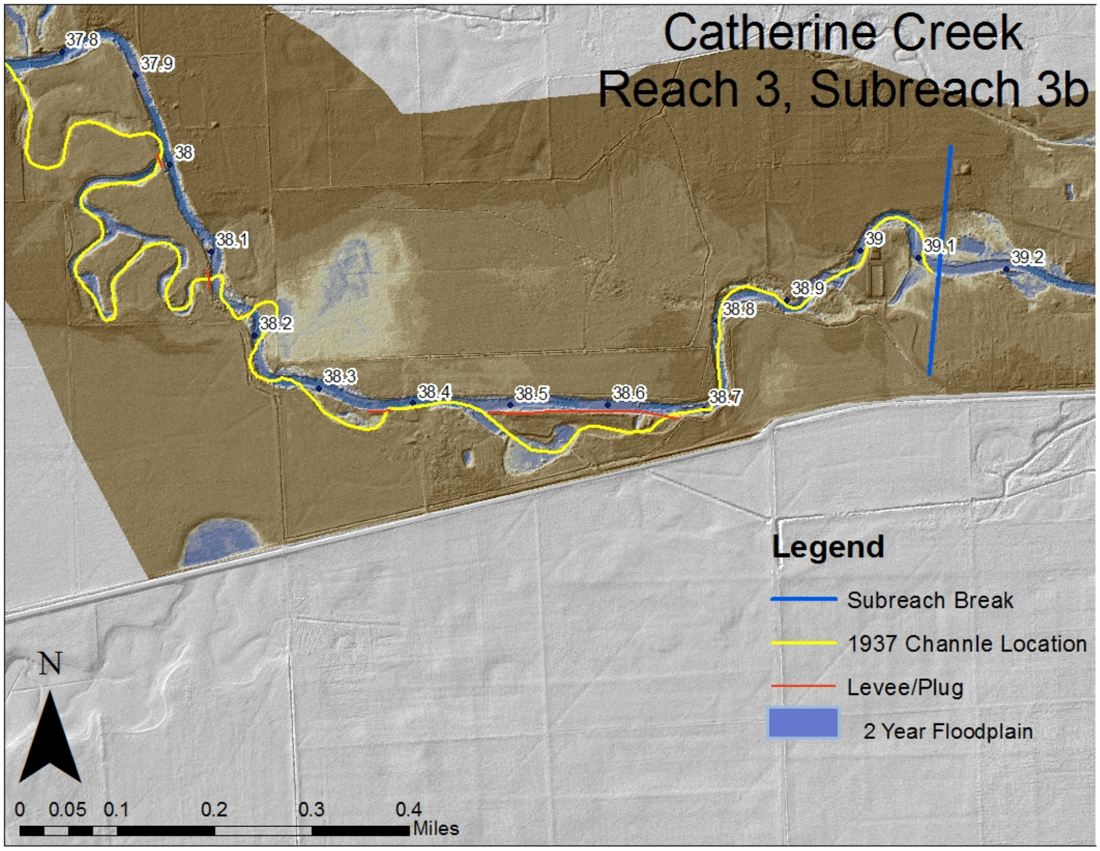

Figure 15. Potential location for floodplain connection via culvert, headgate, or other water-metering device in subreach 3b, reach 3 on Catherine Creek.

Although the target conditions include full reconnection of available floodplain, partial reconnection is beneficial and may be considered as a viable alternative when the constraints dictate. For the most significant habitat benefit connection should focus on the floodplain area that is inundated by flows with more frequent recurrence intervals, such as between 1 and 5 years increasing floodplain function (more frequent inundations) will provide more hydraulic diversity in the channel, provide improved conditions for riparian vegetation, and potentially increase storage in groundwater that may provide low-flow returns to the river.

Off-channel habitat is related to floodplain connectivity. Within reaches 4 and 3, off channel habitat could be developed in areas where the former channel has been artificially blocked, if the former channel has not been filled in (Figure 16).

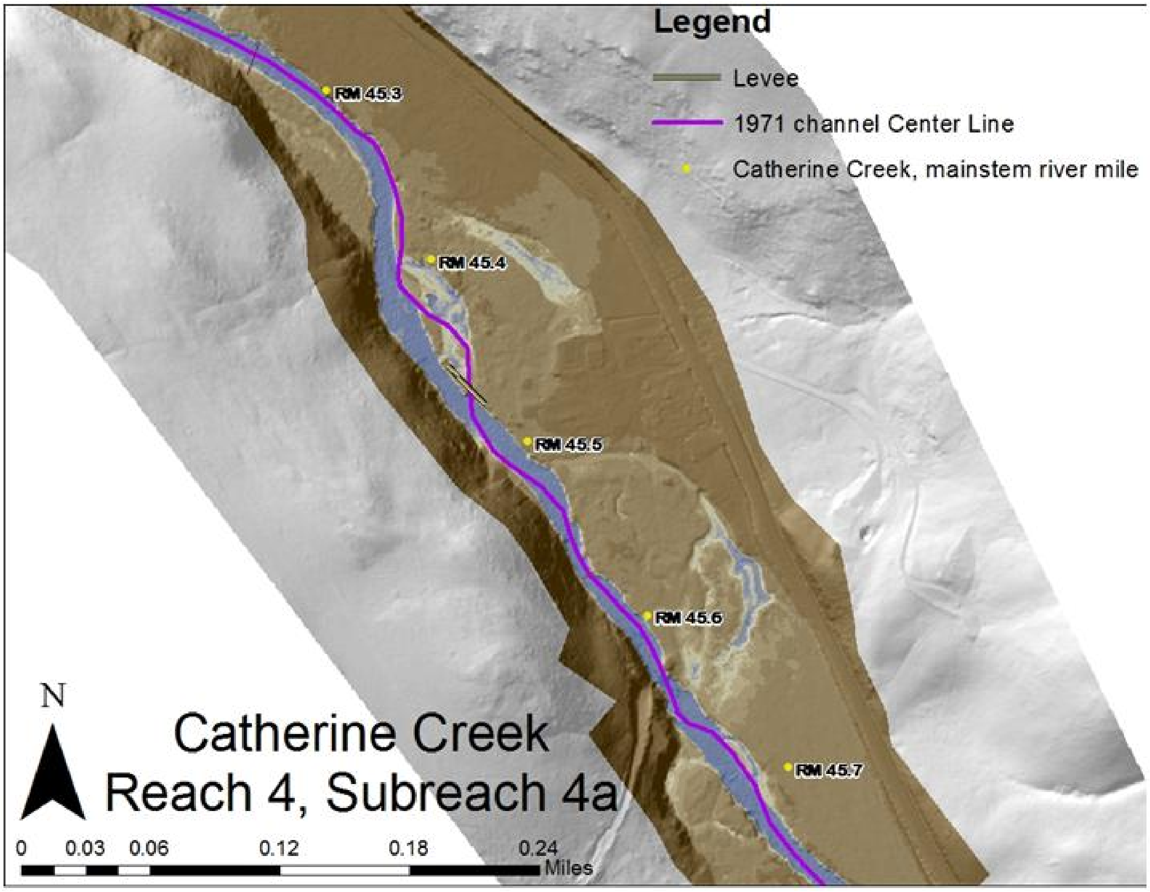

Figure 16. Location in reach 4, subreach 4a where off channel habitat can potentially be developed.

Target conditions within reaches 3 and 4 on Catherine Creek include more large wood located at the inlet of developed side channels at historic main channel locations to improve their longevity and habitat diversity. The off-channel habitat should also contain LWM.

Summary

Target conditions are similar to past conditions with the exception of accommodating major constraints where necessary. Within reach 4, the target conditions are similar to existing conditions due to the natural physical features that provide resistance to change. While this reach overall has few significant alterations to form or process, there are opportunities for specific actions to address areas where the existing conditions do not meet the targets. Table 15 is a summary of the few differences between past, existing, and target conditions and the actions necessary to address these differences to improve the limiting factors for reach 4.

Table 15. Summary of historical, existing, and target conditions in reach 4 on Catherine Creek.

Form	Historical Condition	Existing Condition	Target Condition	Process Needed to Achieve Target Condition	Limiting Factor(s) Addressed
Large Pools	Roughly 5.0 to 8.0 per mile	3.9 per mile	5.0 to 8.0 per mile	Recruitment of appropriate instream structures to force flow convergence locally.	Habitat quantity and quality; water quality (warm summer temperatures).
Sinuosity	Roughly 1.09 – 1.1	Roughly 1.08	Roughly 1.09 – 1.1	N/A	N/A
LWM	Unknown	2.9-3.4 logjams per mile.	5 to 10 logjams per mile; as many individual pieces providing cover along the banks as possible.	LWM recruitment and retention.	Juvenile habitat; instream complexity; cover; adult holding; steelhead spawning.
Channel geometry	Locally entrenched up to 2 feet, locally more narrow in some sections.	Locally entrenched up to 2 feet, local high width-to-depth ratios.	Locally entrenched up to 2 feet, local lower width-to-depth ratios.	Implement appropriate LWM structures to narrow the wetted width.	N/A
Riverbed and banks	Locally armored with coarse alluvium.	Locally armored with coarse alluvium and anthropogenic bank hardening (riprap, concrete).	Locally armored with coarse alluvium, but with an increase in abundance and diversity in bedforms.	Remove anthropogenic bank protection where possible, add LWM where appropriate.	Habitat quality and quantity.
Off-channel habitat	Few side channels.	Fewer side channels.	Few side channels, but more than existing	Channel migration where possible; recruitment and retention of LWM	Habitat quantity quality (Juvenile habitat); Riparian function.

Form	Historical Condition	Existing Condition	Target Condition	Process Needed to Achieve Target Condition	Limiting Factor(s) Addressed
Floodplain connection	Locally limited to narrow active floodplain.	Limited to locally narrow active floodplain and further reduced by levees/channelization.	Locally limited to narrow active floodplain and reduced only by levees protecting vital infrastructure.	Remove and/or selectively breach levees/plugs.	Riparian vegetation and cover; Habitat quantity (off-channel habitat), water quality (temperature).
Riparian condition	Multi-age and species vegetation including mature trees with varied successional stage; riparian area widths dependant on local conditions.	Patchy mature trees; riparian area generally 25 feet wide or less.	Multi-age and species vegetation including mature trees with varied successional stage; riparian area widths dependant on local conditions.	Create buffer areas of varying widths depending on local conditions, plant appropriate vegetation.	Riparian function Habitat quality and quantity water quality (temperature).

Some target conditions in reach 3 are similar to past conditions while others are not. Sinuosity, number of pools per mile, levels of instream complexity (LWM), off-channel habitat, and floodplain connection can be increased. With all potential target conditions, the accommodation of major constraints should be considered.

Table 16 is a summary of the few differences between past, existing, and target conditions, including natural processes necessary to maintain target conditions and the limiting factors addressed for reach 3.

Table 16. Summary of the historical, existing, and target conditions in reach 3 on Catherine Creek.

Form	Historical Condition	Existing Condition	Target Condition	Process Needed to Achieve Target Condition	Limiting Factor(s) Addressed
Large Pools	Roughly 15 to 20 per mile.	5.6 per mile.	13 to 18 per mile.	Recruitment of large instream structures to force flow convergence.	Juvenile habitat; instream complexity; adult holding; water temperatures.
Sinuosity	Roughly 1.5 - 1.7	Roughly 1.2	Roughly 1.5 - 1.7	N/A	N/A
LWM	Few logjams/mile (estimate less than 10).	1.1 - 3.7 logjams per mile.	5 to 10 logjams per mile; as many individual pieces providing cover along the banks as possible.	LWM recruitment and retention.	Juvenile habitat; instream complexity; cover; adult holding; steelhead spawning.
Channel geometry	Locally entrenched up to 3 feet, locally more narrow in some sections.	Locally entrenched up to 3 feet, local high width-to-depth ratios.	Locally entrenched up to 3 feet, local lower width-to-depth ratios.	Implement appropriate LWM structures to narrow the wetted width.	N/A
Riverbed and banks	Locally armored with coarse alluvium.	Locally armored with coarse alluvium and anthropogenic bank hardening (riprap, concrete).	Locally armored with coarse alluvium, but with an increase in abundance and diversity in bedforms.	Remove anthropogenic bank protection where possible, add LWM where appropriate.	Instream complexity; off-channel rearing.
Off-channel habitat	Few side channels.	Fewer side channels.	Few side channels, but more than existing.	Channel migration where possible; recruitment and retention of LWM.	Juvenile habitat; riparian vegetation and cover; off-channel habitat.

Form	Historical Condition	Existing Condition	Target Condition	Process Needed to Achieve Target Condition	Limiting Factor(s) Addressed
Floodplain connection* *Does not apply in subreach 3a.	Limited to narrow active floodplain.	Limited to narrow active floodplain and further reduced by levees.	Limited to narrow active floodplain between terraces and reduced only by levees protecting vital infrastructure.	Remove and/or selectively breach levees/plugs.	Riparian vegetation and cover; off-channel habitat.
Riparian condition	Multi-age and species vegetation including mature trees with varied successional stage; riparian area widths dependant on local conditions.	Partially mature trees; riparian area generally 25 feet wide or less.	Multi-age and species vegetation including mature trees with varied successional stage; riparian area widths dependant on local conditions.	Create buffer areas of varying widths depending on local conditions, plant appropriate vegetation.	Instream complexity; riparian vegetation and cover; off-channel rearing; water temperatures.

Potential Habitat Actions

Within reaches 3 and 4 of Catherine Creek, most subreaches have been relatively static since post glacial times, and will remain so without significant changes to the entire watershed including the hydrology and sediment regime. Other sections show recent increases in channel dynamics and or the potential to enhance the processes that form and maintain habitat due to previous anthropogenic manipulation, such as removal or alteration of the riparian vegetation. Habitat improvement efforts should be aimed at improving and enhancing those forms and processes that currently exist, rather than attempting to create wholly new conditions that may not be appropriate or sustainable.

The proposed reach-scale implementation strategy as summarized in the Catherine Creek tributary assessment (Reclamation 2012a) identifies a prioritized approach to habitat improvement adapted from Roni et al. (2002) including the following categories in order of perceived long-term effectiveness and priority: 1) Habitat Protection, 2) Water Quality and Quantity, 3) Habitat Connectivity, 4) Channel Process, and 5) Instream Habitat. Although the implementation strategy groups habitat improvement actions according to specific categories, most actions complement each other and overlap between categories. Following is a summary of each category of the implementation strategy including those habitat improvement actions appropriate to that category as they apply to reaches 3 and 4 of Catherine Creek.

Habitat Protection

Within reaches 4 and 3 of Catherine Creek, there are no areas where the integrated processes are functioning at or near their natural potential. Some areas are functioning better than others (subreach 4b) but all subreaches lack riparian vegetation needed for streambank stability, stream shading (water quality), and to provide large wood in the channel. Because some form of habitat action is indicated for every subreach in the two reaches, neither reach is identified for “habitat protection.”

Water Quality and Quantity

Existing and ongoing improvements and modernization of irrigation diversions and withdrawals will continue to partially address the issue of water quantity on Catherine Creek. Additionally, improving riparian vegetation will increase shade and help moderate instream temperatures, increase natural instream nutrients, and buffer potential pollutants from agricultural operations. Increased floodplain connection may increase hyporheic flow, potentially affecting water temperatures both in the summer (cooler) and winter (warmer). More instream structures have the potential to increase deep-water pools that provide relatively warm-water refuge for rearing juveniles during the cold winter months.

Habitat Connectivity

For this report, habitat connectivity refers only to the removal of human-constructed barriers to former main-channel locations.

Levee Removal and Breaching

One appropriate action to improve habitat connectivity in reaches 3 and 4 includes removing or breaching levees to reconnect the narrow active floodplain at locations where the active channel or an overflow/side channel previously existed and is still accessible by the creek. In instances where the former active channel has been cut off, the former channel could provide off-channel habitat and could potentially develop into a perennial connected side channel over a long period of time. As an alternative, additional excavation and shaping in the former channel could provide instant connectivity to these habitats.

Planning for levee alteration projects may require the additional evaluation of LWM placement to facilitate and maintain connectivity, evaluation of the invert elevation and the number of inlets to address sediment issues and evaluation of impacts to land uses adjacent to the remnant channel areas. Much of the risk associated with side-channel function and flooding in remnant main channel sections can be addressed by utilizing a flow-regulating device such as a culvert or headgate that passes a controlled volume of water through a levee rather than removing the entire levee. In areas where levee removal is not feasible due to constraints, culvert-fed or regulated side channels represent an option with potentially fewer risks to property and infrastructure behind the levee. In reach 4, the potential to reactivate off-channel habitat in the form of side channels exist in the downstream end of the reach where Highway 203 acts as a levee along the right bank of Catherine Creek at RM 41.3, 41.1, and 41.03 (Figure 17).

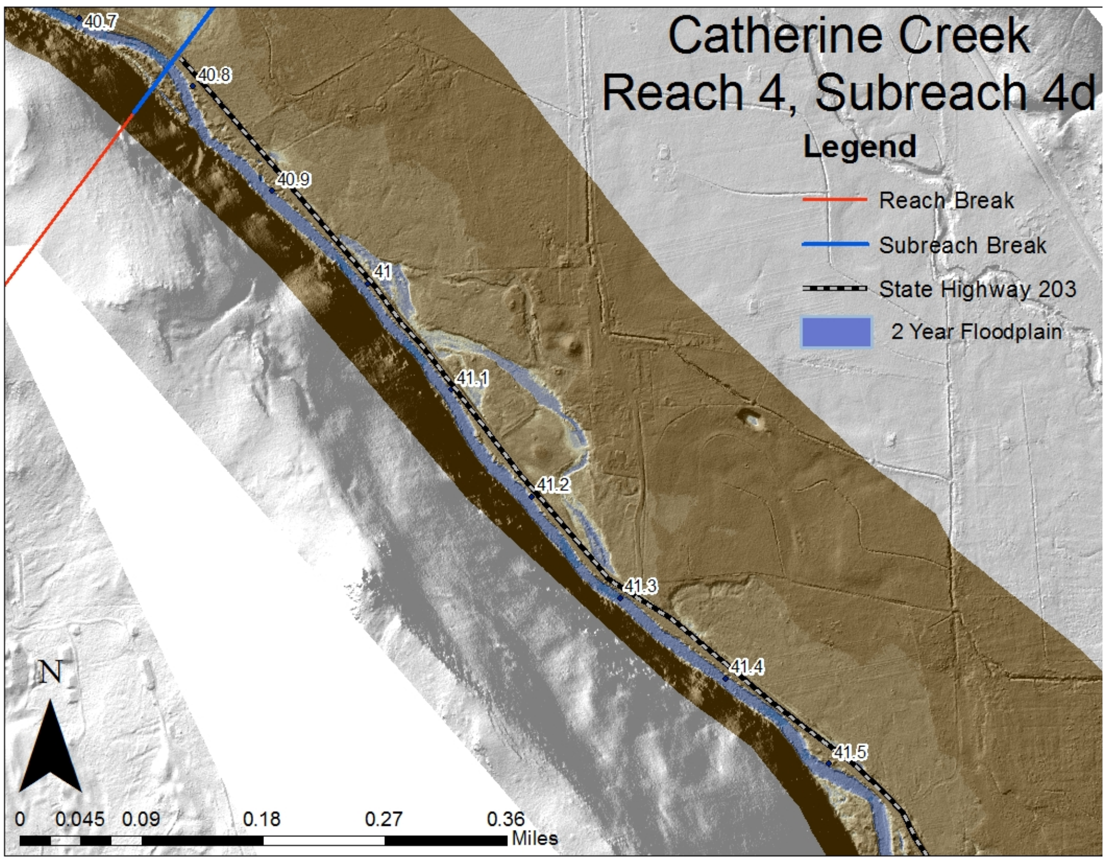

Figure 17. Potential location for floodplain connection via culvert, headgate or other water-metering device at RM 41.3, 41.1., and 41.03 in subreach 4d, reach 4 on Catherine Creek.

Within reach 3, there were likely smaller disconnected distributary channels in the upstream 3a section, and there may have been a few active side channels or overflow channels in subreach 3b. There is potential to breach levees or plugs and connect to off-channel habitat that is located in former main channel locations in subreach 3b at RM 38.65, 38.35, and 38.1.

In addition to side channels and alcoves, removing levees to improve floodplain connection also provides a habitat benefit. Levee removal for habitat benefit should be based on the potential for improved frequency of inundation and the actual habitat derived from that improvement. A floodplain with riparian vegetation that is inundated annually will provide considerably more habitat benefit to salmonids than will a sparsely vegetated floodplain that is only occasionally inundated during extreme flood events. Due to the naturally entrenched and armored conditions in reaches 3 and 4, levee removal may not result in significant changes to instream processes and/or instream habitat.

Channel Process

Channel processes are those actions that work to create and maintain channel forms and habitat. In this discussion, processes are grouped into major categories: hydrology, sediment transport, LWM recruitment, and riparian disturbance and succession. Because most processes are interdependent, improving one process alone may not result in the desired effect to the channel form and habitat. For projects that improve channel process, the linkages between processes and how those linkages are driven by factors inside and outside of the project area and the reach should be considered. Actions that are grouped together to potentially improve channel process will provide the most long-term habitat benefit on Catherine Creek.

Levee Removal and Breaching

Reconnecting habitat through the removal or breaching of levees will have multiple impacts. By allowing high flows to spread out rather than being contained in the channel between levees, the hydrology is altered because the stage (depth) for a given discharge is reduced. Hydraulics is altered with lower shear stresses due to the decrease in depths. Consequently, sediment transport is altered resulting in a reduction in the size of material that is mobilized and transported instream. Fine sediment carried onto the floodplain by overbank flows is deposited in off-channel areas rather than remaining in the main channel to be transported downstream. Levee removal or breaching also helps to improve riparian disturbance and succession processes through increased floodplain connection. Floodplain scour and deposition disturbances provide exposed soil for vegetation establishment; increased inundation that improves seed propagation and soil moisture; and improved nutrient cycling.

Riprap Removal

Riprap has a minor impact on channel form and process in reaches 3 and 4 of Catherine Creek. Local natural coarse bed and bank material and underfit conditions result in local channel confinement, preventing significant local migration. Despite limited migration potential, there are several locations where the addition of riprap has reduced bank erosion processes in areas where channel migration would have otherwise occurred (Figure 18).

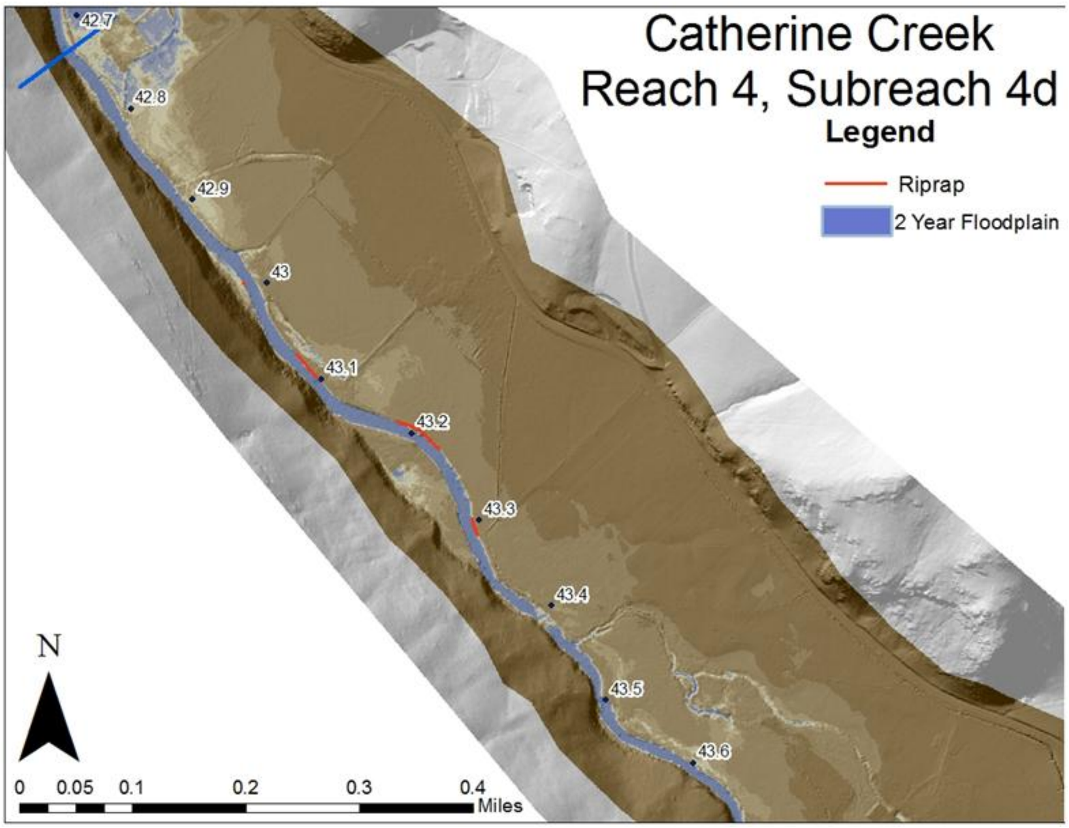

Figure 18. Location of riprap in subreach 4, reach 4, Catherine Creek.

Riprap removal would affect the channel planform and bedform by allowing the river to dissipate energy by eroding the banks laterally rather than forcing vertical migration locally. In general, the most active migration will occur where riprap is removed and channel migration is allowed on the outside of bends. This will increase bar building and floodplain development on the inside of the bend. Riprap removal along a straight stretch of river may not provide any immediate or long-term habitat benefit or improve channel process. If unacceptable risk to property and infrastructure would occur with the removal of riprap, replacement with log and root structures may provide habitat benefit and should be evaluated.

Roadfill Removal

Similar to levees, roadfill potentially blocks floodplain access. Based on results from hydraulic modeling, Highway 203 within subreach 4d acts as a levee, effectively disconnecting side channels located in the historic floodplain. The benefit that may be gained from removal or relocation of Highway 203 would likely not be cost effective or outweigh potential negative impacts associated with the disturbance required.

Throughout the rest of reach 4 and reach 3, the impact of roadfill to the river form and process is negligible. In fact, increasing flow convergence through constrictions associated with bridges and roads has the potential to improve local habitat conditions on Catherine Creek by creating low-velocity backwater conditions upstream while increasing flow velocity at the constriction leading to creation of large scour pools, all of which are desirable conditions in the river. Removal of existing roadfill will not likely improve favorable channel processes and should not be targeted as a priority for habitat improvement.

Riparian Planting and Buffer Establishment

Revegetation efforts, grazing and riparian land use management, and establishment of a broad riparian buffer within the accessible floodplain will provide the most direct benefit to improving riparian processes in Catherine Creek. An adequate riparian buffer based on the potential of the individual site will ensure adequate shade, cover, nutrient input, and future large wood recruitment to the river. The establishment of a riparian buffer would be appropriate at most locations within the assessment area.

Placement of LWM Structures

With very few large trees available along the banks and limited natural channel migration, local LWM recruitment potential in reaches 4 and 3 on Catherine Creek is low. Some large wood is transported from upstream sources, but there are relatively few places for that wood to be retained. All of reach 4 and subreach 3b would benefit in the short term by the direct placement of large wood and in the long term by the establishment and maintenance of a functioning riparian zone from which large wood could be recruited in the future.

Large wood structures include engineered logjams (ELJ) and individual logs. ELJs are constructed from multiple overlapping logs that act as a single large structure. There are several different types of LWM structures that can be used to influence channel processes in within reaches 4 and 3 Catherine Creek. Logjams located on the bank may serve to deflect flow from the bank or simply provide hydraulic variability and cover along the bank. Instream structures may be used to force flow into bedrock or other obstructions to enhance scour, potentially generating pools and velocity breaks needed by juvenile and adult salmonids. Individual logs or small multi-log structures may have very little hydraulic influence on the main stem channel at the reach scale, but can provide valuable cover, local velocity breaks and initiate local scour and bar development. LMW structures also provide potential sites for naturally incorporated LWM to collect by ‘racking,’ thereby, increasing the size and influence of the original LWM structure. Detailed evaluation of the specific project site will be necessary to determine the design, appropriate size, and placement and potential habitat benefit of a given structure or suite of structures.

Placement of Large Boulder Clusters

Large boulder clusters (Figure 19) are groups of large rocks placed in a stream to improve habitat, and create scour pools as well as areas of reduced velocity (Bergstrom 2008). The effect of the boulder cluster on the local hydraulics is forced flow separation around the boulders that leads to the formation of eddy or vortices in their wake. Boulder clusters also affect sediment transport by generating local scour that develops pockets of deeper water and associated bar formation that add to the physical diversity of a stream reach (Fischenich and Seal 2000). Similar to LWM structures, boulder clusters provide a potential site for naturally incorporated LWM to rack on, with the same increase in effect to the local hydraulics and sediment transport. Local habitat is created by the boulder clusters when the vortices diffuse sunlight and create overhead cover.

Figure 19. Constructed instream boulder cluster in the Entiat River, Entiat, Washington (Reclamation 2012a).

Instream Habitat

As a result of the relatively straight planform and underfit conditions, the majority of habitat that historically existed in reaches 4 and 3 on Catherine Creek was instream habitat. Improving instream habitat is vitally important to salmon and steelhead. Appropriate actions to create and maintain instream habitat may include, but are not limited to placement of LWM structures and placement of large boulder clusters.

