Water Quality Evaluation of the Laramie River, North Platte River Basin, 2009-2010

Wyoming Department of Environmental Quality-Water Quality Division

WYOMING DEPARTMENT OF ENVIRONMENTAL QUALITY
WATER QUALITY DIVISION
ATTAINMENT/NON-ATTAINMENT OF CHAPTER 1 STANDARDS
QUICK SUMMARY

Waterbody ID	Laramie River HUC watersheds 101800100401, 101800100501, and 101800100504
Basin Name	North Platte River Basin
Waterbody Classification	Class 2AB
Location	Albany County, Wyoming
Spatial Extent of Evaluation	From the confluence with Fivemile Creek downstream approximately 23 stream miles to the Little Laramie River confluence.
Years assessed	2009-2010
Assigned Designated Uses	Cold-water game fisheries, non-game fisheries, aquatic life other than fish, fish consumption, drinking water, recreation, wildlife, agriculture, industry and scenic value.
Spatial Extent and Description of Chapter 1 Standards Attainment	From the confluence with Fivemile Creek downstream approximately 23 stream miles to the Little Laramie River confluence, **attainment** of numeric criteria established for: ▪ nitrate, arsenic, cadmium, copper, and selenium for the protection of human health (Section 18) ▪ chloride, arsenic, selenium, and dissolved cadmium and copper (Section 21), dissolved oxygen (Section 24), temperature (Section 25), and pH (Section 26) for the protection of aquatic life. From the confluence with Fivemile Creek downstream approximately nine (9) stream miles to the lower extent of the site at 'Above Laramie WWTF', **indeterminate attainment** of narrative criteria described in Section 15 (Settleable Solids) and Section 32 (Biological Criteria).
Spatial Extent and Description of Chapter 1 Standards Non-Attainment	From the lower extent of the site at 'Above Laramie WWTF' downstream fourteen (14) stream miles to the Little Laramie River confluence (*altered reach*), **non-attainment** of narrative criteria described in Sections 15 (Settleable Solids) and 32 (Biological Criteria) due to excessive sedimentation and nutrient enrichment.
Pollutants/Pollution that Result in Non-Attainment	Excess sediment and nutrient enrichment.
Source(s) of Pollutants/Pollution	Excess sediment- erosion of bed and banks within unstable reaches of the river, upstream and within the *altered reach*. Excess nutrients- point source discharges from the City of Laramie wastewater treatment facility, urban stormwater drainage and potential non-point source contributions from the upstream

	watershed.

Cover Page- Study sites on the Laramie River from top to bottom: 'Above UPRR Tie Plant', 'Below Spring Creek' (left), 'Above Laramie WWTF' (right) and 'Below Gravel Pits'.

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Contents

GLOSSARY 8
EXECUTIVE SUMMARY 11
INTRODUCTION AND PURPOSE 15
DESCRIPTION OF EVALUATION AREA 17
STREAM CLASSIFICATION AND DESIGNATED USES 18
SURFACE WATER HYDROLOGY 18
FACTORS THAT AFFECT WATER QUALITY 24
METHODS AND ANALYTICAL APPROACHES 27
Site Selection 27
Data Collection 29
Data Analysis 30
RESULTS 34
CHEMICAL QUALITY (see Appendix 1 for dataset) 34
pH 34
Temperature 34
Dissolved Oxygen 34
Nutrients 34
Specific Conductance, Hardness, Alkalinity & Major Constituents 35
Total & Dissolved Metals 36
Semi-Volatile Organic Compounds 37
PHYSICAL CONDITION 37
Streamflow 37
Rosgen Stream Classification 38
Bankfull Discharge 40
Channel Dimension 42
Channel Pattern 44
Channel Profile 46
Streambank Stability and Cover 47
Streambank Erosion 48
Channel Incision 50
Channel Bed Material 51
Channel Scour and Fill 52
Depositional Patterns 53
Sediment Competence & Capacity 54

WARSSS River Stability Prediction Procedure 55
BIOLOGICAL CONDITION 57
Wyoming Stream Integrity index (WSII) 57
Wyoming River Invertebrate Prediction And Classification System (WY RIVPACS) 58
Aquatic Life Use Decision Matrix 60
Selected Benthic Macroinvertebrate Metrics 61
Selected Periphyton (Diatoms) Metrics 63
DISCUSSION 66
CHEMICAL QUALITY 66
PHYSICAL CONDITION 69
BIOLOGICAL CONDITION 77
CONCLUSIONS 81
CHAPTER 1 STANDARDS ATTAINMENT/NON-ATTAINMENT 88
REFERENCES 90
APPENDICES 97

FIGURES

Figure 1 – Upper Laramie River watershed showing ecoregions, mainstem drainage system, irrigated lands and infrastructure, municipalities and highways. 17
Figure 2 – Daily mean discharge of the Laramie River at USGS gaging stations 06660000 at Laramie, WY and 06658500 near Jelm, WY. 21
Figure 3 – Daily mean discharge at USGS gaging stations on the Laramie River above and below the Pioneer Canal diversion near Woods Landing, WY (period of record from 10/1/1974 to 9/30/2009). 23
Figure 4 – Comparison of 2009 and 2010 daily mean discharge to historical record (1975-2009) at USGS gaging station 06659502, Laramie River below Pioneer Canal near Woods Landing, WY. Because flow was not monitored at the station in 2010, flow measurements made in the river above the Pioneer Canal diversion at 06659500 and in the Pioneer Canal at 06659501 were used to calculate river flow below the diversion 24
Figure 5 – Locations of study sites within the 2009-2010 Laramie River evaluation area, Albany County, Wyoming. WDEQ/WQD sites monitored in the past are labeled in smaller case font. 27
Figure 6 – Channel and riparian vegetation conditions of the Laramie River downstream of the confluence with Spring Creek within Laramie city limits (2010). 38
Figure 7 – Channel and riparian vegetation conditions of the Laramie River at 'Below Gravel Pits' downstream of the City of Laramie (2010). 39
Figure 8 – Overlays of the 2009 and 2010 cross-sections at Pool 10+085, 'Above Laramie WWTF', Laramie River. 43
Figure 9 – Ratios of mean facet slope to bankfull channel slope at sites on the Laramie River (2009-2010). AUPRR=Above UPRR Tie Plant, BSC=Below Spring Creek, AWWTF=Above Laramie WWTF, BGP=Below Gravel Pits 46

Figure 10 – Annual change (2009-2010) in mean facet depths reachwide at sites on the Laramie River. 47
Figure 11 – Bank conditions at a meander bend at 'Above UPRR Tie Plant' on the Laramie River (2010).48
Figure 12 – Searching for a scour chain installed along the glide cross-section at 'Above Laramie WWTF' on the Laramie River (2010). 53
Figure 13 – WSII scores and associated numeric thresholds used in assigning aquatic life use-support ratings to sites on the Laramie River (2009-2010). 57
Figure 14– WY RIVPACS scores and associated numeric thresholds used in assigning aquatic life use-support ratings to sites on the Laramie River (2009-2010). 58
Figure 15 – Relocated channel reach of the Laramie River within the UPRR Tie Treatment Plant facility. Aerial image (2012) from Albany County Assessor, courtesy of USGS, Earthstar Geographics SIO, ©2014 Microsoft Corp. 73
Figure 16 – Recommended extent of the '*altered reach*' (shown in red) on the Laramie River that does not meet the narrative standards described in Sections 15 and 32 of Chapter 1 of the Wyoming Water Quality Rules and Regulations based on the 2009-2010 water quality condition evaluation..... 87

TABLES

Table 1. Adjudicated surface water rights and points of diversion with appropriations greater than 5 cfs on the Laramie River from the Pioneer Canal diversion to the Little Laramie River confluence. Source: Wyoming State Board of Control (https://sites.google.com/a/wyo.gov/seo/documents-data/hydrographer-reports). 20
Table 2. Descriptive information for WDEQ/WQD study sites on the Laramie River and Spring Creek. .. 28
Table 3 – Predicted reachwide bank erosion rates at WDEQ/WQD sites on the Laramie River (2009-2013). 49
Table 4 – WARRSS river stability and sediment supply predictions for sites on the Laramie River (2009-2010). Scores ranging from 1 to 4 for each rating category are provided in parentheses '()'..... 56
Table 5 – Expected taxa with ≥50% probability of capture observed ('X') at Laramie River sites (2009-2010). 59
Table 6 – Sediment competence results at WDEQ/WQD sites on the Laramie River derived from scour-adjusted channel dimensions. 72

APPENDICES

Appendix 1 – Physicochemical results at WDEQ/WQD stations on the Laramie River and Spring Creek, Albany County, WY (2009–2010). 97
Appendix 2 – Channel dimension, pattern and profile attributes and dimensionless ratios at sites on the Laramie River (2009–2010). 99
Appendix 3 – Estimated bankfull discharge and associated velocity and shear stress values derived from baseflow channel dimensions (measured) and scour-adjusted channel dimensions (estimated from bed scour survey results) for sites on the Laramie River (2009–2010). 101
Appendix 4 – Overlays of 2009 and 2010 longitudinal profiles at WDEQ/WQD sites on the Laramie River that illustrate cross-section (XS) locations and annual changes in channel bed thalweg (Chan) and water surface (WS) elevations. Riffle (R), Run (U), Pool (P), and Glide (G) bed features are associated with 2009

profile survey. BKF= bankfull elevation, BKFS= bankfull slope, LB= Low Bank, LBS= Low Bank Slope, AbTer= Abandoned Terrace. 102
Appendix 5 – Percent streambank stability and cover estimates at sites on the Laramie River (2009–2010). 106
Appendix 6 – Observed and predicted average annual stream bank erosion rates and associated BEHI/NBS ratings at permanent cross-sections at Laramie River sites (2009–2010). LB and RB equate to left bank and right bank, respectively. Negative values under bank erosion rate columns represent the rate of bank retreat (lateral accretion). 107
Appendix 7 – Bank profile plots generated from survey data collected at permanent cross-sections at Laramie River sites (2009–2010). LB and RB represent left bank and right bank, respectively. A bank profile survey could not be completed at 'Below Spring Creek' in 2011 because the bank was reshaped to install bank and channel treatments that year, resulting in the loss of reference elevation pins. 108
Appendix 8 – Predicted annual stream bank erosion rates at Laramie River sites. Predictions derived from BANCS model developed from stream data collected in sedimentary/metamorphic geographic regions in Colorado (Rosgen 2006a). 109
Appendix 9 – Channel bed material composition at WDEQ/WQD sites on the Laramie River (2009–2010). 116
Appendix 10 – Reachwide cumulative particle size distribution plots for WDEQ/WQD sites on Laramie River (2009–2010). 117
Appendix 11 – Riffle cumulative particle size distribution plots for WDEQ/WQD sites on the Laramie River (2009–2010). 118
Appendix 12 – Annual change in bankfull cross-sectional areas and reachwide thalweg bed elevations at WDEQ/WQD sites on the Laramie River (2009-2010). A negative change in area or positive change in average bed elevation indicates aggradation, whereas a positive change in area or negative change in average bed elevation indicates degradation. 119
Appendix 13 – Scour chain survey data collected at WDEQ/WQD sites on the Laramie River, (2009-2010). 120
Appendix 14 – Sediment competence calculations used to evaluate channel bed stability at bankfull stage at WDEQ/WQD sites on the Laramie River (2009-2010). With the exception of bar sample particle sizes, all measurements were obtained from the riffle cross-section. 121
Appendix 15 – Categorical scores and narrative ratings from the WARSSS River Prediction Assessment Procedure applied at WDEQ/WQD sites on the Laramie River (2009-2010). 122
Appendix 16 – WSII and WY RIVPACS scores and associated aquatic life use narrative assignments for WDEQ/WQD sites on the Laramie River (2009-2010). F = Full-Support, I = Indeterminate, P/N = Partial/Non-Support 126
Appendix 17 – Benthic macroinvertebrate sample results (riffle habitat) at WDEQ/WQD sites on the Laramie River (2009-2010). Count = Number of Individuals/m^2, PRA = Percent Relative Abundance. 127
Appendix 18 – Selected benthic macroinvertebrate metric results for WDEQ/WQD sites on the Laramie River (2009-2010). 129
Appendix 19 – Diatom metric results for WDEQ/WQD sites on the Laramie River (2009-2010) 130
Appendix 20 – Diatom sample results for WDEQ/WQD sites on the Laramie River (2009-2010). D = cells/cm^2, PRA = Percent Relative Abundance. Values shown in red font represent dominant taxa. 131

GLOSSARY

Aggradation – A raising of local base level due to sediment depositional processes.

Average Water Surface Slope (S) – Elevation of water surface over stream length at the same position above bed features for several riffle/pool or step/pool sequences. The elevation difference from the top of riffle features over the length of a stream reach is used to determine bankfull channel slope (Sbkf).

Bank Erosion Hazard Index (BEHI) – A process-integration approach that evaluates the susceptibility to erosion for multiple erosional processes; incorporated into the BANCS model to predict annual stream bank erosion rates.

Bank-Height Ratio (BHR) – A quantitative measure of the degree of vertical containment or degree of channel incision as determined by the ratio of the lowest bank height (LBH) divided by the maximum bankfull depth.

Bankfull Cross-Sectional Area (A) – The sum of the products of unit width and depth at the bankfull stage elevation.

Bankfull Discharge (Qbkf) – A frequently occurring peak flow whose stage represents the incipient point of flooding and expressed as the momentary maximum of instantaneous peak flows rather than the daily mean discharge. It is often associated with a return period of 1-2 years, with an average of 1.5 years.

Bankfull Stage – The elevation of the water surface associated with the bankfull discharge.

Bankfull Width (W) – The surface width of the stream measured at the bankfull stage.

Belt Width (Wblt) – The width of the full lateral extent of the bankfull channel measured perpendicular to the fall line of the valley.

Channel Confinement – Represents a measure of the lateral containment of a river channel within its valley as measured by meander-width-ratio: the ratio of belt width to bankfull width.

Degradation – A lowering of local base level due to channel incision processes.

Entrenchment – The vertical containment of a river that is quantitatively defined as the width of the flood-prone area divided by the bankfull width.

Floodplain – The floodplain of a river is the flat adjacent to the bankfull channel, which is constructed by the river in the present climate. It is available to the river to accommodate flows greater than the bankfull discharge.

Flood-Prone Area Width (Wfpa) – The width of the channel associated with the elevation that is twice the maximum bankfull depth. It is the area including the floodplain of the river and often the low terrace of alluvial streams.

Incision – The process of a lowering of local base level. The degree of incision is measured by bank-height ratio.

Maximum Bankfull Depth (dmbkf) – Maximum depth of the bankfull channel cross-section or the distance between the thalweg and bankfull stage.

Mean Bankfull Depth (d) – The mean depth of flow at the bankfull stage, determined as the cross-sectional area divided by the bankfull surface width.

Meander Wavelength (Lm) – The longitudinal distance parallel with the fall line of the valley between the apices of two sequential meanders.

Meander Width Ratio (Wblt/W) – The quantitative, morphological measure of confinement that is determined by the ratio of belt width to bankfull width.

Near Bank Stress (NBS) – Assessment in the BANCS model associated with energy distribution against stream banks.

Physical Stability – A river or stream's ability in the present climate to transport the streamflows and sediment of its watershed, over time, in such a manner that the channel maintains its dimension, pattern and profile without either aggrading or degrading.

Radius of Curvature (Rc) – A measure of the tightness of an individual meander bend that is negatively correlated with sinuosity. Rc is measured from the outside of the bankfull channel to the intersection point of two lines that perpendicularly bisect the tangent lines of each curve departure point.

Sediment Competence – The ability of a stream or river to move the largest size (diameter) of sediment particle made available from the immediate upstream supply.

Sediment Transport Capacity – The ability of a stream or river to transport the sediment load produced by its watershed over a wide range of flows, including floods.

Shear Stress (τ) – The frictional force per unit area causing flow resistance along the channel boundary. Shear stress is a product of depth and slope multiplied by the specific weight of water.

Sinuosity – An index of channel pattern determined from the ratio of stream length to valley length or the ratio of valley slope to channel slope.

Stream Bank Erosion – The land associated with stream banks that is eroded by a variety of processes, including fluvial entrainment, mass wasting, freeze-thaw, dry ravel, rill erosion, ice scour and other processes.

Terrace – A flat adjacent to the river in alluvial valleys created by the abandonment of the floodplain.

EXECUTIVE SUMMARY

The Monitoring Program of the Wyoming Department of Environmental Quality-Water Quality Division (WDEQ/WQD) evaluates water quality of streams, rivers, lakes, reservoirs and wetlands in Wyoming. Water quality conditions are determined using water quality standards, with findings of standards attainment and observed pollutant problems and sources described within a water quality monitoring and evaluation report. These reports are then used to assess support of designated water uses using standardized criteria and ultimately incorporated into the State's biennial Integrated 305(b) and 303(d) Report that is submitted to the U.S. Environmental Protection Agency.

The Laramie River is a major perennial tributary of the North Platte River with headwaters that originate in northern Colorado. The river flows north into southeastern Wyoming in Albany County along the east flank of the Medicine Bow Mountain Range, coursing northeasterly through the City of Laramie and then north where it joins the Little Laramie River. Land ownership in the watershed is mostly private with a mixture of federal, state, county and municipal property. Predominant land uses include livestock grazing, irrigated agriculture, recreation and wildlife habitat. Land uses within the City of Laramie include urban/residential, industrial, recreation and wildlife habitat. The Laramie River is a Class 2AB water, protected for the following designated uses: cold-water fisheries, non-game fisheries, drinking water, fish consumption, aquatic life other than fish, recreation, wildlife, industry, agriculture and scenic value.

In 1996, a 22.8 mile reach of the Laramie River between the confluences with Fivemile Creek and the Little Laramie River (evaluation reach) was placed on Wyoming's 303(d) List of impaired waters for partially supporting its cold-water fisheries and other aquatic life uses due to organic stressors from unknown sources. The listing originated in part from observations of elevated ammonia concentrations at a U.S. Geological Survey water quality monitoring station downstream of the City of Laramie. Findings from several toxicology studies, which examined the effects of organic pollutants on the river's aquatic life, were also considered in the impairment decision. Organic compounds originating from groundwater contaminated by creosote adjacent to the river at the Union Pacific Tie Treatment Plant site immediately upstream of the city, and other potentially toxic pollutants entering the river through the urban stormwater sewer system were implicated as environmental stressors. The original listing was removed due to an absence of sufficient credible data needed to substantiate the impairment and subsequently placed in Table E of Wyoming's 1998 305(b) report. As part of the 1997 TMDL Work Plan, WDEQ/WQD committed to collecting the credible data (biological, chemical and physical) needed to determine the validity of several original 1996 listings, including the Laramie River, noted on Table E.

Findings and recommendations from past water quality investigations were used by WDEQ/WQD to develop and implement a two year evaluation plan in 2009 and 2010. The overall objective of the plan was to determine spatial and temporal changes in the river's water quality condition at four study sites upstream, within and downstream of the City of Laramie. Specific objectives were to 1) evaluate chemical, physical and biological conditions with respect to Wyoming water quality standards, 2) determine both natural and anthropogenic factors that affect attainment of water quality standards, and 3) identify source(s) of pollutants that may cause non-attainment of water quality standards. The

monitoring plan placed emphasis on investigating the effects of sediment and nutrients on the river's benthic macroinvertebrate and periphyton (diatoms) communities, or the benthos.

Several lines of evidence gathered from the 2009-2010 Laramie River investigation indicate that excess sediment and nutrient enrichment contribute to observed departures in the river's biological condition from regional reference expectations. The effects of excess sediment on both the benthic macroinvertebrate and periphyton communities are evident throughout the evaluation reach, but increase substantially with distance downstream. Episodic inputs of excess nutrients (nitrogen and phosphorus) to the river may influence benthic organisms to a certain degree in reaches upstream and within Laramie's city limits, but stressors associated with excess sediment appear to "mask" the biological responses typically associated with nutrient enrichment. However, the marked changes observed in the structure and function of the benthic biota downstream of the city are considered to be caused by both excess nutrients and excess sediment.

Though various degrees of departure in biological condition from regional reference expectations are observed throughout the Laramie River, an appreciable decline occurs with distance downstream of the City of Laramie (below the 'Above Laramie WWTF' study site), likely extending approximately 14 stream miles to the confluence with the Little Laramie River (the *altered reach*). Benthic macroinvertebrate richness, compositional and functional measures within the *altered reach* differ markedly from both regional reference expectations and to corresponding measures in upstream reaches. A combination of excess sedimentation, bed scour, high bed mobility and nutrient enrichment are considered the principal stressors responsible for alterations in the macroinvertebrate community. The same environmental stressors are also singled out as those responsible for the appreciable compositional shifts observed in diatom communities with distance downstream. These biological findings did not vary appreciably during the two year evaluation. In summary, the resident benthic organisms are well-adapted to nutrient-rich, chronically unstable, fine sediment-dominated depositional environments.

The available evidence indicates that a majority of the excess sediment in the *altered reach*, consisting of sand and fine gravel, originates from in-channel sources (i.e., bed and bank erosion) within unstable reaches of the river upstream of the City of Laramie and continuing downstream for several miles. Accelerated bank erosion and lateral channel migration is more prevalent in reaches upstream and downstream of the city. Reaches upstream of the city generate a substantial amount of sediment from accelerated bed and bank erosion that is conveyed downstream. Unable to transport the sediment it receives on an annual basis, the river aggrades, which in turn exacerbates bank erosion through lateral channel migration processes (i.e., development and growth of point bar and mid-channel bar features and creation of divergent and convergent flow patterns that are directed against banks). The continual supply of sediment from bank erosion progressively diminishes the river's sediment transport capacity with distance downstream. Delta bar features observed in the river below the city's stormwater drainage outlets suggest that excess sediment is contributed to the river from urban sources. However, the quantity of sediment generated from urban sources is considered secondary to the amount attributed to the river's in-channel sources.

Primary sources of excess nutrients to the *altered reach* include the City of Laramie WWTF point source discharges and urban stormwater drainage. Excess nutrient contributions from non-point sources (i.e., fertilized croplands, livestock feedlots, rural septic systems) are considered minor relative to point sources and urban runoff. During the study, concentrations of total nitrogen (2,700 and 5,174 µg/L) and total phosphorus (420 and 714 µg/L) within the *altered reach* were 10 to 20 times greater than expected regional reference levels, and more than 10 times greater than concentrations measured upstream of the city. Concentrations of both nutrients upstream of the *altered reach* were within the range of regional reference concentrations. Greater than 80% of the total nitrogen in the *altered reach* is composed of inorganic nitrogen (nitrate+nitrite-N), a form readily assimilated by algae and aquatic plants, especially if there is a readily available supply of phosphorus. Total phosphorus concentrations in the *altered reach* are about 40 to 50 times greater than levels measured at sites upstream. Spring Creek, a tributary of the Laramie River that conveys much of the city's urban stormwater drainage, contributes excess nutrients to the river in accordance with its prevailing nutrient load, which may be less than 5% of the river's total load during baseflow. Total phosphorus concentrations in Spring Creek were comparable to mean regional reference values, but nitrate+nitrite-N concentrations were 30 times greater than mean reference values.

The weight of evidence presented in this report indicates that excess sediment and nutrient enrichment cause an adverse alteration to the structure and function of the aquatic biological community within the *altered reach* of the Laramie River, which translates to non-attainment of narrative criteria described in Section 15 (Settleable Solids) and Section 32 (Biological Criteria) of WDEQ/WQD's Chapter 1 Water Quality Rules and Regulations. Though several lines of physical evidence indicate that the river's benthos upstream of the *altered reach* are subjected to a high degree of physical stress associated with excess sedimentation and high bed mobility, there is not a sufficient weight of biological evidence to conclude that the structure and function of the benthic community in this reach is adversely altered by these stressors. Excess nutrients may also influence the benthos upstream of the *altered reach* to a limited degree, but the available evidence suggests there is no appreciable alteration to the resident benthos by excess nutrient inputs. No exceedances of applicable numeric criteria for priority or non-priority pollutants were identified in the water quality data evaluated during the study. Furthermore, no indications of heavy metal toxicity, high salinity or episodes of depressed oxygen levels were inferred from relevant benthic macroinvertebrate and diatom metric results.

During the 2010 spring runoff, the historic peak flow record for the Laramie River was broken. Given the magnitude of this flood event, there was reason to expect that the rivers' benthic community would experience a considerable degree of alteration in response to physical stressors associated with bed scour and sedimentation. Yet the biological evidence gathered after the flood indicated that the communities at each site did not differ appreciably from the corresponding communities observed in 2009, which was considered a relatively normal runoff year. In both years, the community within the *altered reach* consistently exhibited less similarity to the regional reference expectation than communities at sites upstream of the *altered reach*. Though these findings indicate that the river's biological condition declines precipitously with distance downstream of the City of Laramie, it is also recognized that these observations were made during a time period in which annual peak flow

conditions varied widely. With this recognition, it may be assumed that the environmental stressors to which the river's aquatic life are subjected during other times or flow conditions may differ from those observed during this study.

Improvements in the river's biological condition may occur in the future as a result of channel restoration and enhancement efforts initiated in 2009 and completed in 2011 within the urban reaches of the Laramie River by HabiTech, Inc. and WWC Engineering, Laramie Rivers Conservation District (LRCD) staff and community volunteer groups. This work was implemented on behalf of the Beautification Committee of the Laramie Economic Development Corporation, LRCD, Wyoming Game and Fish Department, and several financial supporters. Much of the restoration work was intended to protect valuable public and private property in areas threatened by accelerated bank erosion, and to improve aquatic and riparian habitat through localized hydraulic controls. Evidence gathered during this study indicates that bank erosion potential within the urban reach was reduced appreciably by these efforts, which may ultimately reduce the river's total sediment load, increase sediment transport capacity and improve channel habitat and biological condition in the long-term.

INTRODUCTION AND PURPOSE

The Monitoring Program of the Wyoming Department of Environmental Quality-Water Quality Division (WDEQ/WQD) evaluates water quality of streams, rivers, lakes, reservoirs and wetlands in Wyoming. Water quality conditions are determined using water quality standards, with findings of standards attainment and observed pollutant problems and sources described within a water quality monitoring and evaluation report. These reports are then used to assess support of designated water uses using standardized criteria (WDEQ/WQD 2014a) and ultimately incorporated into the State's biennial Integrated 305(b) and 303(d) Report that is submitted to the U.S. Environmental Protection Agency (USEPA).

In 1996, a 22.8 mile reach of the Laramie River between the confluences with Fivemile Creek and the Little Laramie River was placed on Wyoming's 303(d) List of impaired waters for partially supporting its cold-water fisheries and other aquatic life uses due to organic stressors from unknown sources. The listing originated in part from observations of elevated ammonia concentrations at U.S. Geological Survey (USGS) station 06660070 (Laramie River above Howell, WY) downstream of the City of Laramie. Also considered in the impairment decision were findings from several toxicology studies which examined the effects of organic pollutants on the river's aquatic life aquatic life. Organic compounds originating from groundwater contaminated by creosote adjacent to the river at the Union Pacific Railroad (UPRR) Tie Treatment Plant site immediately upstream of the city (Bergman et al. 1982, Fernandez et al. 1989), and other potentially toxic pollutants entering the river through the urban stormwater sewer system (Conrad 1996) were also implicated as environmental stressors. The Laramie River was ultimately removed from the 1996 303(d) List due to an absence of sufficient credible data needed to substantiate the use impairment and subsequently placed on Table E of Wyoming's 1998 305(b) report. Streams listed on Table E required the collection of credible chemical, physical and biological data to assess designated use-support. As part of the 1997 TMDL Work Plan, WDEQ/WQD committed to collecting the credible data needed to determine the validity of the original 1996 listing.

The WDEQ/WQD initiated monitoring work within the listed reach of the Laramie River in 2000 at two sites above and two sites below the City of Laramie, followed by monitoring in 2001 at additional sites by Laramie Rivers Conservation District (LRCD). Benthic macroinvertebrate data collected in both years suggested that the biological condition of the river within and downstream of the city was not comparable to reference conditions. Suspected causes of the decline included a combination of both natural and human-induced changes in water quality and quantity, channel morphology and streambed sediment. Elevated levels of phosphorus and nitrate-nitrogen along with an abundant growth of macrophytes and filamentous algae were documented in the Laramie River below the confluence with the City of Laramie wastewater treatment facility (WWTF) effluent channel.