Placement of LWM Structures

Catherine Creek is predominantly a single thread channel within reaches 4 and 3, but within reach 4, subreach 4b has multiple sites where split flow conditions around bars occurs and mid-channel LWM structures could be appropriate (Figure 20).

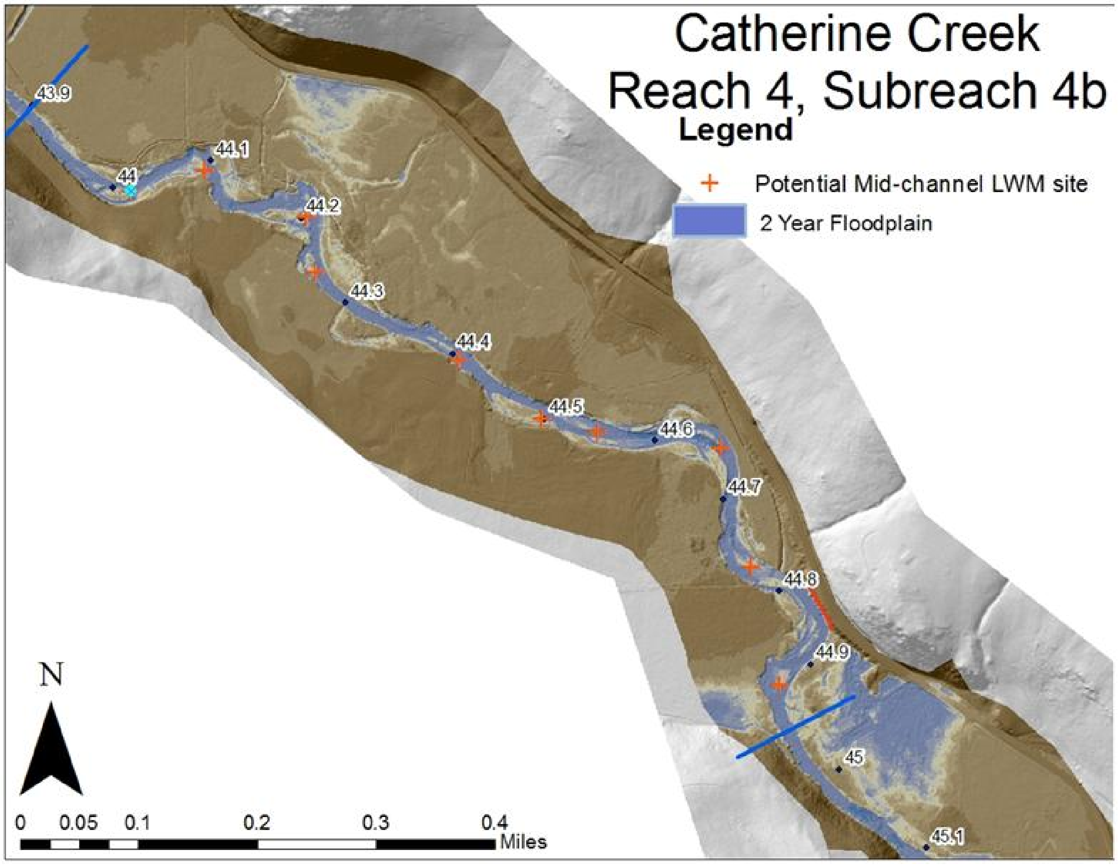

Figure 20. Potential locations of mid-channel LWM structures in subreach 4b, reach 4, Catherine Creek.

Mid-channel ELJs have been used to narrow effective widths in sections of stream that are over widened. They are also appropriate at the apex of existing or emergent islands where they tend to form naturally.

Bank ELJs are LWM structures located along the bank that provide hydraulic variability and cover (Figure 21). Logjams naturally accumulate and are most appropriate in those areas where high flows first overtop the banks and where gravel bars are first exposed in receding flows. Floating logs and debris will accumulate in the shallow waters of these overflow areas where the moving water is forcing the logs against the bank rather than pushing the logs farther downstream. For this reason, bank ELJs are most appropriate at or adjacent to the inlets of overflow channels and floodplain side channels or alcoves. In some instances, a large tree or other obstruction protruding from the bank may begin to rack additional wood and form a logjam. This type of logjam was historically less common in Catherine Creek, but would have occasionally formed along the outside of a bend or near bedrock.

Figure 21. Bank engineered logjam in the Stillaguamish River, Washington (courtesy of Anchor QEA).

Streambank Barbs

Streambank barbs are relatively low profile structures that can be constructed of wood or rock or a combination of both that protrude from the bank and are intended to be overtopped during annual high flows (Figure 22).

Figure 22. LWM barb in the Entiat River, Entiat, Washington.

Barbs affect local hydrology by redirecting streamflow with a very low weir and disrupt the velocity gradient in the near-bank region (NRCS 2001). Barbs are commonly used to alter local sediment transport by scouring pools with subsequent bar formation. A string of barbs spaced appropriately can also be used to redirect the thalweg away from the bank. The angle of a barb can be adjusted to modestly direct flows because water will overtop the barb perpendicular to the barb's longitudinal axis. Using stream barbs in conjunction with bioengineering methods is the most favorable combination. The barbs relieve direct streambank pressure from flow and vegetation provides for energy dissipation and sediment deposition. The vegetation is the long-term stabilizing factor (NRCS 2001). Like other log and rock structures, barb design requires project-specific evaluation to ensure the most appropriate size and positioning.

Single log structures in Catherine Creek will not obstruct flow enough to significantly alter process or form at the reach scale, but they can provide local hydraulic complexity and cover at the channel unit scale. Depending on its location, orientation, and size, a single log structure can be constructed to rack additional available LWM, potentially developing into a logjam. Individual logs can be placed with root wads facing the channel and interacting with flow, or with the bole of the tree complete with branches extending into the channel. Larger root wads or more branches provide a greater volume of cover and hydraulic refuge for juvenile fish. Single logs can be buried into the bank, anchored to the bank, or pinned between existing vegetation for stabilization. When pinned between existing vegetation, the log can potentially pivot up and down with changing water surface levels. Individual log structures are appropriate anywhere a large, mature tree could potentially fall into the river.

Placement of Large Boulder Clusters

Boulder clusters can increase local bed roughness and hydraulic variability, create local scour pools, and provide cover for fish. Boulders can be arranged with gaps between them to force flow convergence or overlapped to force flow divergence. The potential for influencing bank conditions may be beneficial, particularly if flow can be forced against a bedrock or similarly erosion-resistant bank to induce channel bed scour and pool formation. In any case, the added roughness in the channel may influence local bank conditions which should be evaluated prior to construction Boulders should be sized in order to remain stable at bankfull discharges (Fischenich and Seal 2000).

Summary

Habitat improvement actions can be undertaken to address the limiting factors of habitat quality, habitat quantity, water quality (high summer water temperatures), and riparian function in reaches 4 and 3 on Catherine Creek. Levee removal or alteration, riparian area improvement and protection, and placement of instream habitat features, particularly LWM, are the individual actions considered most appropriate for preserving, initiating, and/or creating the identified target conditions in Catherine Creek (Table 17).

Table 17. Summary of habitat improvement actions and their potential to address limiting factors.

Form	Target Condition		Habitat Improvement Action	Potential to address limiting factors (high, med, low)
	Reach 3	Reach4		
Large Pools	13 to 18 per mile	5.0 – 8.0 per mile	Placement of LWM	High
Sinuosity	1.5 – 1.7	1.09 – 1.1	Removal of riprap, access sections of disconnected historic main channel	Low
LWM	5 to 10 logjams per mile; as many individual pieces providing cover along the banks as possible	5 to 10 logjams per mile; as many individual pieces providing cover along the banks as possible	Placement of LWM; riparian planting; fence and maintain a riparian buffer	High
Channel geometry	Locally entrenched up to 3 feet	Locally entrenched up to 2 feet t	N/A	N/A
Riverbed and banks	Locally armored with coarse alluvium	Locally armored with coarse alluvium	Remove riprap	Low

Form	Target Condition		Habitat Improvement Action	Potential to address limiting factors (high, med, low)
	Reach 3	Reach4		
Off-channel habitat	Few side channels, but more than existing	Few side channels, but more than existing	Placement of LWM; removal of levees; excavate side channels	High
Floodplain connection* Does not apply to subreach 3a	Locally limited to narrow active floodplain and reduced only by levees protecting vital infrastructure	Locally limited to narrow active floodplain and reduced only by levees protecting vital infrastructure	Remove levees; breach levees with culverts	Medium
Riparian Condition	Multi-age and species vegetation including mature trees with varied successional stage ; riparian area widths dependant on local conditions	Multi-age and species vegetation including mature trees with varied successional stage ; riparian area widths dependant on local conditions	Riparian planting; fence and maintain a riparian buffer	High

Next Steps

This reach assessment is intended to be used as one tool among many to help guide river process rehabilitation and habitat improvement in Catherine Creek. The actions outlined in this report represent geomorphically appropriate actions for these reaches of Catherine Creek, but are not an exhaustive assessment of all possible actions that can be used to achieve habitat benefits. The potential habitat actions outlined in this report can be grouped in any number of ways or places to form projects. In some instances, only one course of action may be appropriate and project development may be relatively simple. In other instances, multiple groupings may be appropriate requiring detailed and complicated project development and evaluation. In either case, evaluating the proposed action(s) based on the goals and objectives through collaboration with the project stakeholders will ensure the most appropriate suite of actions is developed. Throughout the project development, design, and implementation process, this Reach Assessment can be used as a reference to verify whether project components are appropriate for the geomorphic character and trends prevalent in Catherine Creek. Completed projects can be evaluated to determine the extent to which they helped achieve the identified target conditions. Shortcomings can be addressed through adaptive management of the project and in future project designs.

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Glossary

Term	Definition
action	Proposed protection and/or rehabilitation strategy to improve selected physical and ecological processes that may be limiting the productivity, abundance, spatial structure or diversity of the focal species. Examples include removing or modifying passage barriers to reconnect isolated habitat (i.e., tributaries), planting appropriate vegetation to re-establish or improve the riparian corridor along a stream that reconnects channel-floodplain processes, placement of large wood to improve habitat complexity, cover and increase biomass that reconnects isolated habitat units.
alluvial fan	An outspread, gently sloping mass of alluvium deposited by a stream, esp. in an arid or semiarid region where a stream issues from a narrow canyon onto a plain or valley floor. Viewed from above, it has the shape of an open fan, the apex being at the canyon mouth.
alluvium	A general term for detrital deposits made by streams on riverbeds, floodplains, and alluvial fans; esp. a deposit of silt or silty caly laid down during time of flood. The term applies to stream deposits of recent time. It does not include subaqueous sediments of seas and lakes.
anthropogenic	Caused by human activities.
bank	The margins of a channel. Banks are called right or left as viewed facing in the direction of the flow.
baseflow	That part of the streamflow that is not attributable to direct runoff from precipitation or melting snow; it is usually sustained by groundwater discharge.
basin	The drainage area of a river and its tributaries.
bedrock	The solid rock that underlies gravel, soil or other superficial material and is generally resistant to fluvial erosion over a span of several decades, but may erode over longer time periods.
cfs	Cubic feet per second; a measure of water flows
channel forming flow	Sometimes referred to as the effective flow or ordinary high water flow and often as the bankfull flow or discharge. For most streams, the channel forming flow is the flow that has a recurrence internal of approximately 1.5 years in the annual flood series. Most channel forming discharges range between 1.0 and 1.8. In some areas it could be lower or higher than this range. It is the flow that transports the most sediment for the least amount of energy, mobilizes and redistributes the annually transient bed load, and maintains long-term channel form.
channel morphology	The physical dimension, shape, form, pattern, profile and structure of a stream channel.
channel planform	The two-dimensional longitudinal pattern of a river channel as viewed on the ground surface, aerial photograph or map.
channelization	The straightening and/or deepening of a stream channel, typically to permit the water to move faster, to reduce flooding, or to drain marshy acreage.

Term	Definition
colluvial	A general term applied to loose and incoherent deposits, usually at the foot of a slope or cliff and brought there chiefly by gravity.
control	A natural or human feature that restrains a streams ability to move laterally and/or vertically.
degradation	Transition from a higher to lower level or quality. A general lowering of the earth's surface by erosion or transportation in running waters. Also refers to the quality (or loss) of functional elements within an ecosystem.
discharge	The volume per unit of time of streamflow at a given instant or for a given area. Discharge is often used interchangeably with streamflow.
diversity	Genetic and phenotypic (life history traits, behavior, and morphology) variation within a population. Also refers variations in physical conditions or habitat.
ecosystem	An ecologic system, composed of organisms and their environment. It is the result of interaction between biological, geochemical, and geophysical systems.
erosion	Wearing away of the lands by running water, glaciers, winds, and waves.
fine sediment	Sand, silt and organic material that have a grain size of 6.4 mm or less.
floodplain	That portion of a river valley, adjacent to the channel, which is built of sediments deposited during the present regimen of the stream and is covered with water when the river overflows its banks at flood stages.
fluvial	Produced by the action of a river or stream. Also used to refer to something relating to or inhabiting a river or stream. Fish that migrate between rivers and streams are labeled "fluvial."
fluvial process	A process related to the movement of flowing water that shape the surface of the earth through the erosion, transport, and deposition of sediment, soil particles, and organic debris.
geomorphic reach	An area containing the active channel and its floodplain bounded by vertical and/or lateral geologic controls, such as alluvial fans or bedrock outcrops, and frequently separated from other reaches by abrupt changes in channel slope and valley confinement. Within a geomorphic reach, similar fluvial processes govern channel planform and geometry resulting from streamflow and sediment transport.
geomorphology	The science that focuses on the general configuraion of the earth's surface; specif. the study of the classification, description, nature, origin and development of landforms and their relationships to underlying structures, and the history of geologic changes as recorded by these surface features.
GIS	Geographical information system. An organized collection of computer hardware, software, and geographic data designed to capture, store, update, manipulate, analyze, and display all forms of geographically referenced information.
gradient	Degree of inclination of a part of the earth's surface; steepness of slope. It may be expressed as a ratio (of vertical to horizontal), fraction, percentage, or angle.
groundwater	That part of the subsurface water that is in the saturated zone.

Term	Definition
habitat connectivity	Aquatic and/or terrestrial conditions that are linked together and needed to provide the physical and ecological processes necessary for the transfer of energy (i.e., food web) to maintain all life stages of species that are dependent on the riverine ecosystem.
habitat unit	A segment of a stream which has a distinct set of characteristics.
headwaters	Streams at the source of a river.
hydraulics	The branch of fluid mechanics dealing with the flow of water in conduits and open channels.
hydrograph	A graph relating stage, flow, velocity, or other characteristics of water with respect to time.
hydrology	The applied science concerned with the waters of the earth, their occurrences, distribution, and circulation through the unending hydrologic cycle of: precipitation, consequent runoff, infiltration, and storage; eventual evaporation; and so forth. It is concerned with the physical and chemical reaction of water with the rest of the earth, and its relation to the life of the earth.
indicator	A variable used to forecast the value or change in the value of another variable; for example, using temperature, turbidity, and chemical contaminents or nutrients to measure water quality.
limiting factor	Any factor in the environment that limits a population from achieving complete viability with respect to any Viable Salmonid Population (VSP) parameter.
main stem	The reach of a river/stream formed by the tributaries that flow into it.
peak flow	Greatest stream discharge recorded over a specified period of time, usually a year, but often a season.
perennial stream	A stream that flows all year round. Compare intermittent stream.
reach	A section between two specific points outlining a portion of the stream, or river.
Reclamation	U.S. Department of the Interior, Bureau of Reclamation
recurrence interval	The average amount of time between events of a given magnitude. For example, there is a 1 percent chance that a 100-year flood will occur in any given year.
redd	A nest built in gravel or small substrate materials by salmonids where eggs are deposited; the nest is excavated by the adult fish and the eggs are covered by the female after spawning.
riparian area	An area adjacent to a stream, wetland, or other body of water that is transitional between terrestrial and aquatic ecosystems. Riparian areas usually have distinctive soils and vegetation community/composition resulting from interaction with the water body and adjacent soils.
riprap	Materials (typically large angular rocks) that are placed along a river bank to prevent or slow erosion.
river mile (RM)	Miles measured in the upstream direction beginning from the mouth of a river or its confluence with the next downstream river.

Term	Definition
runoff	That part of precipitation that flows toward the streams on the surface of the ground or within the ground. Runoff is composed of baseflow and surface runoff.
shear stress	The combination of depth and velocity of water. It is a measure of the erosive energy associated with flowing water.
side channel	A distinct channel with its own defined banks that is not part of the main channel, but appears to convey water perennially or seasonally/ephemerally. May also be referred to as a secondary channel.
sinuosity	Ratio of the length of the channel or thalweg to the down-valley distance. Channels with sinuosities of 1.5 or more are called “meandering.”
smolt	A subadult salmonid that is migrating from freshwater to seawater; the physiological adaptation of a salmonid from living in freshwater to living in seawater.
spawning and rearing habitat	Stream reaches and the associated watershed areas that provide all habitat components necessary for adult spawning and juvenile rearing for a local salmonid population. Spawning and rearing habitat generally supports multiple year classes of juveniles of resident and migratory fish, and may also support subadults and adults from local populations.
subbasin	A subbasin represents the drainage area upslope of any point along a channel network (Montgomery and Bolton 2003). Downstream boundaries of subbasins are typically defined in this assessment at the location of a confluence between a tributary and main stem channel.
terrace	A relatively level bench or steplike surface breaking the continuity of a slope. The term is applied to both the lower or front slope (the riser) and the flat surface (the tread).
tributary	Any stream that contributes water to another stream.
valley segment	An area of river within a watershed sometimes referred to as a subwatershed that is comprised of smaller geomorphic reaches. Within a valley segment, multiple floodplain types exist and may range between wide, highly complex floodplains with frequently accessed side channels to narrow and minimally complex floodplains with no side channels. Typical scales of a valley segment are on the order of a few to tens of miles in longitudinal length.
viable salmonid population	An independent population of Pacific salmon or steelhead trout that has a negligible risk of extinction over a 100-year time frame. Viability at the independent population scale is evaluated based on the parameters of abundance, productivity, spatial structure, and diversity (ICBTRT 2007).
watershed	The area of land from which rainfall and/or snowmelt drains into a stream or other water body. Watersheds are also sometimes referred to as drainage basins. Ridges of higher ground form the boundaries between watersheds. At these boundaries, rain falling on one side flows toward the low point of one watershed, while rain falling on the other side of the boundary flows toward the low point of a different watershed.

APPENDIX A
CATHERINE CREEK REACH
ASSESSMENT 3 AND 4 HYDRAULICS

United States Department of the Interior

BUREAU OF RECLAMATION
P.O. Box 25007
Denver, Colorado 80225-0007

IN REPLY REFER TO:

86-68240
RES-3.20

VIA ELECTRONIC MAIL

MEMORANDUM

To: Regional Director, Boise, ID
Attention: PN-3651 (Cuhaciyan)

From: Sean Kimbrel
Hydraulic Engineer, Sedimentation & River Hydraulics Group

Subject: Catherine Creek Reach Assessment 3 and 4 Hydraulics – Tributary Habitat Program for the Federal Columbia River Power System Biological Opinion, Grande Ronde River, OR – Pacific Northwest Region, Revision 1, SRH Report 2013-03

The Bureau of Reclamation and Bonneville Power Administration contribute to the implementation of salmonid habitat improvement projects in the Grande Ronde River subbasin to help meet commitments contained in the 2010 Supplemental Federal Columbia River Power System (FCRPS) Biological Opinion (BiOp) (NOAA Fisheries Service, 2010). This BiOp includes a Reasonable and Prudent Alternative (RPA), or a suite of actions, to protect listed salmon and steelhead across their life cycle. Habitat improvement projects in various Columbia River tributaries are one aspect of this RPA. Reclamation provides technical assistance to States, Tribes, Federal agencies, and other local partners for identification, design, permitting, coordination and other technical services for stream habitat improvement projects that primarily address streamflow, access, entrainment, and channel complexity limiting factors. Reclamation does not provide construction funding but works with project sponsors to implement projects. Reclamation's contributions to habitat improvement are all meant to be within the framework of the FCRPS RPA or related commitments.

Reach assessments are being conducted by Bureau of Reclamation's Pacific Northwest Regional Office (PNRO) to define the existing habitat conditions, present use, and habitat potential within the Catherine Creek Tributary Assessment Area for Endangered Species Act (ESA) listed salmonids, such that habitat enhancement project locations can be identified and prioritized for implementation. To help meet the reach assessment objectives, Reclamation's Sedimentation and River Hydraulics Group at the Technical Service Center utilized and updated a portion of a previously developed one-dimensional (1D) hydraulic model (Russell, 2011) used for the Tributary Assessment (Reclamation, 2012). The updated 1D model extends from river mile

(RM) 36.5 to RM 46.8 of Catherine Creek, which encompasses Reaches 3 (RM 37.2 to 40.8) and 4 (RM 40.8 to 45.8) of the Tributary Assessment (Reclamation, 2012). The previous model was used to analyze the Catherine Creek assessment area hydraulic conditions during higher discharge flows.

The objectives of the model were to:

1. Determine the inundation extent of discharges with recurrence intervals of 2 years, 10 years, and 100 years.
2. Evaluate water surface elevations, energy grade lines, velocities, and shear stresses for discharges with recurrence intervals of 1.05 to 100 years.
3. Assess the sediment transport and geomorphic processes of the channel bed through an incipient motion analysis for discharges with recurrence intervals of 1.05-, 1.5-, and 2-years.

The study was completed by Sean Kimbrel and peer reviewed by Blair Greimann, both with the Sedimentation and River Hydraulics Group. In addition, the study was peer reviewed by Christopher Cuhaciyan, with the Geology and River Systems Analysis Group in the Pacific Northwest Region. If you have questions related to this study, please contact me at 303-445-2539 or email at skimbrel@usbr.gov.

Attachment

cc: 86-68200 (Reading File)
86-68240 (Kimbrel, Greimann, File)
(w/att to ea)

RECLAMATION

Managing Water in the West

Catherine Creek Reach Assessment 3 and 4 Hydraulics

Tributary Habitat Program for the Federal Columbia River Power System Biological Opinion, Grande Ronde River, OR
Pacific Northwest Region
Revision 1, SRH Report 2013-03

U.S. Department of the Interior
Bureau of Reclamation

October 2012

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Photo taken on Catherine Creek near River Mile 44.8 on April 23, 2012.

Catherine Creek Reach Assessment 3 and 4 Hydraulics

Tributary Habitat Program for the Federal Columbia River Power System Biological Opinion, Grande Ronde River, OR
Pacific Northwest Region
Revision 1, SRH Report 2013-03

Peer Review Certification: This document has been peer reviewed per guidelines established by the Technical Service Center and is believed to be in accordance with the service agreement and standards of the profession.

Prepared by

______________________________ DATE: 10/1/12

Technical Service Center
Sedimentation and River Hydraulics (86-68240)
Sean Kimbrel, M.S., P.E. Hydraulic Engineer

Peer reviewed by

______________________________ DATE: 10-1-12

Technical Service Center
Sedimentation and River Hydraulics (86-68240)
Blair Greimann, PhD., P.E. Hydraulic Engineer

______________________________ DATE: 10/1/12

Pacific Northwest Region
Geology and River Systems Analysis Group
Christopher Cuhaciyan, PhD., Hydraulic Engineer

Executive Summary

The Bureau of Reclamation and Bonneville Power Administration contribute to the implementation of salmonid habitat improvement projects in the Grande Ronde River subbasin to help meet commitments contained in the 2010 Supplemental Federal Columbia River Power System (FCRPS) Biological Opinion (BiOp) (NOAA Fisheries Service, 2010). This BiOp includes a Reasonable and Prudent Alternative (RPA), or a suite of actions, to protect listed salmon and steelhead across their life cycle. Habitat improvement projects in various Columbia River tributaries are one aspect of this RPA. Reclamation provides technical assistance to States, Tribes, Federal agencies, and other local partners for identification, design, permitting, coordination and other technical services for stream habitat improvement projects that primarily address streamflow, access, entrainment, and channel complexity limiting factors. Reclamation does not provide construction funding but works with project sponsors to implement projects. Reclamation's contributions to habitat improvement are all meant to be within the framework of the FCRPS RPA or related commitments. The Reach Assessment 3and 4 Hydraulics study described in this document provides technical and scientific information on geomorphology and hydraulics that can be used to help identify, prioritize, and implement a sustainable fish habitat improvement project and to help focus the project on addressing key limiting factors to protect and improve survival of salmon and steelhead listed under the Endangered Species Act (ESA).

Reclamation's Sedimentation and River Hydraulics Group at the Technical Service Center refined a previously developed one dimensional (1D) hydraulic model to analyze the hydraulic conditions of Catherine Creek Assessment Reaches 3 and 4 during flood flows. Approximately 10.3 miles of channel were modeled along Catherine Creek. The steady flow model input consists of channel geometry, infrastructure dimensions and operating conditions, input discharge, a downstream boundary condition, and hydraulic roughness values. Terrain models for channel geometry were developed as topographic input to the hydraulic model based on LiDAR data above water and bathymetric surveys in the wetted channel areas. A total of 207 cross-section lines, spaced 37 feet to 2,141 feet apart with an average spacing of 265 feet were used to represent the 10.3 river miles of Catherine Creek. Levee elements were assigned manually in HEC-RAS. Nine bridges and six diversions were included in the updated HEC-RAS model.

Six discharges were simulated in the HEC-RAS model, including the near annual (1.05-), 1.5-, 2-, 10-, 25-, and 100-year peak discharge events. The downstream boundary is located immediately upstream of the Miller Lane Bridge, near RM 36.5, where a stage-discharge relationship has been derived from a combination of measured and modeled results using the previous HEC-RAS model (Russell, 2011).

Roughness values in the channel were calibrated to fit measured data obtained in 2012. Roughness values outside of the channel were determined in the previous study (Russell, 2011) based on a combination of vegetation and agricultural land use.

During the Tributary Assessment (Reclamation, 2012), four reaches of Catherine Creek were modeled to determine the current conditions. In this study, two reaches (Reaches 3 and 4) are analyzed in further detail. The downstream end of Reach 3 (RM 37.2 - 40.8) and the upstream end of Reach 2 act as a hydraulic transition zone at the base of the Catherine Creek alluvial fan. The relative confinement of the valley within Reach 3 increases from downstream to upstream. Average bed slope within this reach is 0.59%. Channel capacity in this reach is high, where 85% of the model cross-sections contain the 100-year peak discharge. Reach-averaged channel velocities range from 5.3 ft/sec for the 2-year discharge to 6.9 ft/sec for the 100-year discharge. Channel shear stresses in the reach range from about 1 lb/ft^2 for a 2-year discharge to 1.3 lb/ft^2 for a 100-year discharge. Several structures exert hydraulic control at high discharges in Reach 3. These structures include the Pond Slough Bridge, 10th St Bridge, Main St Bridge, and the Hempe-Hutchinson, Townley-Dobbin, and Swackhammer diversions. Incipient motion analyses indicate the potential to transport existing bed material in the upstream portion of Reach 3 during higher (>1.5-year) discharges, however the sediment transport capacity decreases downstream in Reach 3 as Catherine Creek courses over an alluvial fan, creating a zone of gravel deposition.

Reach 4 (RM 40.8 to 45.8) is a relatively narrow valley reach with an average channel slope of 0.83%. The channel capacity in Reach 4 is greater than in Reach 3. Results show that over 90% of model cross sections in Reach 4 contain a flow with a 100-year recurrence interval. The reach-averaged channel cross-section velocity in Reach 4 is approximately 5.8 ft/sec for the 2-year discharge and 7.6 ft/sec for the 100-year discharge. Average in-channel shear stresses in the reach range between 1.1 lb/ft^2 for a 2-year discharge to about 1.5 lb/ft^2 for a 100-year discharge. The most significant hydraulic control within the reach is the Catherine Creek Adult Collection Facility (CCACF) diversion structure. Below the CCACF, incipient motion analyses indicate the potential to transport bed material during flows higher than the annual peak discharge. Hydraulic model results indicate that the hydraulic control exerted by CCACF limits the ability to transport bed material immediately upstream of the structure. From RM 43.5 to 44, model results indicate the potential to transport a large fraction of the bed material during the 1.5- and 2-year discharges. From RM 44 to RM 44.4, results indicate a relative decrease in the potential to transport bed material for the annual, 1.5-, and 2-year discharges compared to upstream and downstream sections. This section that has recently experienced bank erosion and a resulting relative increase in channel width and sinuosity (Sixta, 2011) compared to upstream and downstream sections. From RM 44 to 44.8, model results indicate the potential to transport a large fraction of the bed material during the 1.5- and 2-year discharges. At RM

44.9, an observed alluvial fan is present. Downstream of this alluvial fan, model results indicate the potential to transport a large fraction of the bed material during the 1.5- and 2-year discharges, dependent on the location/presence of channel forms (e.g. riffle or pool). As Catherine Creek courses over the alluvial fan at RM 44.9, model results indicate a decrease in sediment transport capacity, which is characteristic of alluvial fans. Upstream of the depositional zone above the alluvial fan all the way to the upstream end of Reach 4, model results of critical grain size at incipient motion increase for the 1.5- and 2-year discharge, indicating the increased likelihood of entrainment and transport of bed material to the alluvial fan depositional zone near RM 44.9.