Though sediment and nutrients were considered primary pollutants in the Laramie River, the relative influence of each on the aquatic biota could not be differentiated and potential sources of the pollutants could not be determined from the available data. Pollutants originating from the City of Laramie urban stormwater drainage system and release of organic contaminants from the UPRR Tie Treatment site were also suspected environmental stressors. The WDEQ/WQD recommended focusing monitoring efforts on the segment of the river flowing through the City of Laramie to address these concerns.

As part of WDEQ/WQD's commitment to determine the validity of the 1996 303(d) listing, an evaluation plan for 2009 and 2010 was formulated for the Laramie River based on findings and recommendations from past water quality investigations. In April and May 2009, WDEQ/WQD met with Laramie's Public Works personnel and the LRCD to discuss monitoring plans, objectives and potential outcomes of the proposed water quality evaluation. The goal of the two year plan was to determine spatial and temporal changes in the chemical, physical and biological condition of the Laramie River immediately upstream, within and downstream of the City of Laramie. Specific objectives were to 1) evaluate chemical, physical and biological conditions with respect to Wyoming water quality standards, 2) determine both natural and anthropogenic factors that affect attainment of water quality standards, and 3) identify source(s) of pollutants that may cause non-attainment of water quality standards. The monitoring plan placed emphasis on investigating the effects of sediment and nutrients on the river's benthic macroinvertebrate and periphyton (diatoms) communities, or benthos.

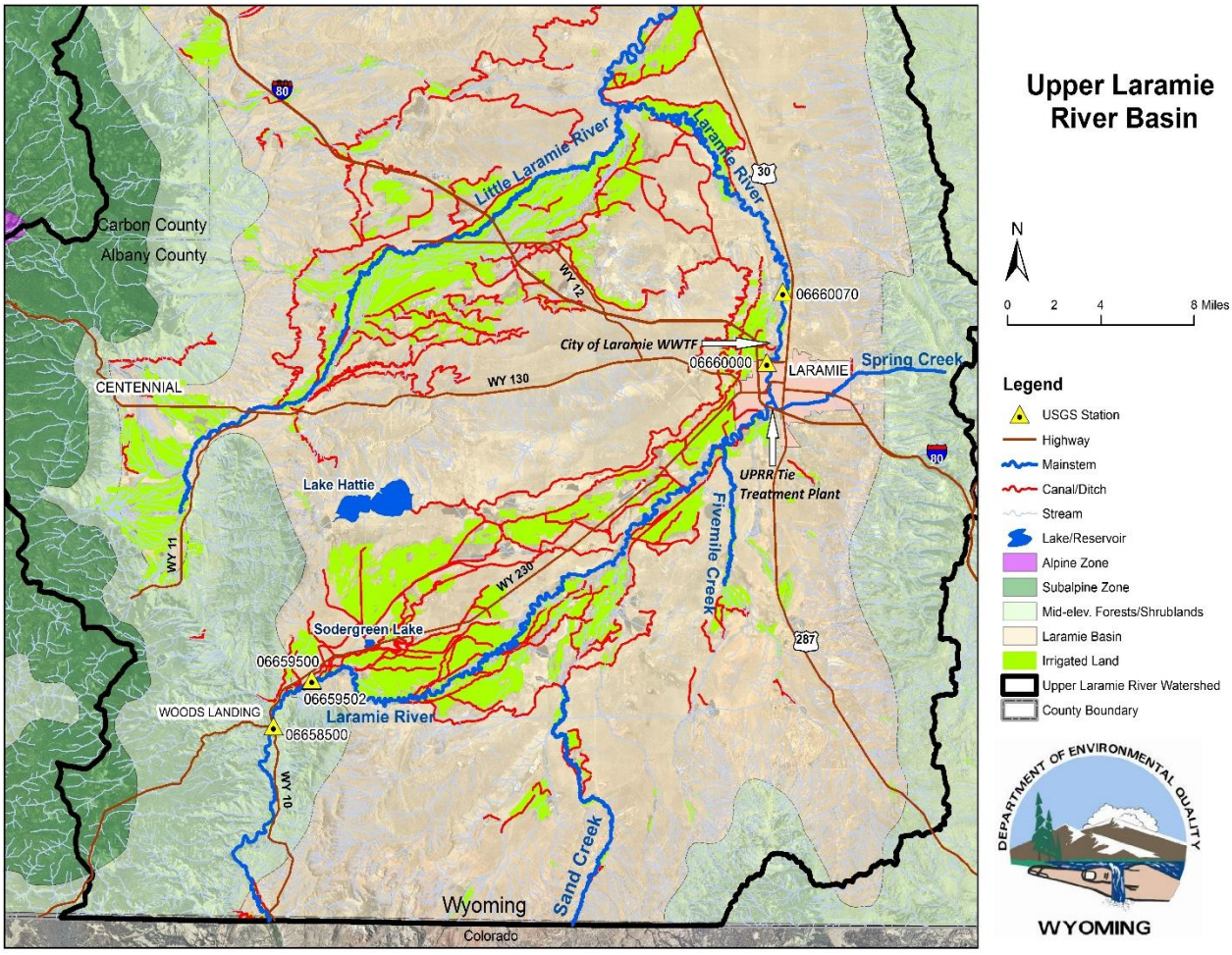
The LRCD expressed interest in using the monitoring data collected by WDEQ/WQD, supplemented with their own monitoring data, to evaluate the success of a three year river restoration plan proposed for urban reaches of the river within Laramie's city limits. The restoration plan developed by HabiTech, Inc. and WWC Engineering (HT-WWC 2009) on behalf of the Beautification Committee of the Laramie Economic Development Corporation (LEDC), LRCD, Wyoming Game and Fish Department (WGFD) and several financial supporters consisted of installing bank stabilization and channel treatments within a 3.6 mile project area. Treatments were intended to minimize bank erosion that threatened public and private property, flush accumulations of fine sediment from the channel and enhance in-stream habitat for fish and aquatic insects through local control of channel hydraulics. The planned restoration work was initiated in 2009 and completed in 2011.

This report presents the findings of the evaluation conducted by the WDEQ/WQD at four study sites on the Laramie River during 2009 and 2010. Supplementary channel survey data collected in 2011 and 2013 by the LRCD, WGFD and WDEQ/WQD at specific study sites are also evaluated to determine temporal change in channel conditions. Results from the physicochemical data collected at two monitoring stations on Spring Creek are also presented and discussed with respect to the relative influence of its inflows on water quality in the Laramie River.

DESCRIPTION OF EVALUATION AREA

The Laramie River originates in the mountains of northern Colorado in the upper North Platte River Basin and flows north into Albany County, Wyoming along the east flank of the Medicine Bow Range past the communities of Jelm and Woods Landing (Figure 1). From Woods Landing the river enters the high plains of the Laramie Basin, coursing northeasterly through the City of Laramie and then north where it joins the Little Laramie River. The evaluation reach for this report encompasses three 12-digit Hydrologic Unit Code (HUC) divisions of the upper Laramie River watershed (101800100401, 101800100501 and 101800100504), extending from the Fivemile Creek confluence approximately three stream miles upstream of the City of Laramie to the Little Laramie River confluence 22.8 miles downstream.

Figure 1 – Upper Laramie River watershed showing ecoregions, mainstem drainage system, irrigated lands and infrastructure, municipalities and highways.



Upstream of the Little Laramie River confluence, the Laramie River drains about 1,036 square miles (mi^2). Elevations within the evaluation area range from over 8,800 feet (ft) in the Laramie Range east of Laramie to 7,060 ft at the confluence with the Little Laramie River. The evaluation reach lies within the Laramie Basin Level IV ecoregion (Chapman et al. 2003) of the greater Wyoming Basin ecoregion

(Omernik and Gallant 1987). It is bounded east and west by the Mid-Elevation Forests and Shrublands Level IV ecoregion (Chapman et al. 2003) within the greater Southern Rockies ecoregion (Omernik and Gallant 1987). The predominant geology of the Laramie Basin upstream and within the evaluation reach is quaternary alluvium and colluvium and glacial deposits consisting of clay, silt, sand and gravel (USGS 1985). Bedrock geology in the upper Spring Creek drainage is composed of the Casper, Forelle Limestone (Member of Goose Egg Formation), Chugwater and Satanka Shale sedimentary formations and quaternary terrace and alluvial deposits in the lower drainage (USGS 1985). Soils along the river corridor within the evaluation reach consist of poorly drained, slightly saline loams and very gravelly sand.

The Laramie Basin is characterized as wide intermontane valley with a high-elevation, semi-arid environment dominated by mixed-grass prairie rangeland (Chapman et al. 2003). Climate conditions in the summer are considered mild, while winters are cold and relatively dry (NOAA 2013). Mean annual precipitation in the evaluation area is about 11 to 12 inches with greater amounts recorded at higher elevations. Predominant land uses in the basin include livestock grazing, irrigated agriculture, recreation and wildlife habitat. Water is used for agricultural, municipal, domestic, recreational and environmental purposes. Riparian alluvial flats occur along perennial drainages that are irrigated for hay production and pasture land. Land ownership in the evaluation area is mostly private with a mix of federal, state, county and municipal properties. Land uses within the City of Laramie include urban/residential, industrial, recreation and wildlife habitat.

The Laramie River upstream of and within the evaluation reach provides recreational opportunities that include fishing, boating, hunting and scenic value uses. The river supports a cold-water game fishery that includes brown trout (*Salmo trutta*), rainbow trout (*Oncorhynchus mykiss*) and brook trout (*Salvelinus fontinalis*). Instream flow rights were filed for a 3.9 mile segment of the Laramie River upstream of Woods Landing for the purpose of maintaining and protecting the cold-water fishery, which is considered to be a high-value resource of regional importance (WGFD 1989). The WGFD estimates that the Laramie River supports about 100 angler days per year within Laramie's city limits (http://www.lrcd.net/lrrp.htm). Boating on the river is seasonal and largely dependent on adequate flows. The Laramie Greenbelt, a five-mile long paved pathway that courses along the river within city limits, is frequently used by outdoor recreational enthusiasts.

STREAM CLASSIFICATION AND DESIGNATED USES

The Laramie River throughout the evaluation reach is a Class 2AB water protected for the following designated uses: cold-water fisheries, non-game fisheries, drinking water, fish consumption, aquatic life other than fish, recreation, wildlife, industry, agriculture and scenic values (WDEQ/WQD 2013a).

SURFACE WATER HYDROLOGY

Flow in the Laramie River is perennial, fed primarily by snow melt from mountain streams. A few spring-fed perennial tributaries emerging from the southern region of the basin contribute a minor amount to the river's flow between Woods Landing and the City of Laramie (Figure 1). Spring Creek, a spring-fed tributary which originates east of Laramie, flows through the southern residential area of the city and is

a major contributor of stormwater runoff to the Laramie River. Sand Creek and Fivemile Creek are two other spring-fed streams with large drainage areas that enter the river upstream of the city. Water supply in the Laramie Basin and the Laramie River flow regime are influenced by agricultural and municipal flow withdrawals, both in Colorado and Wyoming. While the river's annual flow signature (hydrograph shape) appears natural, the magnitude of flow has been substantially altered by historic upstream water uses (HT-WWC 2009).

A trans-basin diversion of water from the headwaters of the Laramie River to the Cache la Poudre River in Colorado has altered the river's natural flow regime since the turn of the 19th century. According to a 1957 Supreme Court decree, cited in the Platte River Basin Plan developed by the Wyoming Water Development Commission (WWDC 2006), Colorado is permitted to divert from the Laramie River Basin a total of 19,875 acre-feet (ac-ft) of water annually. This water is used for agricultural and municipal purposes. The decree further stipulates that Colorado may divert 29,500 ac-ft annually to irrigate high-elevation meadows (WWDC 2006). The total water allocated to Colorado annually amounts to about 135 ac-ft/day or 68 cubic feet per second (cfs).

Municipal water for the City of Laramie is supplied by both surface and ground water sources. Prior to 2010, the city obtained its surface water from Sodergreen Lake (Figure 1), the first in a series of storage reservoirs supplied by the Pioneer Canal diversion on the Laramie River near Woods Landing. The city's surface water is now withdrawn directly from the river by pipeline immediately upstream of the Pioneer Canal diversion. The city possesses the oldest water right (1868) on the Laramie River, with an appropriation of 14.31 cfs. The city's annual water demand is 6.1 million gallons per day (mgd), of which 2.54 mgd (3.9 cfs) is supplied from the Laramie River (WWDC 2006). An average of 4.5 mgd (7 cfs) of treated wastewater is discharged back to the Laramie River north of the city (WWDC 2006). In some low-water years this wastewater may account for 50 percent (%) or more of the total river flow during the summer baseflow period. Based on the difference between demand and treated water releases, average consumptive water use for the city amounts to 1.6 mgd (4.9 ac-ft/day or 2.5 cfs).

Approximately 90,000 acres of hay, alfalfa and pasture land is irrigated in Albany County, Wyoming (WWDC 2006). About half of that acreage lies within the evaluation reach upstream of the Little Laramie River confluence, amounting to about 6% of the total drainage area for this portion of the watershed. The network of diversions, canals and ditches that supply water to most of this acreage is shown in Figure 1. Major water withdrawals from the river are largely dependent on annual runoff conditions. Wyoming State Board of Control (WSBC) annual hydrographer reports indicate that flow is typically regulated from April 1 through September 30, but in drought years may be extended for several months.

Two of the largest irrigation systems in the upper Laramie River sub-basin are the Pioneer Canal and Oasis Canal (Figure 1), controlled by the Pioneer-Lake Hattie Irrigation District and Laramie Valley Irrigation District, respectively (WWDC 2006). The Pioneer Canal, constructed in 1879 and enlarged in 1909-1912, is 32 miles long from its point of diversion three miles downstream of Woods Landing to its terminus three miles northwest of the City of Laramie. Its secondary canals and ditches supply water to several storage reservoirs. The two largest reservoirs include Lake Hattie and Twelve Mile Reservoir,

with a combined permitted capacity of 72,593 ac-ft (WWDC 2006). The Oasis Canal withdraws water from the Laramie River at a point halfway between the City of Laramie and the Little Laramie River confluence. Water delivered by the Pioneer and Oasis Canals is used to irrigate 18,360 acres and 8,636 acres, respectively (WWDC 2006). Information on adjudicated surface water rights with direct points of diversion on the Laramie River from the Pioneer Canal diversion downstream to the Little Laramie River confluence are listed in Table 1. Only diversions with permitted conveyances greater than 5 cfs are listed. Uses assigned to these water rights are for agricultural and municipal purposes.

Table 1. Adjudicated surface water rights and points of diversion with appropriations greater than 5 cfs on the Laramie River from the Pioneer Canal diversion to the Little Laramie River confluence. Source: Wyoming State Board of Control (https://sites.google.com/a/wyo.gov/seo/documents-data/hydrographer-reports).

Priority No. or Permit No.	Diversion/Ditch	Priority Dates (cfs)	Appropriation (cfs)	Point of Diversion (Section-T-R)
1, 6, 25, 53, 57, 66	Pioneer Canal	1868 (14.31), 4-19-1879 (71.43), 10-1-1884 (155.14), 8-23-1897 (9.07), 9-6-1892 & 10-19-1895 (20.31)	270.26	36-14N-77W
6, 1327R, 4127R, 9250R, 24888	Pioneer Canal*	4-19-1879 (0.61), 5-11-1908 (38.85), 9-22-1928 (0.09), 8-1-1975(0.41), 5-1-1986 (50.88)	90.84	36-14N-77W
53, 42, 62, 66, 21	Parker	4-1884 (5.23), 5-1888 (2.93), 9-6-1892 (2.03), 4-6-1896 & 8-23-1897 (6.30)	16.49	36-14N-77W
36, 55	Fisher	3-1887 (1.73), 1-1-1895 (31.70)	33.43	29-14N-76W
19, 22	Riverside No. 2	06-01-1883 (22.70), 05-01-1884 (35.41)	58.11	32-14N-76W
32, 38	Sodergreen No. 1	5-1886 (4.0), 5-1887 (1.89)	5.89	32-14N-76W
35	O.G. Ditch	9-30-1886	8.81	32-14N-76W
9, 33, 1722E, 2304E, 2676E	King	3-1-1881 (46.20), 5-31-1886 (4.37), 12-15-1906 (4.39), 3-3-1909 (8.27), 7-29-1912 (0.69)	63.92	3-13N-76W
13, 21	OM Ditch	3-1-1883 (21.44), 4-1884 (7.54)	28.98	36-14N-76W
15, 30, 56, 4264E	Caldwell & Gardiner	4-11-1883 (22.19), Fall 1885 (13.21), 1-19-1895 & 1-9-1922 (9.42)	44.82	31-14N-75W
52	Haley & Hoge	2-2-1892	28.69	29-14N-75W
909	Dowlin	1868 (32.48), 10-22-1896 (3.62)	36.10	32-15N-74W
1, 63	Hattie Canal	1-11-1895	6.77	13-15N-74W
		Upstream of City of Laramie	Total = 693	
3, 10, 14, 18, 34, 47, 1353E, 1872E	Oasis Canal	10-22-1877 (17.79), 4-30-1881 (3.43), 04-01-1883 (0.43), 05-31-1883 (16.00), 09-22-1886 (18.51), 06-15-1890 (64.57), 12-31-1903 (2.65), 05-06-1908 (6.72)	134.71	19-17N-73W
10, 14, 34, 66	Biddick	4-30-1881 (1.57), 4-1-1883 (1.28), 9-8-1897 (0.55), 9-8-1897 (2.00)	5.40	11-17N-74W
		Downstream of City of Laramie	Total = 140	

* Flow rate calculated from 65,764.5 acre-feet of total adjudicated storage volume of all reservoirs.

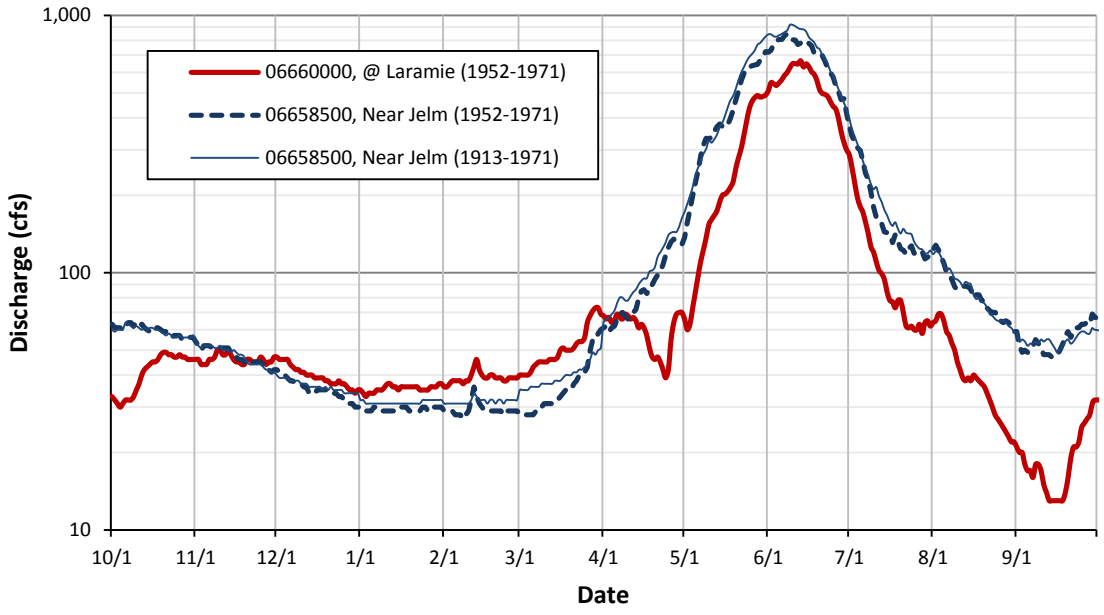
(Source: Water Year 2010 Annual Hydrographer Report, District 4A, Division 1, Wyoming State Board of Control http://seo.wyo.gov/documents-data/hydrographer-reports/division-i-annual-reports)

Relative to agricultural and municipal water uses, domestic and industrial water demands in the Laramie River are minimal. Groundwater is withdrawn from over 2,000 permitted rural and non-community domestic wells distributed throughout the watershed with an estimated total production of about 1.5 mgd (WWDC 2006). About four cfs from surface and ground water sources combined is permitted for industrial purposes (WWDC 2006). The Board of Albany County Commissioners retains surface water permits to use 1.3 cfs from both the Laramie River and Little Laramie River watersheds for road and bridge construction and maintenance. LaFarge North America is permitted to withdraw 1.3 cfs from the Laramie River for their gravel washing facility north of the City of Laramie.

The most current continuous daily flow records within the evaluation reach were recorded at USGS station 06660000 on the Laramie River at Laramie, WY (Figure 1). Though dated, the 40 years of daily flow data collected at the station from 1933-1972 provide a reasonable representation of the river's

present flow regime within the evaluation reach. Present climate and mean annual precipitation yields at the station are similar to those observed during the 1952-1971 flow-gaged period, and no major flow-alteration activity has occurred in the watershed since 1972. The hydrograph produced from the last 20 years of daily mean discharge data collected at station 06660000 for water years 1952-1971 is shown in Figure 2. Hydrographs developed from discharge data collected upstream at USGS gaging station 06658500 on the Laramie River near Jelm, WY (Figure 1) during the same time period and for water years 1913-1971 are also displayed to contrast changes in daily mean discharge with distance downstream.

Figure 2 – Daily mean discharge of the Laramie River at USGS gaging stations 06660000 at Laramie, WY and 06658500 near Jelm, WY.



Peak flows were generally observed in mid-June at both stations (Figure 2), though occurred as early as May 7 near Jelm, and with the exception of a 265 cfs peak flow recorded on October 1, 1965, as late as July 27 at Laramie. The greatest monthly mean discharge occurred in June at both stations. During the 1952 to 1971 period of record, the maximum daily mean flow in June near Jelm was 849 cfs, whereas at Laramie it was 666 cfs. Annual mean discharge was 148 cfs near Jelm and 105 cfs at Laramie. Baseflow conditions occurred in mid-September at Laramie, whereas at near Jelm they occurred during the winter months of January and February. Flows increased in late September at both stations near the end of irrigation season, then declined steadily or leveled off during the winter from January to early March. Daily mean discharge at Laramie in September was 19.0 cfs, which is slightly less than the 20.9 cfs that the WGFD recommends to maintain the river's trout fishery through the City of Laramie (HT-WWC 2009). Over the entire 40 year period of record at station 06660000, this maintenance flow was equaled or exceeded about 78% of the time and about 59% of the time during late summer when trout actively grow (HT-WWC 2009). Daily mean flows less than 10 cfs were recorded on several occasions at Laramie over the period of record during late summer.

In regards to timing and response to major runoff events, the flow signatures of the Laramie River at station 06658500 near Jelm and at station 06660000 at Laramie were similar (Figure 2). However, seasonal differences in both the magnitude and duration of discharge between the two stations were apparent. Considering that the contributing drainage area at Laramie (920 mi^2) is three times greater than that near Jelm (294 mi^2), flows at the Laramie station are expected to be greater. This typically occurred only from November to early April or during periods of extreme flooding, however. Discharge near Jelm increased rapidly in April, whereas at Laramie it decreased. From late April to early October, discharge at both stations tracked at relatively similar rates of change but at different magnitudes. For example, the duration of river flows greater than 70 cfs during this period near Jelm lasted about two months longer on average than those observed downstream at Laramie (Figure 2), and flows at Laramie were on average about 40-50% less than those upstream near Jelm. The greatest disparity in discharge between the two stations typically occurred in September, when flows at Laramie were about 75% less than flows near Jelm. Flows less than 50 cfs occurred at Laramie over a period of about seven months annually, whereas near Jelm these flows were limited to four months from mid-November to late March.

Influence of Flow Alterations

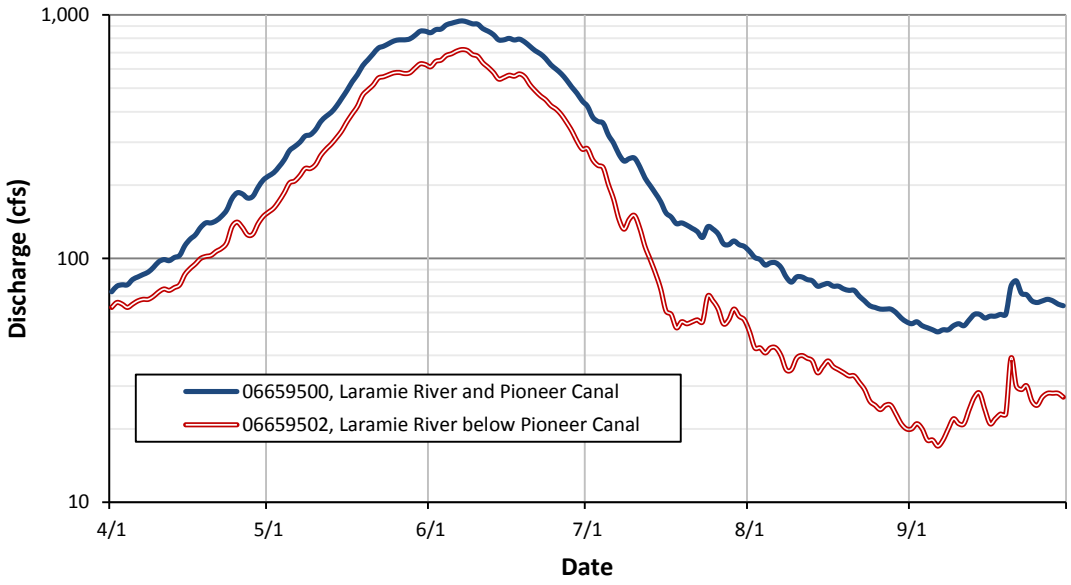
Diversions and reservoirs have a considerable influence on the flow characteristics of most perennial streams in the upper and middle North Platte River basin (Bartos et al. 2006), including the Laramie River. The changes in flow apparent in the river from Jelm downstream to the City of Laramie (Figure 2) are largely attributed to municipal and irrigation water withdrawals at major diversions.

The total flow appropriated for diversion from the Laramie River starting from the Pioneer Canal diversion downstream to the Little Laramie River confluence amounts to more than 800 cfs (Table 1), though the actual amount diverted is regulated by priority date and dependent on annual runoff yield and availability. In the 35 years from 1975 through 2009, the mean monthly flow rate for June in the Pioneer Canal (USGS station 06659501) amounted to 216 cfs, which is less than the total allocation of 361 cfs (Table 1). According to past WSBC flow regulation records, the regulation date typically in effect during most irrigation seasons was the January 29, 1898 Wheatland Irrigation District Reservoir No. 2 storage right, which is several miles downstream of the Little Laramie River confluence. Consequently, the flow available in the river after all senior (earliest in time) water rights upstream of this reservoir are honored is conveyed downstream through the evaluation reach.

Daily mean flow data collected seasonally (April 1 to September 30) at USGS gaging station 06659501 Pioneer Canal near Woods Landing, WY and WSBC flow regulation records provide enough information to estimate flows through the Laramie River evaluation reach during the irrigation season from 1975 to the present. Over the past 35 years of record from 1975 to 2009 there were likely 10 years in which peak flows at Laramie were less than 500 cfs, which is conservative given that flows from the contributing drainage area between station 06659501 and the City of Laramie were not considered in the estimates. In Spring Creek alone, overbank flows ≥32 cfs may be observed during the spring peak runoff period (Gray 1998). This appraisal provides support to the assumption that flow data collected over the previous 20+ years at station 06660000 (Figure 2) provide an accurate representation of the present-day flow regime. Thus, it may be reasoned that peak flows in the Laramie River at Laramie are

reduced approximately 25% to 30% by irrigation withdrawals from the Pioneer Canal diversion downstream. The greatest influence of water withdrawals on river flows through the city was typically observed during the baseflow period from August through October (Figure 2). Daily mean flow data collected at USGS gaging stations above and below the diversion from 1974 to 2009 indicated that approximately 40% to 65% of the river's baseflow in September was diverted through the Pioneer Canal (Figure 3).