Within Reaches 3 and 4 of Catherine Creek low-head diversion structures significantly affect river processes by exerting hydraulic control on flood flows and keeping the channel in a fixed location and elevation. At these features, the channel depth increases, velocities and shear stress reduces upstream of the structure, while the velocity/shear increases and depth decreases downstream of structure. Similar to low-head diversion structures, bridges that exert hydraulic control at flood flows along reaches 3 and 4 also significantly affect river processes in a similar manner upstream and downstream of the structure. The exception with Bridges is that the bed elevation may not be fixed and is allowed to adjust over time. In locations where a large amount of bank erosion has been observed (RM 44 to 44.4) at what is identified as the Smith Project (Sixta, 2011), river processes are relatively different compared to upstream and downstream locations where the bank erosion is not as prevalent and channel width and sinuosity is relatively less. The relative increase in channel width and sinuosity has decreased shear stresses and sediment transport capacity shown in the model results compared to upstream and downstream locations. The presence of alluvial fans in Reaches 3 and 4 was also observed in the hydraulic model results.

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1 Introduction

1.1 Purpose

The Bureau of Reclamation and Bonneville Power Administration contribute to the implementation of salmonid habitat improvement projects in the Grande Ronde River subbasin to help meet commitments contained in the 2010 Supplemental Federal Columbia River Power System (FCRPS) Biological Opinion (BiOp) (NOAA Fisheries Service, 2010). This BiOp includes a Reasonable and Prudent Alternative (RPA), or a suite of actions, to protect listed salmon and steelhead across their life cycle. Habitat improvement projects in various Columbia River tributaries are one aspect of this RPA. Reclamation provides technical assistance to States, Tribes, Federal agencies, and other local partners for identification, design, permitting, coordination and other technical services for stream habitat improvement projects that primarily address streamflow, access, entrainment, and channel complexity limiting factors. Reclamation does not provide construction funding but works with project sponsors to implement projects. Reclamation's contributions to habitat improvement are all meant to be within the framework of the FCRPS RPA or related commitments.

Reach assessments are being conducted by Bureau of Reclamation's (Reclamation) Pacific Northwest Regional Office (PNRO) to define the existing habitat conditions, present use, and habitat potential within the Catherine Creek Tributary Assessment Area for Endangered Species Act (ESA) listed salmonids, such that habitat enhancement project locations can be identified and prioritized for implementation. To help meet the reach assessment objectives, Reclamation's Sedimentation and River Hydraulics Group at the Technical Service Center utilized and updated a portion of a previously developed one-dimensional (1D) hydraulic model (Russell, 2011) used for the Tributary Assessment (Reclamation, 2012). The updated 1D model extends from river mile (RM) 36.5 to RM 46.8 of Catherine Creek, which encompasses Reaches 3 (RM 37.2 to 40.8) and 4 (RM 40.8 to 45.8) of the Tributary Assessment (Reclamation, 2012). The previous model was used to analyze the Catherine Creek assessment area hydraulic conditions during higher discharge flows.

The objectives of the model were to:

1. Determine the inundation extent of discharges with recurrence intervals of 2 years, 10 years, and 100 years.
2. Evaluate water surface elevations, energy grade lines, velocities, and shear stresses for discharges with recurrence intervals of 1.05 to 100 years.
3. Assess the sediment transport and geomorphic processes of the channel bed through an incipient motion analysis for discharges with recurrence intervals of 1.05-, 1.5-, and 2-years.

1.2 Location

Catherine Creek is located in the Grande Ronde River Basin, which is located in northeastern Oregon. The Grande Ronde River Basin drains part of the Blue and Wallowa Mountains. The Grande Ronde River enters the Grande Ronde Valley from the west and exits to the north. Catherine Creek is a major tributary to the Grande Ronde River and enters Grande Ronde Valley from the south and meets the Grande Ronde River at the end of a reach of the Grande Ronde River known as State Ditch. Upstream of Union, OR, Catherine Creek is a mountainous stream with a narrow valley and channel slopes approaching 1% and greater, while downstream of Union the river meanders across a wide valley with a nearly flat slope of less than 0.006%.

Approximately 10.3 miles of channel were modeled (Figure 1) which encompasses two reaches of Catherine Creek; identified in the Tributary Assessment as Reaches 3 and 4. The upstream extent of the model is RM 46.6 near Brinker Creek Road Bridge and the downstream extent is the Miller Lane Bridge (RM 36.5).

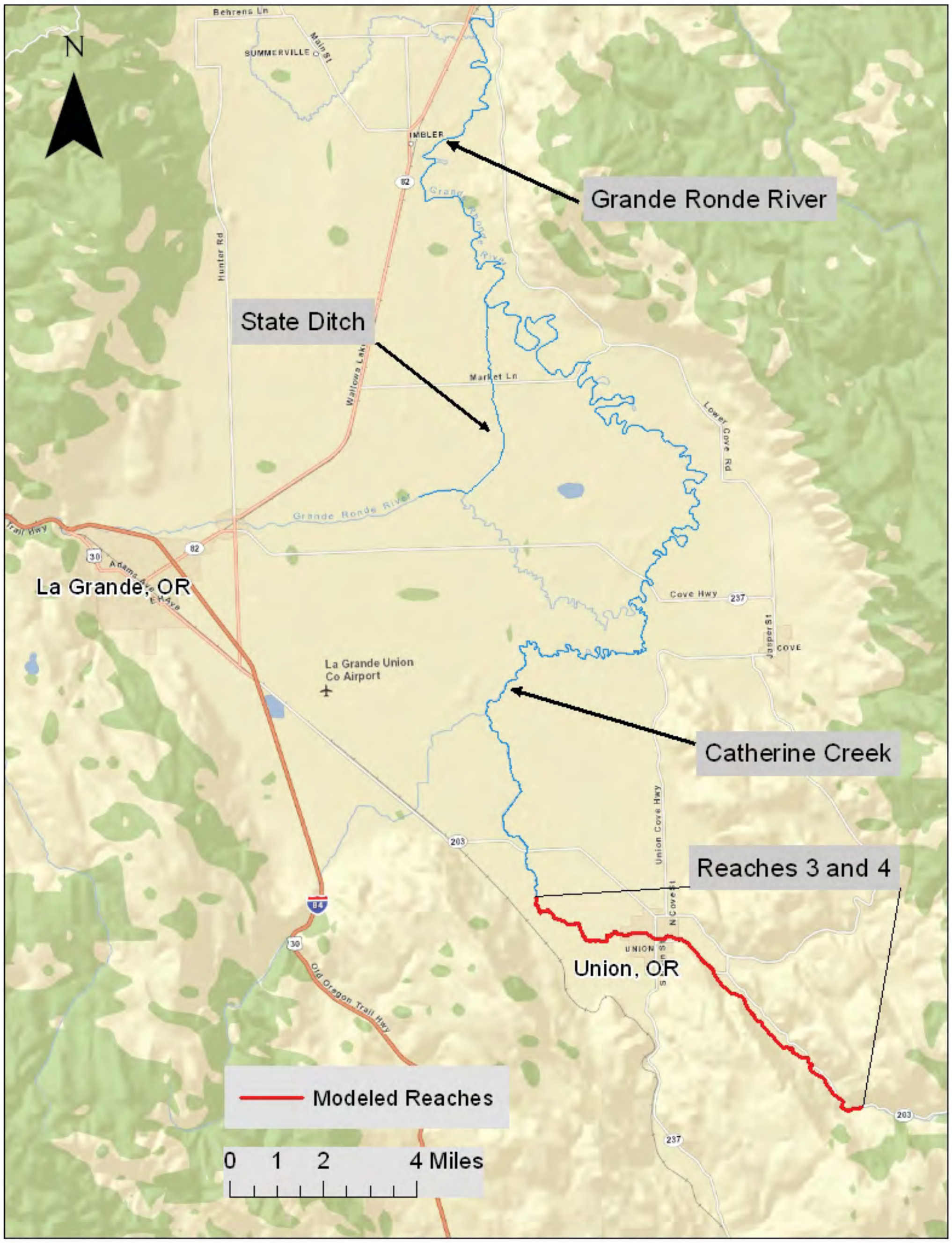

Figure 1. Overview Map of Catherine Creek Reaches 3 and 4

2 Methods

A 1D steady-state hydraulic model developed as part of the Catherine Creek Tributary Assessment (Russell, 2011) was updated to examine the existing hydraulic conditions of Catherine Creek from RM 36.5 to RM 46.8. Steady-state flow model input consists of channel geometry, infrastructure dimensions and operating conditions, input discharges, a downstream boundary condition, roughness values, expansion and contraction coefficients, and computation parameters. Each model input is described in detail in the proceeding sections. The 1D hydraulic model assumed only subcritical or critical flow would occur.

2.1 Model Geometry

2.1.1 Development of Topographic Data

Topographic data were used to generate cross section geometry for the HEC-RAS model. Topographic data were represented with terrain models that were developed from Light Detection and Ranging (LiDAR) and Real Time Kinematic (RTK) topographic survey (longitudinal and cross-sectional) data. Because standard LiDAR (red laser) cannot penetrate the water surface and adequately represent bed elevations in the wetted area of the channel, topographic cross-section surveys were conducted within the wetted channel perimeter.

Over the period of October 2011 to January 2012, Anderson Perry and Associates, Inc. (AP) performed detailed Real Time Kinematic (RTK) topographic surveys of 115 cross-sections spanning the channel, banks, and floodplain along Catherine Creek from RM 37.8 to 45.9. These surveyed cross-sections were collected at a varied spacing with the intent of capturing local non-structural in-channel hydraulic controls (e.g. riffle crests) not fully captured by LiDAR data. In addition, from RM 36.8 to 37.9, the Pacific Northwest Regional Office (PNRO) conducted detailed RTK topographic surveys within the channel. These topographic surveys were combined for development of the in-channel surface.

In October 2007, LiDAR data were collected along Middle Catherine Creek from River Mile (RM) 23.7 to 42.5 (Watershed Sciences, 2007). In 2009, LiDAR were collected along Upper Catherine Creek from RM 42.5 to 52 (Watershed Sciences, 2009).

2.1.2 Combining LiDAR and survey data

Several processing steps were necessary to combine the LiDAR data with the topographic survey data. First, a terrain surface consisting only of LiDAR data from the Middle and Upper Catherine geographic areas was developed in ESRI ArcMap. With no additional topographic survey data collected in Upper Catherine Creek above RM 46, the final terrain model upstream from RM 46 to 46.8 consists only of the processed (bare-earth) LiDAR data. Next, PNRO in-channel topographic survey data used in the previous hydraulics study (Russell, 2011) from RM 36.7 to 37.9 was combined with the LiDAR data. This data was processed by first delineating the wetted channel by polygon in ArcMap, where the LiDAR data was extracted within the delineation boundary. Within the polygon area where in-channel data were collected, the “Spline With Barriers” tool within ArcToolbox was used to rasterize the channel surface. Raster cell sizes ranged between 3 and 5 feet depending on the width of the channel and the necessary cell size to best represent the width of the channel. These rasterized cells were converted to points. To avoid triangulation issues adjacent to the wetted channel polygons, points located within one cell size (3-5 ft) from the wetted channel polygon were deleted (Russell, 2011).

Next, the AP cross-section survey points were imported into ArcMap and cross-section cutlines were digitized across each cross-section of survey points. To ensure that the cross-section cutlines extracted the elevation values from the cross-section survey data points, the survey points were “snapped” to the cross-section cutlines. To prevent LiDAR data points from superseding the cross section data , the snapped cross-section points were used to create a data exclusion polygon that has an extent of 10 feet away from any given cross-section survey point. The LiDAR data was then removed from within the cross-section survey polygon to avoid the influence of LiDAR data with the topographic cross-section survey data used for the HEC-RAS model.

The final Terrain surface for Catherine Creek Reaches 3 and 4 were developed using the points within the channel developed from the Spline with Barriers models, the polygons delineating wetted channel areas (soft edges), the AP cross-section survey points, and the remaining LiDAR data outside of the delineated wetted channel areas and more than 10 feet away from the AP cross-section survey data points

2.1.3 Cross Section Development

HEC-GeoRAS is an interface between HEC-RAS and Geographic Information System (GIS) that provides tools to process geospatial data for use with HEC-RAS. The HEC-GeoRAS program (Version 10 for ArcGIS 10) was utilized to delineate cross sections, banklines, flowpaths, and a centerline along the modeled reaches. A total of 207 cross-section lines, spaced from 37 feet to 2,141 feet apart, with an average of 265 feet apart were applied to cover the 10.3 river miles modeled along Catherine Creek. Figure 2 shows a portion of the cross sections delineated upstream of Union, OR near RM 44.

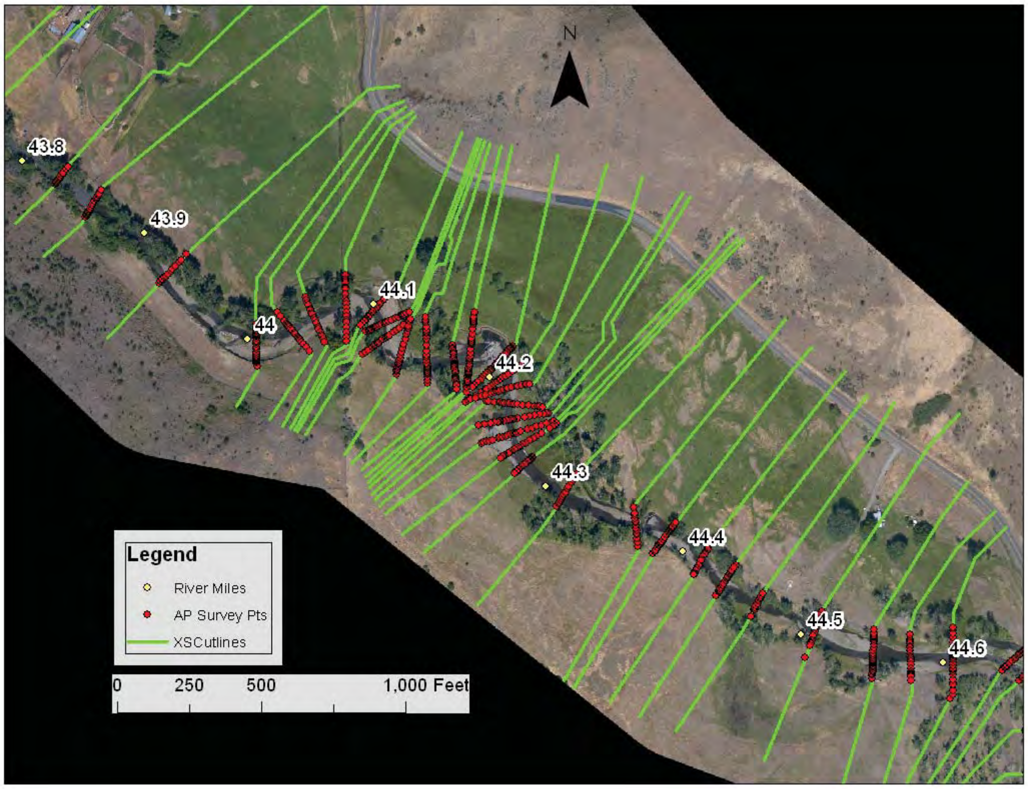

Figure 2. Example Portion of Catherine Creek with Delineated Cross Sections. The LiDAR data extents match those of the aerial photo which was taken during the same flight (Watershed Sciences, 2009).

A module within HEC-GeoRas was then utilized to convert all of the delineated line work and topographic information into a HEC-RAS format. Once imported into HEC-RAS, the banklines were manually adjusted where to ensure that the top of bank was appropriately located. Levee elements were assigned manually in HEC-RAS at bank locations or manmade levees as appropriate. Levee elements do not allow flow to be conveyed outside of the levee station until the levee elevation is exceeded (Brunner, 2008).

2.1.4 **Infrastructure**

Anderson Perry and Associates, Inc. (AP) surveyed 52 structures in the Grande River Basin in 2010 including four river cross-sections (two upstream and two downstream) at each structure. Table 1 presents the nine bridges and six diversions included in the updated HEC-RAS model. The bridge structure dimensions from the AP survey were manually input to the HEC-RAS model. LiDAR data were utilized to supplement the bridge deck and road surface information when necessary. For the diversion structures, only the grade control features were incorporated into the model geometry as weirs. Fish ladders, gates, and flow diversions were not included in the model.

Table 1. Bridge and Diversion Structures Included in the HEC-RAS Model.

Name	Model Station (ft)	River Mile (mi)
Brinker Creek Road Bridge	246853.4	46.8
Hwy 203 #B1 (Private Bridge)	241903.4	45.8
Catherine Creek Adult Collection Facility	225243.4	42.7
Hwy 203 #B2 (Private Bridge)	223943.1	42.4
State Diversion	223510.4	42.3
Hwy 203 #B3	215421.6	40.8
Swackhammer Diversion	215110.1	40.7
Bellwood Bridge	212546.1	40.3
Main St. Bridge	212028.1	40.2
Godley Diversion	211803.1	40.1
Townley Dobbin Diversion	211140.1	40.0
5TH St Bridge	210396.1	39.8
Hempe-Hutchinson Diversion	209911.1	39.8
10TH St. Bridge	209060.1	39.6
Pond Slough (Private Bridge)	199263.8	37.7

Model cross-sections were delineated in HEC-GeoRAS along each field surveyed cross-section location upstream and downstream of bridges and diversions. The cross-section channel topographic information initially derived from the LiDAR terrain model was replaced in HEC-RAS within the channel by the surveyed information.

Bridges

The dimensions of the nine bridges included in the model are presented in Table 2. For all the bridges, the energy equation was used for all flows. If bridges were skewed from the channel centerline, they were projected onto the upstream and downstream cross sections to account for the angle. The bridge opening and pier thickness values in Table 2 are the projected values. All information was based on survey information, ground photographs, aerial photographs, and LiDAR terrain data. In the adjacent upstream and downstream cross-sections, ineffective flow areas were set where the road leading to and from the bridge was higher than the surrounding ground elevations. Ineffective flow areas represent locations where water will pond and the velocity is zero in the downstream direction, as is the case with water which ponds behind a road embankment (Brunner, 2008).

Table 2. Information used to incorporate Bridge Geometry in HEC-RAS Model.

Bridge Name	Bridge Opening (ft)	Width (ft)	Piers	Pier Thickness (ft)	Top Deck Elevation (ft)	Low Chord Elevation (ft)
Brinker Creek Rd.	53	10	NA	NA	3,087.0	3,084.5
Hwy 203 #B1	58	20	NA	NA	3,042.3	3,039.8
Hwy 203 #B2	56	13	NA	NA	2,889.7	2,888.5
Highway 203 #B3	76	54.9	2	2	2,827.8	2,826.2
Bellwood	67	29.6	NA	NA	2,797.7	2,795.4
Main St.	46	63	NA	NA	2,792.9	2,789.5
5th St	69	28.2	NA	NA	2,782.4	2,780.2
10th St.	47	28	NA	NA	2,771.9	2,769.8
Pond Slough	38	14	NA	NA	2,722.1	2,719.7

Diversions

Six diversion dams were included in the updated HEC-RAS model. Only the grade control portion of the diversion dams were included. For example, the Catherine Creek Adult Collection Facility (CCACF) is a series of notched weirs (shown in Figure 3). To include this structure in HEC-RAS, the four adjacent surveyed cross sections were added to the HEC-RAS model. The surveyed cross sections were also supplemented with LiDAR topography data on the adjacent floodplains. Then, the highest weir elevations (typically the most upstream), width, and dimensions were input as an inline weir structure in HEC-RAS. The highest weir acts as a water surface control upstream of the diversion and the other weirs have only a small local effect on the hydraulics.

Figure 3. Catherine Creek Adult Collection facility (CCACF) looking upstream. Photo courtesy of AP, taken on November 16, 2010.

2.1.5 Model Discharges

Six discharges were modeled that represent peak flows with specific recurrence intervals. For details of the hydrologic analysis performed to develop the discharges, refer to the Catherine Creek Tributary Assessment (Reclamation, 2012). Table 3 shows the flow change locations in the model and associated flow magnitudes for the 1.05- (annual), 1.5-, 2-, 10-, 25-, and 100-year peak discharge, which represent the discharges used in this refined modeling effort.

Table 3. Flow Change Locations and Discharges for Modeled Flood Return Intervals.

Hydraulic Model Station (ft)	RM (mi)	Description	Peak Flows Simulated (Qx, where x = return period, ft^3/s)					
			Q1.05	Q1.5	Q2	Q10	Q25	Q100
247207.5	46.7	Catherine Creek near Union, stream gage	402	645	760	1,228	1,458	1,796
209189.3	39.5	Catherine Creek at Union, stream gage	422	677	797	1,288	1,529	1,884
194813.4	36.9	Catherine Creek below Pyles Creek	586	941	1,109	1,791	2,374	2,619

2.1.6 Model Boundaries

The downstream boundary condition for Reaches 3 and 4 is located immediately upstream of the Miller Lane Bridge, near RM 36.5. A stage/discharge rating curve at this location was derived using a combination of information from the previous HEC-RAS model results and from recorded stage/discharge survey data collected by PNRO staff. Corresponding to a surveyed stage value collected on 4/25/2012, a data collection period (from 11AM to 8PM) averaged discharge of 665 ft^3/s, derived from the Catherine Creek near Union, OR stream gage was used. Table 4 presents the stage/discharge rating curve values used as the downstream boundary in the updated HEC-RAS model.

Table 4. Downstream Model Boundary Stage/Discharge Relationship

Stage (NAVD88, ft)	Discharge (ft^3/s)
2700.8	-
2703.5*	30
2703.6*	36
2709.0**	665
2710.4	1,523
2711.1	1,791
2711.7	2,126
2712.1	2,374
2712.5	2,619
2712.8	2,864
2713.0	3,188

*Stage/Discharge data collected previously by PNRO staff

**Stage/Discharge value derived from surveyed edge-of-water point and average discharge at Catherine Creek near Union, OR stream gage during survey data collection period (4/25/2012, 11AM to 8PM)

No additional surveyed stage and measured discharge data is currently available at the Miller Lane Bridge. If more data become available, this downstream boundary condition can be refined.

2.1.7 Roughness Values

Roughness values in the HEC-RAS model are typically separated into two categories, in-channel and floodplain roughness. In-channel and floodplain roughness values from the previous HEC-RAS model (n = 0.045 and 0.075, respectively) were used as the initial roughness values in the updated model. The in-channel roughness at all cross-sections was then adjusted uniformly to calibrate the updated HEC-RAS model water surface elevations to surveyed water surface elevation points collected by PNRO staff on April 25, 2012 (see Model Calibration). The surveyed water surface elevation points were located within the channel, therefore the floodplain roughness values were left unchanged. In the previous study (Russell, 2011), roughness coefficients for floodplain areas were delineated based upon the presence of vegetation cover or agricultural land use. Both floodplain and in-channel roughness values were consistent with guidance presented by Chow (1959). Table 5 summarizes the Manning's n values calibrated in the HEC-RAS model.

Table 5. Hydraulic Roughness Values used in the Updated HEC-RAS Model.

Manning's n value		
Left	Channel	Right
0.075	0.036	0.075

2.1.8 Other computational parameters

Coefficients of expansion and contraction of 0.3 and 0.1, respectively, were used at all cross-sections except upstream and downstream of the bridges. For these cross-sections a value of 0.5 was used for the coefficient of expansion and a value of 0.3 was used for the coefficient of contraction. For the bridges, the weir coefficient used varied between 2.6 and 3.05. A weir coefficient of 3.05 was used for all of the diversion structures. These values could be further calibrated in the future if further refinement is necessary at these locations.

2.2 Model Calibration

Surveyed edge-of-water surface elevations (collected on April 25th, 2012) were used to calibrate the updated HEC-RAS model. Model calibration was performed by adjusting the in-channel Manning's roughness values uniformly at all cross-sections to best fit the modeled water surface elevations to the field surveyed water surface elevations.

Instantaneous discharge data corresponding to the data collection period of 11AM to 8PM on April 25th, 2012 were extracted from the Catherine Creek near Union, OR stream gage. For the data collection period, a mean discharge of 665 ft^3/s was calculated. This discharge value was used as the input discharge in the model for calibration.

Model calibration was achieved by iteratively adjusting the in-channel Manning's roughness until the average difference between modeled and measured water surface elevations was near zero. A secondary objective for the calibration was to minimize the number of modeled water surface elevations more than 0.5 feet from measured water surface elevations. Table 6 presents the model calibration result statistics when varying the in-channel Manning's n roughness value.

Table 6. Model Calibration Statistics for the Updated HEC-RAS Model.

	Difference (Observed - Modeled), feet		
Manning's In-Channel Roughness	**n = 0.035**	**n = 0.040**	**n = 0.036 added LiDAR XS***
Average	0.10	-0.07	-0.01
Standard Deviation	0.48	0.49	0.41
Minimum	-0.72	-0.93	-0.78
Maximum	1.39	1.39	1.01
Number of Surveyed Water Surface Elevation Points Evaluated	**70**	**70**	**70**
Number of Points Outside of +/- 0.5 ft	**17**	**22**	**15**
Low	10	9	6
High	7	13	9
Number of Points Outside of +/- 1 ft	**5**	**2**	**1**
Low	5	2	1
High	0	0	0

*7 additional cross-sections composed of only LiDAR data added to HEC-RAS model to improve model calibration. See below for more information.

An in-channel Manning's roughness of 0.036 accomplished the primary objective of an average difference near zero and the secondary objective of having the most points with differences between +/- 0.5 feet. This roughness value was used for all cross-sections in the updated model. During model calibration, 7 additional cross sections which use only LiDAR topographic data were added to the HEC-RAS model as a means to improve the model calibration results. The addition of these LiDAR cross-sections reduced the sampling distance between surveyed cross-sections, which decreases the interpolated distance of water surface elevations between cross-sections. Table 7 presents the stations of where the 7 LiDAR cross-sections are located.

Table 7. Additional Cross Sections Composed of only LiDAR Topography in the Updated HEC-RAS Model.

Model Station (ft)	RM
219906.4	41.6
219606.4	41.6
214805	40.7
214507.8	40.6
213473.1	40.4
209706.4	39.7
209406.4	39.7

Comparisons of the measured water surface elevations versus modeled water surface elevations on Catherine Creek are presented in Figure 4 and Figure 5. The modeled water surface elevations are within 1 foot of the measured water surface elevations in all but one location where the difference was 1.01 ft. This measured point is located more than 100 feet from the nearest surveyed cross section. If necessary in future studies, additional data can be collected at this location to improve model fit. In 55 of the 70 locations the modeled water surface elevations are within +/- 0.5 foot of the measured water surface elevations.

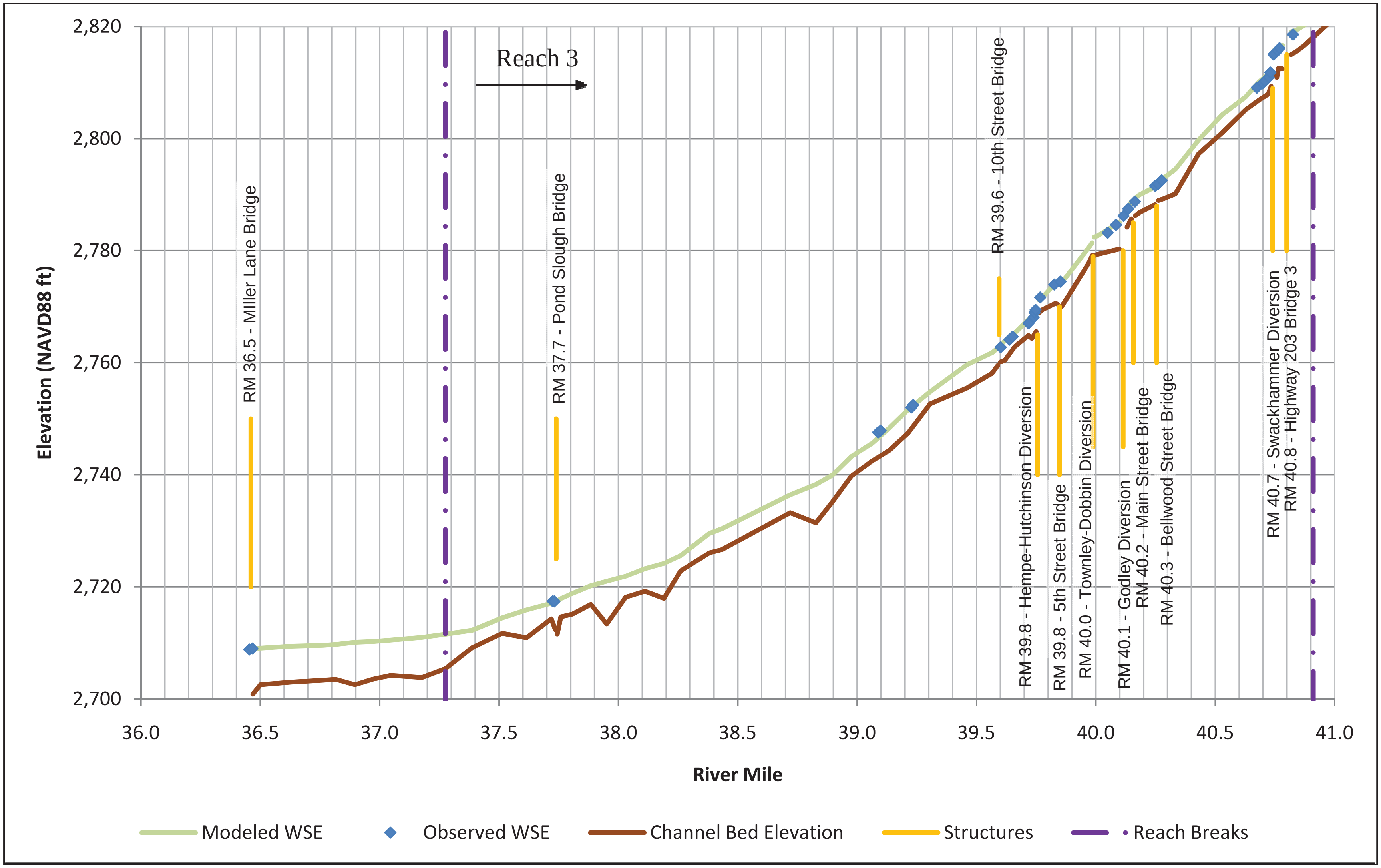

Figure 4. Modeled and observed water surface elevations along Catherine Creek Reach 3 (RM 36.5 to 41).

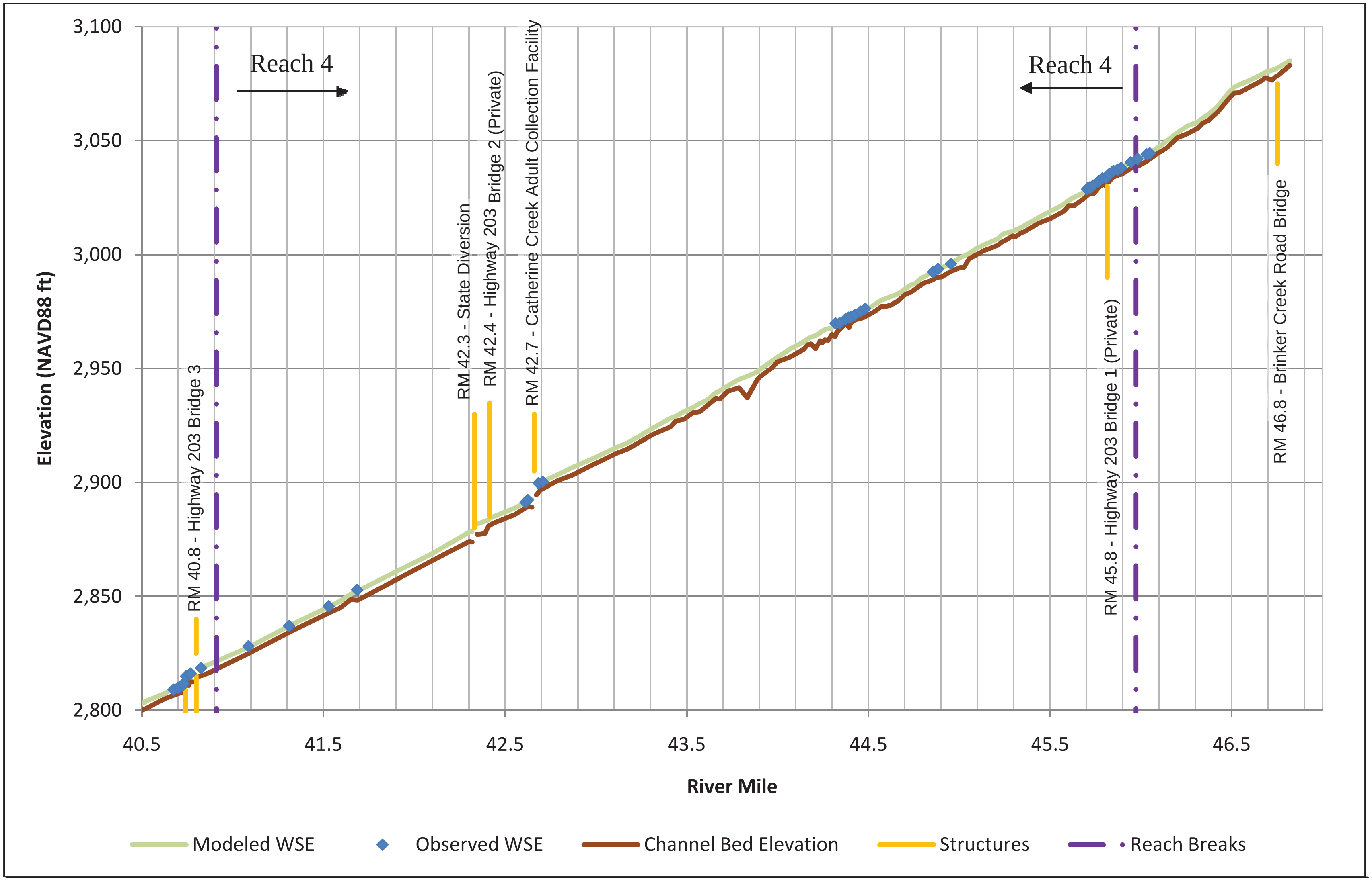

Figure 5. Modeled and observed water surface elevations along Catherine Creek Reach 4 (RM 41 to 46.8).

3 Current Condition Model Results

In the Tributary Assessment (Reclamation, 2012), channel reach breaks along Catherine Creek were delineated based on the common geomorphic characteristics. There were seven reach breaks defined, two of which are included (Reaches 3 and 4) in this hydraulic model. . Table 8 briefly describes each reach as delineated in the Catherine Creek Tributary Assessment (Reclamation, 2012).

Table 8. Catherine Creek Reach Description.

Reach	River Miles (RM)	Model Station (ft)	Description
3	37.2 – 40.8	196810.7 – 216006.4	Catherine Creek alluvial fan and all of the Town of Union, OR.
4	40.8 – 45.8	216006.4 – 242735.5	Upstream of Union, OR in a narrow valley reach with floodplain and steeper channel slopes.

3.1 Water Surface Profiles

Resulting water surface profiles for the 2-, 10- and 100-year discharges in Reach 3 are presented in Figure 6. Results of water surface profiles for the 2-, 10- and 100-year discharges in Reach 4 are presented as two parts, lower Reach 4 (RM 41 to 43.5) in Figure 7 and upper Reach 4 (RM 42.5 to 47) in Figure 8.

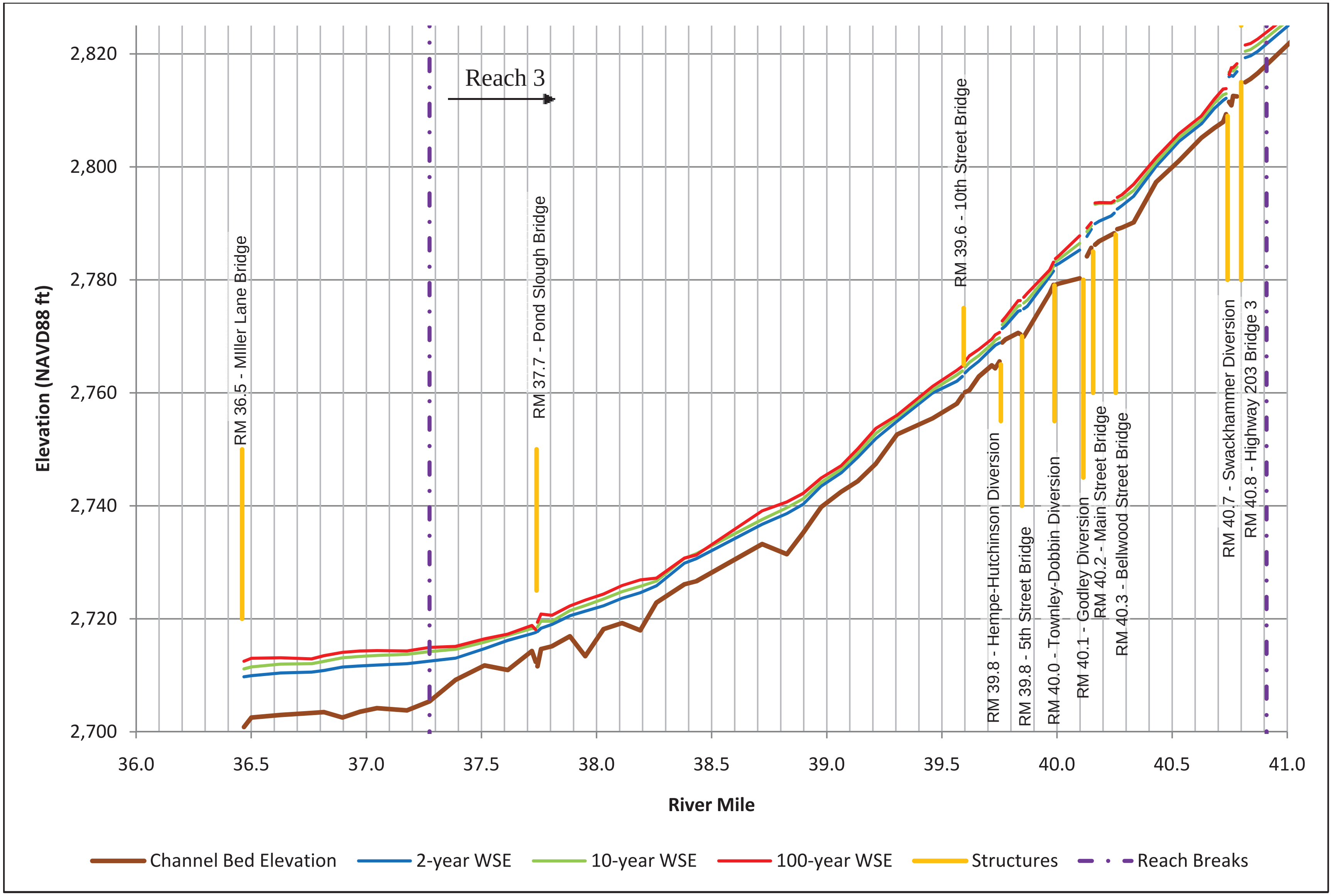

Figure 6. Computed Water Surface Profiles for Reach 3 (RM 36.5 to 41)

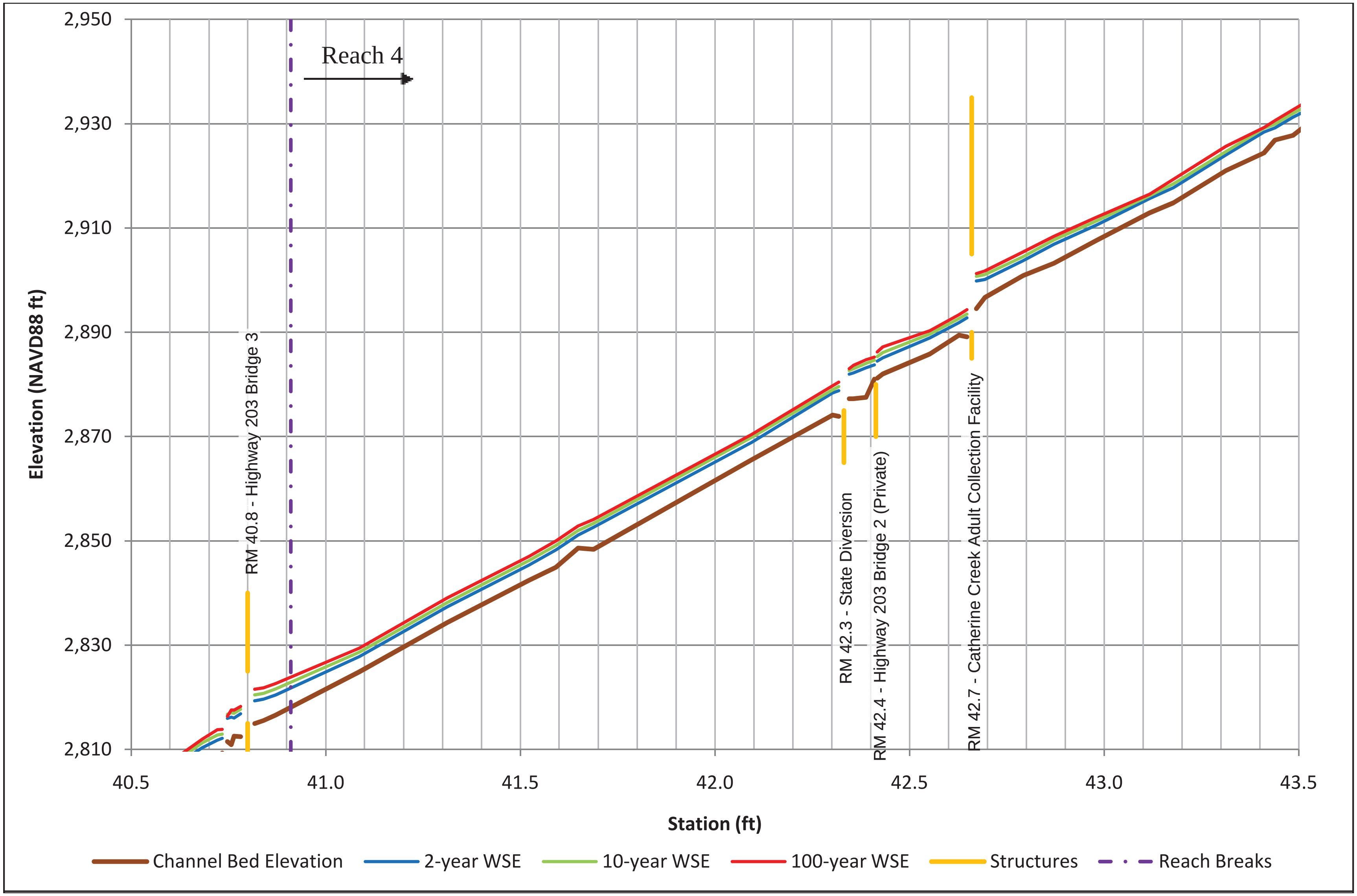

Figure 7. Computed Water Surface Profiles for the lower end of Reach 4 (RM 41 to RM 43.5).

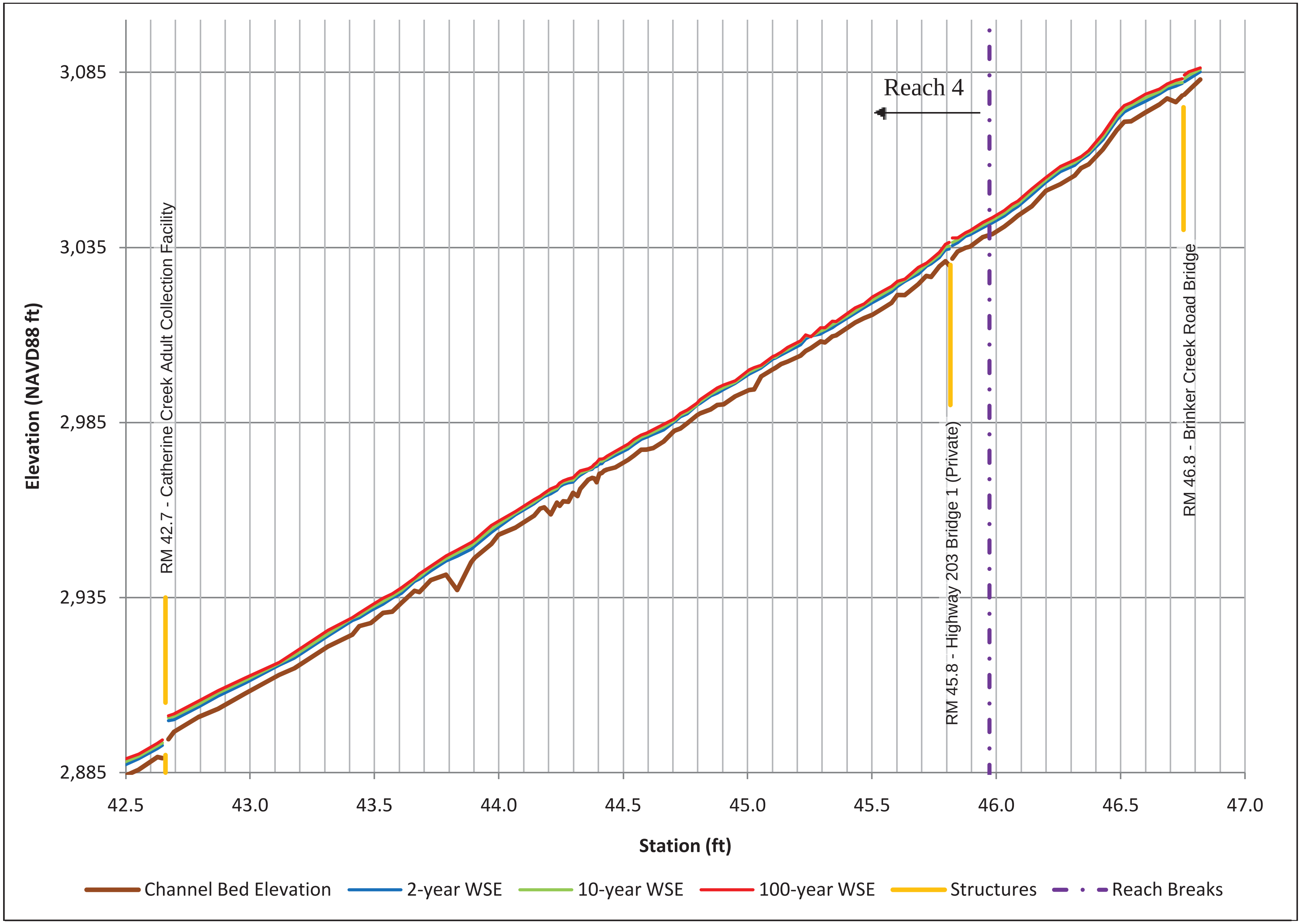

Figure 8. Computed Water Surface Profiles for upper end of Reach 4 (RM 42.5 to RM 47).

As described in the previous hydraulic modeling study, Reach 3 is the most upstream section of Grande Ronde Valley. The average channel bed slope in this Reach 3, 0.59%, is much steeper compared to the lower reaches (Russell, 2011). The modeling results demonstrate the extents to which the structures exert hydraulic control on flows. Hydraulic control is exerted by the Pond Slough Bridge (RM 37.7) and Main Street Bridge (RM 40.2) during the 2-, 10-, 25-, and 100-year discharges. All diversions in Reach 3 exert hydraulic control at the simulated flood flows. At the Swackhammer Diversion (RM 40.7), the 100-year water surface elevation is lower than the 10-year water surface elevation. This result is due to the representation of an ineffective flow area on river left in the model, limiting the amount of cross-sectional area to convey the 100-year discharge.

In Reach 4, the average channel slope is 0.83%, steeper than the average channel slopes in the lower reaches (Russell, 2011). The results show that several structures exert hydraulic control on flood flows in this reach. Hydraulic control is exerted by the Highway 203 #2 Bridge (RM 42.4) for the 10-year and greater discharges. In addition, the Highway 203 #1 Bridge (RM 45.8) exerts a hydraulic control on the 2-year and greater discharges. The CCACF diversion (RM 42.7) and State Diversion (RM 42.3) control the water surface elevations for all flows modeled.

Levee Overtopping

Levee overtopping results in Reach 3 are presented in Table 9 and include overtopping information identified by station (cross section), river mile, discharge return period, and the side of the channel overtopping occurs. The extent and depth of levee overtopping at these locations can be observed in the inundation maps, located in Appendix A.

Table 9. Model Results of Levee Overtopping, Reach 3

Station (ft)	**River Mile**	**Return Period of Overtopping Flow (Side)**
196810.7	37.3	100-yr (Both)
197407.1	37.4	25- & 100-yr (Right)
198070	37.5	100-yr (Both)
198606.4	37.6	25- & 100-yr (Right)
202654.4	38.4	100-yr (Right)
202929.4	38.4	25-yr (Right), 25-yr higher than 100-yr
207533.2	39.3	10-, 25-, 100-yr (Right)
212071.6	40.2	10-yr (Left), 25- & 100-yr (Both)
212169	40.2	10-, 25-, 100-yr (Both)
215421.6BR D	40.8	100-yr (Right)

In Reach 3, no levee overtopping is observed in the results for lower magnitude floods (2-year & less). For the 10-year discharge, 3 out of 66 cross-sections are overtopped (4.5%). For the 25-year discharge, 6 out of 66 cross-sections experience levee overtopping (9%). For the 100-year discharge, 10 out of 66 cross-sections experience levee overtopping (15%). Locations of levee overtopping in Reach 3 are primarily located below Union, OR (at and below Station 207533.2) or where hydraulic control is exerted by structures, for example, upstream of Main Street Bridge at RM 40.2 and upstream of Swackhammer Diversion (RM 40.7).

Model results of levee overtopping in Reach 4 are presented in Table 10, which includes overtopping information identified by station, river mile, discharge return period, and which side of the channel levee overtopping is observed. The extent and depth of overtopping flow at these locations can be observed in the inundation maps, located in Appendix A.

Table 10. Model Results of Levee Overtopping, Reach 4

Station (ft)	River Mile	Flow Return Period of Overtopping (Side)
228690.9	43.3	100-yr (Right)
238143.8	45.1	10-, 25-, 100-yr (All Left)
238187.2	45.1	100-yr (Left)
238834	45.2	10- & 100-yr (Right), 25-yr lower than 10-yr
238944.3	45.3	25-yr (Right), 100-yr lower than 25-yr
239149.9	45.3	100-yr (Right)
239398.8	45.3	100-yr (Right)
239885.8	45.4	25-, 100-yr (Right)
241878.2	45.8	100-yr (Right)
241947	45.8	100-yr (Right)
242060.8	45.8	25- & 100-yr (Right), 100-yr lower than 25-yr

The HEC-RAS model results in Reach 4 show that there was no levee overtopping observed in lower magnitude floods (2-year & less). For the 10-year discharge, 2 out of 109 cross-sections in Reach 4 are overtopped (1%). For the 25-year discharge, 4 out of the 109 cross-sections in Reach 4 experience levee overtopping (3.7%). For the 100-year discharge, 10 out of 109 cross-sections experience levee overtopping (9.2%). Locations of levee overtopping in Reach 4 are primarily located between RM 44.9 and 45.4, which can be viewed in the inundation maps located in Appendix A. This 0.5-mile stretch has a lower average channel slope (0.76%) compared to the upstream and downstream 0.5-mile segments (0.93% and 0.82%, respectively). This location also appears to have an alluvial fan feature which can be seen in the LiDAR contour data (Figure 9). In addition, levee overtopping as a result of hydraulic control exerted by a structure occurs at the Highway 203 #1 Bridge (RM 45.8).

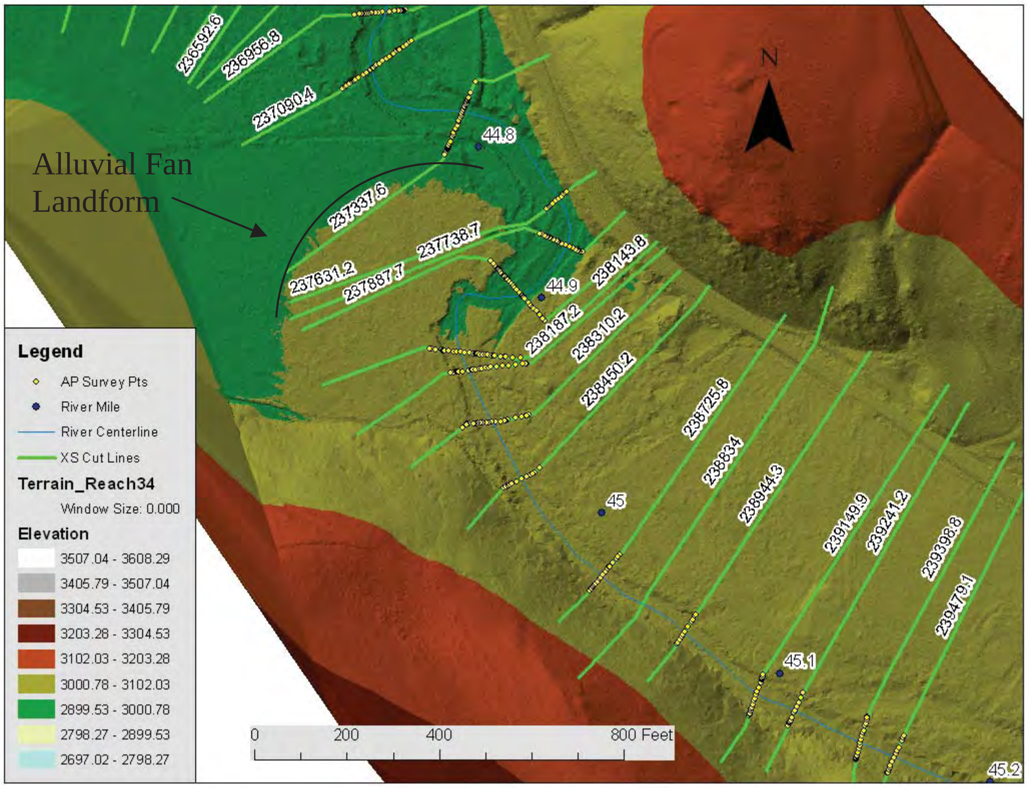

Figure 9. Alluvial Fan Landform Observed in LiDAR Data near RM 44.9.

3.2 Velocity Results

Results of average channel velocity at each cross-section for all discharge frequencies in Reach 3 are presented in Figure 10. Results of average channel velocity profiles for all discharge frequencies in Reach 4 are presented as two parts, lower Reach 4 (RM 41 to 43.5) in Figure 11 and upper Reach 4 (RM 42.5 to 47) in Figure 12.

In Reach 3, the average channel velocity generally increases from downstream to upstream in the reach, and reach-average velocities generally increase with increasing discharge, with the 2-year discharge having a reach-average of 5.3 ft/sec and the 100-year discharge having an average velocity of 6.9 ft/s. Locations of exception in the trend of increasing velocity with increasing discharge are where channel flows exceed channel or levee capacity at larger discharges (e.g. RM 37.6 and 38.4). Model results show that velocities tend to decrease upstream of structures that exert hydraulic control on the flow (bridges and diversions), and then correspondingly increase downstream of the structures.

In Reach 4, the reach-average velocities generally increase with increasing discharge, with the 2-year discharge having a reach-average velocity of 5.8 ft/sec and the 100-year discharge having a reach-average velocity of 7.6 ft/s.

Exceptions to this trend occur where channel flows exceed channel or levee capacity at larger discharges (e.g. RM 43.3 and 45.2). Model results show that velocities tend to decrease upstream of structures that exert hydraulic control on the flow (e.g. CCACF) and then increase downstream of the structures.

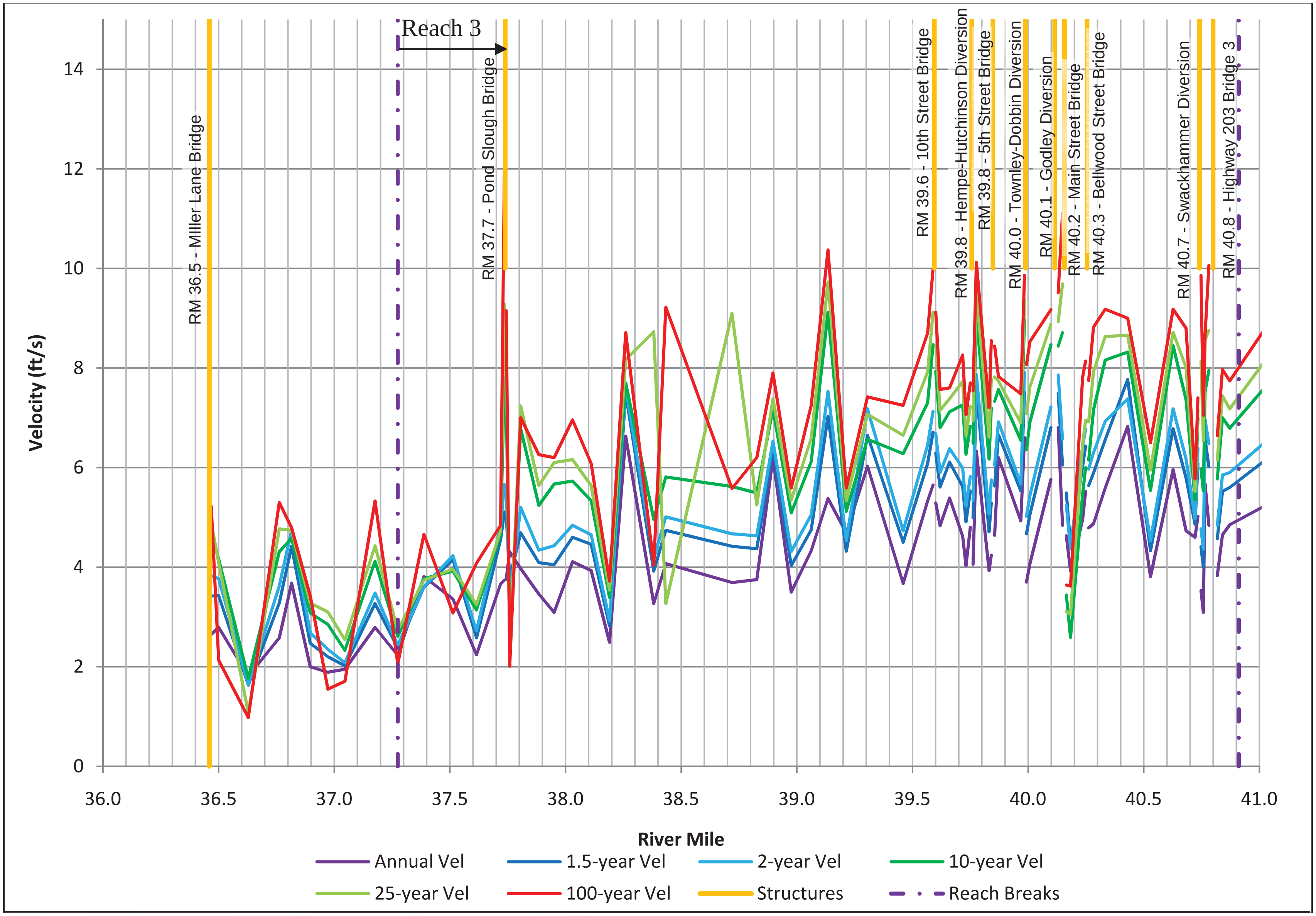

Figure 10. Computed Average Channel Velocities for Reach 3.