Figure 3 – Daily mean discharge at USGS gaging stations on the Laramie River above and below the Pioneer Canal diversion near Woods Landing, WY (period of record from 10/1/1974 to 9/30/2009).



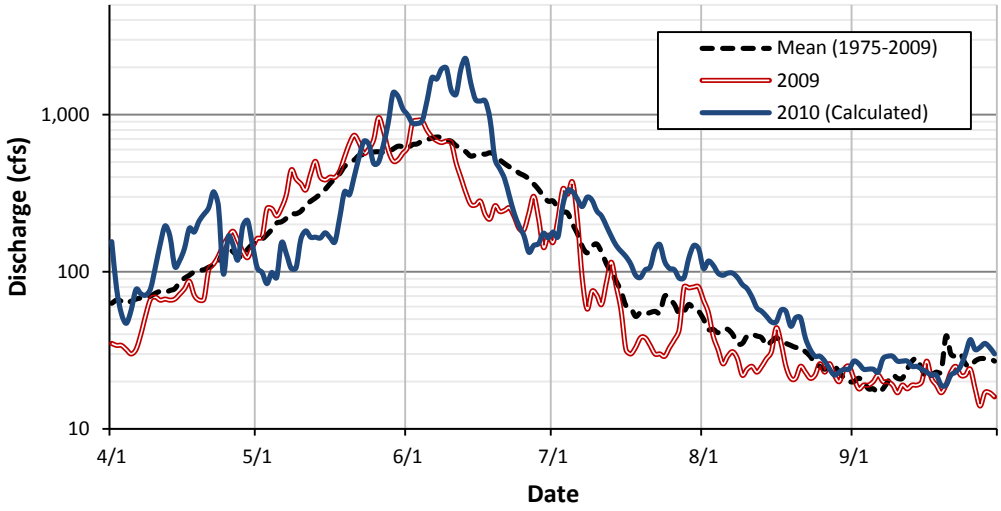
2009-2010 Flow Conditions

Snowpack in the Laramie River drainage for 2009 and 2010 was 101% and 103%, respectively, of the 30 year average snow water equivalent recorded on May 1 (WSBC 2009, 2010). Near-normal snowpack coupled with above average late spring and early summer precipitation contributed to normal to above normal flows in the Laramie River in both years (WSBC 2009, 2010). Runoff in 2010 was atypical with respect to magnitude and duration. Historical annual and daily peak flow records were broken in 2010 at several gaging stations in the region, including the Laramie River.

Continuous daily flow data recorded at USGS gaging station 06659502 on the Laramie River below the Pioneer Canal diversion near Woods Landing, WY (Figure 1) provided a relative perspective of flow conditions observed in the evaluation reach during the 2009-2010 study period (Figure 4). Seasonal data only are collected at the station from April 1 to September 30, thus the winter/spring base flow period is not represented. Daily mean discharge in the river below the diversion from April 1 to September 30, 2009 was 187 cfs, slightly less than the corresponding historical average of 199 cfs. During the same period in 2010, daily mean flow below the diversion was 289 cfs, nearly 1.5 times greater than the historical average. Daily mean peak flows of 955 and 2,271 cfs were recorded at the station on May 26, 2009 and June 13, 2010 (Figure 4), respectively. Peak flows estimated from crest

stage readings recorded at the National Oceanic and Atmospheric Administration's National Weather Service (NWS) station in Laramie (at USGS gaging station 06660000) in 2009 were 1,250 cfs (3 year return period) and between 3,300 and 3,600 cfs in 2010 (NWS 2013). The 2010 peak flow that occurred on June 14 exceeded the historic peak flow record of 3,250 cfs (41 year return period) recorded on June 15, 1957.

Figure 4 – Comparison of 2009 and 2010 daily mean discharge to historical record (1975-2009) at USGS gaging station 06659502, Laramie River below Pioneer Canal near Woods Landing, WY. Because flow was not monitored at the station in 2010, flow measurements made in the river above the Pioneer Canal diversion at 06659500 and in the Pioneer Canal at 06659501 were used to calculate river flow below the diversion.



Flood flows similar in magnitude to those recorded in 2010 were also observed at station 06659502 in 2011, with a recorded daily mean peak of 2,210 cfs on June 18. However, the 2011 peak flow period was of longer duration than in 2010, with continuous daily mean flows ≥1,000 cfs from May 30 to July 10.

As a result of favorable precipitation conditions and an extended high runoff period in 2010, water right regulations on the Laramie River were relaxed from May 29 to the end of the water year (WSBC 2010). Water withdrawals in 2009 were regulated throughout the irrigation season, however, peak runoff in the river was not affected as flow regulation was not initiated until June 11 (WSBC 2009).

FACTORS THAT AFFECT WATER QUALITY

Water quality of the Laramie River within the evaluation reach is influenced by natural basin characteristics, water development activities, urban and industrial development, and permitted point and non-point sources of pollutants.

Poorly drained, but highly permeable soils along the river's riparian corridor provide a medium for close communication between surface water and groundwater. Mineral salts leached from the well-drained saline soils in the valley and sedimentary formations along the Spring Creek drainage contribute to the

solute content in the Laramie River. Brief but frequent peak flow events can increase bank erosion rates and contribute to the river's total sediment load, particularly in unstable reaches with limited vegetative cover. Minerals and nutrients released from bank sediment into the water can also increase the river's total solute load, which can influence water chemistry and biological communities.

Bartos et al. (2006) noted that water development has substantially altered streamflow characteristics in the North Platte River and its tributaries. Surface water diversions and storage both in Colorado and Wyoming upstream of the evaluation area have most likely influenced water quality and sediment transport in the Laramie River. Though it is difficult to determine the extent and degree to which flow alterations have affected ecosystem functions, it is reasonable to expect that reductions in flow (i.e., withdrawals) can effect changes in instream aquatic habitat and channel morphology through sediment transport, erosional and sedimentation processes.

Both the Laramie River and Spring Creek have been channelized where they flow through the City of Laramie to provide flood control and accommodate the urban and industrial development that has occurred over the decades since the city was founded in the 1860's. Channelization can cause long-term instability problems that increase sediment production through accelerated bed and bank erosion processes and reduce sediment transport (Leopold 1994, Rosgen 2006a). Though Spring Creek likely delivered excess sediment to the river after the channel was initially dredged, it has since developed a stable channel form that is well-protected by a dense growth of riparian vegetation, showing minimal signs of erosion and sedimentation. Other historic channel disturbances in reaches of the Laramie River upstream of the city have also likely contributed to long-term instability and increased sediment production. Young et al. (1994) postulated that railroad tie drives executed during the period from 1868 to 1940 in streams and rivers in southeastern Wyoming, including the Laramie River, were responsible for altering channel morphology and riparian vegetation in those drainages through the scouring action caused by unnaturally high-magnitude releases of flow and large timber products. Rosenburg (1984) estimated that between 87,000 to 350,000 ties were driven through the Laramie River from 1876 to 1938.

Several historic and existing industrial facilities may also contribute pollutants to the river through surface and groundwater pathways. Two point source discharge facilities permitted by the WDEQ, Wyoming Pollutant Discharge Elimination System (WYPDES) Program release treated wastewater to the Laramie River. The historic UPRR Tie Treatment Plant facility releases treated wastewater (WYPDES Permit WY0032590) to the river upstream of the Spring Creek confluence (Figure 1). The facility encompasses 80 acres immediately south of the I-80 bridge crossing and east of the river. During the early decades of the 19th century the UPRR facility treated thousands of wooden railroad ties with creosote. Over time the alluvial groundwater system adjacent to the river became contaminated with the toxic organic compounds found in creosote. A groundwater remediation plan was initiated in the 1980's with the primary objective of isolating and treating the contaminated groundwater. The Containment Isolation System (CIS) consisted of four major components, each with specific objectives:

1. Relocate the Laramie River channel to an uncontaminated location. (This step consisted of channelizing approximately ½-mile of the river upstream of the I80 road crossing.)

2. Install a soil-bentonite barrier or “cutoff wall” to enclose the contaminated alluvium.
3. Wastewater Management System- Install a hydraulic barrier to prevent contaminant migration off-site.
4. Water Treatment Plant- Treat contaminated water to levels that meet instream water quality standards for discharge to the Laramie River.

The CIS was successful in removing much of the organic contamination from the site. In September 2006 WDEQ/WQD removed monitoring requirements for total petroleum hydrocarbons, phenols, dissolved iron, copper and zinc. Concentrations of these constituents in the discharge were historically and consistently well below permitted effluent limits and instream standards. Effluent limits are presently set for pH, total arsenic, pentachlorophenol, and total dissolved solids. From September 2006 to June 2009 the reported mean and maximum monthly discharge rates were 0.35 cfs and 0.84 cfs, respectively. Mean monthly discharge rates amount to less than two percent of the average monthly flow recorded in September during the base flow period of the Laramie River at USGS gaging station 06660000. Over the same time period, levels of pentachlorophenol measured in the effluent were below detection (<0.001 milligrams per liter, or mg/L), and the average monthly total arsenic concentration measured 0.0013 mg/L (maximum = 0.00231 mg/L). No exceedances of the permitted effluent limits occurred during the period.

The City of Laramie WWTF (WYPDES Permit WY0022209) discharges treated wastewater to an unnamed drainage that enters the Laramie River downstream of city limits and immediately upstream of USGS station 06660070 (Figure 1). Monthly discharge rates from the facility ranged from 5.6 to 8.4 cfs (mean = 6.5 cfs) from January 2005 to July 2009. Discharges from the facility can augment river flow considerably during the late summer baseflow period, but can also contribute excess nutrients (nitrogen and phosphorus) to the river. Permit effluent limits are established for biological oxygen demand, fecal coliform bacteria, total residual chlorine, total ammonia, total suspended solids and pH. No effluent limit exceedances occurred during the January 2005 to July 2009 reporting period.

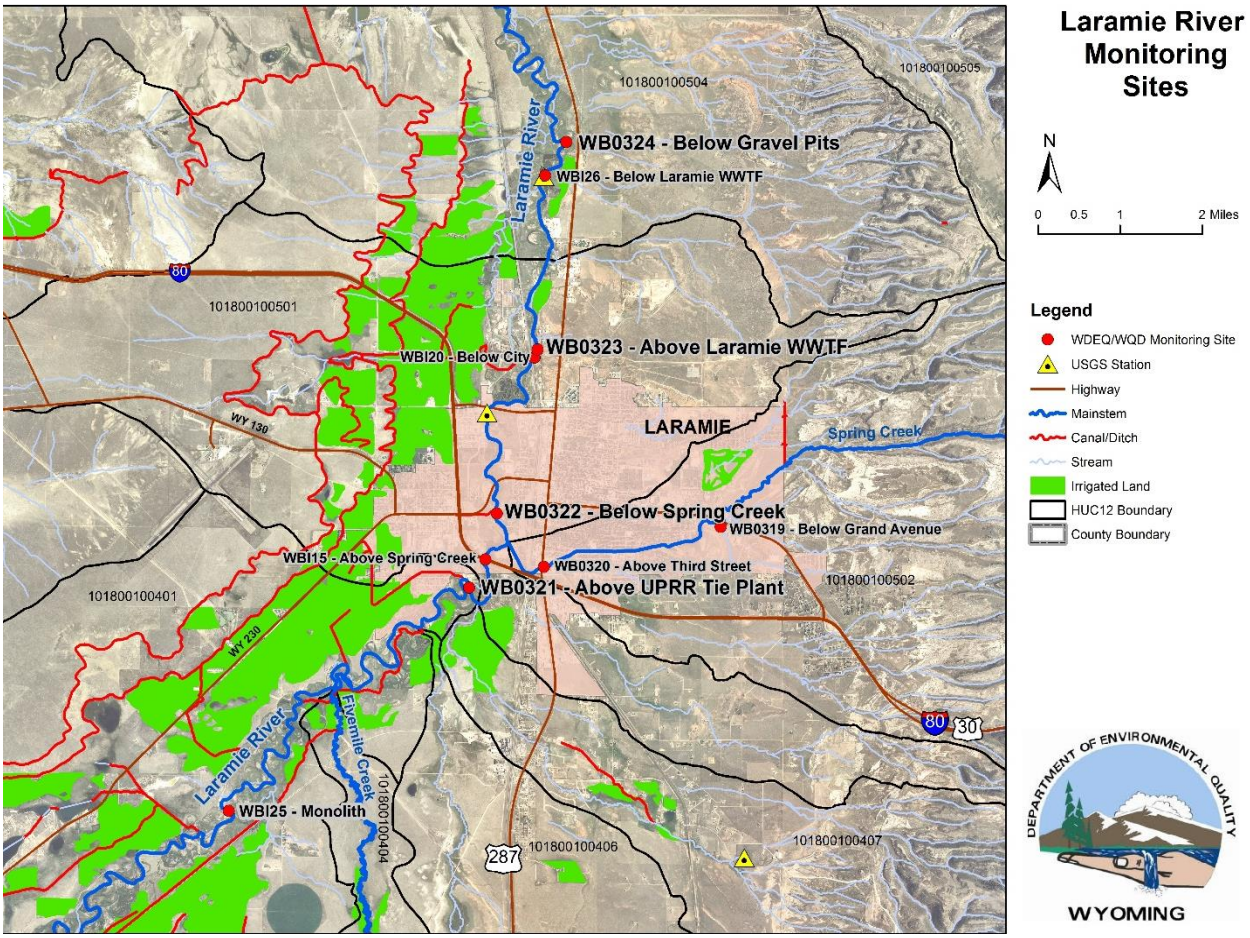
Non-point sources of pollutants upstream and within the evaluation area include urban and industrial stormwater runoff, agricultural lands, septic systems, isolated disturbances (road construction and mine operations) and channel adjustment processes caused by historic alterations to the river and its adjoining floodplain. Potential pollutants from these non-point sources include sediment, nutrients (nitrogen and phosphorus), salts, pesticides, petroleum-based compounds and fecal coliform bacteria from domestic animals, livestock and wildlife (avian and mammalian). Irrigation return flows may be characterized as diffuse subsurface inputs to the river and its tributaries.

METHODS AND ANALYTICAL APPROACHES

Site Selection

The evaluation area encompasses approximately 23 stream miles of the Laramie River from the confluence with Fivemile Creek upstream of the City of Laramie to the confluence with the Little Laramie River (Figure 1). Four study sites on the Laramie River were selected within the evaluation reach to differentiate both the variation in natural watershed characteristics and anthropogenic influences (Figure 5, Table 2). Two water quality-only stations were established on Spring Creek to determine the relative influence of its inflows on water quality in the Laramie River.

Figure 5 – Locations of study sites within the 2009-2010 Laramie River evaluation area, Albany County, Wyoming. WDEQ/WQD sites monitored in the past are labeled in smaller case font.



The 2009-2010 study sites on the Laramie River were stationed above and below major stormwater inputs and permitted point source facilities that discharge to the river (WB0321-'Above UPRR Tie Plant', WB0322-'Below Spring Creek', WB0323-'Above Laramie WWTF', and WB0324-'Below Gravel Pits'). Two sites were closely located to sites monitored by WDEQ/WQD in the past. The historic sites could not be resurveyed due to site suitability and access issues. The uppermost site within the evaluation reach at 'Above UPRR Tie Plant' represented conditions upstream of all urban/industrial stormwater inputs, the UPRR site and its permitted discharge outfall. Conditions downstream of the confluence with Spring

Creek, which receives a large portion of the city's stormwater runoff, were represented by 'Below Spring Creek'. 'Above Laramie WWTF' was sited downstream of most urban/industrial stormwater inputs but upstream of Laramie's permitted WWTF discharge outfall. The site farthest downstream (lowermost) in the evaluation reach was 'Below Gravel Pits', which was stationed below an inactive gravel mine operation and the confluence of the city's WWTF discharge channel.

Table 2. Descriptive information for WDEQ/WQD study sites on the Laramie River and Spring Creek.

Waterbody Name	Laramie River				Spring Creek	
Site Name	Above UPRR Tie Plant	Below Spring Creek	Above Laramie WWTF	Below Gravel Pits	Below Grand Avenue	Above Third Street
Site ID	WB0321	WB0322	WB0323	WB0324	WB0319	WB0320
Stream Classification	2AB	2AB	2AB	2AB	2AB	2AB
Latitude	41.2962008	41.3091453	41.3378208	41.3740828	41.3070597	41.2998462
Longitude	-105.6118405	-105.6054093	-105.5961024	-105.5897791	-105.5529726	-105.5943605
HUC12 Watershed	101800100401	101800100501	101800100501	101800100504	101800100502	101800100502
Watershed Area (mi^2)	1,005	1,060	1,073	1,109	-	-
Elevation (ft)	7,135	7,130	7,125	7,120	7,245	7,150
Legal Location	SWSW Section 5 T15N-R73W	SWSE Section 32 T16N-R73W	SESE Section 20 T16N-R73W	SWNW Section 9 T16N-R73W	SWSW Section 35 T16N-R73W	SWNW Section 4 T15N-R73W
County	Albany	Albany	Albany	Albany	Albany	Albany
Level III Ecoregion[a]	Wyoming Basin	Wyoming Basin	Wyoming Basin	Wyoming Basin	Wyoming Basin	Wyoming Basin
Level IV Ecoregion[b]	Laramie Basin	Laramie Basin	Laramie Basin	Laramie Basin	Laramie Basin	Laramie Basin
Wyoming Bioregion[c]	Wyoming Basin	Wyoming Basin	Wyoming Basin	Wyoming Basin	Wyoming Basin	Wyoming Basin
Soils[d]	MU167—Grenoble-Gerrard complex	MU204—Redrob, frequently flooded-Redrob loams	MU204—Redrob, frequently flooded-Redrob loams	MU167—Grenoble-Gerrard complex	MU170—Gypla-Urban land complex	MU243—Wycolo-Tieside sandy loams
Dominant Bedrock Geology[e]	Quarternary alluvium and colluvium	Quarternary alluvium and colluvium	Quarternary alluvium and colluvium	Quarternary alluvium and colluvium	Chugwater Fm, Forelle Limestone, Satanka Shale, Casper Fm, Quarternary alluvium and colluvium	Chugwater Fm, Forelle Limestone, Satanka Shale, Casper Fm, Quarternary alluvium and colluvium
Data Collected	C, B, P	C, B, P	C, B, P	C, B, P	C	C

[a] Omernik and Gallant (1987)

[b] Chapman et al. (2003)

[c] Hargett 2011 and 2012

[d] Soil mapping unit (MU) information from Natural Resources Conservation Service (http://www.nrcs.usda.gov/wps/portal/nrcs/surveylist/soils/survey/state/?stateId=WY)
MU167: loam-very gravelly sand, 0-3% slopes, somewhat poorly to poorly drained, moderate to very rapid permeability, non-saline
MU204: loam-very gravelly sand, 0-3% slopes, poorly drained, brief frequent flooding May-June, moderate to very rapid permeability, slightly saline, maximum 10% calcium carbonate & 3% gypsum
MU170: loam and gypsiferous material, 0-1% slopes, well drained, moderate permeability, moderately to strongly saline, maximum 14% calcium carbonate & 60% gypsum content
MU243: sandy loam-sandy clay loam and unweathered bedrock, 3-10% slopes, well drained, moderate permeability, non-saline, maximum 25% calcium carbonate & 1-3% gypsum content

[e] USGS (1985)

NOTE: C = Quantitative water chemistry and physical water quality, B = Biological, P = Physical

Water quality conditions in Spring Creek were characterized by data collected at 'Below Grand Avenue', which was upstream of most of the City of Laramie's stormwater outfalls, and 'Above Third Street' stationed about ½-mile upstream of the confluence with the Laramie River.

Because a geomorphic reference condition was not identified within the same physiographic region of the Laramie River evaluation area, a combined impact-gradient and regional biological reference study design was implemented. Impact-gradient designs evaluate both spatial and temporal changes in

chemical, physical and biological variables with increasing distance downstream from an area(s) of potential impact.

Data Collection

Except for methods used to evaluate channel stability and sediment supply, data collection and analytical methods used in this study were conducted in accordance with approved standard operating procedures (WDEQ/WQD 2012). Replicate chemical, physical and biological data were collected annually at all sites on the Laramie River during baseflow conditions in late August and early September of 2009 and 2010. Physicochemical data only were collected concurrently at sites on Spring Creek. With the cooperation of LRCD and WGFD personnel, supplemental channel survey data were collected at 'Above UPRR Tie Plant', 'Below Spring Creek' and 'Above Laramie WWTF' in 2011 and 2013 to determine temporal change in channel condition following the installation of bank and channel treatments described in the Laramie River Restoration Plan (HT-WWC 2009).

Water grab samples were collected at the base of riffles (WDEQ/WQD 2012) to measure turbidity and for analysis of total suspended solids, total alkalinity, chloride, sulfate, nutrients (total nitrogen, total Kjeldahl-N, nitrate+nitrite-N and total phosphorus), total hardness, total selenium, and both dissolved and total arsenic, cadmium and copper concentrations. Semi-volatile organic compound (SVOC) water samples were collected at all Laramie River sites in 2009, including two separate SVOC samples collected from the water column and bed sediment of a backwater region at 'Below Spring Creek'. All SVOC samples were analyzed for 64 different synthetic organic analytes, including several phenolic compounds commonly found in creosote. Water temperature, dissolved oxygen, pH and specific conductance were measured directly in the water column, qualitative observations of water color, odor and visible sheen were noted, and stream discharge was measured at suitable cross-sections (WDEQ/WQD 2012).

Benthic macroinvertebrates were collected with a Surber sampler (500-µm mesh collection net) at eight randomly-selected locations (each 0.09 m^2) within a targeted riffle at each site (WDEQ/WQD 2012). The eight samples were combined into a single composite sample and preserved in the field with 99% ethyl alcohol or isopropanol. Sample processing consisted of a 500-organism fixed-count, sub-sampling procedure following the removal of large and rare organisms (WDEQ/WQD 2012). Periphyton (diatoms and soft-algae) samples were also collected from the target riffle near the randomized benthic macroinvertebrate sample locations using an epilithic (fine gravel and cobble bed substrate) sampling method (WDEQ/WQD 2012). Eight to 16 particles were scraped/brushed of periphyton, composited into a single sample and preserved with 10% Lugol's solution. The area of each sampled particle was measured and recorded. Periphyton were permanently mounted on glass slides and identified and enumerated following standard procedures (WDEQ/WQD 2012). Most macroinvertebrate and periphyton taxa were identified to genus or species.

Methods used to evaluate river channel stability and sediment supply followed procedures described in the geomorphology-based Watershed Assessment of River Stability and Sediment Supply (WARSSS) procedure (Rosgen 2006a). Bankfull channel morphology (dimension, pattern and profile) at each site was determined from cross-section and longitudinal profile survey data, bed substrate measurements

and a channel pattern evaluation throughout a representative reach that was generally 20-30 times the length of the bankfull channel width or encompassing at least two meander cycles (Rosgen 2006a and 2008, WDEQ/WQD 2012). Elevations at the thalweg, water surface, bankfull indicators, low bank and abandoned terraces were surveyed along the entire reach length (i.e., longitudinal profile) and at three permanent cross-sections (representative glide, riffle and pool bed features) of each site. Pool cross-sections were established at meander bends with point bar depositional features situated at the inside bend of the meander. Channel feature elevations captured in the longitudinal profile were also measured at cross-sections to ensure survey control. Wolman pebble count data were collected reachwide and at each cross-section. Point bar sediment samples were collected at representative locations and scour chains were installed in sets of two at riffle and glide cross-sections within each site (Rosgen 2008). Channel pattern measurements (sinuosity, meander wavelength, radius of curvature and belt width) were obtained from recent aerial photographs of the evaluation reach.

Bank Erosion Hazard Index and Near-Bank Stress (BEHI/NBS) estimates were made at each site to predict annual streambank erosion rates using the Bank Assessment for Non-point source Consequences of Sediment (BANCS) model (Rosgen 2006a, 2008). Bank erosion rates were derived from the BANCS model developed for streams found in sedimentary and/or metamorphic geology using paired BEHI/NBS estimates made reachwide and at each bank profile. Permanent bank profiles were surveyed at all pool cross-sections to determine annual bank erosion rates and validate BANCS model predictions.

The WARSSS River Stability Prediction (RSP) evaluation (Rosgen 2006a) was completed for each site to assess channel stability and sediment supply. Additional semi-quantitative evaluations of streambank stability and cover, human influence, pool quality and channel stability were measured at all sites following approved procedures (WDEQ/WQD 2012).

All chemical, physical and biological data collected for this evaluation were found complete, accurate and met approved quality assurance/quality control standards (WDEQ/WQD 2001).

Data Analysis

The WDEQ/WQD determines attainment of applicable surface water quality standards through an evaluation of 'credible data' using a weight of evidence approach (WDEQ/WQD 2014). The approach includes comparisons with numeric and narrative water quality criteria supplemented with several appropriate analytical procedures, statistical tests and/or validation data for interpretation of narrative criteria (WDEQ/WQD 2014). This section describes the analytical procedures used in the weight of evidence evaluation of data collected at WDEQ/WQD sites on the Laramie River and Spring Creek.

Chemical and physical water quality data were evaluated against numeric and narrative criteria associated with applicable standards specified in Chapter 1 of the Wyoming Water Quality Rules and Regulations (WDEQ/WQD 2013). Spatial and temporal changes in water quality were determined at each site. Concentrations of some chemical analytes measured at study sites were compared to a corresponding range of concentrations observed at nine reference sites established within the Wyoming Basin ecoregion to quantify relative degrees of departure from expected regional water quality conditions.

Wyoming's regional biological reference conditions for streams and rivers are derived from data gathered at sites within each relatively homogenous ecotype or bioregion that are least-impacted with respect to anthropogenic activities. The reference biological condition established for the Wyoming Basin bioregion, within which the evaluation area lies (Table 2), was used to evaluate departure in biological condition at each site on the Laramie River.

Benthic macroinvertebrates are used as the primary indicators of cumulative water quality change and with other relevant data and information are evaluated to determine compliance with applicable narrative surface water quality standards intended to protect aquatic life uses (e.g., Section 32-Biological Criteria, Chapter 1, Wyoming Water Quality Rules and Regulations, WDEQ/WQD 2013). Conventional interpretation of benthic macroinvertebrate data in Wyoming is facilitated through the application of two biological indicator models, the Wyoming Stream Integrity Index (WSII) and the Wyoming River InVertebrate Prediction And Classification System (WY RIVPACS).

The WSII is a regionally-calibrated, macroinvertebrate-based multi-metric index designed to evaluate aquatic life use-support in Wyoming streams (Hargett 2011). Metrics included in the WSII are those that best discriminate between reference and degraded waters within a particular bioregion, and encompass taxonomic composition, structure, tolerance and functional guilds. Scores for individual metrics are based on comparisons to bioregional reference values that reflect minimal impacts by human disturbance. Index scores for the WSII are calculated by summing the standardized metric scores derived from the riffle-based benthic macroinvertebrate sample. The evaluation of biological condition is made by comparing the index score for a site of unknown biological condition to an expected value derived from bioregional reference sites. Observed index scores that fall within the range of expected or reference values imply high biological condition, whereas observed scores lower than reference threshold values imply biological degradation. Based on numeric thresholds for each bioregion, derived from the assemblage of corresponding reference sites, observed index scores are codified into one of three narrative aquatic life use categories of 'full-support', 'indeterminate' and 'partial/non-support'.

The WY RIVPACS is a statewide macroinvertebrate-based predictive model that evaluates stream biological condition by comparing taxa observed at a site of unknown biological condition to taxa expected to occur in streams with minimal human disturbance (Hargett 2012). Expected taxa are identified from an appropriate dataset of least-impacted reference sites. The deviation or ratio of observed from expected taxa, known as the O/E value, is a measure of compositional similarity expressed in units of taxa richness and thus is a community level measure of biological condition. Values of O/E near 1 imply high biological condition whereas values appreciably less than 1 imply some degree of biological degradation. Observed/expected values are codified into one of three narrative aquatic life use categories of 'full-support', 'indeterminate' and 'partial/non-support' for each Wyoming bioregion.

Results from both the WSII and WY RIVPACS models are treated as quantitative biocriteria that when incorporated into Wyoming's aquatic life use-support decision matrix (WDEQ/WQD 2014a) are used to evaluate attainment of applicable narrative aquatic life criteria. Because results from both indices represent biological conditions that exist over a multi-year period, they generally carry a strong weight

when used in the weight of evidence approach for evaluating attainment of narrative aquatic life criteria. In addition to using the biological indicator models to compare biological condition at each Laramie River site to the regional reference condition, the WSII and WY RIVPACS scores among sites were compared to evaluate temporal and spatial patterns in biological condition. Supplemental benthic macroinvertebrate metrics were also used to evaluate aspects of community structure and function and identify potential causes of community shifts within the evaluated reach.

Periphyton (benthic diatom and soft algae) are also useful biological indicators of water quality, and in some cases are more precise in diagnosing particular environmental stressors than macroinvertebrates. As primary producers, periphyton are sensitive to changes in certain environmental conditions, particularly with respect to nutrient enrichment, salinity, metal toxicity and sedimentation. Select periphyton metrics provided additional evidence to aid in the detection/identification of potential cause(s) for spatial and temporal shifts in the benthos.

Channel stability and sediment supply was evaluated using the geomorphology-based Watershed Assessment of River Stability and Sediment Supply (WARSSS) procedure (Rosgen 2006a, 2008). Channel stability for this study is defined as the ability of a river, over time and in the present climate, to transport the flows and sediment produced by its watershed in such a manner that its dimension, pattern and profile are maintained without either aggrading or degrading (Rosgen 2006a).

Spatial and annual (2009-2010) changes in channel morphology and sediment dynamics at all Laramie River sites were quantified from channel attributes influenced by the bankfull discharge, often referred to as the channel forming or effective discharge. It performs much of the work required to maintain river form and function (Dunne and Leopold 1978, Rosgen 1996, Wolman and Miller 1960). Regional curve relationships for bankfull discharge and related channel dimensions vs. drainage area are often used to estimate bankfull discharge at ungaged sites within the same hydro-physiographic province from which they are developed (Rosgen 1996, 2006a). Recurrence intervals associated with the bankfull discharge typically range from 1.0 to 2.5 years, with the 1.5 year interval representing a reasonable average (Leopold 1994). Because recurrence intervals for bankfull discharge fluctuate regionally, due to variations in precipitation and other factors, reliance on regional curves alone to determine discharge is not recommended. Preferably, field-identified bankfull stage elevations and corresponding channel dimensions at ungaged sites are calibrated to a known discharge recurrence interval (expected condition) determined at one or more flow gaging stations in the same or similar drainage (Leopold 1994, Rosgen 1996 and 2006a). This field-validation process could not be performed at USGS gaging station 06660000 on the Laramie River at Laramie, WY. Reference elevations (benchmarks) established at the station could not be identified to relate present-day flow-stage measurements to historic flow-gaged data. However, flood-frequency plots generated from annual peak flow data collected at station 06660000 from 1933 to 1972 were used to relate bankfull discharge estimates made at sites to the expected recurrence interval or return period. Four commonly used hydraulic estimation methods applicable to low/moderate-gradient channels were used with bankfull attribute data to calculate mean bankfull discharge at sites on the Laramie River.

Bankfull channel attributes obtained from cross-section and longitudinal profile survey data were used to classify each site by Rosgen stream-type (Rosgen 1996), quantify spatial and temporal changes in gradient, bed substrate composition, dimension, perform hydraulic calculations, and generate dimensionless ratios for comparisons among sites and between years. Reachwide water surface and bankfull channel slopes, including water surface slopes and depths of individual bed features (riffle, run, pool and glide facets), obtained from longitudinal survey data were used to evaluate changes in channel profile. Annual change in channel capacity due to bed scour/incision (degradation) or filling (aggradation) was determined at each site by measuring differences in dimension (bankfull area) and bed elevations from permanent cross-section, longitudinal profile and scour chain survey data. Mean annual change of the channel thalweg was determined by calculating the mean difference of all paired bed elevation measurements obtained from replicate profile data. Survey data collected at riffle and glide scour chain installations were used to determine annual depth of bed scour (i.e., degree of incision), net change in bed elevation following high flows, and to identify the largest particle sizes entrained during those flow events. Bank profile survey data results and reachwide BEHI/NBS estimates were integrated into the BANCS model developed for streams that occur in sedimentary and/or metamorphic geology (Rosgen 2006a, 2008) to predict annual bank erosion rates (tons/yr/ft). Reachwide bank erosion sediment yield predictions among sites and between years were compared to evaluate changes in channel stability.

Predictions of sediment competence at bankfull stage were derived from a modified version of Shield's (1936) threshold of motion relation for gravel-bed streams (Rosgen 2006a). Existing shear stress, channel slope, mean depth and the largest particle (D_{100} or D_{max}) size obtained from a bar sample were related to predicted values to quantify the potential of each site to aggrade, degrade or remain stable given existing bankfull channel conditions (Rosgen 2006a).

Bank-height ratios (BHR) generated from profile data were used to quantify the degree of *recent* channel incision. The BHR is calculated by dividing the lowest bank height (LBH) by the maximum bankfull depth recorded at riffle and pool features (Rosgen 2006a, 2008). Bank-height ratios greater than 1.0 indicate that a greater portion of the bank surface is exposed above the bankfull elevation, making banks more susceptible to erosion from hydraulic action, collapse or slumping, rotational slipping and freeze/thaw processes (Knighton 1984, Rosgen 2006a). Bank-height ratios equal to or near 1.0 indicate that the LBH is at or near the elevation of the active floodplain (i.e., bankfull stage) which represents a vertically stable channel condition. In addition to quantifying the degree of channel incision, the relative difference between the LBH and bankfull maximum depth calculated at upstream and downstream ends of a reach can be used to determine the direction and extent of incision (Rosgen 2006a).

The semi-quantitative RSP procedure, completed at each site, considers sixteen variables that are incorporated into the following five stability condition categories: lateral stability, vertical stability for excess sediment or aggradation, vertical stability for channel incision, channel enlargement, and Pfankuch channel stability. An overall sediment supply prediction is then assigned based on the total score determined from the five categorical ratings. This information is useful to identify the specific

processes responsible for channel instability and to target sources of excess sediment supply within a watershed (Rosgen 2006a).

RESULTS

CHEMICAL QUALITY (see Appendix 1 for dataset)

pH

All pH values were within the criteria range of 6.5 to 9.0 standard units established in Chapter 1 of the Water Quality Rules and Regulations (WDEQ/WQD 2013a) for all years and sites. The pH levels measured at all sites in 2009 were more basic than corresponding values in 2010.

Temperature

Excluding a 20.4°C reading at 'Above UPRR Tie Plant' in 2009, water temperatures at all sites during the two-year study were less than the maximum criterion of 20°C protective of a Class 2AB cold-water game fishery (WDEQ/WQD 2013a). Lower water temperatures were measured at all sites in 2010 compared to those recorded in 2009. Water temperature in Spring Creek increased 50% between the upstream (11.6°C) and downstream (17.4°C) sites in 2009, though in 2010 temperatures between sites differed by less than 1°C.

Dissolved Oxygen

Instantaneous dissolved oxygen concentrations at Laramie River sites were lower in 2010 (range: 7.1-7.9 mg/L) relative to the supersaturated conditions observed in 2009 (range: 8.1-9.5 mg/L). Though dissolved oxygen concentrations at sites on the Laramie River in 2010 were less than the 8.0 mg/L minimum criterion protective of early cold-water fish life stages (WDEQ/WQD 2013a), their associated percent saturation levels were greater than values expected at their elevation-dependent atmospheric pressures (Standard Methods for the Examination of Water and Wastewater http://www.standardmethods.org/). Dissolved oxygen concentrations at both sites on Spring Creek in 2009 and 2010 ranged from 8.6 to 10.6 mg/L. No consistent spatial change in dissolved oxygen concentrations was observed among sites on the Laramie River, but concentrations in Spring Creek increased with distance downstream each year.

Nutrients

Total phosphorus (TP) and total nitrogen (TN) concentrations in the Laramie River rose steadily with distance downstream through the City of Laramie in both 2009 and 2010, increasing abruptly at the lowermost site ('Below Gravel Pits'). The greatest concentrations for both nutrients were observed in 2010 at all sites on the river. In both years, TP concentrations increased from about 10 to 15 micrograms per liter (µg/L) at the three upper sites to over 40 times those levels at 'Below Gravel Pits' (420 to 714 ug/L). Total nitrogen concentrations increased by more than 10 fold between the uppermost and lowermost river sites from 200 to 2,700 µg/L in 2009, and 341 to 5,174 µg/L in 2010. The greatest increases in both TP and TN concentrations occurred between 'Above Laramie WWTF' and 'Below Gravel Pits' in both years. Whereas all or most of the TN at the three upper sites was organic in

origin (65-75% total Kjeldahl-nitrogen, or TKN), greater than 80% of the TN at 'Below Gravel Pits' was composed of inorganic nitrogen (nitrate+nitrite-N, or N+N).

Total phosphorus concentrations at sites on Spring Creek during the study were less than the 10 µg/L analytical reporting limit (or detection limit). Greater than 90% of the TN measured at the two sites on Spring Creek in both years (range: 1,800 to 2,600 µg/L) was composed of N+N. Despite Spring Creek's minimal influence on baseflows in the Laramie River, it appeared to contribute a considerable amount of N+N to the river. During the two-year study, N+N in the Laramie River upstream of the Spring Creek confluence was not observed at detectable levels (<10 µg/L), but below the confluence it accounted for about one-third of the TN measured in the river. The greatest TKN concentrations were measured at the lowermost sites on both Spring Creek and the Laramie River, suggesting that much of the bioavailable inorganic nitrogen was readily assimilated into organic matter.

Mean annual concentrations of TN at the three upper sites on the Laramie River (271 to 550 µg/L) were elevated relative to a mean regional reference value of 162 µg/L, but were comparable to the range of reference values (<100 to 719 µg/L). Mean concentrations of TP at the three upper Laramie River sites and both sites on Spring Creek were at least two times less than the mean regional reference value of 37 µg/L. At 'Below Gravel Pits', mean levels of TN and TP during the study were 10 to 20 times greater than their respective mean regional reference concentrations. Mean annual N+N concentrations at 'Below Gravel Pits' and at both sites on Spring Creek were more than 40 times and 27 times greater, respectively, than the mean regional reference value of 74 µg/L. Mean N+N concentrations at 'Below Spring Creek' and 'Above Laramie WWTF' were about two times greater than this reference concentration, whereas levels at 'Above UPRR Tie Plant' (<10 µg/L) were well below the reference value. Concentrations of N+N measured at all sites on the Laramie River and Spring Creek were less than the respective human-health drinking water and fish consumption criterion of 10,000 µg/L applicable to all Class 2AB waters (WDEQ/WQD 2013a).

Specific Conductance, Hardness, Alkalinity & Major Constituents

Specific conductance, an indirect measure of the total dissolved solids (TDS) in water, increased with distance downstream in the Laramie River. From the uppermost site to lowermost site, conductance increased by 43% in 2009 and 23% in 2010. Conductivity at all sites on the river in 2010 (1,421 to 1,729 µS/cm) was about two times greater than corresponding readings in 2009 (701 to 996 µS/cm). Similar spatial and temporal changes were observed in the concentrations of total hardness (as $CaCO_3$), an indirect measure of the mineral content (primarily, calcium and magnesium) in water. From the uppermost site to lowermost site, hardness increased 34% in 2009 (range: 244 to 361 mg/L) and 48% in 2010 (range: 472 to 631 mg/L). Concentrations of total alkalinity (as $CaCO_3$), a measure of the pH buffering capacity of water, ranged from 127 to 201 mg/L in the river, increasing steadily with distance downstream by about 15-20% from the uppermost site to lowermost site in both years. Total alkalinity was about 33% greater at all sites on the river in 2010 than in 2009. The greatest increases in conductivity, hardness and alkalinity in the Laramie River occurred between *both* the two uppermost sites and two lowermost sites, suggesting that inflows from Spring Creek and the WWTF were adding to the river's TDS load.

Sulfate and calcium were the dominant ions found in the Laramie River each year, both of which influenced conductivity, hardness and alkalinity. At all sites on the river, concentrations of sulfate (range: 218 to 642 mg/L) and calcium (range: 58 to 122 mg/L) were respectively about two times and 1.5 times greater in 2010 than in 2009. From the uppermost site to lowermost site, sulfate concentrations increased 45% in 2009 and 19% in 2010, similar to the spatial and temporal changes observed in associated conductivity measurements. Calcium concentrations in the river were consistently about 38% greater at the lowermost site compared to the uppermost site each year, correspondingly similar to the spatial changes observed in total hardness concentrations. Chloride and magnesium concentrations also increased with distance downstream, with values that were about two to three times greater in 2010 than in 2009. Chloride concentrations in the Laramie River in both years ranged from 8 to 43 mg/L, well below the applicable chronic aquatic life criterion of 230 mg/L (WDEQ/WQD 2013a).

In the 2.5-mile span from the upper site ('Below Grand Avenue') to lower site ('Above Third Street') on Spring Creek, more than a 3.5-fold increase in specific conductance was observed in both 2009 and 2010 (mean values of 452 to 1,639 µS/cm). A similar spatial change was observed in total hardness concentrations, with mean values that were nearly four times greater at 'Above Third Street' than at 'Below Grand Avenue' (217 to 843 mg/L). Temporal differences in conductivity and hardness values at each site were less than 5%. With the exception of the 2009 measurement made at 'Above Third Street', total alkalinity concentrations did not vary greatly among sites during the study. Between the upper and lower sites on Spring Creek, mean concentrations of sulfate increased by more than 5-fold from 13 to 714 mg/L, whereas mean concentrations of calcium increased by more than 3-fold from 58 to 195 mg/L. Chloride concentrations in Spring Creek were ≤21 mg/L during the study, with values at the lower site that were four times greater than the upper site each year.

Based on conductivity measurements, TDS levels at sites on both the Laramie River and Spring Creek were 1.5 to six times greater than the mean regional reference condition (305 µS/cm), with the greatest levels measured at the lowermost sites. The elevated ionic activity in both waters was attributed primarily to their elevated levels of calcium and sulfate. Mean annual concentrations of calcium and sulfate at the lowermost site on the Laramie River, for instance, were about 2.7 times and 17 times greater than their respective mean regional reference levels (calcium= 37 mg/L; sulfate= 28 mg/L). Among all sites, only the solute levels observed at 'Below Grand Avenue' on Spring Creek were reasonably similar to the regional reference condition.

Total & Dissolved Metals

The concentrations of dissolved arsenic and total selenium measured in both the Laramie River and Spring Creek were well below the most stringent criteria established for each - 10 µg/L arsenic and 5 µg/L total selenium protective of human health and aquatic life uses, respectively (WDEQ/WQD 2013a). The greatest concentrations of dissolved arsenic (2 µg/L) and total selenium (2.5 µg/L) were measured in Spring Creek. Total cadmium was not detected (<0.1 µg/L) and total copper concentrations were no greater than 1.4 µg/L at any of the sites on the Laramie River and Spring Creek in 2009. Dissolved concentrations of both cadmium and copper were not detected (<10 ug/L) at any site in 2009 and were well below their respective hardness-based chronic aquatic life use criteria. Therefore, these metals were not evaluated in 2010.

Semi-Volatile Organic Compounds

None of the 64 SVOCs analyzed from water samples collected at all sites on the Laramie River in 2009 were detected at their respective analytical reporting levels, and therefore, were considered not present in concentrations that exceeded their associated human health and/or aquatic life use criteria (WDEQ/WQD 2013a). Separate water column and sediment samples were collected from a backwater region of the reach at 'Below Spring Creek' in 2009 upon observing an oil sheen form on the water surface and detecting a hydrocarbon odor when bed deposits were disturbed. The water column sample was collected after bed deposits were disturbed and allowed to mix with the overlying water. Both the water column and sediment sample results showed no detectable levels of the SVOCs analyzed. Because of the non-detect results observed from all samples in 2009, sampling for SVOCs was not repeated in 2010.

PHYSICAL CONDITION

Results and information for streamflow, stream classification, channel geometry (dimension, pattern and profile), bed materials, hydraulic geometry, sediment supply, and channel stability for sites on the Laramie River are presented in Appendices 2 through 15.

Due to high bed mobility at all sites, transitions between glide, riffle and run bed features were often not readily distinguishable, and their positions shifted either upstream or downstream annually due to differential scouring and deposition. In addition, changes in water surface slope typically used to differentiate bed features were not readily apparent in longitudinal profile plots (Appendix 4). Based on these observations, riffle and runs were considered to have similar hydraulic characteristics and were treated as a single bed feature (riffle/run) where applicable to facilitate hydraulic analyses and evaluate change in bankfull attributes. With the exception of the riffle cross-section established at 'Below Spring Creek', mean riffle depths among sites differed by no more than 0.05 ft annually (Appendix 2). Hydraulic characteristics of the riffle at 'Below Spring Creek' were substantially altered in 2010 when sediment deposited at a mid-channel bar feature was removed, resulting in a 0.35 ft increase in mean depth from 2009 to 2010 (Appendix 2). The riffle shifted upstream, but the cross-section still retained its position within the 2009 riffle/run boundary limits.

Streamflow

Instantaneous discharge measurements made in 2009 and 2010 indicated that the Laramie River and Spring Creek were gaining streams during the summer base flow period (Appendix 1). Based on gaged data collected on the Laramie River below the Pioneer Canal, river flows in late August to early September in 2009 and 2010 (range = 13 to 26 cfs) were similar to the long-term mean (Figure 4). Nonetheless, small temporal differences in flow were observed at sites, presumably due to relative differences in groundwater recharge to the river and water regulation. The greatest change in flow among sites occurred in 2010 when an increase of 9.5 cfs was observed between 'Above Laramie WWTF' and 'Below Gravel Pits'. Wastewater releases to the river from the City of Laramie WWTF likely accounted for 6.5 to 7.5 cfs of this difference, which is the typical discharge rate for the facility during late summer. The remainder may have been attributed to inflows of subsurface water to the river. Spring runoff and summer precipitation were greater in 2010 than in 2009, which presumably translated

to increased water stored in the alluvium and soil for eventual release to surface waters later in the summer (Figure 4).

Rosgen Stream Classification

Valley and landform features of the Laramie River evaluation reach were reflective of Valley Type VIII characteristics defined by Rosgen (1996) – broad, low-gradient (< 2%) valleys and meadows with well-developed, unconfined floodplains bordered by glacial and Holocene alluvial terraces. The most prevalent stream-types for this valley type include Rosgen C and E channels. The alluvial terrace and floodplain deposits through which these channels course are highly susceptible to streambank erosional processes under disequilibrium conditions and can produce a high sediment supply (Rosgen 1996). The flood-prone width of the Laramie River valley that existed prior to urban and industrial development within the City of Laramie likely ranged from about ½ to ¾ mile, which provided a relatively broad expanse for the river to migrate laterally between valley slopes and to develop the meandering, sinuous, riffle/pool pattern characteristic of Valley Type VIII channels. Numerous meander scrolls and abandoned oxbow channels evident in aerial photography upstream and downstream of the city indicated that the river had full access to its floodplain, altering its course several times over the past few decades.

Each of the three upper sites supported a diverse (composition and age-class structure) riparian vegetation community consisting of cottonwood and boxelder trees, willows, alder, sedges and grasses (Figure 6). A less diverse riparian community of willows, grasses, sedges and forbs existed at 'Below Gravel Pits' (Figure 7). The stability of C channels is largely dependent on the presence and condition of riparian vegetation which maintains the structural integrity of streambanks (Rosgen 1996). Alterations to the riparian vegetation community, changes in flow regime and channelization can rapidly destabilize C channels by accelerating streambank erosion, degradation and aggradation processes.

Figure 6 – Channel and riparian vegetation conditions of the Laramie River downstream of the confluence with Spring Creek within Laramie city limits (2010).

The valley and channel within the Laramie River evaluation reach no longer resembles what existed prior to urban and industrial development. Valley width (flood-prone area width) at all sites was no more than 1,000 ft, which was measured at 'Below Gravel Pits' (Appendix 2). The three upper sites occurred within a much more laterally confined region in the valley (flood-prone area widths ranging from 150 to 280 ft), and accordingly, exhibited the greatest degree of channel entrenchment (ratios of 2.2 to 3.6) compared to 'Below Gravel Pits' (entrenchment ratio of 12.4 to 12.5). All sites were characterized as low-gradient (<1%), slightly entrenched Rosgen C stream-types, which was expected given the prevailing valley morphology. Reachwide bed material at the three upper sites consisted mostly of a mixture of fine and coarse gravel (C4), whereas sand was the prevalent bed substrate at 'Below Gravel Pits' (C5). Exposed bedrock was observed occasionally at all sites upstream of 'Below Gravel Pits', providing localized grade-control. Bankfull width to depth ratios (W/d) increased with distance downstream, ranging from 23 at 'Above UPRR Tie Plant' to 45 at 'Below Spring Creek' (Appendix 2).

Figure 7 – Channel and riparian vegetation conditions of the Laramie River at 'Below Gravel Pits' downstream of the City of Laramie (2010).

Bankfull Discharge

Based on observed flood indicators (i.e., sediment/debris deposits and scour lines), flows greater than bankfull discharge were achieved within the Laramie River evaluation reach in 2009, 2010 and 2011. Estimated mean bankfull discharge at study sites increased with distance downstream as expected from 322 cfs at 'Above UPRR Tie Plant' to 378 cfs at 'Below Gravel Pits' (Appendix 3). With the exception of estimates made at 'Below Spring Creek', the relative percent difference between 2009 and 2010 mean bankfull flows within sites was less than 4%. Mean annual bankfull flow estimates at 'Below Spring Creek' differed by about 10%, which was presumably attributed to field identification of bankfull stage at the riffle cross-section. From 2009 to 2010 substantial changes at the riffle occurred as a result of bed scour/incision (Appendix 2), making selection of the actual bankfull stage difficult. Small changes in bankfull elevation resulted in substantial differences in the hydraulic variables used to estimate discharge at 'Below Spring Creek'. Mean bankfull velocity estimates ranged from 1.8 to 2.9 ft/s (Appendix 3). The greatest velocities were observed at 'Above UPRR Tie Plant' and 'Above Laramie WWTF', both of which exhibited the steepest channel slopes among sites (Appendix 2). The lowest bankfull velocity estimates occurred at 'Below Spring Creek', which relative to the other sites had channel features that provided greater flow resistance (wetted perimeter, bed roughness).

Verification of bankfull stage at flow-gaged stations on rivers in southeast Wyoming has shown that the flows associated with the 1.3 to 1.5 peak flow recurrence intervals accurately represent bankfull discharge in the region (Foster 2012, WDEQ/WQD 2013b, WDEQ/WQD 2014b). Given this range of recurrence intervals, bankfull flows from 545 to 725 cfs would be expected for the Laramie River at Laramie (determined from a frequency analysis of peak flow data collected from 1933 to 1972 at USGS station 06660000). From this analysis, mean bankfull discharge computed from all estimates made at Laramie River sites (347 cfs) was 36% less than the expected 1.3 year return period discharge of 545 cfs. Such a large disparity between estimated and expected bankfull flows suggested that either 1) the field-

identified bankfull stage at sites was selected at an elevation lower than actual, or 2) actual channel dimensions at the time of bankfull flow differed considerably from those determined from channel survey data collected after peak flows receded (i.e., short-term changes in bed elevation as a result of scour and fill processes).

The former argument was not supported based on field observations, available survey data and hydraulic evaluations. Identification of bankfull features in actively incising channels can be problematic, but given the presence of exposed bedrock at the three upper sites, incision processes in the Laramie River were limited. Thus, morphologic adjustments that normally follow incision such as channel widening and reestablishment of a new floodplain were active. Though bankfull discharge may be underestimated if the top of the floodplain is used as an indicator of bankfull stage in aggrading rivers (Copeland et al. 2000), a well-developed floodplain nonetheless served as the consistent, defining bankfull stage feature throughout the evaluation reach. Though narrow, the floodplain was well-defined by the presence of a densely vegetated bank and occurred at elevations well above unvegetated depositional features. The elevation of the active floodplain was identified from various field-indicators including a distinct break in slope between the active channel and vegetated bank, exposed roots immediately below the top of bank and near the apex of depositional features (e.g., point bars and central bars) in the active channel (Leopold and Wolman 1957, Leopold 1994, Rosgen 1996). Vegetation density increased at higher elevations where the active floodplain adjoined steeper, willow-dominated banks and the previously abandoned floodplain (terrace). Cross-section and longitudinal profile survey data were compared to ensure consistency in the identification of bankfull stage. In addition, there was minimal interannual variability in bankfull discharge estimates made at each site indicating that despite evidence of high bed mobility, selection of bankfull stage indicators was consistent from one year to the next. While bankfull flow estimates generated from data obtained at stages higher than the field-identified bankfull stage fell within the range of expected flow values, reasons for raising bankfull stage above selected elevations could not be justified.

A more reasoned argument could be made that the disparity between estimated and expected bankfull flows in the Laramie River was attributed primarily to temporal differences in channel cross-sectional area, governed by flow and bed load transport. Andrews (1980) demonstrated that the greatest amount of sediment transport occurs at the effective discharge, which closely coincided with discharges near bankfull stage. Leopold (1994) further noted that while flows greater than bankfull may be very effective in the erosion-deposition process, it was the bankfull flow that transported the greatest volume of sediment. Based on this understanding, it may be assumed that channel capacity in the Laramie River during peak flow increased to a point where sediment transport capacity was exceeded (i.e., near bankfull). In other words, peak flows scoured the channel to a depth greater than would be achieved at bankfull, but erosion was countered by deposition as sediment transport capacity diminished at flows greater than bankfull. Evidence that opposing erosional and depositional processes were operational in the river at flows greater than bankfull was corroborated by channel profile, cross-section and scour chain survey results (provided later in the report), which showed considerable vertical and lateral shifts in bed elevations and sediment bar features from 2009 to 2010. Scour/fill survey

results further demonstrated the highly dynamic nature of sediment transport in the river, with over one foot of scour and two feet of net deposition measured at the same station at more than one site.

Considering the high degree of bed mobility observed in the Laramie River from 2009 to 2010, there was reason to infer that the baseflow channel survey data collected at sites did not accurately represent channel dimensions that would have been observed at the time of bankfull or peak flow. Though bankfull channel dimensions at riffle cross-sections were not measured concurrently with bankfull flow, reasonable estimates were generated from interpretations of scour chain survey data. Bed elevation changes determined from these data provided the means to create a channel bed at each site that likely resembled the condition at the time of maximum bed load transport. Bed elevations at riffle cross-sections were conservatively adjusted in accordance with observed scour/fill patterns across the width of their active beds to create 'scour-adjusted' channels. Using the same field-identified bankfull stage elevations, estimates of bankfull discharge generated from the scoured channel dimensions of each site ranged from 495 cfs at 'Above UPRR Tie Plant' to 612 cfs at 'Below Gravel Pits' (Appendix 3), values which were reasonably similar to expected flow rates.

Channel Dimension

The shape and size of a channel in cross-section are characterized by width, depth and area either at a station or as a reach average. Channel dimensions are adjustable over a range of spatial and temporal scales and are most susceptible to changes in discharge and sediment load, within the additional constraints of valley slope and composition of boundary materials (Knighton 1984, Petts and Foster 1985).

Riffles

Bankfull channel dimensions in natural rivers increase in proportion to downstream increases in contributing drainage area and discharge (Lane 1955, Leopold et al. 1964, Leopold 1994). This general relationship was observed on the Laramie River, with mean bankfull riffle area (2009-2010) increasing from about 111 ft^2 at 'Above UPRR Tie Plant' to 183 ft^2 at 'Below Gravel Pits' (Appendix 2). These downstream increases were attributed mostly to increases in width, as mean depth varied by no more than 0.10 ft from the uppermost site to lowermost site. Among all sites, mean riffle areas at 'Below Spring Creek' and 'Below Gravel Pits' were the greatest. Their larger riffle areas relative to the other two sites were attributed to their lower channel gradients, which necessarily required greater cross-sectional area to convey bankfull flow at lower velocities (Appendix 3). With the exception of 'Below Spring Creek', there were minimal interannual differences in mean bankfull riffle area within sites. Bankfull riffle area at 'Below Spring Creek' increased 29 ft^2 from 2009 to 2010, due in large part to the removal of sediment stored in a 40 ft wide section of a mid-channel bar by the 2010 flood flows that resulted in a 0.35 ft increase in mean depth.