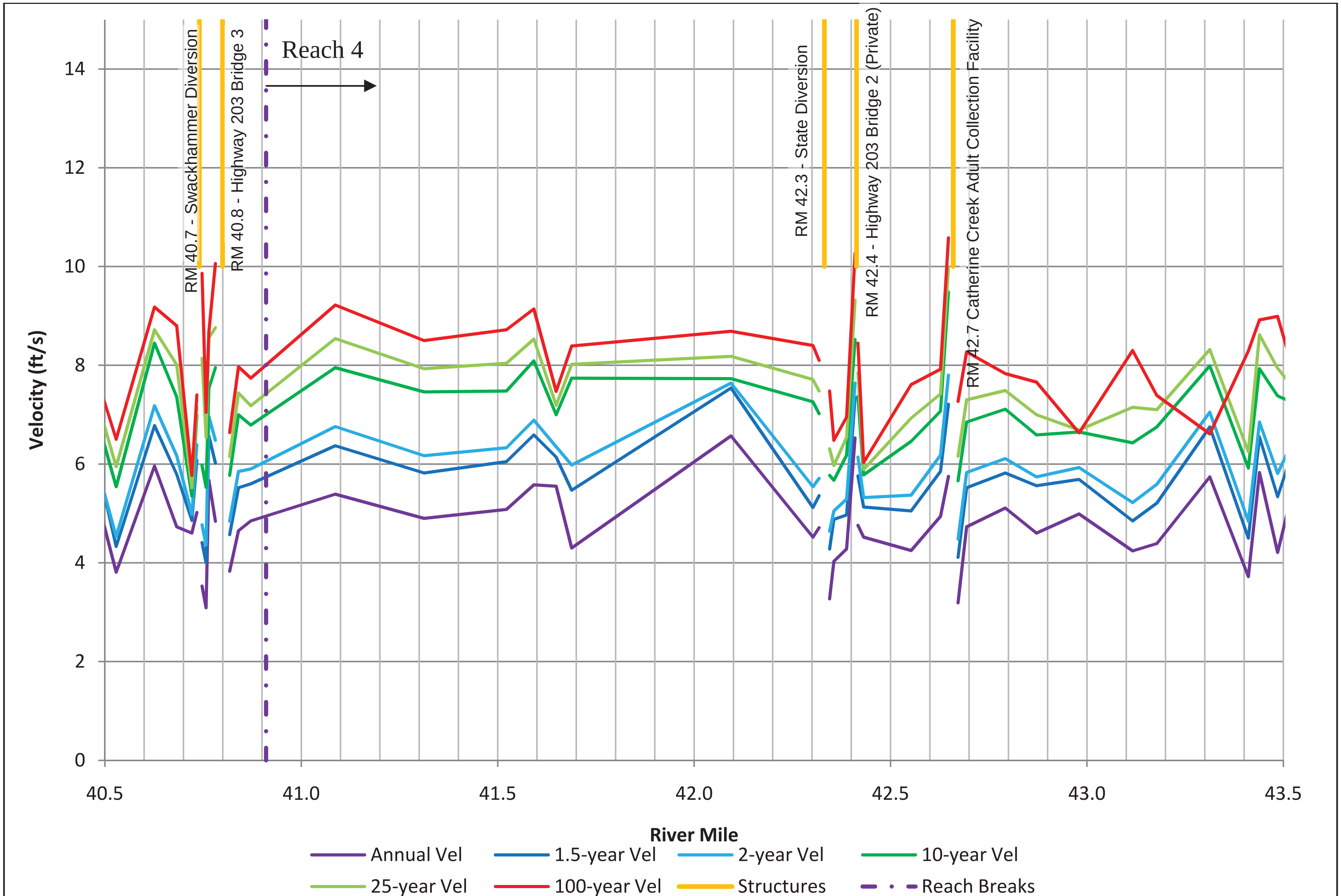

Figure 11. Computed Average Channel Velocities for lower Reach 4 (RM 41 to 43.5).

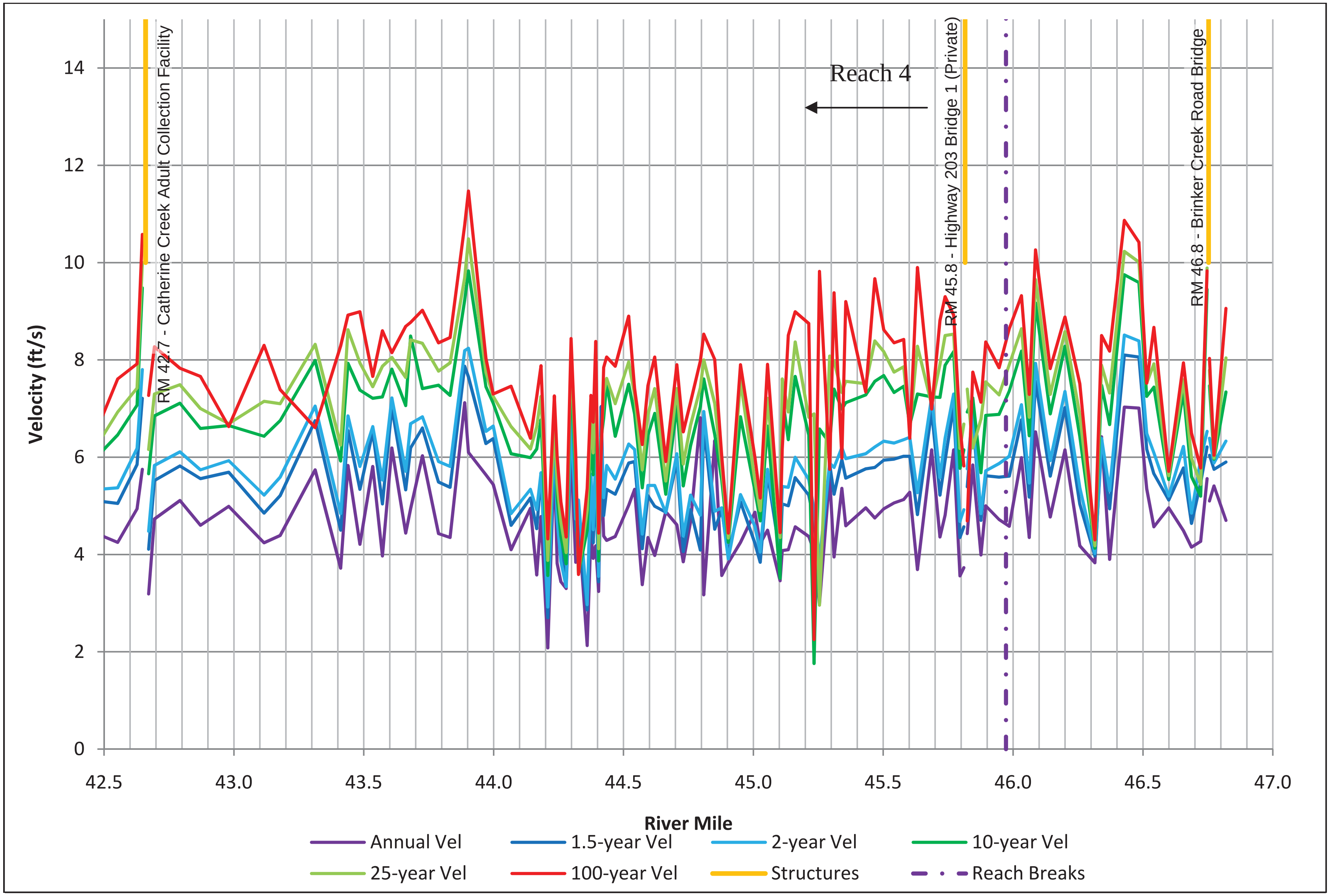

Figure 12. Computed Average Channel Velocities for upper Reach 4 (RM 42.5 to 47).

3.3 Shear Stress Results

Profiles of cross-section averaged channel shear stress for all discharge frequencies in Reach 3 are presented in Figure 13. Channel shear stress profiles for all discharge frequencies in Reach 4 are presented as two parts, lower Reach 4 (RM 41 to 43.5) in Figure 14 and upper Reach 4 (RM 42.5 to 47) in Figure 15. A five-point moving cross-section average of the average channel shears stress was selected in order to threshold the variability of 1D hydraulic model results in order to make trends in shear stress more apparent in both reaches. The moving-average calculation was cutoff upstream and downstream of structures, in order to still capture upstream and downstream trends.

In Reach 3, the channel shear stress follows a similar trend to the channel velocity, (Figure 10), increasing from downstream to upstream in the reach. The reach average shear stress increases with increasing discharge, with the 2-year discharge having an average of 0.8 lb/ft^2 and the 100-year discharge having a reach average channel shear stress of 1.3 lb/ft^2. Locations where channel shear stress decreases with increasing discharge occur where channel flows exceed channel or levee capacity at larger discharges (e.g. RM 37.6 and 38.4). Model results show that shear stress tends to decrease upstream of structures that exert hydraulic control on the flow (bridges and diversions) and then increase downstream of the structures.

In Reach 4, the reach-average shear stress generally increases with increasing discharge, with the 2-year discharge having a reach-average of 1.0 lb/ft^2 and the 100-year discharge having a reach-average shear stress of 1.5 lb/ft^2. Locations of exception in this trend are where channel flows exceed channel or levee capacity at larger discharges (e.g. RM 43.3 and 45.2). Model results show that shear stress tends to decrease upstream of structures that exert hydraulic control on the flow (e.g. CCACF) and then increase downstream of the structures.

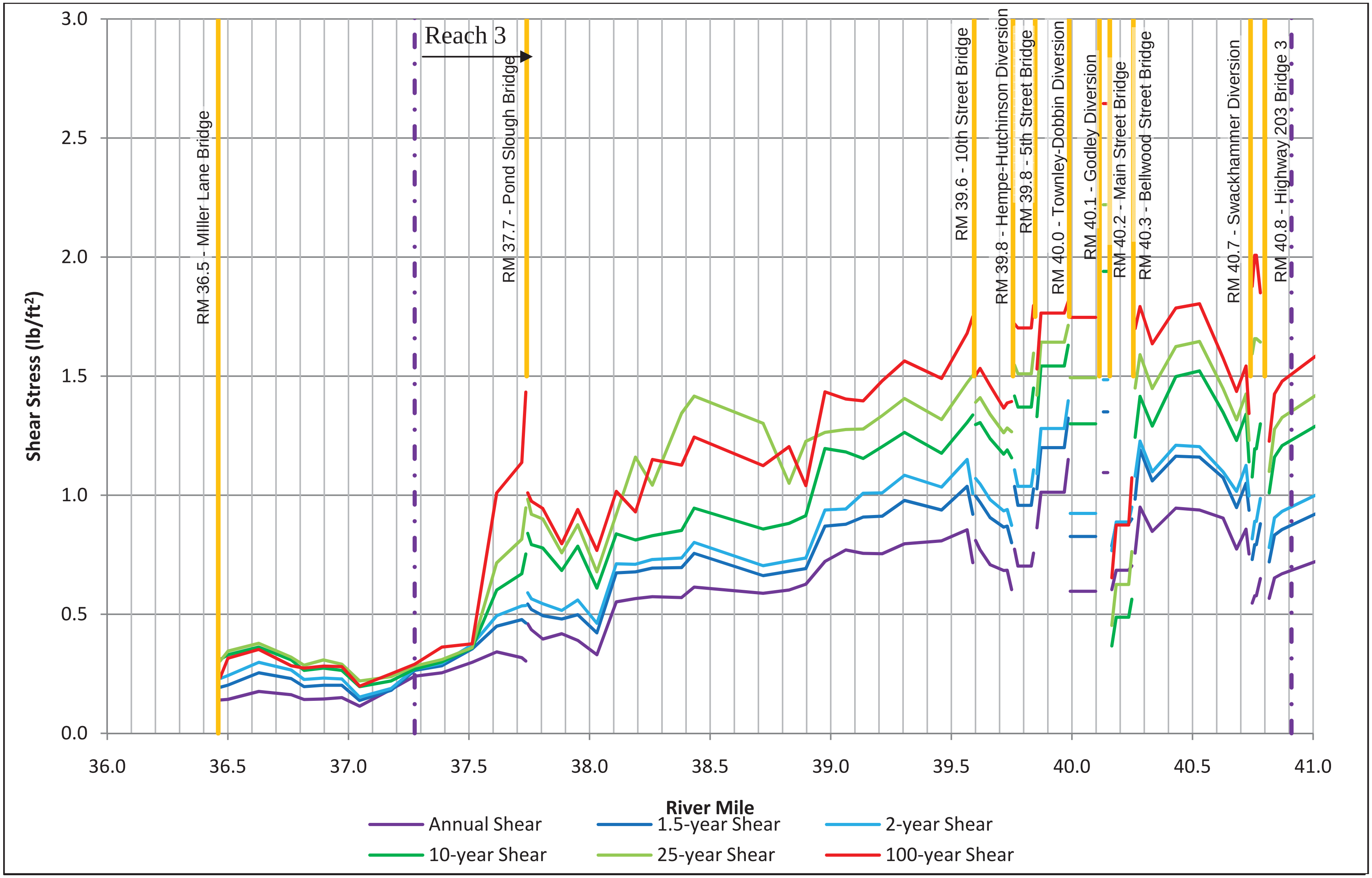

Figure 13. Computed Average Channel Shear Stress for Reach 3.

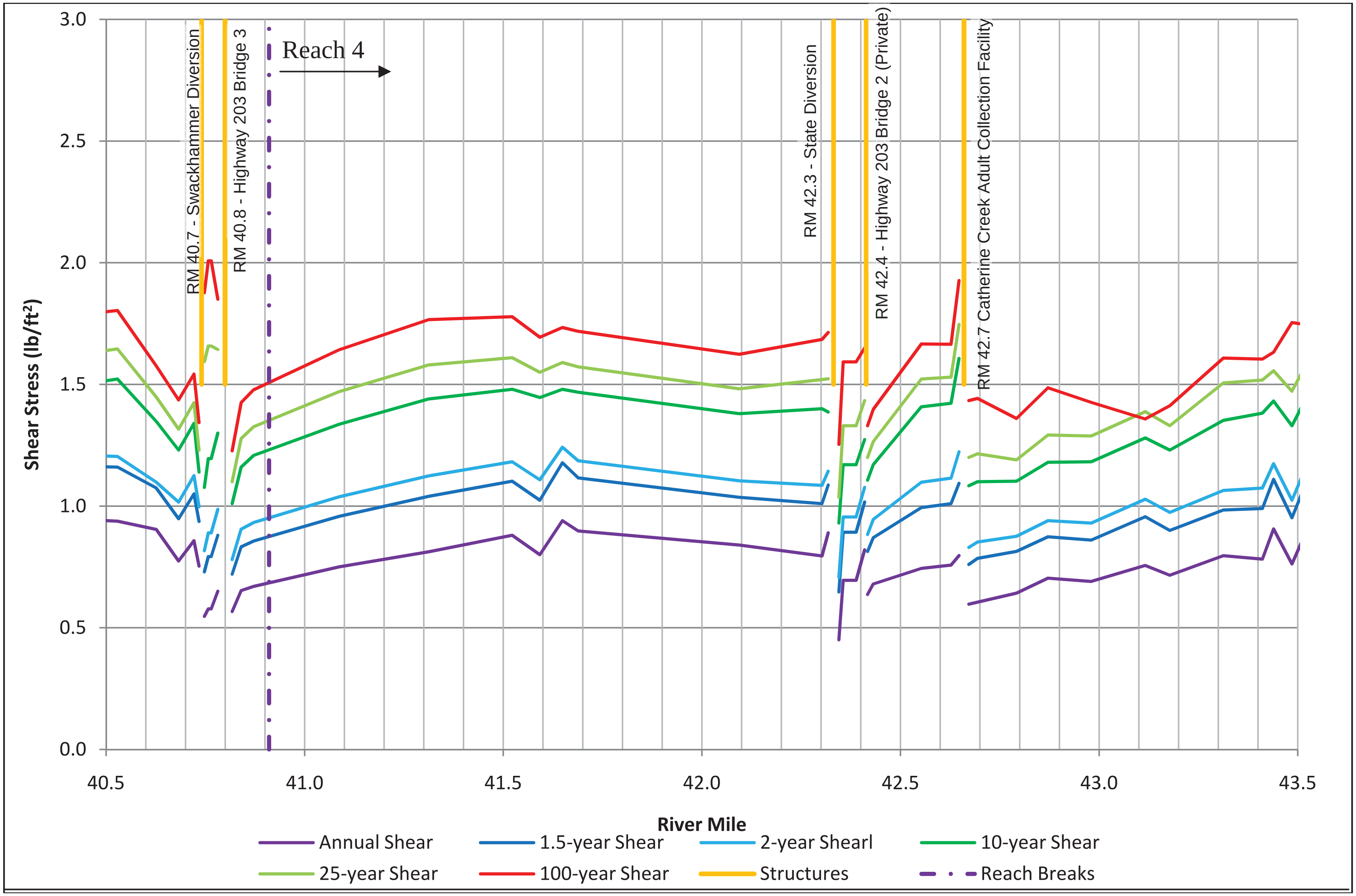

Figure 14. Computed Average Channel Shear Stress for lower Reach 4 (RM 41 to 43.5).

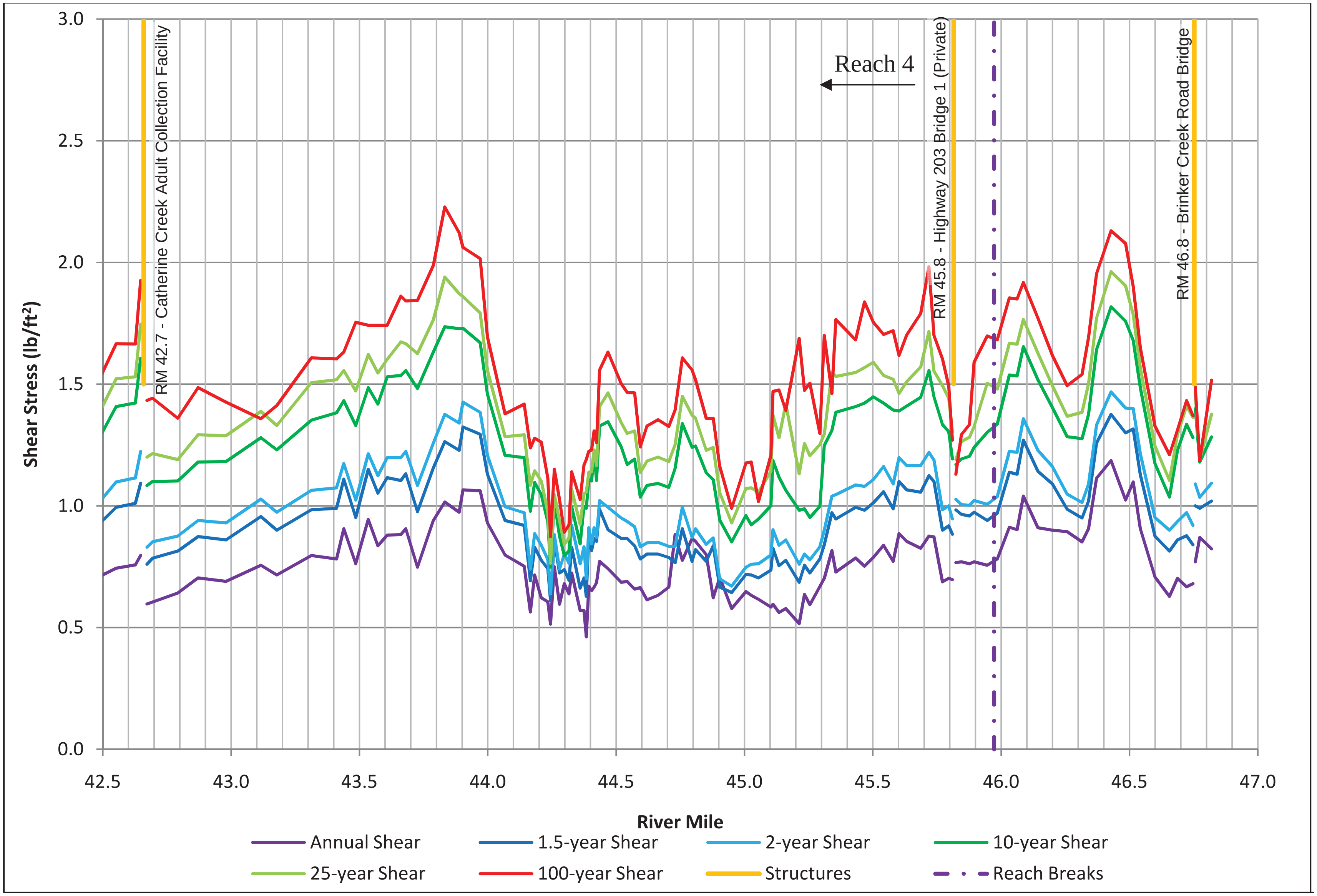

Figure 15. Computed Average Channel Shear Stress for upper Reach 4 (RM 42.5 to 47).

3.4 Inundation Depth Maps

Digital geospatial files of depths for the 2-, 10-, and 100-year discharges were produced for this study. Figure 16 presents an example location in Reach 3 showing the 10-year depth extent. A full suite of maps illustrating depths along Reaches 3 and 4 are shown in Appendix A.

The process used to create the maps included creating a TIN of the water surface elevations derived from the HEC-RAS model for the given discharge, subtracting the water surface TIN from the terrain models, and manually adjusting the wetted areas to account for the effects of levees or other high points in the terrain that would prevent water from reaching certain overbank areas. Areas that were not directly connected to the channel, i.e. “islands” of water, were removed from the inundation mapping since there was no direct pathway for the water to reach these locations.

Several limitations apply to the depth maps. The depths in the overbank areas are the maximum depths expected. The steady-state 1D model does not have the ability to simulate the dynamic filling and emptying of these overbank areas. In addition, locations of levee overtopping may occur only at one cross section and not at the adjacent upstream and downstream cross sections, and therefore the extent of inundation resulting from a particular levee overtopping is uncertain. It was assumed that the inundation would extend until the overtopping elevation is less than the ground elevation.

Figure 16. Example Map of Flood Depths in Reach 3 of Catherine Creek

3.5 Predicted Sediment Size at Incipient Motion Analysis

A prediction of sediment grain size at incipient motion was made using methods from Shields (1936), and was performed in Reaches 3 and 4. The grain size at incipient motion was calculated at each cross-section for three different steady-state flows: the annual (1.05-year), 1.5-year, and 2-year discharges. The Shields number, θ, is defined as:

$$\theta \quad \frac{\tau_g}{\gamma(s-1)D_{50}} \qquad \text{Equation 1}$$

where θ = dimensionless Shield's number; τ_g = grain shear stress; γ = specific weight of water; *s* = relative specific density of sediment; and D_{50} = median sediment size.

Often, there is a specific value of the dimensionless Shields number above which initiation of bed motion is assumed to begin. However, sediment motion is better thought of as a probabilistic process and the probability of motion increases with increasing shear stress. Parker (1990) suggests that the concept of initiation of motion be replaced by a reference amount of sediment motion described by a specific amount of non-dimensional sediment transport:

$$W^* \quad \frac{(s-1)gq_s}{\rho_s\left(\tau_g/\rho\right)^{1.5}} \quad 0.002 \qquad \text{Equation 2}$$

where s = relative specific density of sediment; g = acceleration of gravity; q_s = sediment transport rate; ρ_s = sediment density; τ_g = grain shear stress; ρ = water density. The Shields number that gives W^* = 0.002 is termed the reference Shield's stress (θ_r). The reference Shield's stress can be described at the condition when many particles are moving and there is a small, but measurable, sediment transport rate. The non-dimensional reference shear stress (θ_r) show considerable variation in literature. A typical value for the reference Shield's stress is about 0.02 to 0.04 (Parker, 1990; Buffington and Montgomery, 1997; Andrews, 2000; Wilcock and Crowe, 2003), with significant variation found to vary between 0.01 and 0.1. This reference Shield's stress varies by grain size, shape, sorting, packing (Buffington and Montgomery, 1997), channel slope (Lamb et al, 2008; Mueller et al, 2005), and sand fraction (Wilcock and Crowe, 2003).

Embedded in the method to compute the reference shear stress is the computation of grain shear stress (τ_g). The total shear stress is composed of the morphologic shear stress, the grain shear stress, and the wall shear stress (Lamb et al., 2008). The morphologic shear stress (also known as form drag) is shear stress caused by bed forms and large channel features such as log jams or vegetation. Appendix B Reference Sediment Motion contains detailed information on the method of computing the grain shear stress and Reference Shield's stress for a variety of flows. The calculation of sediment motion should only include the grain shear stress. For this study, a reference Shield's stress θ_r = 0.035 is assumed for each frequency discharge, with an uncertainty bound ranging from 0.03 to 0.04. This uncertainty bound gives an average range of +/- 5 to 10 mm in the critical grain size for a given discharge.

The critical grain size at incipient motion was calculated at each cross-section for a given discharge. A five cross-section moving average of the hydraulic results at each cross-section was selected for the analysis, in order to capture the trends in both reaches and to threshold the sensitivity of shear stress values produced from the 1D hydraulic model results. The moving-average calculation was cutoff upstream and downstream of structures in order to still capture upstream and downstream trends. Figure 17 presents the critical grain size at incipient motion in Reach 3 for the three discharges. Figure 18 and Figure 19 present the predicted critical grain size at incipient motion at each cross section in Reach 4. Also included for comparison are the incipient motion results for the 15th percentile (d15), the median (d50), and 84th percentile (d84) grain size diameters from the results of the pebble counts performed along Reaches 3 and 4 (McAffee, personal communication).

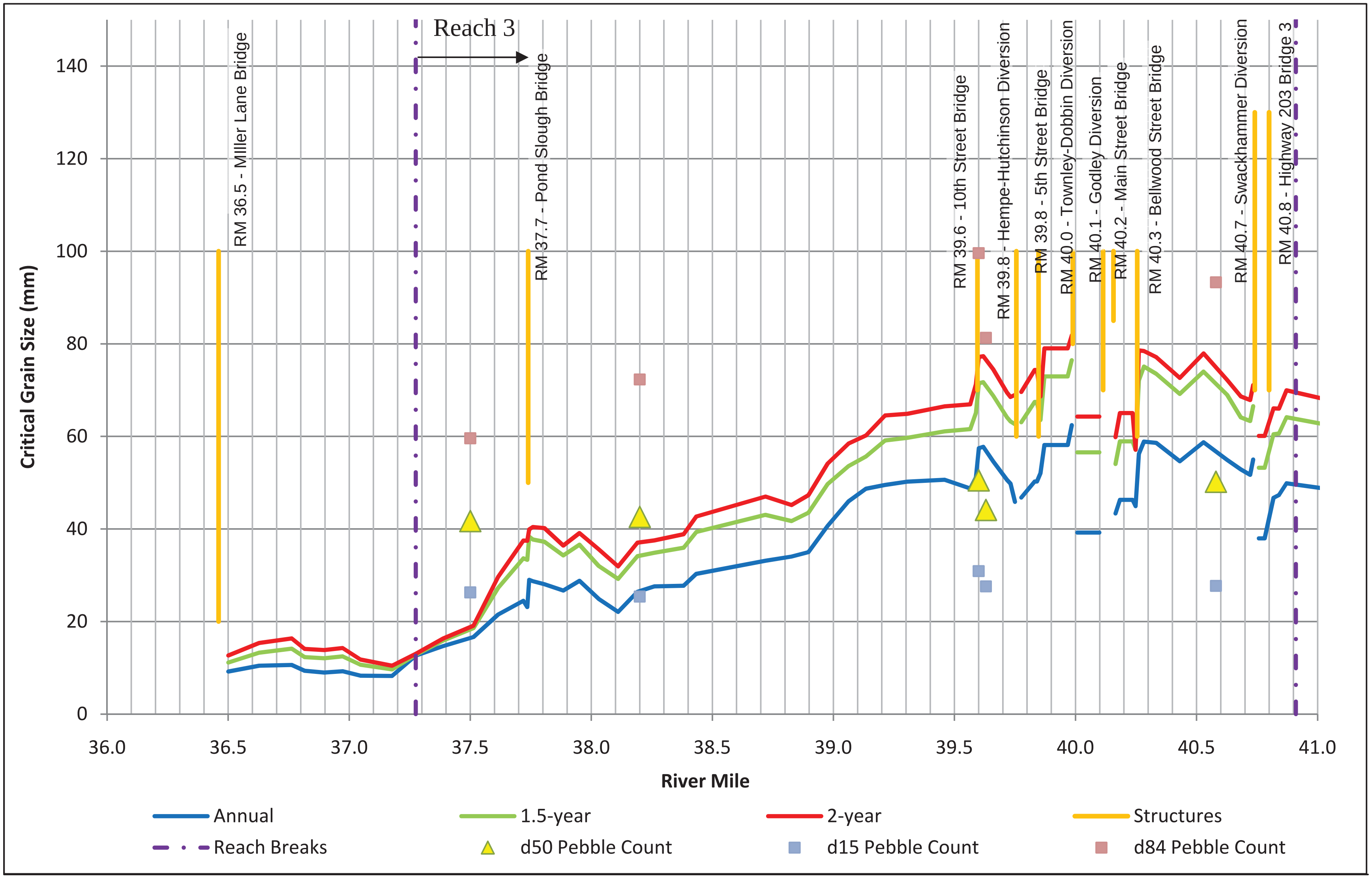

Figure 17. 5-Cross-Section Moving-Average Predicted Critical Sediment Size at Incipient Motion in Reach 3.

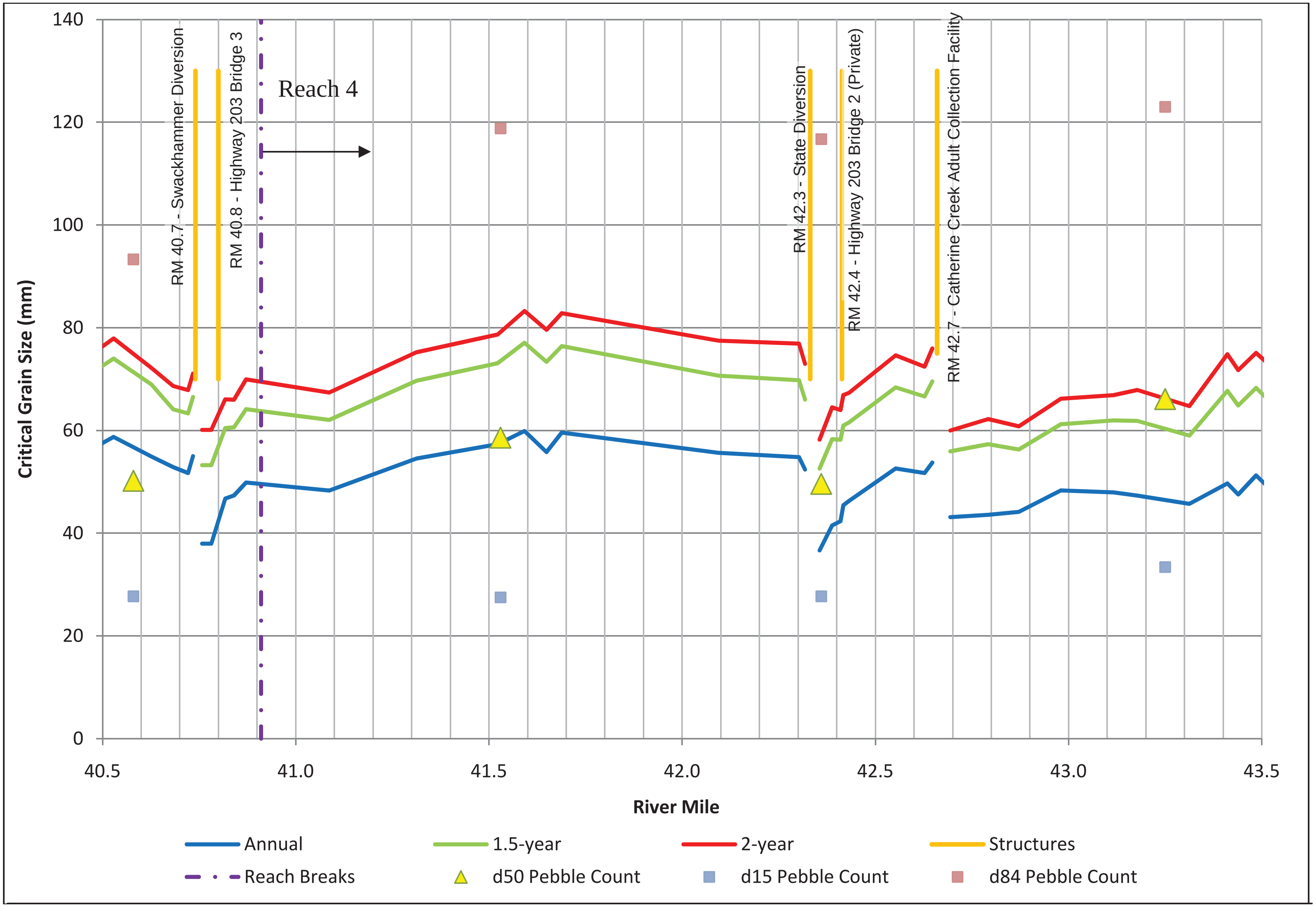

Figure 18. 5-Cross-Section Moving-Average Predicted Sediment Size at Incipient Motion in lower Reach 4 (RM 41 to 43.5).

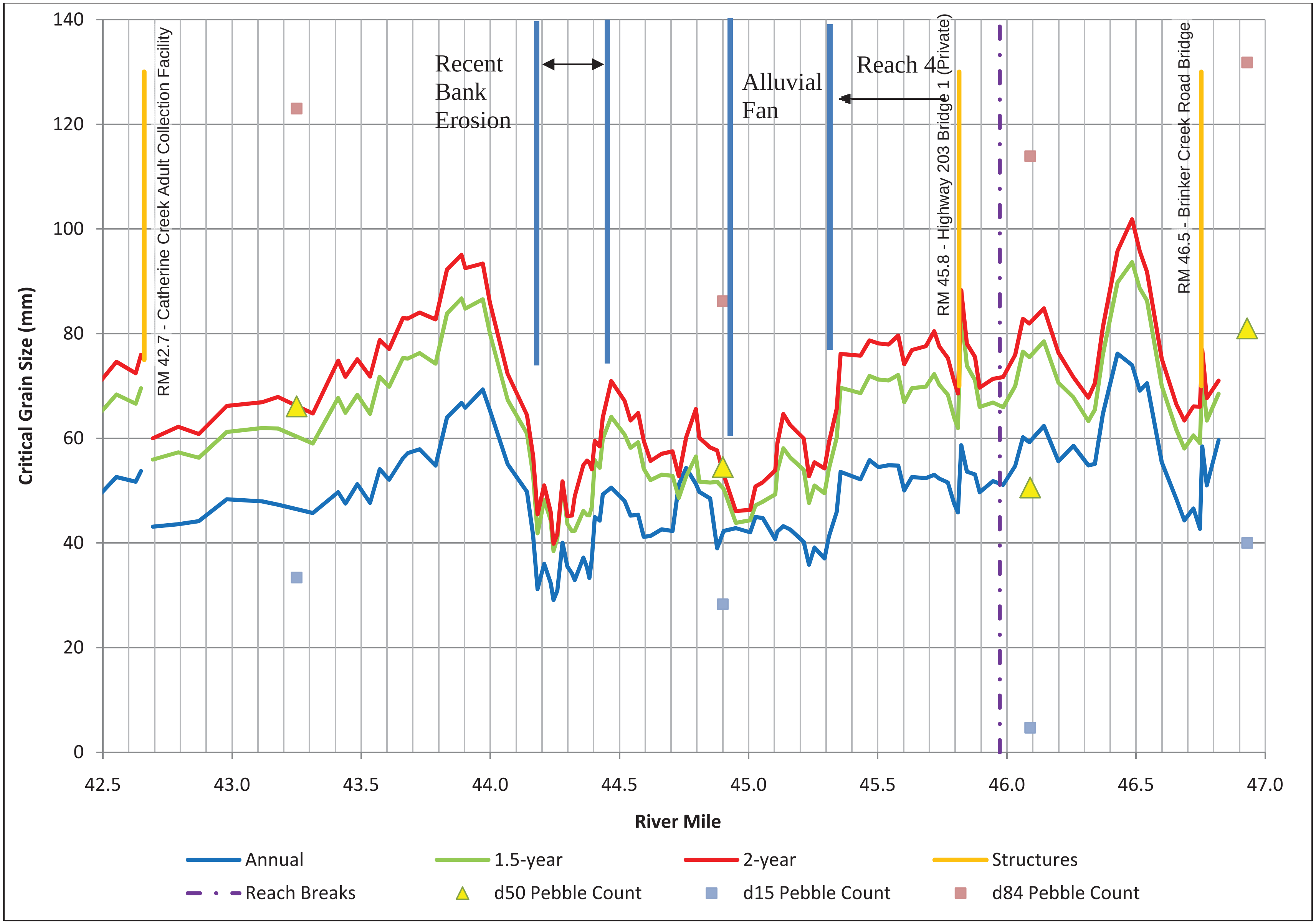

Figure 19. 5-Cross-Section Moving-Average Predicted Sediment Size at Incipient Motion in upper Reach 4 (RM 42.5 to 47)

In Reach 3, the critical grain size at incipient motion for the three discharges is observed to increase moving from downstream to upstream in the reach. From the downstream end of Reach 3 (RM 37.2 to RM 38.4), the computed critical grain sizes for all 3 discharges are lower than the median particle size from the pebble count samples. The annual, 1.5-, and 2-year discharge critical grain size results are larger than the d50 pebble count grain sizes upstream from the 10th Street Bridge (RM 39.5) to the upstream extent of Reach 3, predicting the potential for motion to occur at these discharges for particles near these sampled grain sizes.

In Reach 4 below the State Diversion (RM 42.3), the critical grain size computed for all discharges are near or above the sample median particle size collected near RM 41.5 (Figure 18). These results indicate the potential for the median particle size to be near incipient motion or in motion, depending on the local hydraulics and surface material characteristics in this stretch. Between the State Diversion (RM 42.3) and the Catherine Creek Adult Collection Facility (CCACF, RM 42.7), the critical grain size results for all 3 discharges are near or larger than the sample median grain size collected near RM 42.3. However, the critical grain size calculations in this locale are influenced by nearby structures (State Diversion and Highway 203 Bridge 2) which exert a hydraulic control during flood flows. Depending on the influence of bed surface material characteristics, results indicate the potential for the median particle size to be near incipient motion or in motion in this location. Upstream of the CCACF (RM 42.7), the critical grain size for the annual and 1.5-year discharges are lower than the sample median grain size collected near RM 43.2 and the 2-year critical grain size is near and above this sample median grain size in this location. The critical grain size calculations in this locale are influenced by CCACF, which exerts a hydraulic control during flood flow, and presents less mobility relative to the results upstream and downstream of this structure.

In the results in the upstream portion of Reach 4 (Figure 19), from RM 43.5 to 44, the 1.5- and 2-year discharge critical grain size results are greater than the median sample size collected near RM 43.2. From RM 44 to RM 44.4, the critical grain size results decrease for all discharges, and are below the both sample median grain size samples collected at RM 43.2 and 44.9. This stretch has recently experienced bank erosion and a resulting relative increase in channel width and sinuosity (Sixta, 2011, Figure 20). From RM 44.4 to 44.8, the 1.5- and 2-year discharge critical grain size results are near and greater than the sample median grain size collected at RM 44.9, predicting the potential for motion to occur at these discharges for particles near the sampled median grain sizes. From RM 44.9 to 45.3, the critical grain size results for all three discharges relatively less compared to the adjacent downstream and upstream stretches. In this stretch, an alluvial fan is present (Figure 9), which is generally a zone of sedimentation/deposition from an upland sediment source (Parker, 1997), depending on the current influx of upstream sediment supply. From RM 45.3 to the upstream end of Reach 4 (near RM 46), the critical grain sizes for all three discharges increases and are larger than the sampled median grain sizes collected near RM 44.9 and 46.1, providing support that particle motion of the median grain size is occurring at these discharges in the upper end of Reach 4.

Figure 20. Map of Reach 4 from RM 43.5 to 45.2

4 Discussion and Summary

Hydraulic modeling conducted for this assessment provides a within reach-scale evaluation of impacts to flood processes along Catherine Creek Reaches 3 and 4. The information presented in this report documents the modeling effort to estimate current water surface profiles, velocities, shear stresses, and critical grain sizes at incipient motion that are experienced during floods on Catherine Creek. Results from this most recent modeling effort can be used to verify hypotheses related to other disciplines, such as biology, geomorphology, and vegetation, and can be integrated with other disciplines to form conclusions related to flooding potential and resultant impacts to habitat.

4.1 Hydraulics Related to Flooding and Anthropogenic Features

Similar to the results in Russell (2011), within Reaches 3 and 4 of Catherine Creek, the model illustrates that the presence of low-head diversion structures and bridges impact current river processes and impact localized hydraulic controls on water surface elevations. Model results also depict the confinement of flood flows within the channel with the presence of levees and roads (e.g. Highway 203 from RM 40.7 to 41.7), where the majority of flood flows remain in-channel at the 100-year discharge. Incision or entrenchment of the channel bed due to levee/road confinement could have historically occurred along both reaches, however, a comparison of historical to current channel bed elevation data would be required to verify this process.

In Reach 3, model results indicate that the majority of flood flows with a recurrence interval of 2-yr or less are contained within the channel and levees constructed along Catherine Creek (Table 9). Flows up to the 2-year event are all in-channel, and the 10-, 25-, and 100-year discharges overtop 4.5, 9, and 15% of model cross-sections, respectively. Hydraulic modeling results also show that several bridges (e.g. Pond Slough, 10th St., & Main St.) and diversions (e.g. Hempe-Hucthinson, Townley-Dobbin, & Swackhammer) exert hydraulic control during flood flows, affecting several hydraulic parameters, such as depth and velocity (Figure 6), where generally flood depth is higher and velocity and shear stresses are lower upstream of these structures, and downstream of these structures the flood depth is lower and velocities and shear stresses are higher.

In Reach 4, the modeling results indicate that an even lesser amount of levee overtopping and an increase in channel confinement is present compared to Reach 3 (Table 10). Discharges at and more frequent than the 2-year event are all in channel, and the 10-, 25-, and 100-year discharges overtop 1, 3.7, and 9.2% of all model cross-sections, respectively. Hydraulic modeling results also show (Figure 6 and Figure 12) that diversions (e.g. State Diversion & CCACF) and the

Highway 203 Bridge #1 exert hydraulic control during flood flows, affecting several parameters of flow.

4.2 Hydraulics Related to Sediment Transport Processes and Geomorphology

In Reach 3, the hydraulic processes that affect the geomorphology of Catherine Creek change moving upstream to downstream. Beginning at the upstream end of Reach 3 and moving downstream to the 10th Street Bridge, the predicted critical grain size results for the annual, 1.5-, and 2-year discharges are either near or greater than the nearby sample median grain size values. The incipient motion analysis provides support for the potential that these higher frequency floods have sufficient sediment transport capacity to move a large fraction of the available channel bed material, depending the location of local hydraulic features (e.g. riffles, glides, pools) and properties of the bed surface material (e.g. sorting, packing, imbrications, sand fraction). Moving downstream in Reach 3, below RM 38.4 results in Figure 17 show that, with the exception of local scale hydraulic variability created by the Pond Slough Bridge (RM 37.8) and at station 202654.4 (RM 38.3), the predicted grain size at incipient motion for the annual, 1.5-year and 2-year flows are all below the pebble count median grain size values, showing a potential limited motion of the median bed material sizes at these flows. It is likely that bed mobility in Reach 3 is limited to low frequency events. Therefore this area is potentially depositional, depending upon the sediment supply upstream. The modeling results in this location support anecdotal information provided by a landowner that dredging/removal of gravel in the channel (near RM 37.7) has historically occurred to maintain channel capacity (Cuhaciyan, personal communication, 2012) and that this portion of Reach 3 is coursing over an alluvial fan (Russell, 2011), which is generally a zone of sedimentation/deposition from an upland sediment source (Parker, 1997), depending on the upstream sediment supply.

In Reach 4, the critical grain size computed for all discharges are near or above the sample median particle size collected near RM 41.5. These results indicate the potential for the median particle size to be near incipient motion or in motion, depending on the local hydraulics and surface material characteristics in this stretch. Between the State Diversion (RM 42.3) and the Catherine Creek Adult Collection Facility (CCACF, RM 42.7), the critical grain size results for all 3 discharges are near or larger than the sample median grain size collected near RM 42.3, indicating the potential for the median particle size in this reach to be near/above threshold conditions in this location. However, the critical grain size calculations in this locale are influenced by the nearby structures (State Diversion and Highway 203 Bridge 2) which exert a hydraulic control during flood flows. Upstream of the CCACF (RM 42.7), the critical grain size for the annual and 1.5-year discharges are lower than the sample median grain size collected near RM

43.2 and the 2-year critical grain size is near and/or above this sample median grain size in this location. The critical grain size calculations in this locale are influenced by CCACF, which exerts a hydraulic control during flood flow, and presents less mobility relative to the critical grain sizes for a given discharge upstream and downstream of this structure. From RM 43.5 to 44, the 1.5- and 2-year discharge critical grain size results are greater than the median sample size collected near RM 43.2. The channel in this stretch is relatively straight and located along the left of the valley (Figure 20). From RM 44.2 to RM 44.4, the critical grain size results decrease for all discharges, and are below the both sample median grain size samples collected at RM 43.2 and 44.9. This stretch has recently experienced bank erosion and a resulting relative increase in channel width and sinuosity (Sixta, 2011) compared to the upstream and downstream subreaches (Figure 20). From RM 44.9 to 45.3, the critical grain size results for all three discharges relatively less compared to the adjacent downstream and upstream stretches. In this stretch an alluvial fan is present (Figure 20), which is generally a zone of sedimentation/deposition from an upland sediment source (Parker, 1997), depending on the upstream sediment supply. From RM 44.4 to 44.8, the 1.5- and 2-year discharge critical grain size results are near and greater than the sample median grain size collected at RM 44.9, predicting the potential for motion to occur at these discharges for particles near the sampled median grain sizes, predicting the potential for entrainment of the bed material deposited on the downstream end of the alluvial fan. From RM 45.3 to the upstream end of Reach 4 (near RM 46), the critical grain sizes for all three discharges increases and are larger than the sampled median grain sizes collected near RM 44.9 and 46.1, providing support that particle motion of the median grain size is occurring at these discharges in the upper end of Reach 4.

4.3 Model Accuracy

4.3.1 Model Calibration

Calibration of the updated HEC-RAS model was performed using surveyed water surface elevations along Reaches 3 and 4 to iteratively adjust Manning’s roughness values so that the differences in modeled water surface elevations and measured water surface elevations were minimized to an average near zero. Comparisons of the measured water surface elevations versus modeled water surface elevations on Catherine Creek are presented in Figure 4 and Figure 5. Results suggest that the model provides a good fit given the model calibration objectives set. In all but one location are the modeled water surface elevations within 1 foot of the measured water surface elevations. In 55 of the 70 locations the modeled water surface elevations are within +/- 0.5 foot of the measured water surface elevations. Further detail of the model calibration are presented in Section 2.2

4.3.2 Limitations

Several limitations exist with a 1D model. In some cases, these limitations result from 2D and three dimensional (3D) processes that are not possible to capture with a 1D model. The 1D model cannot capture complex in-channel and floodplain hydraulics, which may be important when there are complex changes in channel form or when there is often water outside the channel. Within the channel, the 1D model values are cross-section average, which do not provide detail of local flow patterns (e.g. pools, eddies). The model can also not represent the effects an upstream cross section has on a downstream cross section, especially in the case of levee breaching. Additional information could be collected and applied to improve the 1D model results, but additional data will not impact the ability of the 1D model to replicate 2D and 3D processes.

4.4 Data Gaps

Several different measures could be performed to reduce data gaps in the model in order to decrease uncertainty and improve model results. First, if more detailed studies are called for near the downstream model boundary, the downstream stage/discharge rating curve should be improved with measured data rather than model data. Second, to verify the fluctuation in model result parameters and improve model calibration, additional sampling of cross-sections could be performed if detailed results at specific locations are necessary. Next, to improve predictions of incipient motion in the modeled reaches, additional bed material sampling at hydraulic controls (riffles) would better predict/ capture the variability of sediment transport processes. Next, an inventory of riparian vegetation present along Catherine Creek would help support hypotheses of the recent observed changes in channel location and planform observed in Reach 4. Last, if inundation extent is important at the Main Street Bridge (RM 40.2) and near the alluvial fan at RM 44.9, additional topography in the river left floodplain should be collected to capture the 100-year discharge extent all the way to the valley wall.

5 References

	Complete Citation
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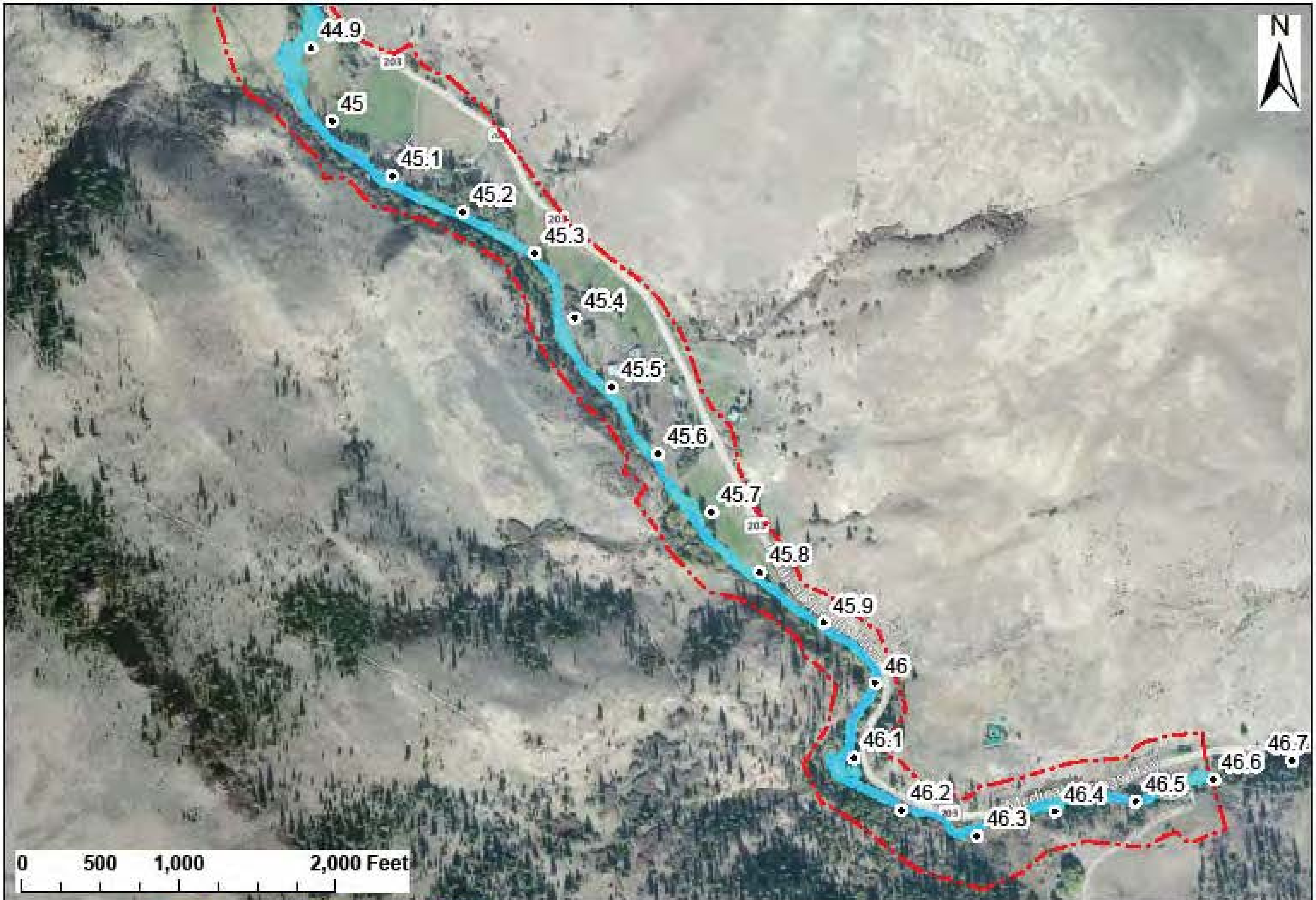
Appendix A – 2-, 10-, & 100-year Peak Discharge Depth Maps



Depth, Feet
- 0 - 2
- 2.1 - 4
- 4.1 - 6
- 6.1 - 8
- 8.1 - 10
- 10.1 - 12
- 12.1 - 14
- 14.1 - 16
- 16.1 - 18

• River Miles

Cross-Section Boundary

Catherine Creek Reach 3 & 4 Hydraulics

Flow Depths, 2-year Discharge

Map 1 of 6

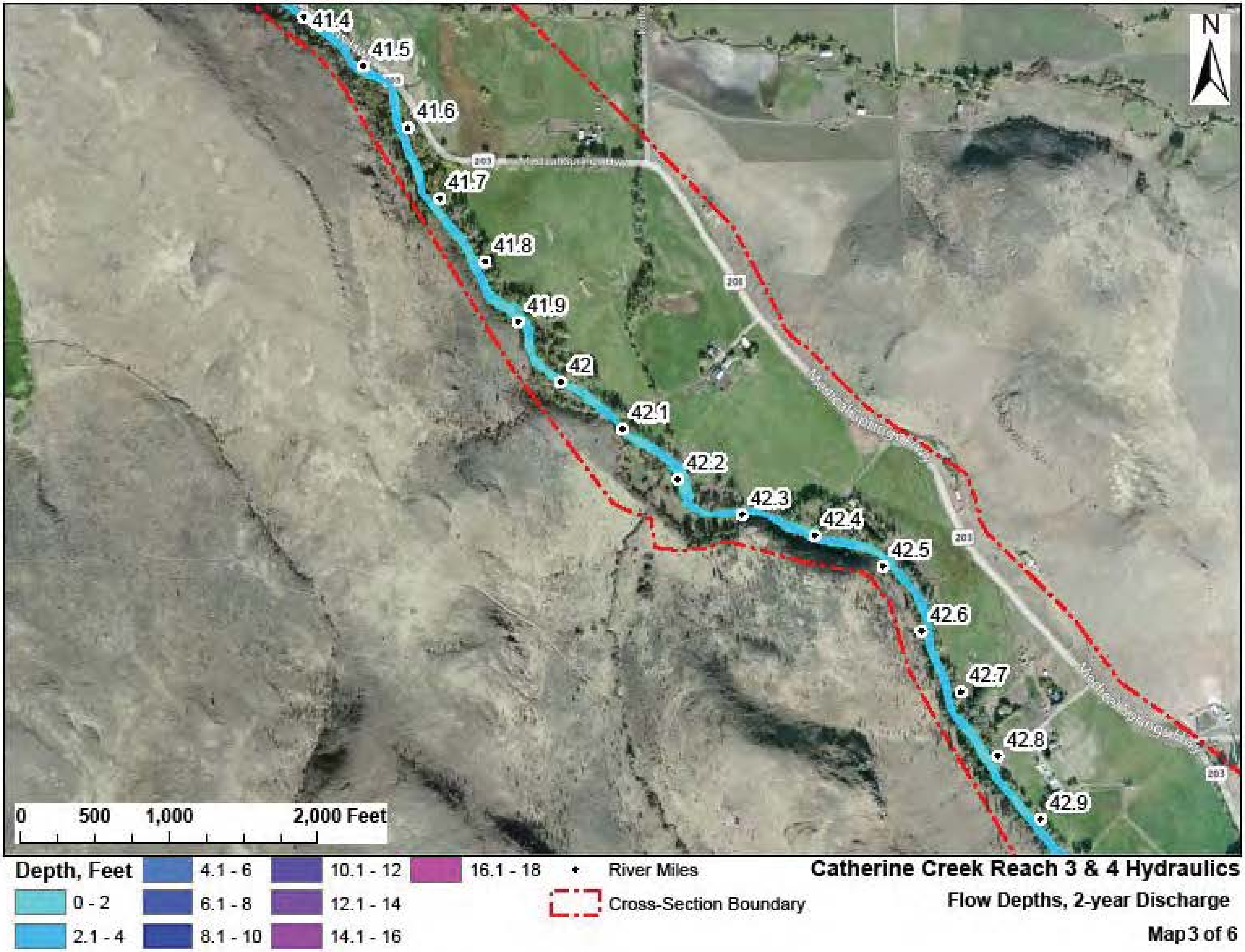
Depth, Feet

0 - 2	4.1 - 6	10.1 - 12	16.1 - 18	River Miles
2.1 - 4	6.1 - 8	12.1 - 14		Cross-Section Boundary
	8.1 - 10	14.1 - 16		