Mean bankfull riffle width to depth (W/d) ratios increased with distance downstream from 23.4 at 'Above UPRR Tie Plant' to 41.7 at 'Below Spring Creek', then decreased to 34.0 and 35.2 at the two lowermost sites (Appendix 2). The more than 1.5-fold increase in mean W/d in the relatively short distance from 'Above UPRR Tie Plant' to sites downstream indicated a notable shift in channel morphology between the upper and lower extent of the evaluation reach. The degree of entrenchment

(i.e., vertical containment) at each site appeared to have a controlling influence on the direction of interannual change in riffle W/d within sites. From 2007 to 2008, decreases in W/d were observed at 'Below Spring Creek' and 'Above Laramie WWTF', both of which were the most entrenched among sites (Appendix 2). Conversely, W/d increased slightly at the least entrenched channels ('Above UPRR Tie Plant' and 'Below Gravel Pits'). The greatest temporal change in riffle W/d (-7.3 units) was observed at 'Below Spring Creek', attributed to a correspondingly large increase in mean depth (0.35 ft).

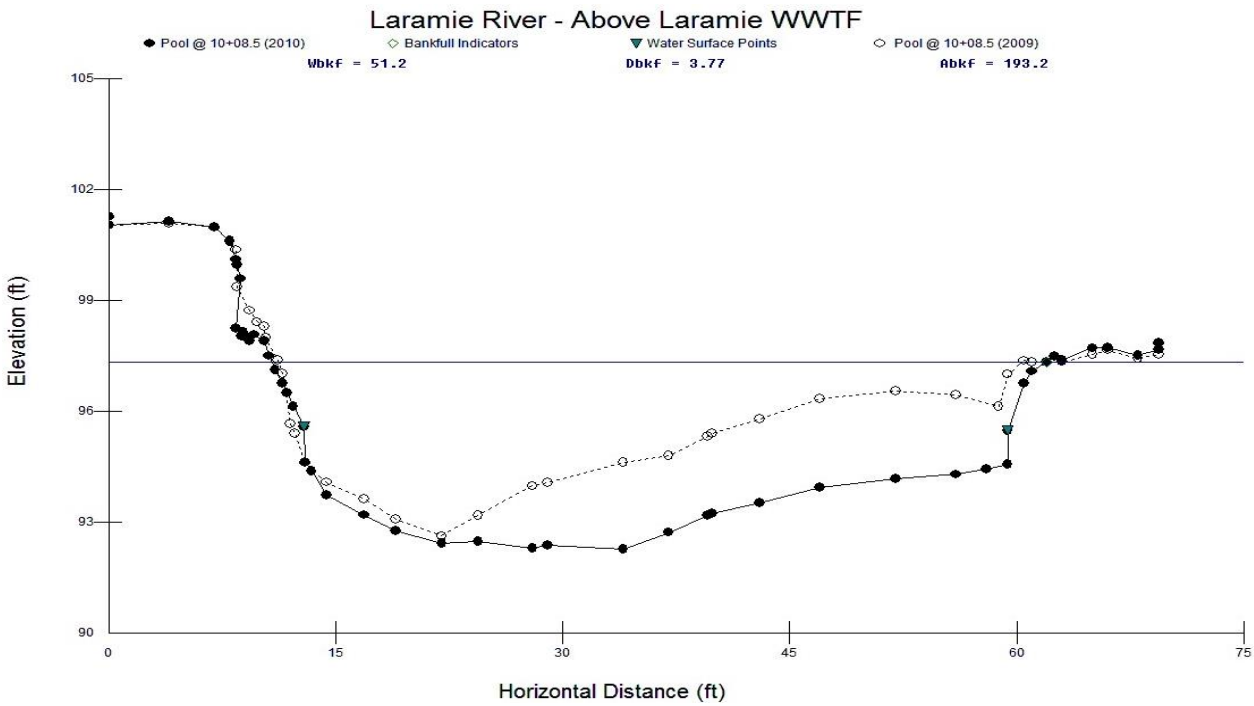
Pools

During the two year study, mean bankfull pool area increased steadily with distance downstream from 144 ft^2 at 'Above UPRR Tie Plant' to 154 ft^2 at 'Above Laramie WWTF', then decreased abruptly to 124 ft^2 at 'Below Gravel Pits' (Appendix 2). The same spatial response was observed in mean bankfull pool depths. Conversely, mean bankfull pool widths decreased with distance downstream from 77.4 ft at 'Above UPRR Tie Plant' to 54.0 ft at 'Above Laramie WWTF', then increased marginally to 57.1 ft at 'Below Gravel Pits'. Thus, downstream changes in pool area were attributed entirely to changes in depth. This was most apparent between 'Above Laramie WWTF' and 'Below Gravel Pits', where even though mean pool width increased downstream by about 12%, there was a corresponding decrease in mean pool depth of 29%, resulting in a 19% decrease in mean bankfull pool area.

The greatest temporal change in pool dimensions among sites occurred at 'Below Spring Creek' and 'Above Laramie WWTF' where pool area increased by about 9 ft^2 and 78 ft^2, respectively (Appendix 2). Whereas the increase in pool area at 'Below Spring Creek' was due to erosion of the outer bank and some bed scouring, the large increase at 'Above Laramie WWTF' was attributed mostly to the removal of a large portion of the sediment stored on the point bar (Figure 8). Not surprisingly, the greatest temporal change in mean pool depth (+1.42 ft) among sites was also observed at 'Above Laramie WWTF'. A depositional environment created by a partially breached beaver dam located about 150 ft downstream of the pool was likely responsible for much of the sediment stored on the point bar in 2009. The remainder of the dam was removed by the record peak flow in 2010.

Dimensionless ratios of mean pool depth/mean riffle depth (d) and maximum pool depth/d are indicators used to evaluate the effects of sediment supply in streams with riffle-pool bed morphology. Ratios greater than 1.0 indicate pool depths exceed those of riffles, a condition expected of Rosgen C stream types. Annual mean pool/d values were greater than 1.0 at 'Below Spring Creek' and 'Above Laramie WWTF' (Appendix 2), suggesting that sediment transport within these reaches was sufficient to maintain expected bed conditions. Mean pool depths at 'Above UPRR Tie Plant' and 'Below Gravel Pits' were less than their respective depths at riffles, suggesting that pools in these reaches were filling. The annual mean of maximum pool depth/d values among sites increased generally as expected with distance downstream (Appendix 2), but the decrease in ratios from 2.48 at 'Above Laramie WWTF' to 2.21 at 'Below Gravel Pits' also provided some evidence of pool filling below the City of Laramie.

Figure 8 – Overlays of the 2009 and 2010 cross-sections at Pool 10+085, 'Above Laramie WWTF', Laramie River.



Channel Pattern

Adjustments in channel dimension typically accompany changes in pattern. Sinuosity, radius of curvature (Rc), meander wavelength (Lm), belt width (Wblt), and spacing between riffles and pools (riffle-pool sequence or pool-to-pool spacing)

are variables used to evaluate channel form and stream energy utilization/dissipation (Leopold 1994). Measures of Rc, Lm, Wblt and pool-to-pool spacing are expressed as dimensionless ratios in relation to bankfull riffle width (W). Channel pattern attributes for sites on the Laramie River are provided in Appendix 2. Percentages of pool and non-pool habitat features are presented in Appendix 4.

Sinuosity, Meander Wavelength & Radius of Curvature

Channel sinuosity (ft/ft) increased with distance downstream from 1.1 to 1.2 at the three upper sites to 1.3 at 'Below Gravel Pits' (Appendix 2). Among all sites, sinuosity was lowest at 'Above Laramie WWTF' (1.08). The downstream increase in sinuosity reflected what was expected given the same change in channel entrenchment (i.e., sinuosity increased as channel confinement decreased). Generally an increase in slope is accompanied by a decrease in sinuosity, such as what was observed between 'Below Spring Creek' and 'Above Laramie WWTF'. This relationship is not always straightforward, however, as changes in sinuosity and slope vary with relative rates of discharge, bed-material load and other factors (Lane 1955, Leopold and Wolman 1957, Schumm 1969).

Ratios of Rc/W and Lm/W are used to evaluate avulsion (channel abandonment) potential and risks of accelerated bank erosion and lateral channel migration. Results from a number of empirical studies of river pattern show invariably that Lm and Rc are respectively about 10 to 14 (mean: 11) and 2 to 3 (mean: 2.3) times channel width (Knighton 1984, Leopold 1994), though the generality of the latter is debatable (Knighton 1984). Departures from these expected range of values typically represent channel

forms with varying degrees of instability. Decreases in Rc/W and Lm/W are associated with increases in width/depth and near-bank boundary shear stress and accelerated lateral migration rates, all of which are indicative of an unstable river with an excess sediment supply (Rosgen 1996, Schumm 1969).

Typically, Rc and Lm decrease with increases in sinuosity. This general relationship was observed on the Laramie River. Among the four sites, 'Above UPRR Tie Plant' and 'Above Laramie WWTF' had the lowest sinuosity (~1.1) and greatest mean reachwide Rc and Lm values (Appendix 2). Mean Rc/W ratios were within the expected range of 2 to 3 at 'Above UPRR Tie Plant' and 'Above Laramie WWTF', but mean ratios of 1.6 and 1.9 were observed at 'Below Spring Creek' and 'Below Gravel Pits', respectively. Individual meander bends with Rc/W values much less than 2 were observed at each site, indicating that the river was undergoing various degrees of accelerated lateral channel movement. Using Rosgen's (2006a) method for rating boundary shear force at meander bends, reachwide mean Rc/W values at all sites would receive very low to very high NBS ratings. Very high to extreme NBS ratings are assigned to meander bends with Rc/W values <2. Mean Lm/W ratios at all sites were less than the expected range of 10-14, further suggesting a certain degree of departure in channel planform. The lowest mean Lm/W ratios were observed at 'Below Spring Creek' (3.1) and 'Below Gravel Pits' (3.2), both of which had the widest channels among all sites. Negligible interannual change was observed in Rc/W and Lm/W values within sites.

Meander Width Ratio

The meander width ratio (Wblt/W) is an index used to evaluate the degree of confinement, or lateral containment of a channel. Channel enlargement, lateral accretion, accelerated bank erosion and sediment transport problems often accompany increases in channel confinement (Rosgen 2006a). Mean Wblt/W ratios on the Laramie River increased generally with distance downstream, indicating a corresponding decrease in channel confinement (Appendix 2). The greatest belt widths were observed at 'Below Gravel Pits' (mean: 3.3), which was expected considering that its wider flood-prone area, relative to the more confined reaches upstream, accommodated greater lateral channel extension. Belt widths at the three upper sites were 1.4 to 2.6 times their respective channel widths. Temporal change in Wblt/W within sites was negligible.

Riffle-Pool Sequence

Pool-to-pool spacing for both straight and meandering perennial channels with coarse sand to cobble beds, typically occurs at a regular, repeating distance of 5 to 7 bankfull channel widths (Keller and Melhorn 1978, Knighton 1984, Leopold et al. 1964). This range of pool-pool spacing to channel width (p-p/W) ratios is expected of Rosgen C stream-types, with appreciable deviations representing adjustments in stream energy and sediment transport (Rosgen 1996). Typically, increases in gradient result in p-p/W values <5, whereas values appreciably >7 suggest increases in channel width which can cause reductions in sediment competence and sediment transport capacity.

The expected pool spacing sequence was observed at the three upper sites on the Laramie River only in 2009 and at the lowermost site in 2010 (Appendix 2). Mean p-p/W ratios in 2009 increased with distance downstream from 6.5 at 'Above UPRR Tie Plant' to 7.3 at 'Above Laramie WWTF', and then abruptly to 10.8 at 'Below Gravel Pits'. In 2010, the p-p/W ratio at 'Below Spring Creek' and 'Above

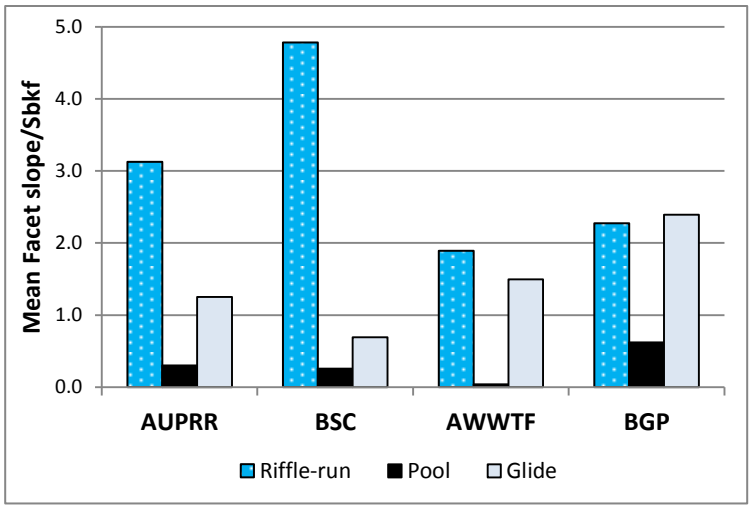
Laramie WWTF' was about four, approaching values typically found in high-gradient streams with step-pool bed morphology (Leopold 1994). From 2009 to 2010, p-p/W ratios within sites decreased by as much as 29% at the uppermost site (6.5 to 4.6) to 50% at the lowermost site (10.8 to 5.6). The temporal reductions in p-p/W ratios at all sites were attributed primarily to appreciable decreases in pool-pool spacing, as channel width remained relatively constant. The greatest temporal change in bed form among sites was observed at 'Below Gravel Pits' where mean pool-pool spacing decreased 50%, mean individual pool length increased 61% and mean riffle length decreased 79%.

Channel Profile

With the exception of 'Above UPRR Tie Plant' in 2009, bankfull channel slopes (Sbkf) at sites on the Laramie River were less than 0.1%, which categorized them as low-gradient (designated by "c-" post-script) Rosgen C channels (Appendix 2). Mean bankfull slopes decreased with distance downstream from about 0.1% at 'Above UPRR Tie Plant' to 0.04% at 'Below Gravel Pits'. As expected, Sbkf values at all sites were slightly less than their associated valley slopes. Measured valley and bankfull channel slopes at 'Above UPRR Tie Plant' and 'Above Laramie WWTF' were the greatest among all sites and above or slightly below the gradient threshold (0.1%) that differentiates low-gradient and moderate-gradient C channels. The low Sbkf at 'Below Gravel Pits' was expected considering its channel was not as laterally confined as the three upper sites. Relative to sites upstream, the channel at 'Below Gravel Pits' had access to a broader valley over which it could develop a more sinuous and lower gradient course. The relatively abrupt shifts in Sbkf between the three upper sites were inconsistent, considering that the degree of channel confinement (i.e., entrenchment) at each was similar. From 2009 to 2010, Sbkf at each of the two uppermost sites decreased by about 15% (Appendix 2) due to differential scouring/deposition at the upper and lower extent of each reach. Negligible temporal increases in Sbkf were observed at the two lowermost sites.

Mean ratios of all facet slopes to Sbkf varied considerably among sites (Figure 9, Appendix 2), revealing no consistent downstream change. Mean pool slope to Sbkf ratios decreased from 'Above UPRR Tie Plant' to 'Above WWTF', but then increased abruptly by more than 15-fold from 0.04 to 0.62 at 'Below Gravel Pits' (Appendix 2). Ratios of mean pool slope to Sbkf ranging from 0.61 to 1.0 imply high to very high shear stress along the outer banks of meander bends where pools typically form and instability associated with excess sedimentation is most apparent (Rosgen 2006a). Ratios of riffle/run and glide

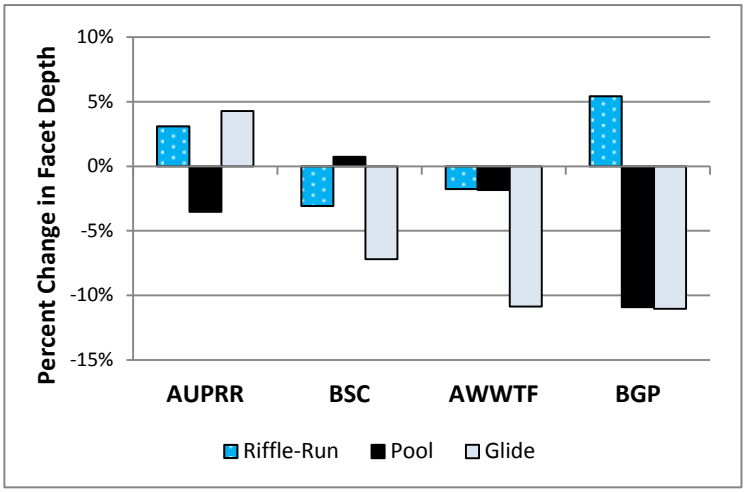
Figure 9 – Ratios of mean facet slope to bankfull channel slope at sites on the Laramie River (2009-2010). AUPRR=Above UPRR Tie Plant, BSC=Below Spring Creek, AWWTF=Above Laramie WWTF, BGP=Below Gravel Pits.



slope to Sbkf also increased between the two lowermost sites, but to lesser degrees than observed at pools. A notable difference among facets within sites was observed at 'Below Gravel Pits', where the mean glide slope to Sbkf ratio exceeded the mean riffle-run slope to Sbkf ratio (Figure 9). This typically occurs when unconsolidated bed material at the riffle erodes headward (upstream) into the glide as a result of localized gradient adjustments to accommodate alterations in flow and/or sediment (Rosgen 2006a). Among the three facets evaluated, the greatest disparities in mean facet slope to Sbkf ratios were observed at riffle-run features within the two upper sites, where riffle-run slopes were more than three times greater than their respective Sbkf values (Figure 9). These relatively high ratios were attributed to bed elevation changes from 2009 to 2010 at each site that resulted in increases in riffle-run slopes and respective decreases in Sbkf values. From 2009 to 2010 at all sites, mean riffle-run to Sbkf ratios increased (22-204%), whereas mean pool slope to Sbkf ratios decreased (31-56%), indicating that various degrees of gradient adjustment occurred throughout the river following the 2010 peak flows.

Channel depth typically increases with distance downstream in proportion to increases in bankfull discharge and drainage area (Leopold 1994). This was observed for all facet depth/mean riffle depth (d) ratios from the upper to lower sites on the Laramie River (Appendix 2). Other than some minor decreases (11%) in mean glide depth at 'Above Laramie WWTF' and mean glide and pool depths at 'Below Gravel Pits', there was negligible interannual change in mean facet depths among sites (Figure 10). Given the temporal decreases observed in glide and pool facet depths at 'Below Gravel Pits', and considering that greater than 63% of the entire reach was composed of these bed features combined in 2010 (Appendix 2), these results suggested that the channel filled slightly during the two-year study. This was corroborated by observed increases in channel thalweg elevations from 2009 to 2010 (see results in *Channel Scour and Fill* section). The greatest interannual change in mean facet depth/d ratios was observed at 'Below Spring Creek', attributed to a 0.35 ft increase (18%) in mean riffle depth (d) at the cross-section (Appendix 2). Negligible temporal change in facet depth/d ratios was observed at the other three sites.

Figure 10 – Annual change (2009-2010) in mean facet depths reachwide at sites on the Laramie River.



Streambank Stability and Cover

Over the two-year study period, greater than 65% of the total length of streambank (both banks combined reachwide) at or below the bankfull elevation at 'Below Spring Creek' and 'Above Laramie WWTF' was considered stable (Appendix 5). By comparison, mean annual estimates of streambank stability at the uppermost and lowermost sites were less than 55%. Much of the instability observed at all sites was attributed to bank fracture and slumping, particularly along the apex of meander bends

where NBS is typically high. Riparian vegetation, particularly willow growth (Figure 6), provided a majority of the bank cover at all sites. Reaches with the greatest percentage of bank cover exhibited the least amount of bank instability. Bank cover estimates within the reaches at 'Below Spring Creek' and 'Above Laramie WWTF' ranged from 62% to 86% compared to 31% to 48% at the uppermost and lowermost sites (Appendix 5). Among sites, streambanks at 'Above UPRR Tie Plant' during the 2009-2010 evaluation exhibited the least amount of stability (mean = 44%) and cover (mean = 39%).

In addition to exhibiting the greatest degree of bank instability, the greatest temporal changes in bank conditions were observed at 'Above UPRR Tie Plant'. From 2009 to 2010, bank stability at the site increased 29%, whereas bank cover decreased 17% (Appendix 5). The dichotomy in these two measures may be explained by temporal differences in the percentage of bank susceptible to erosion. Unstable bank segments identified in 2009 subsequently slumped into the channel following the 2010 peak flow period, forming new bankfull benches (Figure 11) which were then classified as "stable" features. The temporal decrease in bank cover was attributed to the expansion of point bars composed of mobile sediment (Figure 11), where the rate of vegetation colonization was outpaced by the rate of sediment deposition. Similar temporal responses in bank stability and cover were observed at 'Below Gravel Pits'. Temporal changes in bank conditions at 'Below Spring Creek' were nominal. Bank stability at 'Above Laramie WWTF' decreased from 2009 to 2010 due to an increase in bank fracturing and slumping, whereas bank cover increased as a result of vegetation colonizing previously bare banks and removal of unvegetated bar deposits by high flows (Figure 8).

Figure 11 – Bank conditions at a meander bend at 'Above UPRR Tie Plant' on the Laramie River (2010).

Streambank Erosion

Using the Colorado River Basin BANCS model developed by Rosgen (2006a), the 2009 predicted bank erosion rates at three of the four bank profiles exceeded their corresponding 2010 measured (observed) erosion rates by about 0.30 to 2.65 ft/yr (Appendices 6 and 7). The most accurate prediction was made at the 'Below Gravel Pits' bank profile, where the observed erosion rate (2.45 ft/yr) was 0.30 ft/yr less than predicted. The 2010 bank erosion rates predicted for profiles at 'Above UPRR Tie Plant' and 'Above Laramie WWTF' were respectively about two times and ten times less than their corresponding observed rates. Though differences between annual observed to predicted bank profile erosion rates were large at some sites, the combined total of the 2010 and 2011 observed rates at both 'Above UPRR Tie Plant' and 'Above Laramie WWTF' were reasonably close to their respective predicted rates (approximately 10% relative difference).

The BANCS model was mostly inaccurate in predicting bank erosion rates annually, but the relative magnitude of long-term predicted bank retreat among sites was nonetheless reflective of observed rates (i.e., the greatest amount of bank erosion was measured at sites predicted to have the greatest erosion potential). From 2009 to 2011 the total observed bank erosion rate at the 'Above UPRR Tie Plant' bank profile was nearly 2.5 times greater than that observed at the 'Above Laramie WWTF' profile, which among the two profiles, was predicted to be the least susceptible to bank erosion (Appendix 6).

Based on the 2009 BANCS predicted reachwide bank erosion rates (Appendix 8) and streambank stability and cover estimates (Appendix 5), sites exhibiting the greatest bank erosion potential included 'Above UPRR Tie Plant' and 'Below Gravel Pits', with predicted reachwide rates of 103 tons/yr and 91.1 tons/yr per 1,000 ft of channel (Table 3), respectively. Banks most susceptible to erosion within these reaches (primarily along outside meander bends) exhibited minimal bank surface protection, vegetation root density and depth; steep bank angles; and high bank-height ratios. High bank-height ratios indicate that a disproportionate amount of the bank surface is exposed above the bankfull elevation and thus is more susceptible to erosion by freeze/thaw, bank slumping/collapse and other mass erosion processes (Rosgen 2006a). The 2010 predicted reachwide bank erosion rates at 'Above UPRR Tie Plant' and 'Below Gravel Pits' were less than their corresponding 2009 predicted rates (Table 3), primarily as a result of localized reductions in bank height and angle.

Table 3 – Predicted reachwide bank erosion rates at WDEQ/WQD sites on the Laramie River (2009-2013).

Study Reach	Year	Total Predicted Reachwide Erosion (tons/yr)	Surveyed Reach Length (ft)	Predicted Reachwide Erosion (tons/yr/ft)	Total Reachwide Erosion per 1000 ft (tons/yr)	Percent (%) Change from 2009	*Number of Dump Truck Loads per 1000 ft
Above UPRR Tie Plant	2009	118.5	1,150	0.1030	103.0	-	5.2
	2010	109.8	1,150	0.0955	95.5	-7.3	4.8
	2011	97.7	1,150	0.0849	84.9	-11.1	4.2
	Mean	**108.7**		**0.0945**	**94.5**		**4.7**
Below Spring Creek	2009	74.9	1,200	0.0624	62.4	-	3.1
	2010	212.3	1,200	0.1769	176.9	183	8.8
	2011	20.5	1,200	0.0171	17.1	-72.6	0.9
	2013	18.8	1,200	0.0157	15.7	-74.9	0.8
Untreated Mean (2009-10)		**143.6**		**0.1197**	**119.7**		**6.0**
Treated Mean (2011-13)		**19.7**		**0.0164**	**16.4**		**0.8**
Above Laramie WWTF	2009	40.9	1,500	0.0273	27.3	-	1.4
	2010	53.2	1,500	0.0355	35.5	30.2	1.8
	2011	63.6	1,500	0.0424	42.4	55.4	2.1
	Mean	**52.6**		**0.0350**	**35.0**		**1.8**
Below Gravel Pits	2009	191.2	2,100	0.0911	91.1	-	4.6
	2010	117.91	2,100	0.0561	56.1	-38.3	2.8
	Mean	**154.6**		**0.0736**	**73.6**		**3.7**

*Based on a 2-axle highway-qualified truck with an estimated maximum load of 20 tons.

With the exception of the reach at 'Above Laramie WWTF', predictions of reachwide bank erosion at all sites decreased over their respective study periods (Table 3). The greatest reductions were observed at 'Below Spring Creek' (75% decrease from 2009 to 2013), which was expected given that bank protection treatments were installed in the reach in 2010 and 2011. Bank erosion potential increased by more than

180% within this reach from 2009 to 2010 due to increases in bank surface area (Appendix 8) susceptible to erosion following the record peak flow event in 2010. Bank erosion potential at 'Below Spring Creek' was dramatically reduced by more than 10-fold when bank treatments were installed immediately after the 2010 predictions were made. The 2011 and 2013 reachwide predictions made at the site reflect the degree of protection afforded by the bank treatments installed in 2010. Among the three untreated reaches, the least amount of change in predicted bank erosion was observed at 'Above UPRR Tie Plant' (11% decrease from 2009 to 2011). Annual reductions in reachwide bank erosion potential at the untreated sites were attributed primarily to overall decreases in bank heights and angles (Appendix 8). Conversely, bank heights and angles increased temporally at 'Above Laramie WWTF', which contributed to annual increases in predicted reachwide bank erosion rates. Despite the temporal decline in bank stability at 'Above Laramie WWTF', the 2009-2010 mean annual estimated bank erosion rate was nonetheless three times less and two times less than the corresponding rates at 'Above UPRR Tie Plant' and 'Below Gravel Pits' (Table 3), respectively.

Channel Incision

Channel incision processes are initiated through increases in gradient and stream power, which result in the lowering of the channel bed, abandonment of the active floodplain and channel enlargement through bank erosion processes (Rosgen 2006a). Longitudinal profile plots produced from survey data collected at all Laramie River sites (Appendix 4) showed that the channel has experienced several incision events in the past as evidenced by the presence of abandoned channel terrace features (former floodplains).

Streams with high BHR values generally contribute disproportionate amounts of sediment from streambanks and channel beds due to high shear stress resulting from channel incision (Rosgen 2006a). Among sites, incision depths were greatest at 'Above UPRR Tie Plant' where BHR values as high as 1.46 were observed at the downstream end of the reach (Appendix 2). Based on the channel incision rating scale developed by Rosgen (2006a), channels at 'Below Spring Creek', 'Above Laramie WWTF' and 'Below Gravel Pits' were categorized as slightly incised (BHR 1.1 – 1.3), whereas the channel at 'Above UPRR Tie Plant' fell within the lower end of the moderately incised category (BHR 1.3 – 1.5). Negligible temporal change in BHR values was observed at the lower end of the reach at 'Above UPRR Tie Plant' and throughout the reach at 'Below Gravel Pits' (Appendix 2). No temporal change in BHR values was observed at the other two sites. Considering that there was little to no temporal change in BHR ratios among sites following the high magnitude flows in 2010, it could be inferred that incision processes in the river were limited. Exposed bedrock observed at various locations throughout each of the three upper sites provided supporting evidence that controls on bed incision were indeed present.

In addition to quantifying the degree of channel incision, the relative difference between the LBH and bankfull maximum depth calculated at upstream and downstream ends of a reach may be used to determine where recent incision processes were initiated (Rosgen 2006a). An increase in BHR values with distance downstream indicates a headward (upstream) advancement in incision, whereas a decrease with distance downstream indicates incision originated upstream (Rosgen 2006a). The slight differences in BHR values at the upper and lower ends of the reach at 'Above UPRR Tie Plant', suggested that incision was initiated downstream and had advanced upstream (Appendix 2), terminating at the

exposed bedrock and low-head dam at the upper end of the reach. The direction of incision is depicted graphically in the longitudinal profile of the reach which shows a "wedge" created by the low bank and bankfull slope best fit lines (Appendix 4). The negligible change in BHR values from the upper to lower extent of each site downstream of 'Above UPRR Tie Plant' suggested no recent channel incision activity.

Channel Bed Material

Reachwide channel bed material at 'Above UPRR Tie Plant' and 'Above Laramie WWTF' was composed predominantly of gravel (D_{50} = 4 to 8 mm) in 2009 and 2010 (Appendix 9). In both years, approximately equal percentages of sand and gravel were observed reachwide at 'Below Spring Creek' (D_{50} = 2 mm), whereas the bed at 'Below Gravel Pits' was sand-dominated (D_{50} <2 mm). Temporal increases in sand were observed reachwide at all sites, with the exception of 'Above UPRR Tie Plant' where minimal change was observed in all size fractions less than the D_{84} (coarse gravel). The greatest temporal change in reachwide particle size distributions was observed at 'Above Laramie WWTF' where sand and silt content increased 19% as a result of an equivalent decrease in gravel (Appendices 9 and 10). Reachwide bed material greater than 6 mm (fine gravel) increased from 2009 to 2010 at 'Below Spring Creek' (Appendix 10), primarily as a result of sand and silt being flushed from pools. Bedrock was exposed at various locations throughout each of the three upper sites.

In gravel-bed rivers, the reachwide D_{84} represents the size of particle moved by flows approximately equal to the bankfull discharge (Andrews 1983, Leopold 1994, Rosgen and Leopold 2006), and it is often used to represent the channel roughness factor in hydraulic calculations. Reachwide D_{84} values decreased approximately 67% from the uppermost to lowermost site in 2009 and 2010 (Appendix 9), suggesting an overall reduction in competence and/or sediment transport capacity (stream power) with distance downstream. Reachwide D_{84} values at 'Below Spring Creek' increased temporally, indicating that much of the fine sediment (sand and fine gravel) stored in-channel was transported from the reach after the 2010 high flow period, thereby increasing channel roughness and the interstitial spaces in the bed substrate used by benthic organisms. An equal but less desirable temporal change was observed reachwide at 'Above Laramie WWTF' where all particles less than the D_{98} decreased in size (Appendices 9 and 10), suggesting an overall reduction in competence and/or capacity throughout the reach. A negligible amount of temporal change was observed in reachwide particle indices less than the D_{95} at the uppermost and lowermost sites.

Gravel-sized particles composed 60% to 97% of the bed substrate at all riffle cross-sections on the Laramie River during the 2009-2010 study (Appendix 9). Greater than 50% of riffle gravel at all sites consisted of particles ranging in size from 2 to 16 mm (Appendix 10). Similar to the changes in reachwide D_{84} particle sizes, mean riffle D_{50} sizes decreased with distance downstream by more than 50% from the uppermost to lowermost site. The greatest temporal change in riffle particle size distributions among sites occurred at 'Above UPRR Tie Plant' and 'Below Spring Creek', where the percentage of sand (<2 mm) increased 20% from 2009 to 2010. As a result of these increases in fine sediment, riffle D_{50} values decreased by 55% at 'Above UPRR Tie Plant' and 60% at 'Below Spring Creek'. Negligible temporal change was observed in riffle D_{50} values at the two lower sites.

The mean bar sample D_{100}, or largest particle made available from the immediate upstream supply, decreased with distance downstream by more than 50% from 50 mm at 'Above UPRR Tie Plant' to 22 mm at 'Below Gravel Pits (Appendix 9). Bar sample D_{100} sizes were slightly smaller than corresponding reachwide D_{100} values, suggesting that much of the bedload was in transit during bankfull discharge.

Channel Scour and Fill

Between 2009 and 2010, net losses in bankfull area (aggradation) were observed at all cross-sections at 'Above UPRR Tie Plant' (Appendix 12), whereas net gains in bankfull area (degradation) were observed at all cross-sections at 'Below Spring Creek'. Net change in annual bankfull area at 'Above Laramie WWTF' and at 'Below Gravel Pits' was variable; non-pool features aggraded, while pools scoured. The greatest temporal change in bankfull area among all cross-sections was measured at the pool at 'Above Laramie WWTF' where a net gain of 78 ft^2 was observed, attributed primarily to the removal of sediment stored behind a breached beaver dam removed by the 2010 flood flows (Figure 8).

While temporal changes in bed elevations at cross-sections represented channel adjustments at a local scale, differences in paired channel thalweg elevations along the longitudinal profile within each site provided insight into changes that occurred reachwide. Based on differences computed from the 2009 and 2010 longitudinal profile data sets, no appreciable net change (<0.10 ft) in average thalweg elevations occurred at any site (Appendix 12). Average thalweg elevations increased (aggraded) slightly at 'Above UPRR Tie Plant' and 'Below Gravel Pits', whereas at 'Below Spring Creek' and 'Above Laramie WWTF' they decreased (degraded) slightly. These results agreed generally with mean annual bed elevation changes observed among sites at most cross-sections.

Scour chains installed at riffle and glide cross-sections within each site in 2009 were resurveyed in 2010. The survey data collected represented scour depths and particle sizes that were entrained at flows much greater than bankfull. According to flow stage records kept by the NWS (2013) at the discontinued USGS gaging station 06660000 at Laramie, the estimated peak flow on June 14, 2010 (3,300 to 3,600 cfs) exceeded the historic peak of 3,250 cfs (41 year return period) recorded by the USGS on June 15, 1957.

Scour chain survey results showed that bed scour occurred at all riffle and most glide features (Appendix 13) during the 2010 high flow period. Mean scour depths determined from the total combined depth of scour measured at both riffles and glides were greatest at 'Below Spring Creek' (0.67 ft), followed by 'Above Laramie WWTF' (0.41 ft), 'Above UPRR Tie Plant' (0.20 ft) and 'Below Gravel Pits' (0.03 ft). Mean scour depths at riffle and glides at 'Below Spring Creek' and 'Above Laramie WWTF' were conservative estimates. Scour chains installed at the glides of each site could not be located after excavating to a depth of at least two feet below the 2010 bed surface (Figure 12). The chains at these locations were either scoured entirely from the bed or the actual scour depth was greater than the depth of excavation. Despite the record peak flows that occurred in 2010, only a negligible amount of bed scour was observed at the glide-riffle sequence at 'Below Gravel Pits' – 0.10 ft of scour was measured at only one riffle scour chain and no scour occurred at the glide.

Bed elevations at all riffle and glide scour chain installations downstream of 'Above UPRR Tie Plant' increased (Appendix 13), suggesting that the channel aggraded locally subsequent to the bed scour that

occurred during the exceptionally high peak flow event in 2010. In addition to experiencing the greatest depth of scour among sites, the greatest degree of sedimentation was measured at scour chain installations at 'Below Spring Creek' and 'Above Laramie WWTF', where mean net deposition (scour depth + change in bed elevation) at the glide-riffle sequence of each site measured 1.22 ft and 0.97 ft, respectively. Mean net deposition measured at the 'Below Gravel Pits' glide-riffle sequence was 0.21 ft. At scour chain installations 'Above UPRR Tie Plant', there was negligible change (<0.05 ft) in bed elevations at the glide, whereas the riffle bed decreased on average 0.23 ft. Mean bed elevation changes at scour chains installed at all cross-sections mirrored those observed at their corresponding thalweg stations (Appendix 4). Upon closer inspection of longitudinal profile and cross-section plots, the increases in bed elevation that occurred at the riffle-glide sequences at 'Below Spring Creek' and 'Above Laramie WWTF' appeared to be attributed primarily to sedimentation and expansion of bar features. At 'Below Gravel Pits', the bed elevation increases at the riffle and glide were attributed to a combination of sedimentation along each cross-section and a 25 ft downstream migration of the head of the riffle (Appendix 4).

Figure 12 – Searching for a scour chain installed along the glide cross-section at 'Above Laramie WWTF' on the Laramie River (2010).

Substantial decreases in maximum particle sizes measured at scour chain installations were observed both spatially and temporally throughout the Laramie River. Mean values of maximum particle sizes at riffle and glide scour chains combined decreased by more than 60% from 76 mm at the uppermost site to 29 mm at the lowermost site (Appendix 13). From 2009 to 2010, maximum particle sizes measured at all riffle and glide scour chains decreased on average 65% and 51%, respectively. The greatest interannual changes in bed substrate at scour chains were observed at 'Below Spring Creek' and 'Below Gravel Pits' where mean maximum particle sizes at riffles and glides combined decreased 73% and 70%, respectively. Decreases in the size of particles entrained annually at scour chain installations correspond to decreases in sediment competency and/or capacity (Rosgen 2006a).

Depositional Patterns

Numerous depositional features (sediment bars) typically found in unstable streams with an excess sediment supply were found at all sites on the Laramie River. As expected for Rosgen C channels, point bars were present, but most appeared to be expanding at rates that outpaced vegetation colonization (Figure 11). Point bars in stable channels typically expand at rates that approximate the rate of erosion at the outer, opposite banks of meander bends (Leopold 1994, Rosgen 1996) and do not exceed the

rates at which vegetation can colonize newly deposited sediment. Side and mid-channel bars 2-3 times longer than the bankfull channel width (Figure 7) were observed at each site. These large bar features appreciably alter the distribution of local flow velocity gradients, stream power and shear stress that cause accelerated bank erosion (Rosgen 2006a). Delta bars were present below the mouth of Spring Creek and the stormwater drainage outlet immediately upstream of 'Above Laramie WWTF', suggesting that the City of Laramie contributes excess sediment inputs to the river.

Sediment Competence & Capacity

In order for a river to maintain its dimension, pattern and profile without either aggrading or degrading, it must be competent to entrain the largest particle (D_{100} or D_{max}) supplied from its watershed and have the power or capacity to transport its sediment load (Rosgen 2006a). Sediment competency was predicted at each site on the Laramie River using both the existing D_{max} observed *within* a site and the corresponding particle made available from the *immediate upstream supply* (i.e., upstream site) at bankfull stage. Ratios of existing to predicted shear stress were used to evaluate the relative degree of sediment competence within sites, with values appreciably less than or greater than 1.0 representing insufficient shear stress (aggradation) or excessive shear stress (degradation), respectively. Existing mean riffle depth and bankfull channel slope values were also related to corresponding predicted values to evaluate competence. Comparisons of sediment competency results using D_{max} values found *within* sites to those found *immediately upstream* provided a means to evaluate the degree of change in sediment transport with distance downstream.

Sediment competence predictions for all sites indicated that the channel throughout the evaluation reach was aggrading (Appendix 14). According to predictions, bankfull flows were capable of transporting particles that were on average 18% to 59% smaller than the existing D_{max} measured *within* sites and 34% to 64% smaller than the D_{max} made available from the *immediate upstream supply*. Sediment competency at 'Below Spring Creek' was the lowest among all sites – existing shear stress was about 70% less than predicted on average during the two-year study. Existing shear stress at 'Below Gravel Pits' was on average about 30% less than predicted, whereas at 'Above UPRR Tie Plant' and 'Above Laramie WWTF' it was about 40% less than predicted. Given that the existing D_{max} at 'Below Gravel Pits' in both years was about 50% less than corresponding values at sites upstream, it was not unexpected to see that the ratio of existing to predicted shear stress was the greatest among all sites (Appendix 14).

Substantial increases in depth, slope or a combination of these and other factors would be required at all sites to achieve the shear forces necessary to mobilize the largest particles supplied by the watershed. For instance, in order for the 50 mm D_{max} particle supplied to the riffle at 'Below Spring Creek' from the reach at 'Above UPRR Tie Plant', the existing mean depth at the riffle (2.30 ft in 2010) must increase approximately 6.27 ft to achieve the predicted mean depth of 8.57 ft (Appendix 14). This increase in depth alone would be unreasonable given existing morphologic limitations and bed constraints. A more reasonable assumption would likely entail a combination of adjustments in depth, slope and width needed to achieve the necessary tractive forces required to mobilize the largest particles supplied to the reach. Similar adjustments in varying degrees would also be required within other reaches of the river depending on local morphologic conditions.

WARSSS River Stability Prediction Procedure

The RSP categorical scores, associated narrative ratings and overall sediment supply prediction assigned to each site on the Laramie River for the 2009-2010 study period are provided in Appendix 15 and are summarized in Table 4.

Lateral Stability

Laterally unstable channels exhibit an accelerated horizontal (lateral) migration rate that exceeds the natural rate across the floodplain (Rosgen 1996). For example, point bar formation on the inside of meander bends of C channels should occur at about the same rate as erosion of the opposite banks. Lateral stability is evaluated based on width-to-depth ratio, depositional and meander patterns, stream bank erosion potential and lateral confinement criteria (Rosgen 2006a).

Based on evaluations at three of the four sites, the lateral stability of the Laramie River was overall considered *'highly unstable'*. The unfavorable ratings were attributed primarily to moderate to high width/depth ratios and moderate to high risk of accelerated bank erosion along meanders and straight sections due to atypical meander and depositional patterns. An *'unstable'* rating was assigned to the channel at 'Above Laramie WWTF', which relative to the other three sites, exhibited a more stable meander pattern and overall lower potential of reachwide bank erosion.

Vertical Stability for Excess Sediment or Aggradation

The degree to which a stream is subject to sediment deposition or aggradation (increase in local base elevation of the channel bed) is evaluated using sediment competency, capacity, width-to-depth ratio, stream-type shift, depositional patterns and debris/blockage evaluation criteria (Rosgen 2006a).

All sites were assigned ratings of *'aggradation'* for this stability category. Among all sites, signs of aggradation were more apparent at 'Below Gravel Pits', which received the highest (least favorable) rating score. The poor ratings were attributed to sediment competency and capacity limitations, increases in channel width/depth, and increases in the size and frequency of depositional features.

Vertical Stability for Channel Incision or Degradation

The degree to which a stream is subject to degradation is evaluated using sediment competency, capacity, degree of channel incision, stream succession and lateral confinement evaluation criteria (Rosgen 2006a). Ratings for this category were variable with no apparent spatial change observed among sites. Minimal indicators of channel incision were observed at 'Below Spring Creek' and 'Below Gravel Pits', both of which received ratings of *'not incised'*. Ratings of *'slightly incised'* and *'moderately incised'* were assigned to the channels at 'Above Laramie WWTF' and 'Above UPRR Tie Plant', respectively. Channels at these sites exhibited the greatest degree of lateral confinement and steepest gradients among all sites, factors which likely contributed to their slightly greater sediment competence and bank height ratios. Though all sites experienced various degrees of deep channel incision in the past, indicators of recent incision (namely BHR data) were most apparent at 'Above UPRR Tie Plant' and 'Above Laramie WWTF'. Among the two categories for evaluating vertical stability, the relative influence of degradation on the overall stability of the Laramie River was less than that attributed to

aggradation. This statement is supported by the sediment competency evaluation results and measurements of net deposition at scour chain installations at each site.

Channel Enlargement

Enlargement of channels can be caused by incision and bank erosion processes, which can lead to loss of land and habitat, increased sediment supply from bed and banks, increased sediment deposition, increased water temperatures, and evolutionary shifts in stream-type (Rosgen 2006a). In contrast to expected rates of lateral erosion that occur in stable streams (i.e., the rate of point bar formation equals the bank erosion rate), channel enlargement results in accelerated lateral migration, often due to concurrent erosion along both banks. Channel enlargement is evaluated from observations of stream-type shifts and potential lateral and vertical instability (Rosgen 2006a).

The three lowermost sites received *'moderate increase'* ratings, whereas the uppermost site received an *'extensive'* rating for this stability category. The less than desirable rating scores at all sites was attributed to higher than expected W/d ratios relative to stable Rosgen C channels, a high degree of lateral instability and signs of extensive aggradation. Among sites, 'Above UPRR Tie Plant' exhibited the greatest degree of incision, which typically results in lateral instability and accelerated bank erosion.

Modified Pfankuch Channel Stability Rating

The modified Pfankuch channel stability rating is determined from numerical ratings of fifteen attributes of the upper and lower banks and channel bottom (Pfankuch 1975, Rosgen 2008). The total numerical score from all attributes is then adjusted according to the expected stream-type and assigned to one of three narrative stability ratings (Rosgen 2008). Greater numerical scores imply greater instability and sediment supply.

Pfankuch channel stability ratings of *'unstable'* were assigned to the reaches at 'Above UPRR Tie Plant' and 'Below Gravel Pits', whereas the reaches at 'Below Spring Creek' and 'Above Laramie WWTF' were rated as *'moderately unstable'*. The most influential factors that accounted for the unstable ratings included insufficient bank vegetation protection (particularly at 'Above UPRR Tie Plant' and 'Below Gravel Pits'), channel incision, lateral instability, accelerated bar development and highly mobile bed conditions (scour and deposition). Spatial and temporal changes in channel dimension, pattern, profile and bed material composition measurements among and within sites support the Pfankuch ratings.

Overall Sediment Supply Rating

Overall sediment supply ratings of *'very high'* were assigned to the 'Above UPRR Tie Plant' and 'Below Gravel Pits' (Table 4), whereas *'high'* ratings were assigned to 'Below Spring Creek' and 'Above Laramie WWTF'. Factors associated with incision processes were primarily responsible for the least favorable rating at 'Above UPRR Tie Plant', whereas the instability observed at sites downstream was attributed mostly to factors associated with aggradation (Appendix 15).

Table 4 – WARRSS river stability and sediment supply predictions for sites on the Laramie River (2009-2010). Scores ranging from 1 to 4 for each rating category are provided in parentheses '()'.

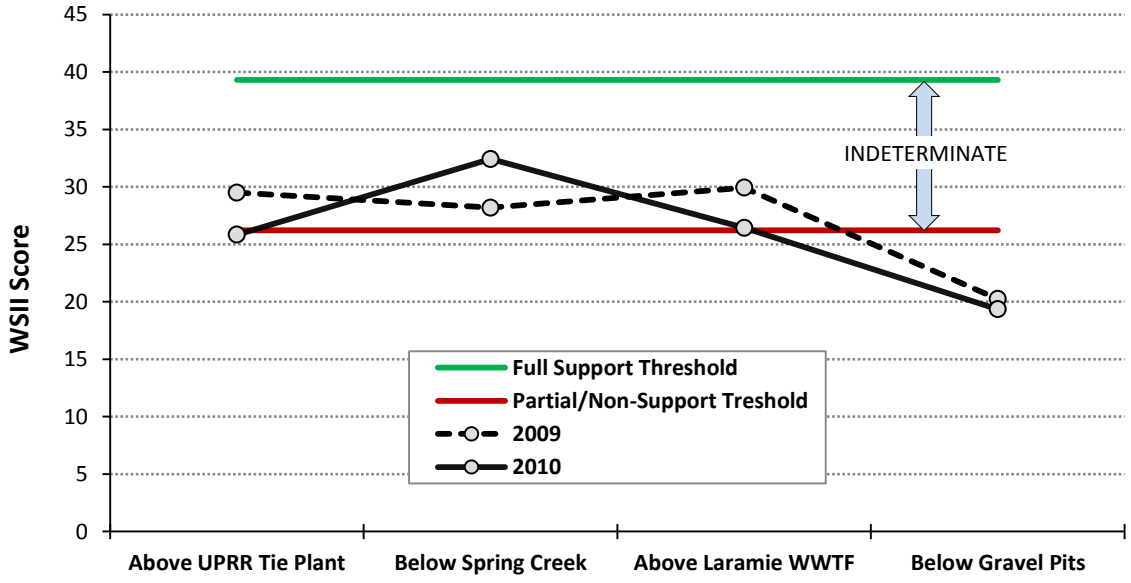
	Above UPRR Tie Plant	Below Spring Creek	Above Laramie WWTF	Below Gravel Pits
Lateral Stability	Highly Unstable (4)	Highly Unstable (4)	Unstable (3)	Highly Unstable (4)
Vertical Stability (Aggradation)	Aggradation (4)	Aggradation (4)	Aggradation (4)	Aggradation (4)
Vertical Stability (Degradation)	Moderately Incised (3)	Not Incised (1)	Slightly Incised (2)	Not Incised (1)
Channel Enlargement	Extensive (4)	Moderate Increase (3)	Moderate Increase(3)	Moderate Increase (3)
Pfankuch Channel Stability Rating	Unstable (4)	Moderately Unstable (3)	Moderately Unstable (3)	Unstable (4)
Overall Sediment Supply Prediction	**Very High (19)**	**High (15)**	**High (15)**	**Very High (16)**

BIOLOGICAL CONDITION

Wyoming Stream Integrity index (WSII)

Scores generated from the WSII Wyoming Basin bioregion model indicated that biological condition within sites varied little during the 2009-2010 study (Figure 13 and Appendix 16). In both years, WSII scores for the benthic macroinvertebrate communities at each of the three upper sites fluctuated within the mid to lower range of the indeterminate aquatic life use-support rating scale, including the 2010 score at 'Above UPRR Tie Plant', which when the model's confidence interval was applied, fell within the indeterminate category. The community at 'Below Gravel Pits' received consistent scores that fell well below the partial/non-support numeric threshold in both years.

Figure 13 – WSII scores and associated numeric thresholds used in assigning aquatic life use-support ratings to sites on the Laramie River (2009-2010).



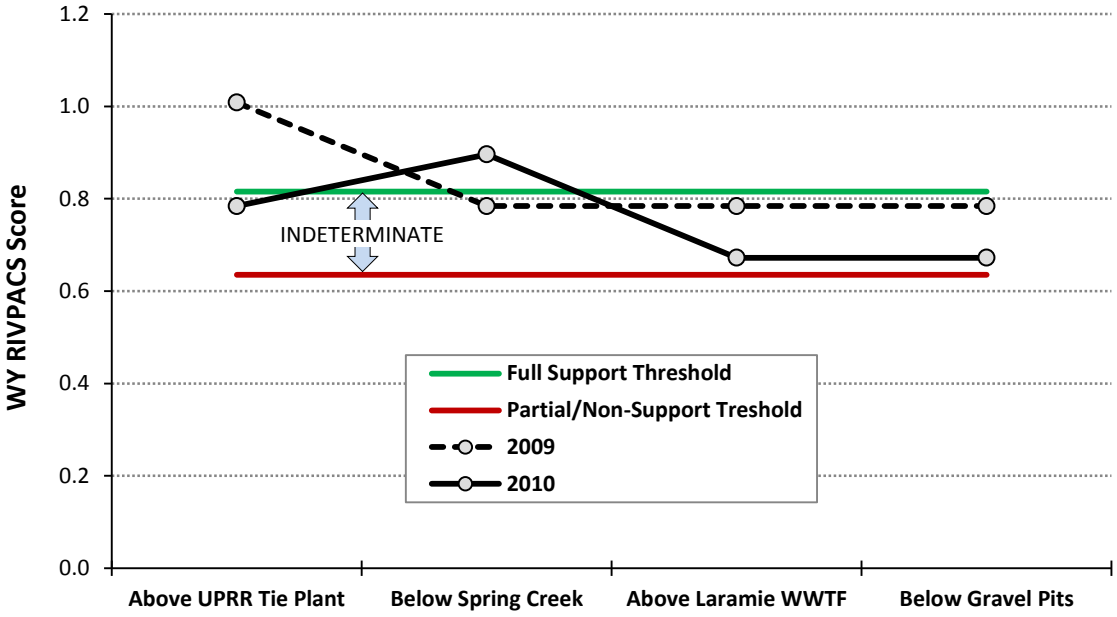
The lower WSII scores at 'Below Gravel Pits' relative to the upper three sites during the two-year study was attributed to three primary factors: 1) lower diversity and relative abundance of a discriminatory group of intolerant to moderately-intolerant Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) taxa (collectively called EPT), 2) fewer long-lived (semivoltine) taxa, and 3) greater relative abundance of taxa tolerant to environmental stressors. The increase in WSII scores at

'Below Spring Creek' from 2009 to 2010 was due entirely to a two-fold increase in the relative abundance of intolerant to moderately-intolerant EPT taxa (Appendix 16). This favorable temporal response was attributed mostly to an appreciable increase in the abundance of *Acentrella*, a moderately intolerant mayfly which accounted for 56% of the total community abundance at the site in 2010 compared to 9% in 2009 (Appendix 17). The temporal decrease in scores at 'Above UPRR Tie Plant' was attributed to a loss of four model-relevant EPT taxa, whereas the lower score at 'Above Laramie WWTF' in 2010 was attributed entirely to the absence of semivoltine taxa - a burrowing dragonfly (*Ophiogomphus*) and two aquatic beetles (*Optioservus* and *Zaitzevia*) were present at the site in 2009 (Appendices 16 and 17).

Wyoming River Invertebrate Prediction And Classification System (WY RIVPACS)

The spatial and temporal changes observed in the WY RIVPACS results (Figure 14) were similar to the WSII. The RIVPACS scores at 'Below Spring Creek' increased from 2009 to 2010; scores for remaining sites decreased between years, and generally, with distance downstream (Figure 14 and Appendix 16). In contrast to the WSII, WY RIVPACS scores at the two uppermost sites fluctuated annually above and below the full support condition threshold, whereas the two lowermost sites received indeterminate ratings in both years. Similar to the 2009-2010 WY RIVPACS results, indeterminate ratings were assigned to two benthic macroinvertebrate communities sampled in 1996 on the Laramie River at site WBI15, immediately upstream of 'Below Spring Creek', and WBI20, immediately upstream of 'Above Laramie WWTF' (Figure 5). In 2000, the macroinvertebrate community sampled at site WBI26, just upstream of 'Below Gravel Pits' (Figure 5), was assigned a partial/non-support rating based on a low O/E score of 0.448. (Note: The WSII model could not be used evaluate the community data collected in years prior to 2009 because samples were not collected using the Surber sampling method).

Figure 14– WY RIVPACS scores and associated numeric thresholds used in assigning aquatic life use-support ratings to sites on the Laramie River (2009-2010).



From 'Above UPRR Tie Plant' to 'Below Gravel Pits', there was a 22% and 11% loss of common expected taxa (>50% probability of occurrence- see Hargett 2012) in 2009 and 2010, respectively. Taxa expected to occur at all sites but not observed during the study period, included damselflies within the family Coenagrionidae, the aquatic beetle *Microcylloepus*, and *Hemerodromia* within the order Diptera (Table 5). Despite the absence of three expected taxa at 'Above UPRR Tie Plant' in 2009, the site nonetheless supported a community that was comparable to the expected condition. The improvement in the WY RIVPACS score in 2010 at 'Below Spring Creek' was attributed to the occurrence of *Fallceon quilleri* and the black fly *Simulium*), both of which were absent from the 2009 community (Table 5).

Table 5 – Expected taxa with ≥50% probability of capture observed ('X') at Laramie River sites (2009-2010).