Catherine Creek Reach 3 & 4 Hydraulics

Flow Depths, 2-year Discharge

Map 2 of 6



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41.5
41.6
41.7
41.8
41.9
42
42.1
42.2
42.3
42.4
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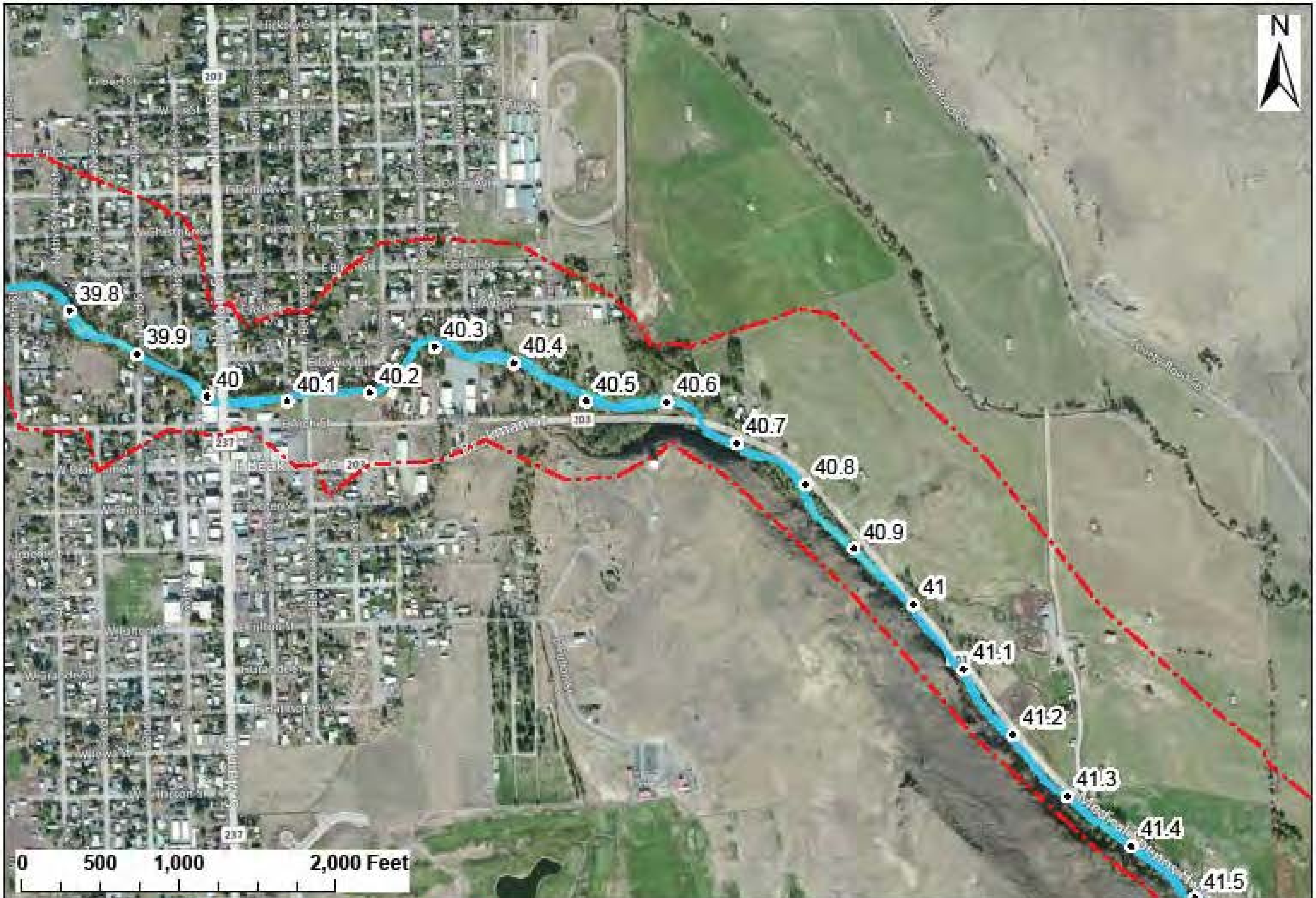
42.6
42.7
42.8
42.9
0 500 1,000 2,000 Feet
Depth, Feet
0 - 2
2.1 - 4
4.1 - 6
6.1 - 8
8.1 - 10
10.1 - 12
12.1 - 14
14.1 - 16
16.1 - 18
River Miles
Cross-Section Boundary
Catherine Creek Reach 3 & 4 Hydraulics
Flow Depths, 2-year Discharge
Map 3 of 6



Depth, Feet

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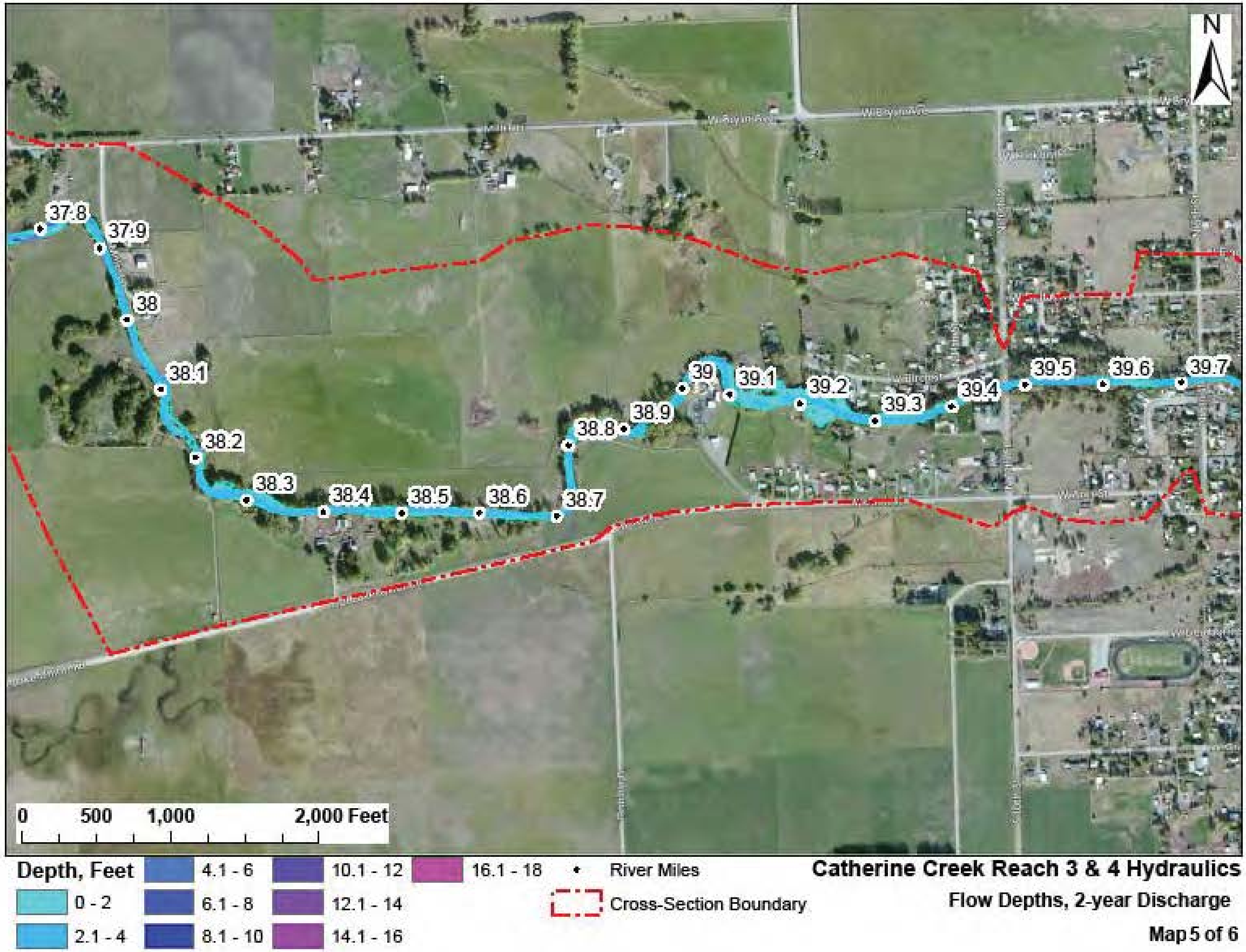
16.1 - 18

River Miles
Cross-Section Boundary

Catherine Creek Reach 3 & 4 Hydraulics

Flow Depths, 2-year Discharge

Map 4 of 6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39.5
39.6
39.7
0 500 1,000 2,000 Feet
Depth, Feet
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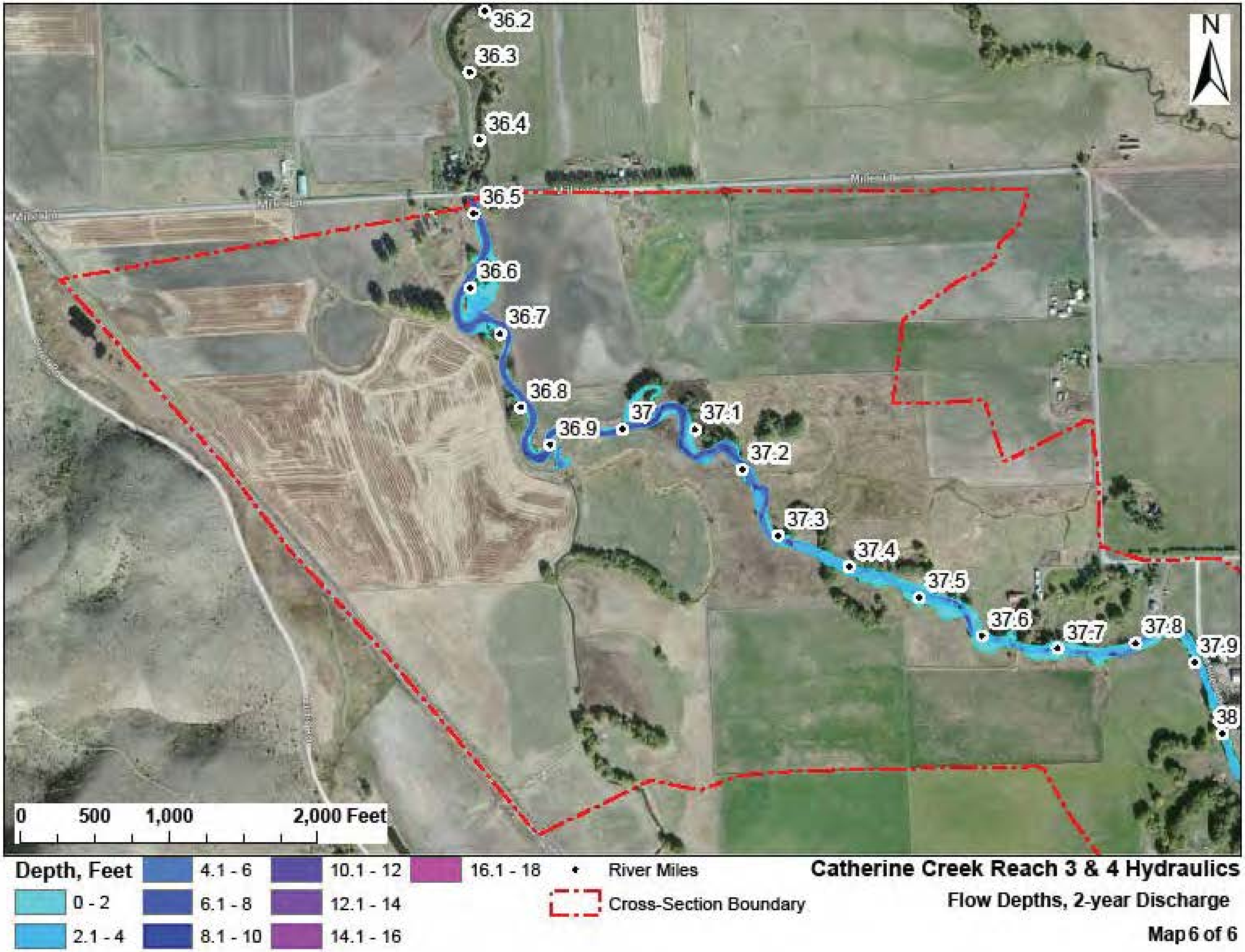
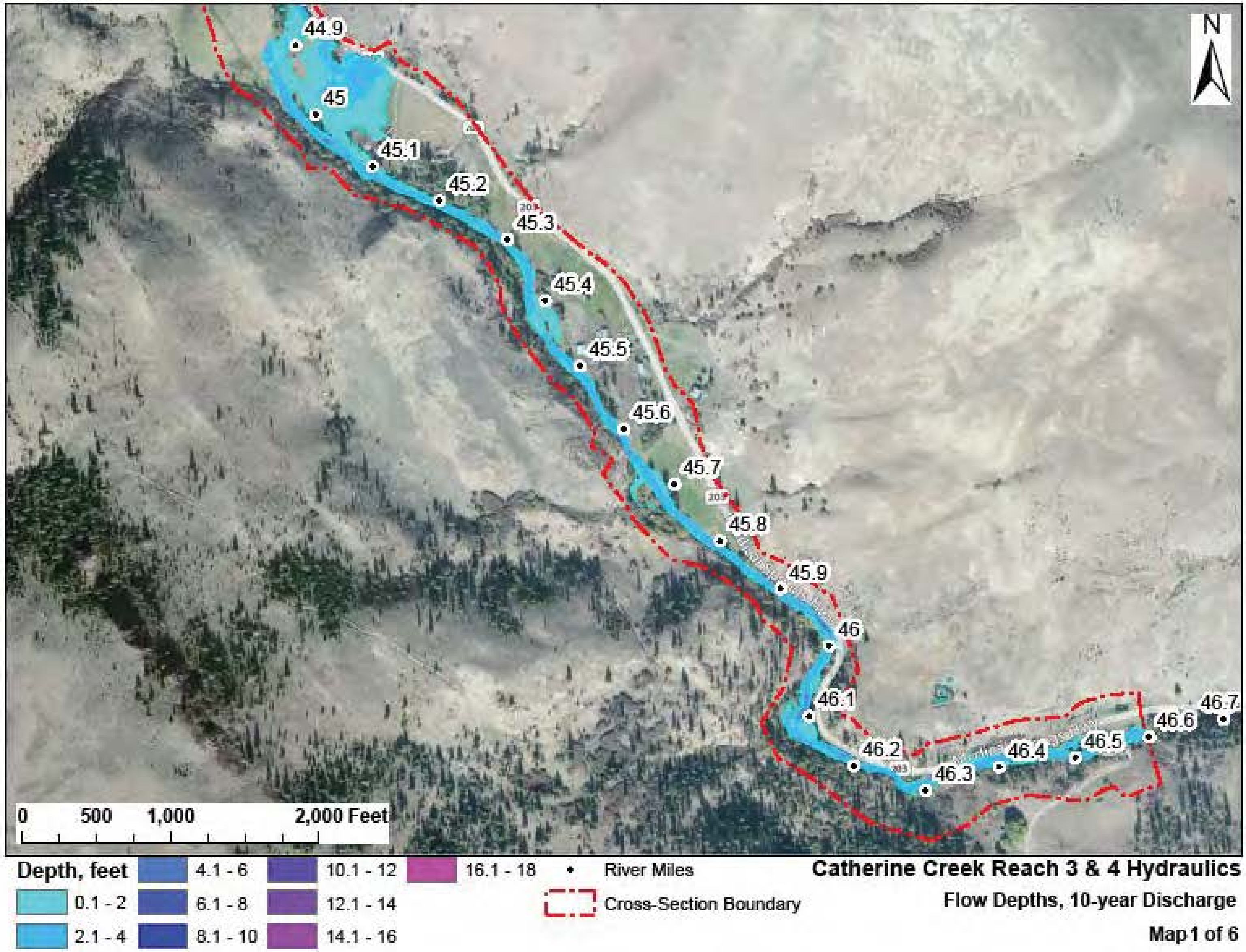
16.1 - 18
River Miles
Cross-Section Boundary
Catherine Creek Reach 3 & 4 Hydraulics
Flow Depths, 2-year Discharge
Map 5 of 6



Catherine Creek Reach 3 & 4 Hydraulics

Flow Depths, 2-year Discharge

Map 6 of 6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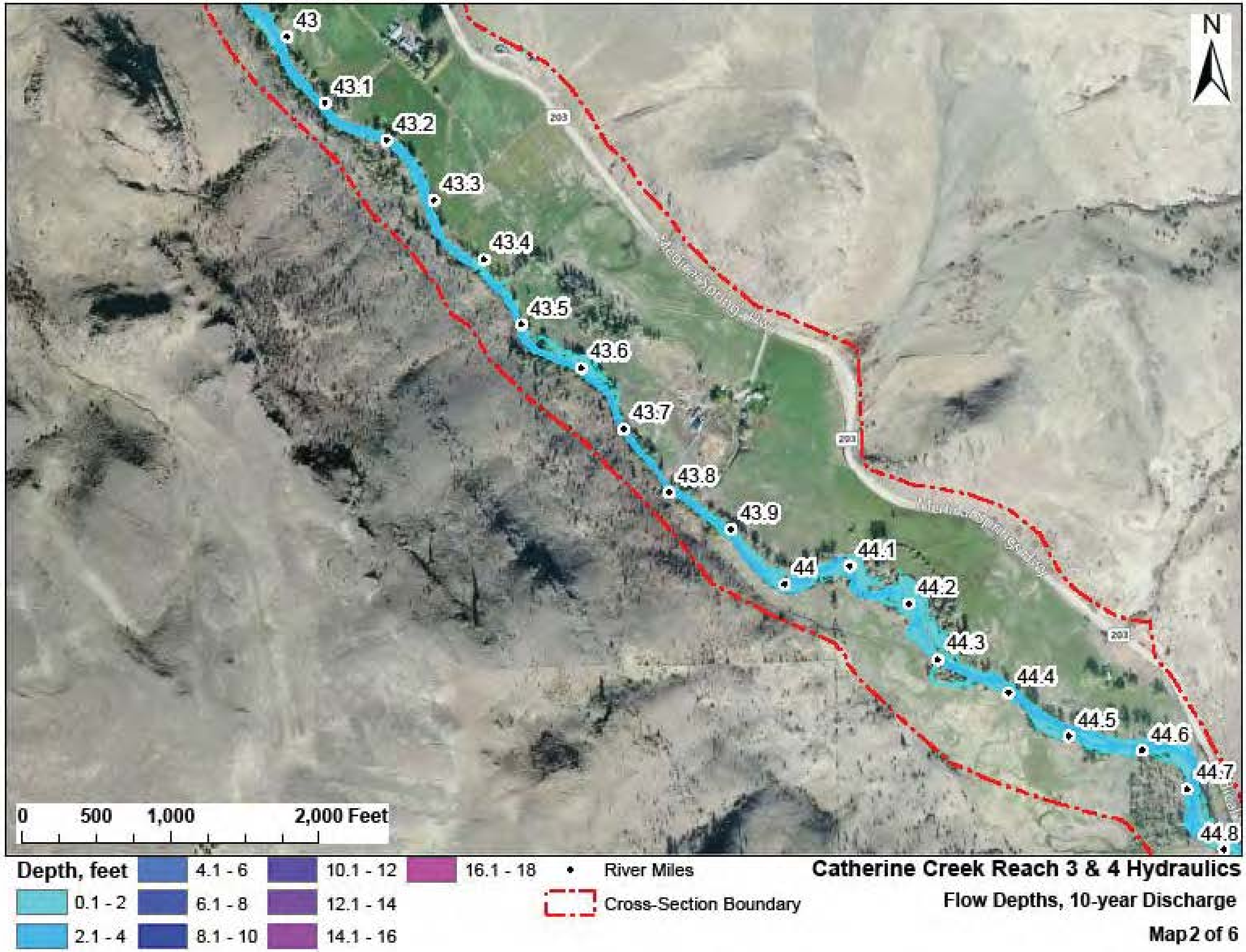
River Miles
Cross-Section Boundary
Catherine Creek Reach 3 & 4 Hydraulics
Flow Depths, 10-year Discharge
Map 1 of 6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Depth, feet
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8.1 - 10
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12.1 - 14
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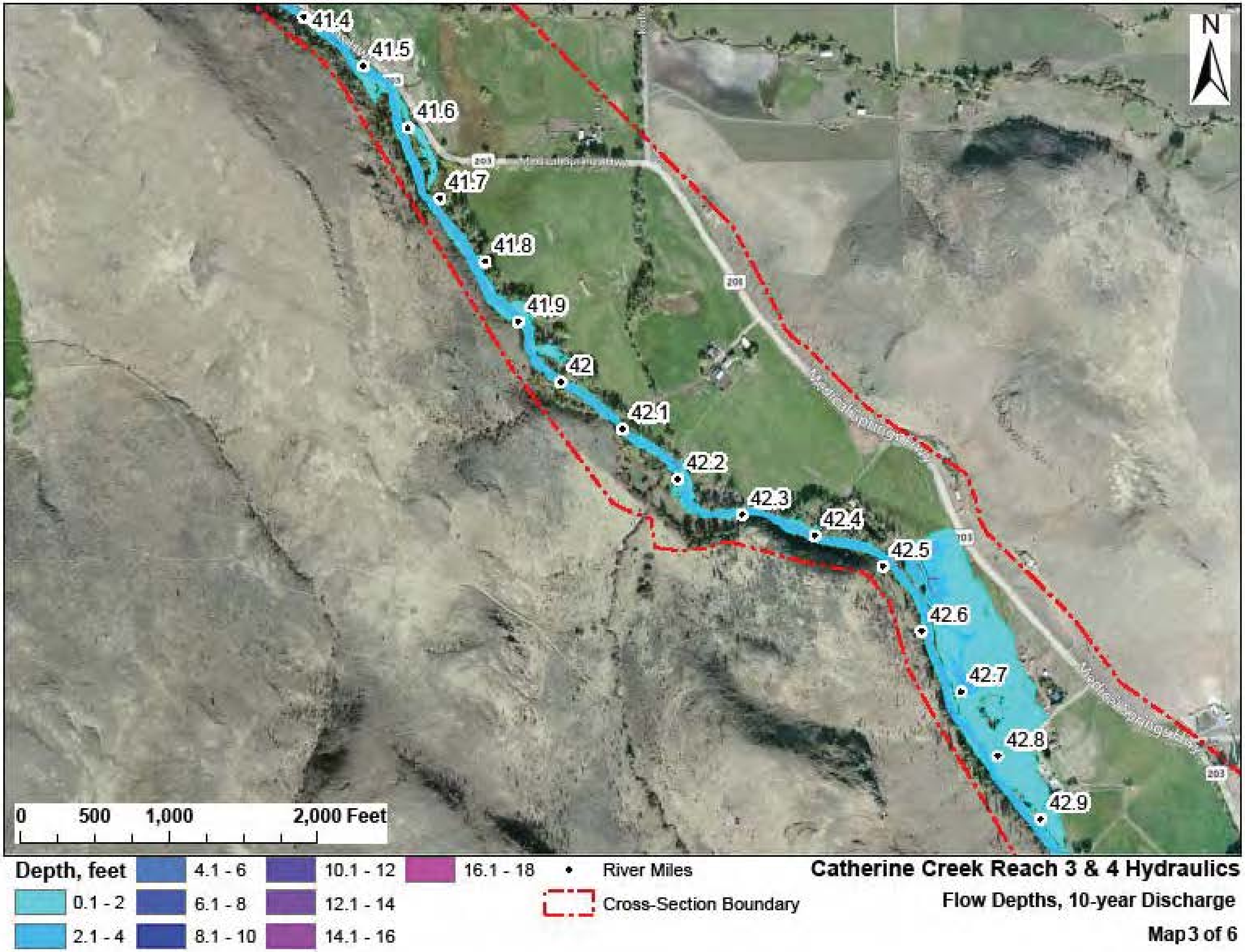
16.1 - 18
River Miles
Cross-Section Boundary
Catherine Creek Reach 3 & 4 Hydraulics
Flow Depths, 10-year Discharge
Map 2 of 6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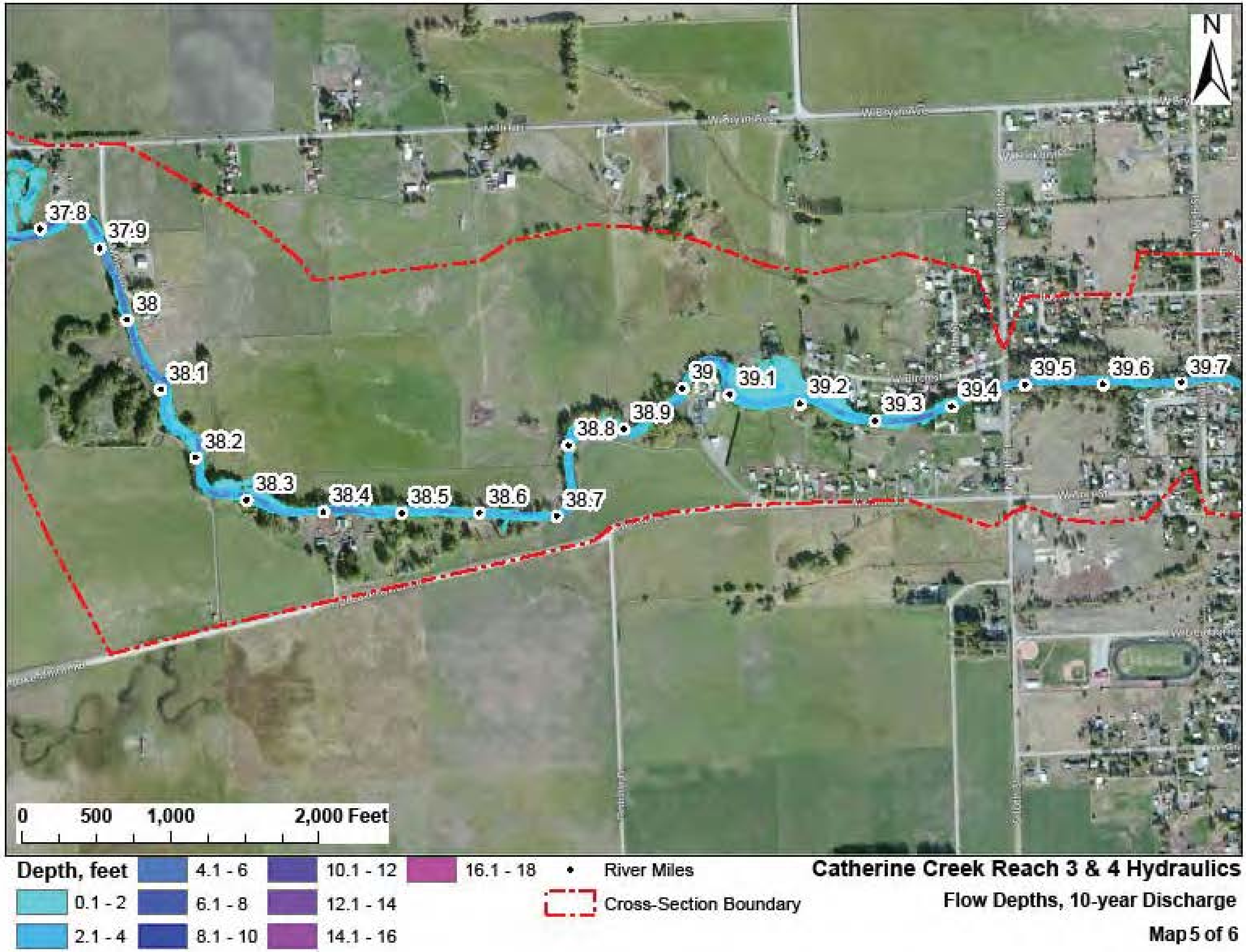
River Miles
Cross-Section Boundary
Catherine Creek Reach 3 & 4 Hydraulics
Flow Depths, 10-year Discharge
Map 3 of 6