	Taxa Group	Taxon	Probability of Capture	Above UPRR Tie Plant WB0321		Below Spring Creek WB0322		Above Laramie WWTF WB0323		Below Gravel Pits WB0324	
				2009	2010	2009	2010	2009	2010	2009	2010
Non-Insects	Oligochaeta (aquatic worms)	Naididae	0.64	X	X	X	X	X	X	X	X
	Amphipoda (shrimp)	*Hyalella*	0.57	X							
	Acari (water mites)	Acari	0.93	X	X	X	X	X	X	X	X
Insects	Coenagrionidae (damselflies)	Coenagrionidae	0.50								
	Ephemeroptera (mayflies)	*Fallceon quilleri*	0.50		X		X		X		
		Tricorythodes	0.86	X	X	X	X	X	X	X	X
	Trichoptera (caddisflies)	*Cheumatopsyche*	1.00	X	X	X	X	X	X	X	
		Hydropsyche	0.86	X	X	X	X		X		X
	Coleoptera (beetles)	*Dubiraphia*	0.71	X	X	X	X				
		Microcylloepus	0.50								
		Optioservus	0.57	X		X	X	X		X	
	Non-midge Diptera	*Hemerodromia*	0.50								
		Simulium	0.93	X	X		X	X	X	X	X
	Chironomidae (midge flies)	*Rheotanytarsus*	0.50	X	X	X	X	X	X		X
		Thienemannimyia	0.57	X				X	X	X	X

The temporal decrease in WY RIVPACS scores at 'Above Laramie WWTF' and 'Below Gravel Pits' was attributed to an 11% loss of expected taxa at each site (Figure 14). In addition to the absence of the expected Coenagrionids and *Microcylloepus,* the aquatic beetle *Dubiraphia* and the freshwater shrimp *Hyalella* were missing from both sites each year (Table 5). These missing taxa exhibit moderate-to-high tolerances to environmental stressors (Appendix 17) and are commonly found in depositional environments along stream margins with emergent vegetation used for reproduction and cover (Merrit and Cummins 1996, Ward 1992). Also notable was the periodic absence of the caddisflies *Cheumatopsyche* (2010) and *Hydropsyche* (2009) at 'Below Gravel Pits'. *Cheumatopsyche,* typically observed in relatively high abundance throughout the Laramie River, was one of the top five dominant taxa at 'Below Gravel Pits' in 2009, but in 2010 it was absent from the community. Both *Cheumatopsyche* and *Hydropsyche* are generally tolerant to increases in fine sediment and nutrient enrichment provided that sufficient coarse substrate (fine gravel to cobble) is available for constructing their retreats and nets from which they filter organic detritus (Relyea et al. 2000, Ward 1992). They are usually some of the last EPT taxa found in abundance as water quality declines (Barbour et al. 1999).

Aquatic Life Use Decision Matrix

Based on the combined WSII and WY RIVPACS ratings and application of the aquatic life other than fish use-support decision matrix (WDEQ/WQD 2014a), biological condition in the Laramie River generally declined with distance downstream in both 2009 and 2010. Because of the annual variability in WY RIVPACS scores at 'Above UPRR Tie Plant' and 'Below Spring Creek', the overall aquatic life use-support ratings assigned to each site differed between years (Appendix 16). The benthic macroinvertebrate community at 'Above UPRR Tie Plant' was assigned a full-support rating in 2009 and a partial/non-support rating in 2010 (primarily due to a 22% loss of expected taxa). At 'Below Spring Creek', the

aquatic life use rating improved from indeterminate in 2009 to full support in 2010, suggesting an attenuation of environmental stress at the site. The aquatic life use-support assignments for communities at 'Above Laramie WWTF' and 'Below Gravel Pits' were temporally consistent, with ratings of indeterminate and partial/non-support (Appendix 16), respectively. The overall aquatic life use ratings assigned to sites suggested that environmental stressors in the Laramie River increased considerably with distance downstream of 'Above Laramie WWTF'.

Selected Benthic Macroinvertebrate Metrics

A select number of diagnostic metrics were reviewed to evaluate spatial and temporal biological changes in the benthic macroinvertebrate community at each site on the Laramie River. Several relevant measures of taxa richness, composition, functional feeding-group, pollution tolerance, habit (mode of locomotion, attachment or concealment) and life cycle suggested that benthic fauna were likely subjected to stressors associated with sedimentation, bed scour and nutrient enrichment, which tended to increase in severity with distance downstream. Benthic macroinvertebrate taxa and abundance data for each site are provided in Appendix 17 and select metric results are presented in Appendix 18.

Total Number of Taxa

The total number of distinct taxa is one measure of the diversity or richness of a community. Generally, taxa richness is positively correlated with niche space, habitat heterogeneity and food resources required to support survival and propagation of many species (Barbour et al. 1999). The diversity of the benthic macroinvertebrate assemblage in the Laramie River during the 2009-2010 study decreased overall with distance downstream from an average of 33 taxa at the uppermost site to 24 taxa at the lowermost site. Among all sites, the community at 'Below Spring Creek' exhibited the greatest diversity (44 total taxa in 2009). With the exception of 'Below Gravel Pits', each site lost at least five taxa from 2009 to 2010. Both spatial and temporal decreases in total taxa numbers between sites were attributed partly to losses in Ephemeroptera and Trichoptera taxa, most of which were intolerant organisms. Within the Ephemeroptera alone, the number of taxa decreased by more than 50% from the uppermost (6-8) to lowermost (2-3) sites in both years.

Taxa Dominance

The relative abundance of dominant taxa is a simple measure of community balance or evenness, with a community dominated by only a few taxa indicative of environmental stress (Barbour et al. 1999). The relative abundance of the top five dominant taxa observed at each site indicated that the benthic macroinvertebrate assemblage in the Laramie River became less balanced with distance downstream. Based on average annual values, five taxa dominated about 60% of the community at 'Above UPRR Tie Plant' relative to 80% at 'Below Gravel Pits'. Relative abundance values for the top five taxa within sites were greater in 2010 than in 2009, suggesting a corresponding temporal increase in stressor response. *Acentrella* was the dominant taxon found at all sites in at least one of the two years of study. This mayfly composed more than 40% of the community at 'Above Laramie WWTF' in both years and at 'Below Spring Creek' and 'Below Gravel Pits' in 2010. Other dominant taxa and taxa groups repeatedly observed at sites in both years included *Tricorythodes*, *Simulium, Cheumatopsyche*, oligochaetes (aquatic worms) and gastropods (snails). The 100-fold increase in the relative abundance in

oligochaetes at 'Below Gravel Pits' from 2009 to 2010 is particularly noteworthy. Oligochaetes are very tolerant of organic pollution and fine sediment (Barbour et al. 1999).

Life Cycle Relationships

The ratio of multivoltine (several life cycles per year) taxa to the combined total of univolitine and semivoltine (life cycles of one or more years) taxa is a measure used to provide insight into the relative stability of the aquatic environment available to benthic macroinvertebrates. A community composed primarily of multivoltine taxa may indicate that chronic environmental perturbations disrupt the life cycles of long-lived organisms (Stribling et al. 2000, Barbour et al. 1999). Based on mean annual ratios of short-lived to long-lived taxa, the three upper sites supported relatively balanced communities with respect to voltinism (ratios of 1 to 1.25). At 'Below Gravel Pits' organisms with short-term residence periods were predominantly favored, outnumbering long-lived taxa by about 2 to 1.

Acentrella

With the exception of the two upper sites and the lowermost site in 2009, the mayfly *Acentrella* (formerly *Pseudocloeon* within the family Baetidae) was the dominant taxon in the Laramie River. Habitat conditions at 'Above Laramie WWTF' were particularly favorable to *Acentrella,* as it accounted for about 60% of the total sampled benthic macroinvertebrate community during the two-year study. *Acentrella* densities increased by more than 10% within sites from 2009 to 2010, with the greatest temporal increase (47%) observed at 'Below Spring Creek'. Species of the *Acentrella* genus are wide-spread, short-lived collector/gatherers that feed on particulate organic matter (Merritt and Cummins 1996). Their primary mode of locomotion is by drift and swimming, an opportunistic behavior which allows them to move about freely between food sources in the erosional stream environments they inhabit (Merritt and Cummins 1996). They are somewhat intolerant to stressors in general (Barbour et al. 1999), but are more tolerant to fine sediment (<2 mm) than other mayflies (Lenat et al. 1979, MNHP 2014). Because of their short-term reproductive rates and mode of dispersal, Baetids such as *Acentrella* are considered to have competitive advantages over long-lived sessile taxa in exploiting disturbed habitats more rapidly after bed disturbances (Culp and Davies 1983, Erman and Mahoney 1983, Hess 1969, Wallace and Gurtz 1986).

Tricorythodes

Tricorythodes was another prominent member of the mayfly community in the Laramie River and one of the top 5 dominant taxa found at all sites in at least one of the two years of study. Though there was no evident spatial pattern among sites, the relative abundance of *Tricorythodes* at three of the four sites decreased by about 10% from 2009 to 2010, with a temporal increase of 5% observed at 'Above Laramie WWTF'. *Tricorythodes* are wide-spread generalists that inhabit stable gravel and sand-dominated channels and are tolerant to a wide-range of environmental conditions (Ward 1992). They thrive in streams with low to moderate levels of human disturbance and may increase as a result of short-term sedimentation (Gray and Ward 1982, Winget and Mangum 1991, Ward 1992). However, some data suggest *Tricorythodes* may decline with more severe levels of sedimentation (CSB 2002). The variable bed scouring and sedimentation that occurred at most sites during the 2010 record flows likely played a large role in the temporal changes observed in *Tricorythodes* densities.

Collector-Gatherers and Filterers

Collector-gatherers and filterers are organisms that feed predominantly on particulate organic matter deposited on or trapped within fine sediment and detritus (gatherers) or in suspension (filterers). They can be a common component of benthic macroinvertebrate communities in some streams (Merritt and Cummins 1996). Human activities that appreciably increase the amount of fine sediment or organic matter in streams may result in a community shift that favors the success and dominance of collector-gatherers and filterers (Barbour et al. 1999, Ward 1992). Collector-gatherer taxa found in relatively high abundance in the Laramie River included oligochaetes, snails, midge fly larvae and the mayflies *Acentrella* and *Tricorythodes*. Dominant filterer taxa included the caddisfly *Cheumatopsyche* and the black fly *Simulium*. During the 2009-2010 study, the combined relative abundance of collector-gatherer and filterer taxa in the river increased progressively with distance downstream from 69% at 'Above UPRR Tie Plant' to 90% at 'Below Gravel Pits'.

Within all sites, the relative abundance of collector-gatherers increased from 2009 to 2010, whereas filterer densities fluctuated. At 'Below Gravel Pits' for example, the relative abundance of collector-gatherers increased 41% from 2009 to 2010, but filterers decreased 33%. The highly mobile bed conditions observed throughout the Laramie River were likely responsible for the compositional shifts in these two functional feeding groups. Relative to the predominantly immobile filterer taxa, such as *Cheumatopsyche* and *Simulium*, the dominant collector-gatherers had modes of dispersal that included swimming (*Acentrella*), sprawling (*Tricorythodes*) and burrowing (oligochaetes), all adaptations which would be advantageous to thrive in a chronically unstable channel bed environment.

Selected Periphyton (Diatoms) Metrics

Like macroinvertebrates, diatoms are useful indicators of water quality condition. As primary producers they are responsive to environmental perturbations, particularly physical disturbances to the channel bed and nutrient enrichment. Several diatom metrics provided additional evidence that the magnitude of environmental stressors at sites on the Laramie River increased with distance downstream during the 2009-2010 study. Resident benthic diatom communities appeared to be subjected to stress associated with sedimentation and nutrient enrichment in the form of both inorganic and organic nitrogen. Despite inferences of nutrient enrichment, diatom metrics diagnostic of dissolved oxygen conditions indicated that episodes of depressed oxygen concentrations were infrequent. Diatom taxa and abundance data for each site are provided in Appendix 19 and select metric results are presented in Appendix 20.

***Achnanthidium minutissimum* (synonym- *Achnanthes minutissima*) –** The mean relative abundance of this diatom increased appreciably from 3% at 'Above UPRR Tie Plant' to 18% and 21% at the two successive sites downstream, then decreased abruptly to 5% at 'Below Gravel Pits' during the two-year study. It was consistently the dominant or second-most dominant species at 'Below Spring Creek' and 'Above Laramie WWTF' in both years, and one of the top five dominant species at 'Below Gravel Pits' in 2009. *Achnanthidium minutissimum* is very widespread and abundant in waters with low to moderate concentrations of organic pollution and commonly found in streams contaminated by heavy metals (Kelly et al. 2005). It prefers a nitrogen or phosphorus-rich environment (Stevenson et al. 1991) and is usually present in high densities on recently scoured substrate (Peterson and Stevenson 1990). Often

one of the first species to colonize a recently scoured site, the relative abundance of *A. minutissimum* has been found to be directly proportional to the time elapsed (lag response) since the last scouring flow or episode of chemical insult (Barbour et al. 1999). It is non-motile and has a prostrate growth form (Potapova 2009), which presumably gives it an adaptive advantage over other diatoms in benthic habitats susceptible to chronic scour. Despite its tolerance of bed scour, *A. minutissimum* is considered intolerant to environmental stress in general (Bahls 1993). As a consequence of this categorization and its proliferation in most waters, *A. minutissimum* may skew the results of metrics diagnostic of specific stressors.

Cocconeis and Rhoicosphenia abbreviata – These diatoms were among the top five dominant taxa found at all sites. Among the three upper sites, mean relative abundances of *Cocconeis* diatoms during both years were comparably similar at 5% to 8%, but increased to 28% at 'Below Gravel Pits'. The dominant *Cocconeis* species typically found at all sites was *C. placentula*, which also happened to be the dominant taxon found at 'Below Gravel Pits' in both years. Among the three upper sites, mean relative abundances of *Rhoicosphenia abbreviata* were comparable (1% to 5%) in both years. At 'Below Gravel Pits' *R. abbreviata* was one of the top three dominant taxa, accounting for 19% of the diatom community on average during the two-year study.

Cocconeis placentula is a widely distributed, fast-growing, early colonizer of bare substrates (algae, rock and sand) and is relatively resistant to scour and selective grazing by nature of its adnate growth habit (Kelly et al. 2005). It is non-motile, responds very favorably to phosphorus enrichment (McCormick and Stevenson 1989), yet is considered intolerant to pollution in general (Kelly et al. 2005). Taxonomic and ecological descriptions provided for *R. abbreviata* (Kelly et al. 2005) indicate that it also exhibits a growth form and tolerance to environmental stressors similar to *Cocconeis*. The dominance of both *C. placentula* and *R. abbreviata* at 'Below Gravel Pits' affected the results of other metrics at the site as described below.

Epithemia – *Epithemia* diatoms are considered nitrogen-autotrophs (capable of fixing atmospheric nitrogen via blue-green algae that live within the cell). They typically decrease in response to increases in organically-bound nitrogen (Potapova and Charles 2007) and are typically attached to macrophytes and other firm substrate (Kelly et al. 2005). During both years of study, an abrupt decrease in the mean density of *Epithemia* was observed with distance downstream from 10% at 'Above UPRR Tie Plant' to 1% at 'Below Spring Creek' to <1% at 'Above Laramie WWTF'. *Epithemia* was not found in either year at 'Below Gravel Pits'. Considering the low macrophyte densities (≤1% at riffles) and highly mobile bed conditions observed throughout the Laramie River during the study, it could be inferred that changes in nitrogen content influenced densities of *Epithemia* more so than substrate characteristics.

Navicula + Nitzschia – Relative abundances of *Navicula* and *Nitzschia* typically increase in response to nutrient enrichment, excess sediment and/or salinity (Pan et al. 1996, Van Dam et al. 1994). The mean combined relative abundance of *Navicula* and *Nitzschia* increased gradually with distance downstream from 13% at 'Above UPRR Tie Plant' to 25% at 'Above Laramie WWTF', then dropped to 14% at 'Below Gravel Pits'. *Nitzschia* species that were conspicuous at the three lower sites, and typically among the top five dominant taxa found at each site, included *N. dissipata, N. inconspicua* and *N. palea*. All of

these species are tolerant of very heavy organic pollution (Kelly et al. 2005). *Navicula* and *Nitzschia* taxa are capable of moving freely through fine sediment deposits, thus increases in the total abundance of these genera is also thought to reflect the amount and frequency of siltation (Barbour et al. 1999).

Nitrogen-Uptake Metabolism – Diatoms categorized as obligate nitrogen-heterotrophs, high organic nitrogen-autotrophs and facultative nitrogen-heterotrophs can tolerate elevated concentrations of organic nitrogen and tend to increase in response to severe, chronic and episodic organic enrichment, respectively (Van Dam et al. 1994). The mean relative abundance of all three of these trophic categories combined was comparable among sites (73% to 80%). The greatest temporal change in the mean total abundance of the three categories was observed at 'Below Gravel Pits' where densities increased from 70% in 2009 to 90% in 2010. Among the three categories, high organic nitrogen-autotrophs were the dominant group, accounting for more than 60% of the total diatom density at each site in both years. The mean relative abundance of low organic nitrogen-autotrophs, diatoms that tend to decrease in response to increasing levels of organically-bound nitrogen (Van Dam et al. 1994), decreased steadily with distance downstream from 13% at 'Above UPRR Tie Plant' to 3% at 'Below Gravel Pits'.

Trophic State – Eutraphentic and hypereutraphentic diatoms (taxa tolerant to high and very high concentrations of inorganic nutrients, respectively) increase in relative abundance with the severity of nutrient-related stressors (Fore 2003, Hill et al. 2000, Van Dam et al. 1994). The mean relative abundance of eutraphentic and hypereutraphentic taxa combined, decreased with distance downstream at the three upper sites from 64% to 42%, but then increased abruptly to 80% at 'Below Gravel Pits'.

Oxygen Conditions – The relative abundance of diatoms that commonly occur in waters with dissolved oxygen saturation levels that are very low (around 10%) to low (30% to 50%) typically increase in proportion to the severity of nutrient-related stressors (Van Dam et al. 1994). These taxa combined accounted for less than 10% of the total diatom abundance at all sites in both years, suggesting that episodes of depressed oxygen levels in the river were infrequent.

Pollution Tolerance – The abundance of intolerant (sensitive) diatom taxa is expected to decrease in response to increases in general environmental stress (Barbour et al. 1999, Fore 2003). Contrary to this expectation, the mean relative abundance of sensitive taxa in the Laramie River increased steadily with distance downstream in both years from 48% at 'Above UPRR Tie Plant' to 72% at 'Below Gravel Pits'. The downstream increases in the abundance of sensitive taxa were largely attributed to corresponding increases in *A. minutissimum, C. placentula* and *R. abbreviata* and decreases in the moderately tolerant *Diatoma moniliformis*. All of these species were among the top five dominant diatoms observed at all sites in at least one of the two years of study. Because the pollution tolerance metric is an indicator used to assess general stressors overall, its diagnostic capability in identifying specific stressors is limited relative to the individual taxonomic metrics.

Siltation Index – This index evaluates the combined relative abundance of 28 diatoms that have been shown to increase in response to increased sedimentation from fine sediment (Bahls and Teply 2005, Bahls 1993, Fore and Grafe 2002). Higher index scores (0 to 100) represent proportional increases in siltation. Mean scores for this metric over the two year study were relatively low (<30), suggesting that

levels of fine sediment (<2 mm) deposition were not excessive. However, mean scores increased marginally with distance downstream from 15 at 'Above UPRR Tie Plant' to 29 at 'Above Laramie WWTF', followed by a score of 21 at 'Below Gravel Pits'. Relative differences in scores among sites were influenced entirely by fluctuations in the densities of *Navicula* and *Nitzschia* species. Mean relative abundances of *Navicula* and *Nitzschia* combined at 'Below Spring Creek' and 'Above Laramie WWTF' (20% and 25%, respectively) were suppressed to a limited degree by the dominance of *A. minutissimum*, whereas at 'Below Gravel Pits' their combined mean density (14%) was reduced by the dominance of *C. placentula* and *R. abbreviata*.

Heavy Metal Index – This index evaluates the percent relative abundance of 14 diatom genera that increase in response to metal toxicity (Bahls 1993). Increases in index scores represent proportional increases in the severity of metal toxicity. Mean scores for this metric were low at all sites and increased marginally with distance downstream from 5 at 'Above UPRR Tie Plant' to values of 8 to 9 at the three lower sites during the two-year study. All scores suggested that the river's periphyton community was subjected to negligible stress associated with metal toxicity.

Salinity Index – The mean relative abundance of diatoms tolerant to brackish (high salinity) water was low (<2%) and comparable among all sites in both years. The abundance of brackish diatoms tends to increase in response to increased salinity (Fore 2003, Van Dam et al. 1994).

DISCUSSION

CHEMICAL QUALITY

With the exception of the instantaneous water temperature of 20.4°C measured in 2009 at 'Above UPRR Tie Plant', temperature readings at all sites on the Laramie River and Spring Creek during the 2009-2010 study were less than the maximum criterion of 20°C protective of a Class 2AB cold-water game fishery (WDEQ/WQD 2013a). The slight downstream decrease in water temperatures observed in the Laramie River each year was most likely due to the relative differences in discharge, air temperature and the degree of insolation at each site when measurements were made. These same factors were also likely responsible for the lower water temperatures observed at all sites on the Laramie River in 2010 compared to 2009. The downstream increase in water temperature in Spring Creek in 2009 may have been partly attributable to inflows of warm water from the urban stormwater drainage system (e.g., rainfall and lawn irrigation water runoff from streets and parking lots).

Field-measured pH values were within the target range of 6.5 to 9.0 standard units (WDEQ/WQD 2013a) at all sites on the Laramie River and Spring Creek during the study period. Other than minor differences in pH values among sites, most likely attributed to changes in temperature and photosynthetic activity of algae and aquatic vegetation, no spatial change was evident. Temporal differences in the photosynthetic activity of aquatic plants and algae were most likely responsible for greater pH values observed at all sites in 2009 relative to values measured in 2010.

Instantaneous dissolved oxygen concentrations at all sites on the Laramie River and Spring Creek in 2009 and 2010 were greater than the one-day 4.0 mg/L minimum criterion protective of cold-water fish adult

life stages and generally no less than 1 mg/L below the 8.0 mg/L minimum criterion protective of corresponding early life stages (WDEQ/WQD 2013a). Supersaturated dissolved oxygen levels were observed at all Laramie River sites in 2009 and at both sites and years on Spring Creek, presumably attributed to oxygen production from plant and algae photosynthesis. Though dissolved oxygen concentrations at Laramie River sites in 2010 were less than the instantaneous cold-water fish early life stage minimum, their corresponding % saturation levels were well above elevation-dependent values. Inferences drawn from select diatom metrics further suggested that episodes of oxygen depletion did not occur at any Laramie River site during the study.

Though Wyoming does not have numeric criteria for nitrogen and phosphorus to protect fisheries and other aquatic life uses, nutrient enrichment is a concern in both the Laramie River and Spring Creek. In the ten years prior to the 1996 303(d) listing, elevated concentrations of nitrogen and phosphorus were recorded on a regular basis in the Laramie River at USGS station 06660070 Above Howell, WY (period-of-record 1980–1989), immediately downstream of the City of Laramie WWTF effluent. Additionally, exceedances of WDEQ/WQD aquatic life chronic criteria for ammonia were documented on two separate occasions in 1989 at station 06660070. Based on the less restrictive ammonia criteria currently in place, however, these values were well below levels considered toxic. Nonetheless, elevated levels of ammonia measured at the time indicated a relatively high degree of nutrient enrichment was occurring in the river.

Concentrations of TP and TN in the Laramie River in both 2009 and 2010 increased with distance downstream by more than an order of magnitude from the uppermost site to lowermost site. The greatest increases were observed between the two lowermost sites, which were intended to represent water quality conditions above and below the City of Laramie WWTF effluent inflows. From 'Above Laramie WWTF' to 'Below Gravel Pits', mean annual concentrations of TN and TP increased by more than 7-fold and 45-fold, respectively. Concentrations of N+N, a readily bioavailable form of inorganic nitrogen, were more than 20 times greater each year at 'Below Gravel Pits' than corresponding levels at 'Above Laramie WWTF'. Levels of N+N at 'Below Gravel Pits' were four to five times greater than total Kjeldahl levels, indicating that inorganic nitrogen was present in excess of what could be fully assimilated into organic forms. With the exception of the high levels of phosphorus and nitrogen observed at 'Below Gravel Pits', mean annual nutrient concentrations at the three upper Laramie River sites were comparable to regional reference levels. The higher levels of nitrogen and phosphorus measured in the river in 2010 relative to those in 2009 were presumably due to a greater influx of nutrients to the river in response to the previous record spring flooding and above normal summer precipitation in the region.

Inflows from Spring Creek appeared to contribute a substantial amount of inorganic nitrogen to the Laramie River. During the study period no detectable amounts of N+N were observed in the river above the Spring Creek confluence, but below the confluence about one-third of the total nitrogen in the river consisted of N+N, at concentrations 1.5 to 3.5 times greater than the regional reference level. Greater than 90% of the total nitrogen in Spring Creek in 2009 and 2010 was composed of N+N, with concentrations that were 20 to 35 times greater than the mean regional reference concentration of 74 µg/L. Nitrate+nitrite-N concentrations at all sites on the Laramie River and Spring Creek during the two-

year study were less than the applicable numeric human-health drinking water and fish consumption criterion of 10,000 µg/L for Class 2AB waters (WDEQ/WQD 2013a).

Not all forms of phosphorus are bioavailable, though it is commonly accepted that TP concentrations >100 µg/L are unacceptably high due to the deleterious influence that excessive phosphorus loading can have on aquatic ecosystems (Dodds et al. 2002, Redfield 1934, Spruill et al. 1998, Vollenweider 1971). Total phosphorus concentrations at 'Below Gravel Pits' were four to seven times greater than this target level in 2009 and 2010, respectively. In contrast, TP concentrations at the three upper Laramie River sites and at both sites on Spring Creek were well below the 100 µg/L target level. Ratios of TN:TP at the three upper Laramie River sites ranged from approximately 20 to 53, compared to the much lower ratios of 6 and 7 at 'Below Gravel Pits' in 2009 and 2010. Similar to the findings at the three upper Laramie River sites, concentrations of TN in Spring Creek were comparatively much greater than TP by more than two orders of magnitude. These results combined with the substantial increase in nutrient concentrations downstream of 'Above Laramie WWTF' suggested that nutrient enrichment in this reach of the Laramie River could potentially result in adverse alterations to the aquatic biota.

Relatively high TN:TP ratios typically indicate that without any additional inputs of phosphorus, aquatic plants and algae may not readily assimilate the available nitrogen. This correlation was validated to a certain degree at the three upper Laramie River sites where the growth of aquatic macrophytes and filamentous algae within the reach of each site was not excessive (Appendix 1). However, despite the ample and readily-bioavailable mixture of inorganic nitrogen and phosphorus found at 'Below Gravel Pits' each year, instream vegetative growth in the reach was similar to that observed at upstream sites. The absence of excessive vegetative growth at 'Below Gravel Pits' was not unexpected though, considering that the site's highly mobile sand substrate did not provide a firm, stable bed for filamentous algae to attach and aquatic plants (macrophytes) to root. Any vegetation that does establish at the site would be periodically subjected to scour and sedimentation, placing limits on the long-term establishment and full expression of algal and macrophyte growth that typically accompanies high nutrient loading.

Based on measurements of conductivity, TDS concentrations in the Laramie River and Spring Creek increased with distance downstream in both years of study. The greatest spatial changes in solute levels in the Laramie River occurred at sites downstream of the Spring Creek and City of Laramie WWTF inflows. Increases in conductivity and total hardness among sites were driven primarily by increases in sulfate and calcium, which were dominant ions in both waters. Relative to regional reference levels, concentrations for both of these analytes were greater than expected. Similar spatial changes in chloride concentrations were observed, though values were well below the applicable chronic aquatic life criterion of 230 mg/L (WDEQ/WQD 2013a).

The dominance of both sulfate and calcium ions and the relative differences observed in their concentrations and salinity among sites on both the Laramie River and Spring Creek appeared to be largely governed by interactions of their source waters with the surrounding sedimentary geology and alkaline/saline soils. The predominant source of sulfate and calcium in both waters is most likely the gypsum-bearing formations found in the nearby foothills of the basin (Table 2). Other sources of

calcium (and magnesium) that contribute to hard water conditions in the drainage include the limestone and dolomite formations found in the basin. Concentrations for all the constituents measured at all sites on the Laramie River were greater in 2010 than in 2009, despite moderate differences in the flow measured each year. For instance, the flow at 'Below Spring Creek' in both years was virtually the same, yet conductivity was nearly twice as high in 2010 as it was in 2009. These data suggested that there was a large influx of solutes to the river in 2010, rather than changes associated with dilution effects. The above normal precipitation received in the region in 2010 saturated soils which may have leached more solutes to surface waters than would have occurred under drier conditions. In addition to natural source contributions, salts and minerals from anthropogenic sources contribute to the total solute load in the Laramie River and Spring Creek, including point source discharges, urban stormwater drainage, diffuse inputs from irrigated lands and sediment originating from streambank and upland erosion. Though solute levels were elevated relative to regional reference levels, they were typical of levels observed in other large basin rivers in southeastern Wyoming (Bartos et al. 2006).