Catherine Creek Reach 3 & 4 Hydraulics

Flow Depths, 10-year Discharge

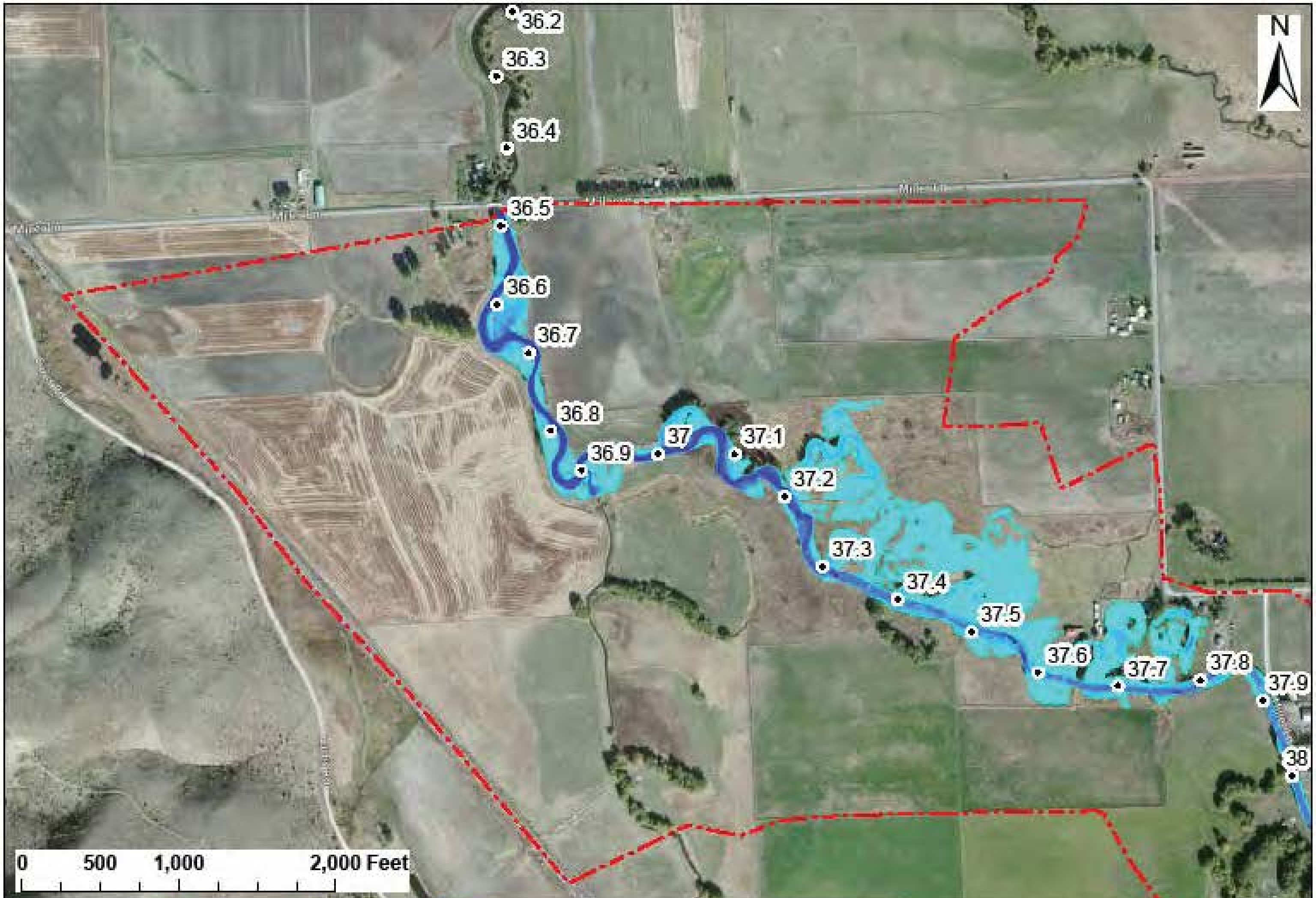
Map 4 of 6



Catherine Creek Reach 3 & 4 Hydraulics

Flow Depths, 10-year Discharge

Map 5 of 6



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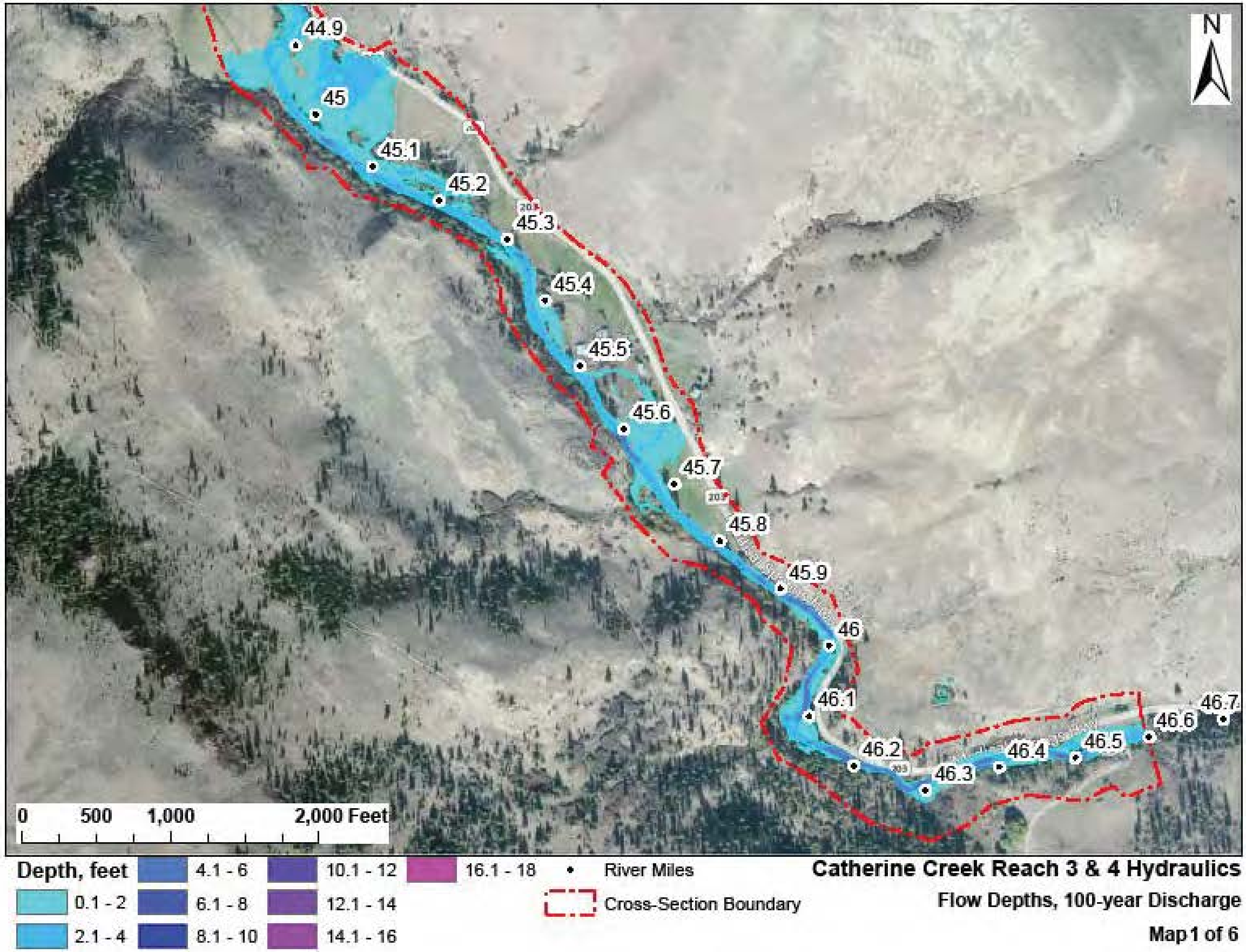
16.1 - 18

• River Miles
Cross-Section Boundary

Catherine Creek Reach 3 & 4 Hydraulics

Flow Depths, 10-year Discharge

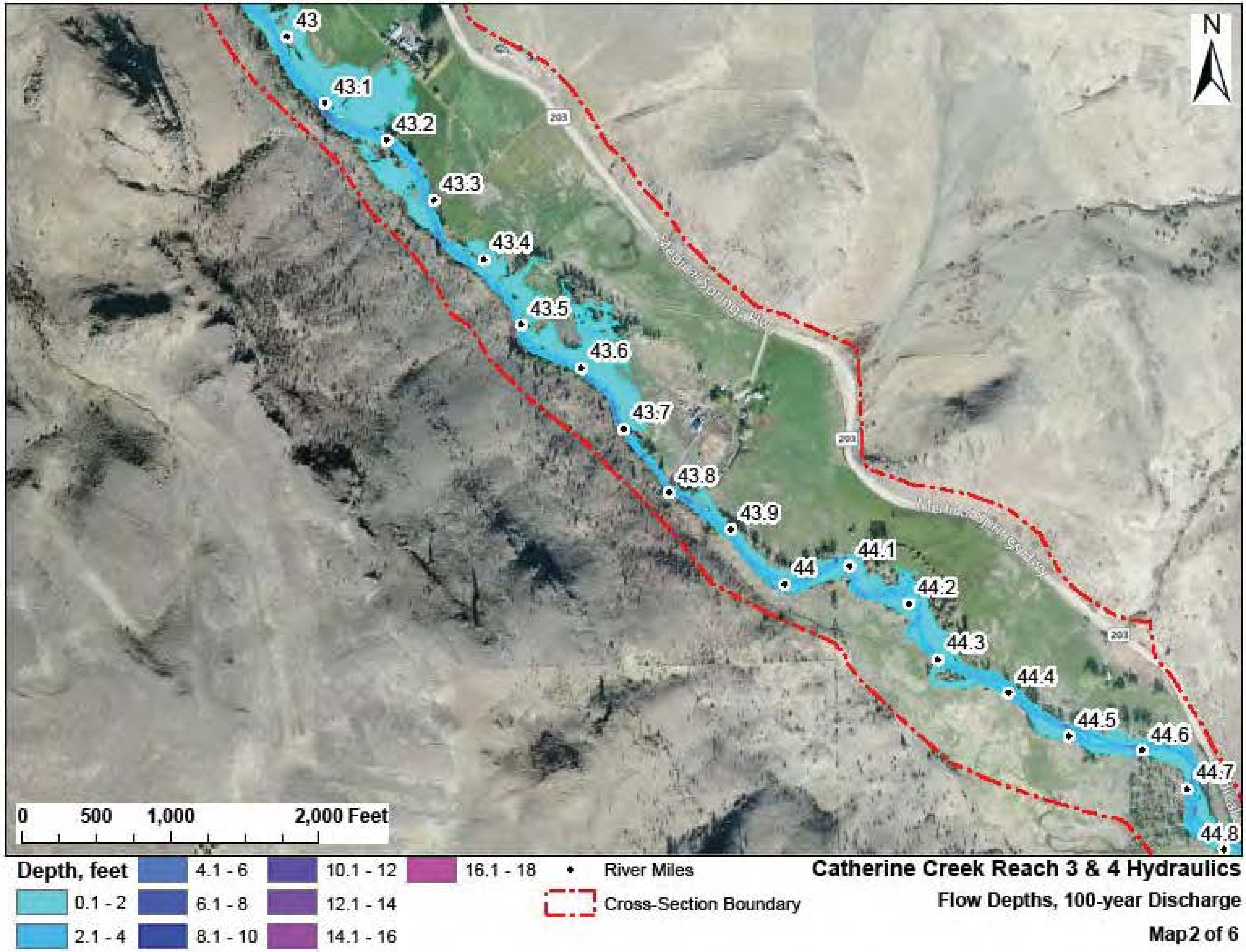
Map 6 of 6



Catherine Creek Reach 3 & 4 Hydraulics

Flow Depths, 100-year Discharge

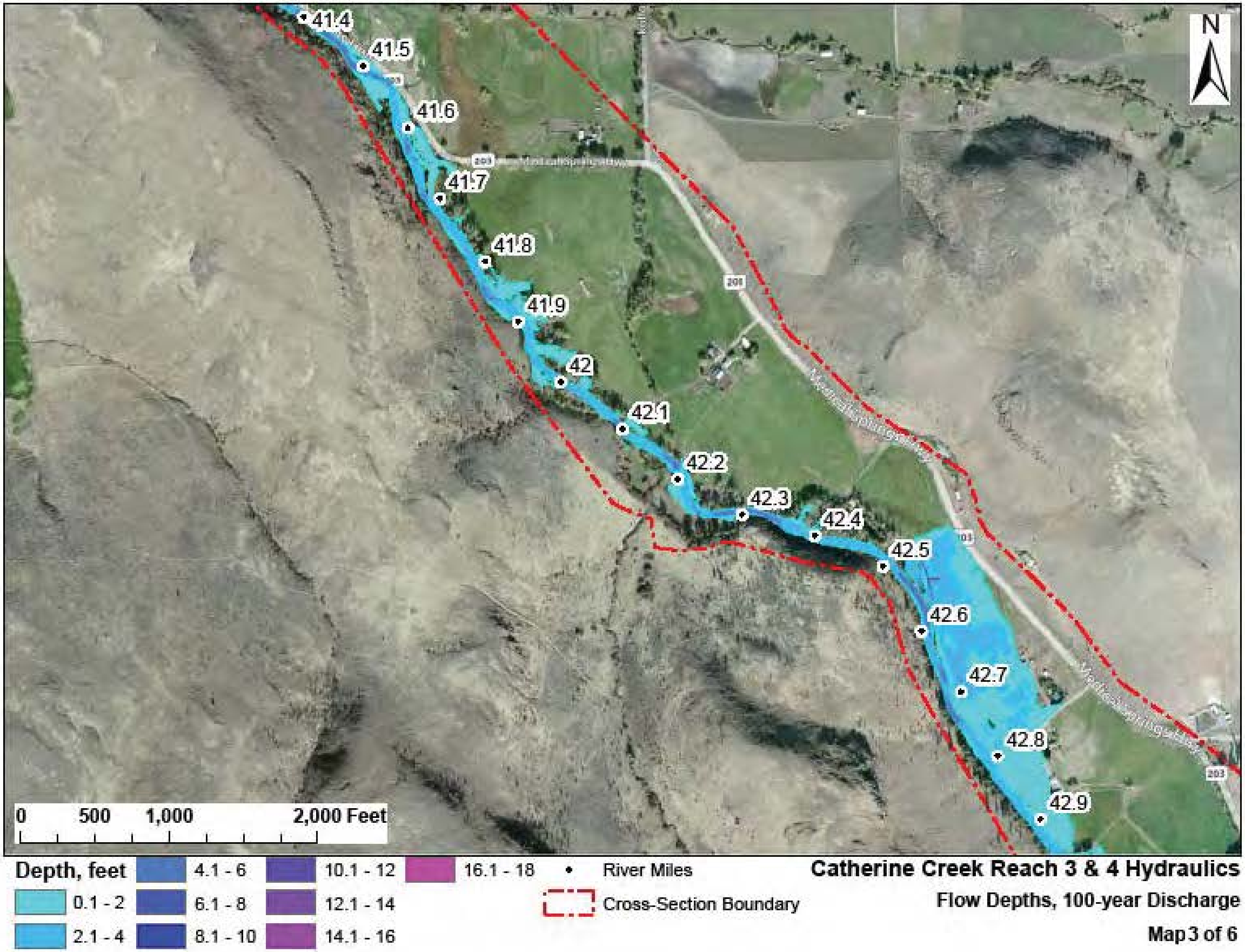
Map 1 of 6



Catherine Creek Reach 3 & 4 Hydraulics

Flow Depths, 100-year Discharge

Map 2 of 6



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14.1 - 16
16.1 - 18
River Miles
Cross-Section Boundary
Catherine Creek Reach 3 & 4 Hydraulics
Flow Depths, 100-year Discharge
Map 3 of 6


39.8
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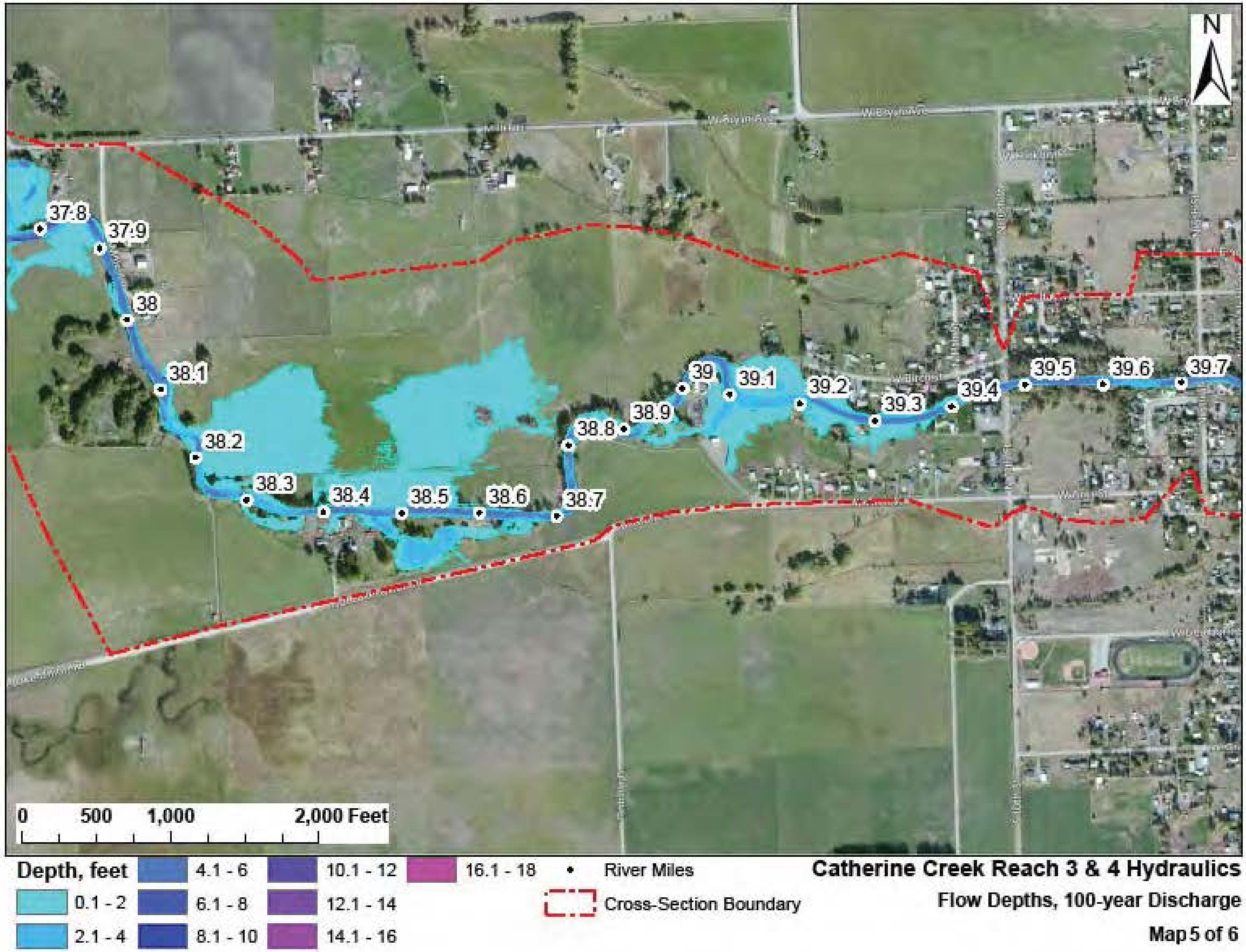
River Miles
Cross-Section Boundary
Catherine Creek Reach 3 & 4 Hydraulics
Flow Depths, 100-year Discharge
Map 4 of 6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12.1 - 14
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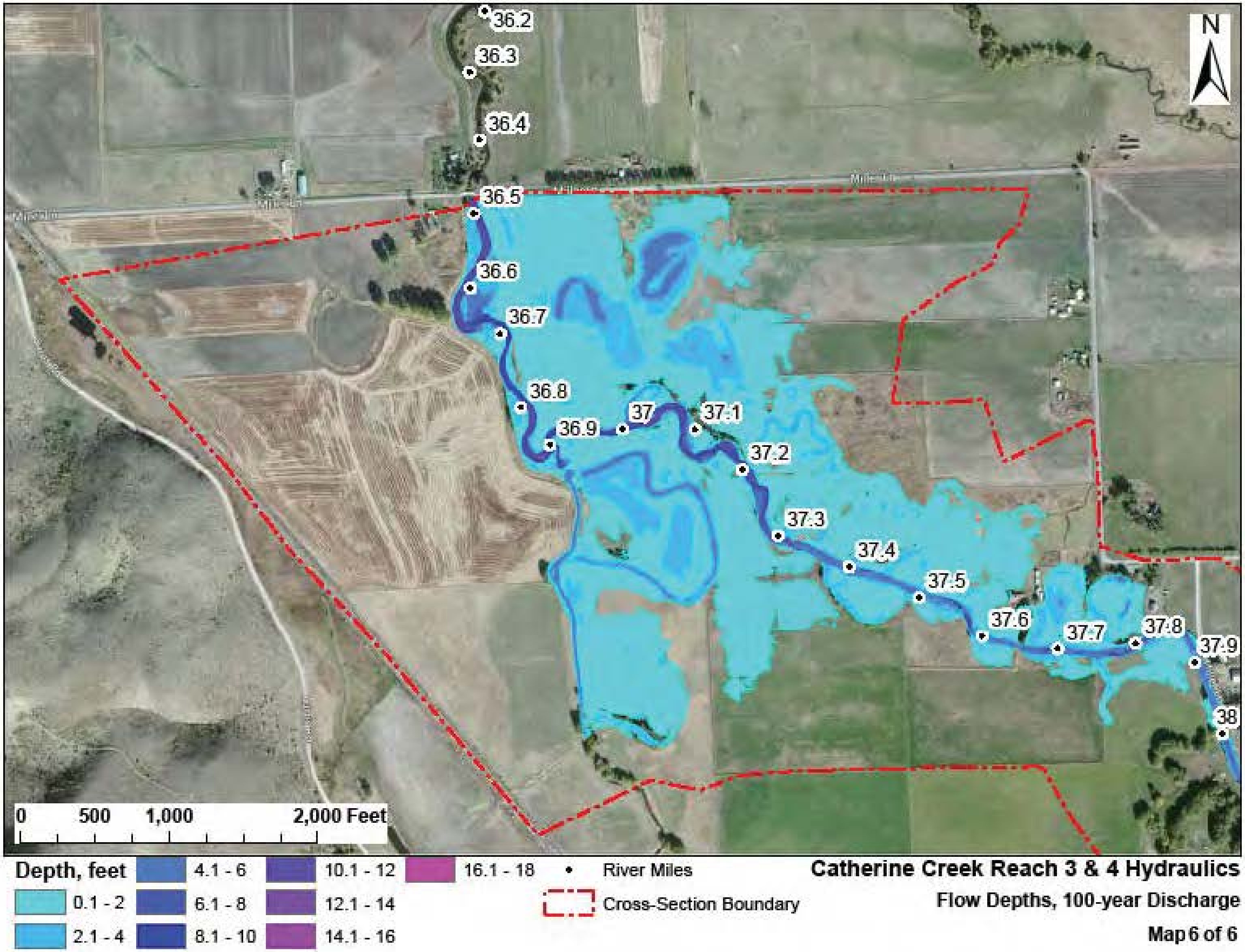
16.1 - 18
River Miles
Cross-Section Boundary
Catherine Creek Reach 3 & 4 Hydraulics
Flow Depths, 100-year Discharge
Map 5 of 6



Catherine Creek Reach 3 & 4 Hydraulics

Flow Depths, 100-year Discharge

Map 6 of 6

Appendix B – Reference Sediment Motion

The reference condition that is most commonly used is where the non-dimensional transport rate, W^*, is equal to 0.002 (Parker, 1990).

$$W^* \quad \frac{(s-1)gq_s}{\rho_s(\tau_g/\rho)^{1.5}} \quad 0.002 \qquad \text{Equation 3}$$

where s = relative specific density of sediment; g = acceleration of gravity; q_s = sediment transport rate; ρ_s = sediment density; τ_g = grain shear stress; ρ = water density. The transport rate, q_z, is primarily dependent on the Shield's number, θ, defined as:

$$\theta = \frac{\tau_g}{\gamma(s-1)D_{50}} \qquad \text{Equation 4}$$

where θ = dimensionless Shield's number; τ_g = grain shear stress; γ = specific weight of water; s = relative specific density of sediment; and D_{50} = median sediment size. The Shields number that gives W^* = 0.002 is termed the reference Shield's stress (θ_r). The reference Shield's stress can be described at the condition when many particles are moving and there is a small, but measurable, sediment transport rate. In this study, it corresponds to an assumed Shields number of 0.035.

The total shear stress can be separated into grain shear stress and form drag (morphological stress). Grain shear stress is commonly understood to be responsible for bedload transport and the shear stress due to form drag is commonly ignored. The channel grain shear stress (τ_g) is calculated as:

$$\tau_g \quad \gamma R' S_f \qquad \text{Equation 5}$$

where R' = channel hydraulic radius due to grain shear stress; and S_f = friction slope. The total shear stress is partitioned into that due to form drag and that due to grain roughness. Manning's equation is valid for the channel hydraulic radius due to grain shear stress:

$$U \quad \frac{C_m}{n_g} R'^{2/3} S_f^{1/2} \qquad \text{Equation 6}$$

where U = cross-section average channel velocity, C_m = 1.0 for SI units, and 1.486 for English units, or $C_m = (g/9.81)^{1/3}$, n_g = Manning's roughness coefficient for bed grains. Dividing this equation by the Manning's equation gives:

$$\frac{R'}{R} = \left(\frac{n_g}{n}\right)^{1.5}$$ Equation 7

where R is the total hydraulic radius and n is the total Manning's roughness coefficient. The Manning's roughness coefficient for the bed grains, n_g, can be computed from the roughness height. First, the logarithmic velocity distribution is integrated over the depth to yield (López and Barragán, 2008):

$$\frac{U}{u_*'} = \frac{1}{\kappa}\ln\frac{R'}{k_s} + 6.25$$ Equation 8

where κ is the von Karman constant (0.4), u_* is the shear velocity, and the log-law constant is assumed to be 6.25. Equation 8 can be approximately fit by the power law relation:

$$\frac{U}{u_*'} = 8.1\left(\frac{R'}{k_s}\right)^{\frac{1}{6}}$$ Equation 9

where k_s is a representative roughness height. Parker (1991) also used Equation 9 to approximate the roughness coefficient in gravel bed streams. The fit is best for R/k_s values between 5 and 200, which is the value most natural rivers will fall into. The error associated in predicting Manning's n values with this approximation is less than 3%, shown in Figure 21.

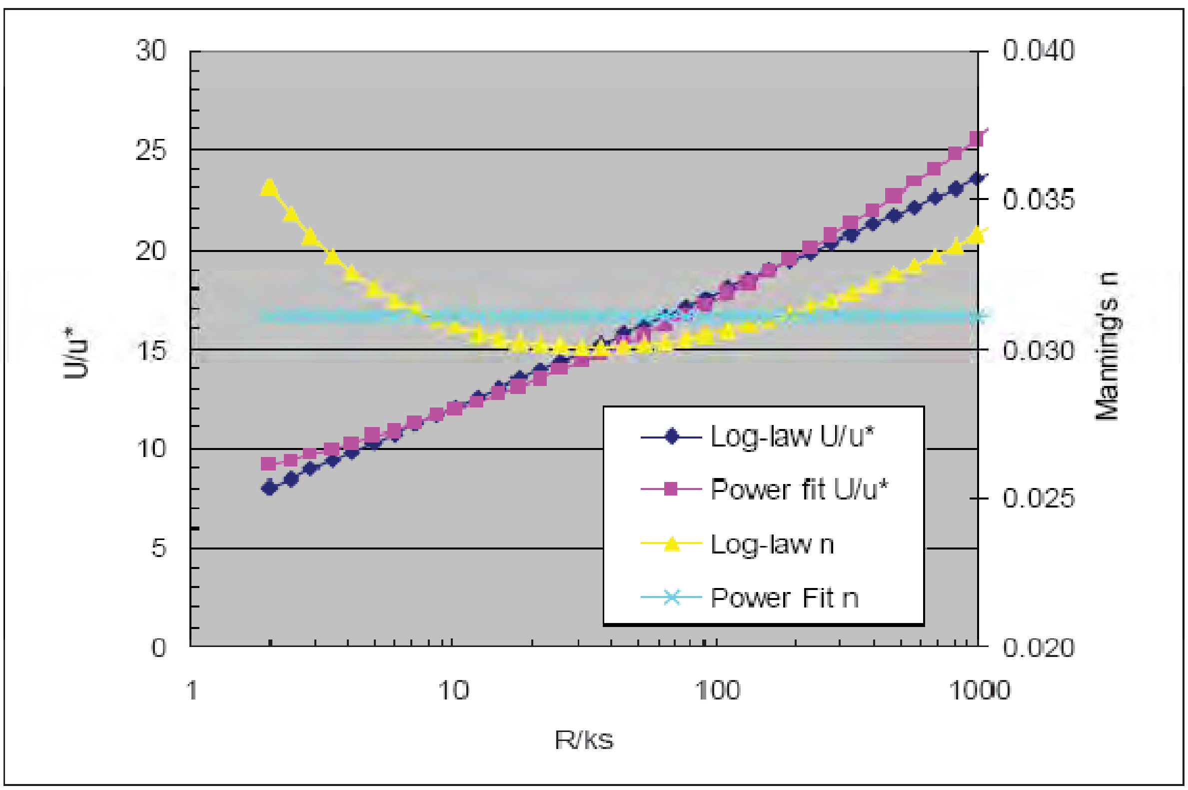


Figure 21. Comparison between log-law and power law approximations. Also shown on the figure is the comparsion between assuming k_s = 240 mm.

The Manning's roughness coefficient due to grain shear, n_g, can then be computed from the roughness height using the following dimensionally consistent formula:

$$n_g = 0.058\left(\frac{k_s}{g}\right)^{\frac{1}{6}} \qquad \text{Equation 10}$$

Several different relations in alluvial rivers have been proposed for k_s ranging from $0.95D_{50}$ (Federal Highway Administration, 1975) to $3D_{90}$ (van Rijn, 1982). A more recent publication, López and Barragán (2008), suggests that $2.4D_{90}$, $2.8D_{84}$, and $6.1D_{50}$ all give equivalent predictions of Manning's roughness coefficient for river beds with gravel size or larger sediment, with a nonsinuous alignment and a flow path free of vegetation or obstacles. In their publication, they use the log-law approximation (Equation 8) to compute Manning's n, but as shown above, the error associated with using the power fit approximation (Equation 9) is less than 3%.