Total and/or dissolved concentrations of arsenic, cadmium, copper and selenium in both the Laramie River and Spring Creek in 2009 and 2010 were well below their respective human health and chronic aquatic life use criteria (WDEQ/WQD 2013a). Water hardness levels in the Laramie River and Spring Creek were high enough to exclude chronic toxicity by most metals. No detectable amounts of synthetic organic compounds were found in any of the SVOC samples collected at sites on the Laramie River. Other water quality measurements made at sites either met applicable numeric and narrative criteria, or were comparable to regional expectations given the existing climate, flow regime, soils, geology and other basin characteristics.

PHYSICAL CONDITION

Major disruption to a river's natural morphology such as channelization, encroachment, changes in vegetation and alterations to flow regime and/or sediment supply can disrupt multiple, interrelated fluvial processes that result in predictable changes in channel morphology and sediment transport (Arnold et al. 1982, Booth 1990, Lane 1955, Leopold 1994, Rosgen 2006a, Schumm 1969, Simon 1989). Rivers that fully support their designated aquatic life uses are considered biologically functional, have minimal physicochemical ailments, and invariably, are physically stable fluvial environments. Terms such as channel stability and dynamic equilibrium are often used to describe streams and rivers that, over time and in the present climate, maintain a form to accommodate the wide range of flows and sediment produced by their watersheds without either aggrading or degrading (Leopold 1994, Rosgen 2006a).

Rivers that maintain a balance between erosion and sediment deposition exhibit a morphology that does not vary appreciably over time nor experience the erratic behavior observed in unstable rivers. Any disruption to flow and/or sediment supply ultimately affects channel stability. Natural sediment inputs occur gradually over time and can be incorporated by stream processes into non-destructive forms and quantities (Waters 1995) that do not appreciably compromise channel stability and sediment transport functions. It is *excess* sediment, caused by anthropogenic disturbances and land use changes that can overwhelm the assimilative capacity of the river and result in long-term channel instability and

alter aquatic ecosystem functions. Excess sediment not only negatively impacts the survival and reproduction of aquatic life, but also interferes with surface water supply intakes and irrigation diversions, damages road infrastructure, and ultimately results in the loss of land and other property through accelerated erosional processes and increased flooding.

Several indicators of excess sedimentation, channel enlargement and accelerated lateral erosion were evident throughout and upstream of the Laramie River evaluation reach during the 2009-2010 study. Excess sediment deposition is often manifested in the expansion of point bar features and the development of mid-channel, transverse, delta and side bars (Barbour et al. 1999, Rosgen 2006a, Schumm 1977), all of which were observed at each study site. The expansion and development of depositional features appreciably alters local flow velocity gradients and stream power, creating a disproportionate distribution of energy in the near-bank region of the channel which ultimately accelerates bank erosion and lateral channel migration rates (Rosgen 2006a, 2008). Observations of accelerated bar development and growth, in addition to indicators of lateral instability and channel enlargement, documented in the WARSSS RSP evaluations of each site indicated that the river had the potential to generate a high to very high sediment supply. Several lines of quantitative evidence from morphologic and hydraulic analyses supported these predictions. The strongest quantitative evidence supporting the claim that excess sediment was compromising channel stability in the river came from observed temporal and spatial changes in channel dimension, bed elevation (scour and fill), bed material composition, sediment competence and bank erosion.

The greatest changes in channel dimension occurred at the three lowermost sites where indicators of excess sedimentation were most apparent. Bed elevation changes measured at riffle and glide scour chain installations (Appendix 13) indicated that flows equal to or greater than bankfull stage were capable of mobilizing a large portion of the bed sediment stored in-channel, thereby increasing cross-sectional area in the short term. Much of the gains in bankfull channel area acquired during peak flow were lost, however, as flows receded and sediment was redeposited. With the exception of 'Below Spring Creek', cross-sectional area at riffles and glides of each site decreased (range: -1 to -16 ft^2) from 2009 to 2010. Within some sites, maximum scour depths of 2.0 ft were observed, followed by an equal amount of deposition. In these cases, the resultant difference in bed elevation between the 'scoured' channel and channel subsequent to scour amounted to about 4.0 ft (net deposition). Similar temporal changes in bed elevation and sediment storage were documented in the urban reaches of Crow Creek as it flows through the City of Cheyenne in southeastern Wyoming (WDEQ/WQD 2009).

Based on the temporal changes in cross-sectional area and bed elevation measured at sites, there was reason to infer that differences in bankfull channel dimension between baseflow and bankfull flow periods could be substantial depending on sediment transport dynamics and the amount of sediment stored in-channel at a particular time within a given reach. Comparisons of bankfull discharge estimates (Appendix 3) to an expected range of associated annual peak flows for the region provided some support to this assumption. Bankfull discharge estimates derived from baseflow survey data were about 35% to 40% less than the lower limit of expected flows (545 cfs with a 1.3 year recurrence interval). After ruling out the possibility that the field-identification of bankfull stage was too low, it was reasoned that the marked disparity between estimated and expected bankfull flows was more likely attributable

to temporal differences in channel cross-sectional area (bankfull flow vs. baseflow conditions). Estimates of bankfull discharge derived from scour-adjusted channel dimensions (Appendix 3), intended to represent channel conditions at the time of maximum bed load transport (i.e., bankfull stage), were found to be reasonably similar to expected flow rates.

Water withdrawals in the Laramie River watershed have altered the river's natural flow regime for over 100 years, affecting both the magnitude and duration of high and low flows (Figure 2). However, bankfull or channel forming flows appear to have been maintained through the evaluation reach on a relatively frequent basis. An assessment of USGS gaged flow data and WSBC flow regulation records collected over the 35 years prior to 2009 indicated that annual peak flows ≥500 cfs were likely achieved in the evaluation reach about 70% to 75% of the time (every 1.3 to 1.4 years). This evaluation agrees well with both the estimated bankfull discharge of 541 cfs derived from the scour-adjusted channel dimensions at 'Above Laramie WWTF' (Appendix 3) and the 1.3 year return period flow of 545 cfs determined immediately upstream at USGS station 06660000.

Sediment competency calculations and bed material characterizations at sites indicated that bankfull flows were capable of entraining a vast majority of the sediment available for transport in both 2009 and 2010. Greater than 85% of the sediment measured in all bar samples was composed of particles less than or equal to the D_{max} values predicted to be mobilized at the existing bankfull shear stress (Appendices 9 and 14). In addition, bankfull flows at three of the four sites mobilized 90% to 100% of the bed material at riffles (Appendices 11 and 14). Despite the evidence of high bed mobility, competency predictions indicated that flows at bankfull stage were overall incompetent in transporting the largest particles (D_{100}) supplied by the watershed. Decreases in the D_{100} measured at all scour chain installations from 2009 to 2010 (Appendix 13) confirmed these predictions – values at all but one of the 16 riffle and glide stations in 2010 were 58% to 86% smaller than corresponding values in 2009. Combined, these findings indicated that much of the fine bed material (fine gravel and sand) at all sites was readily transported, yet the coarser particles (>medium-sized gravel) were not. This type of response suggests that sediment transport in the river was capacity-limited (constrained by hydraulics), rather than supply-limited.

The dynamic character of the river bed was no more apparent than at 'Below Spring Creek', where the largest riffle particle predicted to be mobilized at bankfull stage was 18 mm (coarse gravel). In 2009, only 35% of riffle particles were equal to or less than this predicted size, but in 2010 that proportion increased to 75%. Given these findings, it was apparent that substantial increases in channel capacity could be realized at bankfull stage. However, any gains in channel capacity were lost as flows receded to baseflow levels and sediment mobilized at bankfull stage was redeposited. Changes in bed material at each site suggested that there was a large influx of fine sediment (sand and fine-sized gravel) to the river after the 2010 peak flow period. Riffle D_{50} particle sizes at the two uppermost sites decreased by more than 50% from 2009 to 2010, approaching the 4 to 7 mm D_{50} values measured at the two lowermost sites (Appendix 9). Temporal increases in the percentage of sand reachwide at the three lower sites (Appendix 9) further implied that the river was supplied with an unlimited quantity of highly mobile bed material.

Considering that bankfull discharge estimated from baseflow survey data was considerably less than expected, it followed then that sediment competency results derived from those data also could differ from results generated from data collected concurrently at bankfull stage. With this in mind, sediment competency was reevaluated at each site using bankfull data obtained from the scour-adjusted channels created at riffle cross-sections. Given that velocity increases substantially with discharge at a cross-section (Leopold 1994), channel slope was increased marginally at each riffle to reflect a slope and velocity presumed to represent actual bankfull flow conditions in 2010. For this exercise, local or valley slopes determined at each site were substituted for measured channel slopes in the calculations (given that channel slope approaches the slope of its valleys as discharge increases). Assuming that the channel bed at each riffle scoured to the adjusted elevations, only one of the four sites achieved the depth and slope necessary to generate a shear stress sufficient to entrain the largest particle supplied to it (Table 6). Additional adjustments in depth and slope could be made within reason at some sites to achieve a state of sediment competency, but the existing channel and valley morphology of a particular reach imposes limits to what can be adjusted (e.g., channel depth and valley slope at 'Below Spring Creek').

Table 6 – Sediment competence results at WDEQ/WQD sites on the Laramie River derived from scour-adjusted channel dimensions.

Competence to mobilize Dmax made available from immediate upstream sediment supply (i.e., upstream study reach).

								[a]Sediment Competence Predictions					
Reach	Riffle D50	Bar Sample D^50	[b]Upstream Dmax (mm)	Channel Slope (ft/ft)	Hydraulic Radius (ft)	Mean Depth (ft)	Existing shear stress (lbs/ft^2)	Predicted Dmax at existing shear stress (mm)	Predicted shear stress to mobilize upstream Dmax (lbs/ft^2)	Predicted mean depth to mobilize upstream Dmax (ft)	Predicted slope to mobilize upstream Dmax (ft/ft)	Ratio of Existing to Predicted Shear Stress	Competence Evaluation
[d] Above UPRR Tie Plant	16.4	-	56	0.0013	2.32	2.37	0.19	45	0.26	3.17	0.0017	**0.75**	Aggrading
[e] Below Spring Creek	22.3	6.6	52	0.00047	2.46	2.30	0.07	21	0.23	7.93	0.0016	**0.29**	Aggrading
[d] Above Laramie WWTF	5.5	4.4	41	0.0011	2.40	2.55	0.18	42	0.17	2.45	0.0011	**1.04**	Competent
[c,e] Below Gravel Pits	4.6	<2	37	0.00046	2.87	2.96	0.08	25	0.15	5.10	0.00079	**0.58**	Aggrading

Note: With the exception of bar sample particle sizes, all measurements were obtained from the riffle cross-section.

[a] Predicted Dmax, shear stress, depth and slope values were computed from a modified version of Shield's critical shear stress relation for gravel bed streams (Rosgen 2006). Only data collected at 'Below Spring Creek' in 2009 were appropriate for applying dimensionless shear stress relations - predictions generated from that data set were less accurate compared to those derived from dimensional relations.

[b] Upstream Dmax is the largest particle (D100) measured from the bar sample collected in the immediate upstream study reach. Dmax for 'Above UPRR Tie Plant' is represented by the largest particles measured at scour chains, which are considered the size of particles mobilized at bankfull stage.

[c] Sediment competence predictions are normally not made for sand-bed streams as the existing Dmax is assumed mobile at flows ≤ bankfull discharge. The predictions shown are based on the expectation that the bed should be dominated by gravel-sized particles. Based on this premise, the existing Dmax was used to approximate the size of particle made available from the immediate upstream reach which exhibited a gravel-dominated bed.

[d] Local gradient used

[e] Valley gradient used

Based on results presented in Table 6, flows equal to or greater than bankfull stage within the reach at 'Above Laramie WWTF' were likely competent in mobilizing the largest particles made available from upstream sediment sources, suggesting a limited risk of aggradation. Considering that channels form to accommodate (or convey) the water and sediment produced from their watersheds, adjustments in either area or velocity are required to satisfy this principle. At 'Above Laramie WWTF', adjustments in

velocity (or slope) appeared to play a greater role in accommodating the flow and sediment supplied to it than did other hydraulic attributes. Adjustments in width were limited by the confinement imposed on the channel, whereas depth was controlled by the resistant bedrock layer exposed by past incision. As a consequence, a balance between channel area and slope was achieved such that the bankfull flow was more competent in mobilizing stored bed sediment than in reaches with channel hydraulics less capable of transporting the sediment supplied by the watershed (Table 6).

Research on sediment transport in rivers has shown that rivers can aggrade despite exhibiting the ability to mobilize particles larger than the dominant channel bed material (Pitlick and Wilcock 2001, Rosgen 2006b). Though some results of this study suggested that bankfull flow in the Laramie River may be competent at some sites, several lines of evidence indicated that the river overall had insufficient capacity to transport the sediment load supplied to it on an annual basis. Greater than expected width/depth ratios, high lateral instability, spatial and temporal reductions in bed material sizes, high bed mobility, and abnormal depositional patterns all showed that the river was receiving an excess supply of sediment. A vast majority of this excess sediment was believed to originate from in-channel sources (bed and banks).

The bed and bank instability observed in the Laramie River evaluation reach was most likely attributable to channel incision processes initiated by long-term confinement and channelization by past urban and industrial development (HT-WWC 2009). The most recent channelization project on the river occurred immediately upstream of the I80 highway crossing at the UPRR Tie Treatment Plant property, where approximately ½ mile of river channel was relocated and straightened (Figure 15) to accommodate groundwater pollution remediation efforts. However, inspection of aerial photography indicated substantial changes in the river's morphology have occurred over the past several decades for many miles upstream and downstream of the City of Laramie. This suggests that other historic channel disturbances and intensive land use practices were to a certain degree also likely responsible for the channel instability observed in the river. Channel adjustments may still be occurring in response to the decades of the channel scouring railroad tie drives that occurred in the drainage prior to 1940 (Young et al. 1994). Though this activity ceased over six decades ago, it can sometimes take years for streams and rivers to reestablish a stable channel form (Rosgen 1996). Past water development activities have also altered the magnitude and duration of flows, which can influence sediment transport and channel morphology (Pitlick and Wilcock 2001, Richter et al. 1996).

Figure 15 – Relocated channel reach of the Laramie River within the UPRR Tie Treatment Plant facility. Aerial image (2012) from Albany County Assessor, courtesy of USGS, Earthstar Geographics SIO, ©2014 Microsoft Corp.

The degree of encroachment imposed on the Laramie River through the evaluation reach was reflected in the relative differences observed in channel entrenchment (vertical containment) among sites (Appendix 2). Relative to the naturally unconfined channel at 'Below Gravel Pits', channels upstream were deeply entrenched, with entrenchment ratios that were about three to five times less than the lowermost reach. The entrenchment ratio at 'Above Laramie WWTF' (2.2) was near the threshold used to differentiate Rosgen B and C stream-types (Rosgen 1996). Channel pattern and profile data collected by WDEQ/WQD further corroborated what HT-WWC (2009) considered was the underlying cause of the channel incision observed throughout the urban reaches of the river. As a result of past encroachment, sinuosity was reduced approximately 40%, concomitantly increasing channel gradient and stream power, and ultimately increasing the erosive capability of the river's flows. A near-equivalent increase in bankfull channel slope and stream power observed with distance upstream of 'Below Gravel Pits' (Appendices 2 and 3) confirmed that the estimated reduction in sinuosity was accurate. The abrupt changes in bankfull channel slope measured between the three upper sites perhaps reflect the gradient adjustments that have and may still be occurring throughout the evaluation reach as a result of past channel disturbances and confinement. Decreases in meander belt width with distance upstream of 'Below Gravel Pits' (Appendix 2) provided additional evidence that the channel bed and bank instability observed throughout the evaluation reach was most likely attributable to imposed channel confinement.

The degree of channel incision, measured by bank-height ratios, among Laramie River sites was greatest at 'Above UPRR Tie Plant' (Appendix 2). Increases in bank-height ratios greater than one indicate that a disproportionate amount of the bank surface is exposed above the bankfull elevation, which ultimately increases near-bank shear stress and the potential for mass erosion such as freeze/thaw and bank

slumping/collapse (Rosgen 2006a). Among all sites, predictions of both bankfull shear stress and bank erosion were also greatest at 'Above UPRR Tie Plant' (Appendix 3 and Table 3). Bank-height ratios at the three lower reaches indicated a slight to negligible degree of incision, with each undergoing various stages of floodplain development, a response that typically follows lateral expansion of the channel.

Lateral erosion typically follows bed incision, resulting in an enlarged channel and increases in the amount of sediment supplied to the river (Rosgen 2006a). Bank erosion estimates and several bankfull dimensionless metrics indicated that the Laramie River throughout the evaluation reach was enlarging through lateral erosion and sedimentation processes. According to reachwide BANCS model prediction results, bank erosion potential was greatest in reaches upstream of the City of Laramie (represented by 'Above UPRR Tie Plant'). During the 2009-2010 study, the predicted annual bank erosion rate for the reach at 'Above UPRR Tie Plant' was about three times greater than the corresponding rate at 'Above Laramie WWTF' and 1.3 times greater than the rate at 'Below Gravel Pits' (Table 3).

Based on bank-height ratio measurements, lateral erosion at 'Above UPRR Tie Plant' was most likely attributable to increases in NBS associated with channel incision, whereas the lateral channel migration at downstream reaches was due primarily to expansion of bar features. At 'Below Gravel Pits', the main channel was branching or splitting at mid-channel bars. These types of flow patterns at depositional features create a disproportionate energy distribution in the near-bank region immediately downstream of the converging split channels (Rosgen 2006a) that can accelerate bank erosion and ultimately contribute additional material to the existing sediment load.

According to 2009-2010 and 2010-2011 bank profile survey results, predictions of bank erosion derived from the BANCS model at Laramie River sites were overall disproportionate to measured rates (Appendix 6). Considering the numerous factors that influence channel adjustment and bank erosion processes (Knighton 1984), it is not surprising that highly variable bank erosion rates may occur in channels undergoing various stages of disequilibrium. Much of the bank erosion observed at sites on the Laramie River was attributed to mass wasting processes (bank slumping/collapse), which can vary regionally due to a number of factors (i.e., soil-bulk density and bank failure mechanics), and ultimately affect model accuracy (Rosgen 2006a, 2008). The factor that most likely had the greatest influence on predicted bank erosion rates was the NBS component of the BANCS model. Near-bank stress ratings assigned to segments within each site were based on bankfull stage channel dimensions, which were dependent on channel depths at the time estimates were made. Based on scour and fill survey results and changes in depth at pool cross-sections (Figure 8), it was apparent that bed elevation differences between peak and base flow periods at meander bends were likely substantial. Thus, it was reasonable to infer that the actual shear stress that banks were subjected to during the prolonged flooding that occurred in 2010 and 2011 were likely greater than estimated at baseflow.

The large disparity between the 2010 predicted and 2011 observed bank profile erosion rates also could be attributable to progressive weakening of banks following two consecutive years of extreme flooding. For example, average annual ratios of observed to predicted bank erosion rates for the 2009-2010 study period at both 'Above UPRR Tie Plant' and 'Above Laramie WWTF' were respectively 0.28 and 0.04, whereas corresponding ratios of 2.05 and 9.6 were computed from the 2010-2011 data (Appendix 6).

Based on these results, factors influenced by prolonged, high-magnitude flooding (e.g., antecedent bank moisture levels, soil bulk density, soil particle cohesion) not accounted for in the BANCS model could potentially limit the accuracy of predictions. Regardless of the cause(s) responsible for the large annual differences in observed vs. predicted values, the BANCS model accurately predicted the longer-term bank erosion rates observed at sites evaluated from 2009 to 2011 (Appendix 6).

The consequences of channel enlargement processes in the Laramie River were apparent from a review of measured width/depth ratios among sites. Relative to a reference width/depth ratio of 13, which is considered representative of stable Rosgen C stream-types (Rosgen 2006a), ratios at sites were 1.5 to three times greater than this expected value (Appendix 2). An abrupt 1.5-fold increase in channel width/depth was observed at sites below 'Above UPRR Tie Plant', suggesting that lateral channel expansion processes (due to sedimentation and bank erosion) within the City of Laramie may have occurred over a longer period of time than reaches upstream of the city. The lower width/depth ratio at 'Above UPRR Tie Plant' relative to sites downstream suggested that lateral expansion of the channel had yet to be fully expressed. A low-head dam located immediately upstream of the 'Above UPRR Tie Plant' reach appeared to prevent further advancement of bed incision and moderation of the relatively steep channel gradient measured at the site.

Indicators of excess sedimentation were evident throughout the Laramie River evaluation reach, but its influence on channel morphology increased with distance downstream. Despite flows in 2010 that were of sufficient magnitude and duration to flush fine sediment from the channel, the percentage of sand and silt increased reachwide at all sites downstream of 'Above UPRR Tie Plant' from 2009 to 2010 (Appendix 9). An influx of fine sediment at 'Below Spring Creek' resulted in the conversion of a gravel-dominated bed to one dominated by sand. Side, mid-channel and point bars observed at all sites were mostly unvegetated with lengths exceeding two to three bankfull channel widths (Appendix 15), all indicators of accelerated bar development. Bar features were removed and reformed, changing channel dimensions at both riffles ('Below Spring Creek') and pools (Figure 8), and causing localized shifts in facet slopes and reachwide water surface gradients (Appendix 4). Spatial and temporal gradient shifts are typically indicative of active channel adjustment processes associated with changes in sediment and/or flow regime (Rosgen 2006a, Schumm 1977). Some bar features at the lower sites exacerbated bank erosion through progressive expansion and formation of divergent/convergent flow patterns. Such flow pattern shifts are indicative of channel adjustments that occur in rivers that receive a continual supply of excess sediment (Knighton 1984, Petts and Foster 1985, Rosgen 1996).

Several morphologic measures indicated that the Laramie River was aggrading downstream of the City of Laramie. Bankfull stage elevations at 'Below Gravel Pits' increased slightly from 2009 to 2010 (Appendix 4), presumably as a result of localized increases in bed elevation. This finding was corroborated by corresponding increases in the average reachwide thalweg bed elevation (Appendix 12) and decreases in mean depths at pool and glide features (Figure 10), both of which accounted for 63% of the entire reach length in 2010 (Appendix 2). The increase in channel slope that occurred at 'Below Gravel Pits' from 2009 to 2010 (Appendix 2) was a typical response of rivers that receive an excess supply of sediment to increase sediment transport (Knighton 1984, Rosgen 2006a, Schumm 1969). The relatively abrupt temporal increases in all facet slope to bankfull slope ratios between 'Above Laramie

WWTF' and 'Below Gravel Pits' (Figure 9), and progressive temporal decreases (29% to 50%) in mean pool-pool spacing observed with distance downstream (Appendix 2) were presumably adjustments made to accommodate an ever-increasing sediment load and to uniformly distribute power expenditure (Leopold 1994, Lisle 1982).

Delta bars observed in the Laramie River below the confluence with Spring Creek and the stormwater drainage outlet upstream of 'Above Laramie WWTF' provided some indication that the City of Laramie is a minor contributor of excess sediment to the river. Both the size and prevalence of other depositional features observed in the river above and below the city were similar, suggesting that a majority of the sediment originated from sources upstream of urban inflows. The available quantitative evidence collected at 'Above UPRR Tie Plant' provided some validation that excess sediment produced from bed incision and bank erosion processes likely outweighed the amount contributed from urban sources.

BIOLOGICAL CONDITION

Excess sediment, whether in suspension or deposited, may lead to biological impairment by one or more of several possible outcomes. Based on information from Waters (1995) and Ward (1992), excess sediment while in *suspension* (such as during high flows) can adversely affect aquatic biota by four main pathways: (1) impairment of filter feeding, by filter clogging or reduction of food quality; (2) reduction of light penetration and visibility in the stream, which may alter interactions between visually-cued predators and prey, as well as reduce photosynthesis and growth by submerged aquatic plants, phytoplankton and periphyton; (3) physical abrasion by sediments, which may scour food sources such as algae or directly abrade exposed surfaces (i.e., gills) of fishes and invertebrates; and (4) increased heat absorption, leading to increased water temperatures. Excess *deposited* sediment may lead to biological impairment by three main pathways: (1) increased coverage by fine particles, which can alter benthic habitats (i.e., increasing fine substrate habitats favored by burrowing insects and tolerated by nest cleaning fishes, or reducing deeper pool habitats) and bury relatively sessile taxa and life stages (i.e., fish eggs); (2) clogging interstitial spaces, leading to reduced interstitial flows and habitats; and (3) reduction of substrate size, leading to reduced substrate diversity and stability. Deposited sediments can indirectly affect aquatic biota by reducing oxygen levels either by restricting flow through streambed substrates or by oxygen consumption by bacterial respiration, especially when sediments contain a high concentration of organic matter.

Accelerated stream bank erosion, a form of channel degradation that can contribute excess sediment to a channel, can affect aquatic biota through (1) decreased coverage and availability of stream bank habitat (i.e., overhanging vegetation, woody debris, aquatic macrophytes) used for survival and reproduction; (2) increased localized velocities and scour that can dislodge biota, alter habitat and food resources and favor clinger and filter-feeding macroinvertebrates; (3) large-scale alterations in habitat availability and increased severity of seasonal floods to biota; (4) increased heat absorption, leading to increased water temperatures; and (5) decreased terrestrial organic matter inputs (i.e., insects, plant matter, etc.) for growth and survival of aquatic biota (Saunders and Fausch 2009, Ward 1992, Waters 1995).

Evaluations of the chemical, physical and biological data collected during the 2009-2010 study indicated that excess sediment was the primary pollutant and environmental stressor responsible for the downstream decline in biological condition in the Laramie River. Channel bed incision and enlargement processes occurring throughout the evaluation reach provide a continual supply of excess sediment to the river, resulting in excess sedimentation and high bed mobility. These physical disruptions to the river's bed caused continuous disruption to the benthic habitat, and correspondingly, to the composition, structure and function of benthic flora and fauna. The continual supply of excess sediment to reaches downstream of the City of Laramie (i.e., 'Below Gravel Pits') resulted in marked departures in the biological condition of benthic macroinvertebrates in this river segment from regional reference expectations and from conditions observed at sites upstream. Changes in select biological metrics also showed evidence of nutrient enrichment, particularly at 'Below Gravel Pits'. But based on the available evidence, the relative influence that nutrients had on the biota could not be readily differentiated from the physical stressors associated with bed scour and sedimentation.

According to overall aquatic life use ratings assigned from the combined WSII and WY RIVPACS model results, the biological condition of benthic macroinvertebrate communities at sites declined considerably with distance downstream of the City of Laramie. Though communities in the three upper sites were subjected to a considerable degree of stress related to excess sedimentation and bed instability, the overall biological condition of the river within and upstream of the city was not considered adversely altered to the degree observed downstream at 'Below Gravel Pits'.

Notably, some of the paired WY RIVPACS and WSII narrative aquatic life use-support ratings assigned to sites on the Laramie River were dissimilar. The different ratings assigned by the models did not indicate conflicting results, but rather represented different ecological attributes of the benthic macroinvertebrate community. Together, the model results provide valuable insight into the structure and function of each community. An evaluation of the macroinvertebrate community at 'Below Gravel Pits' is useful for understanding the differences in the ratings assigned by each model. The 'indeterminate' WY RIVPACS ratings assigned to this community in 2009 and 2010 indicated that a majority (65% to 80%) of the taxa expected to occur at the site were observed (Figure 14), but were less than the ideal 'full support' reference condition. The community however was not judged favorably by the richness, composition and tolerance metrics of the Wyoming Basin WSII model due to both the low relative abundances of expected taxa and the dominance of short-lived, opportunistic, tolerant taxa (Appendix 16). Only one of the five EPT taxa observed at the site was considered in the EPT richness metric of the WSII model, which had a reference criterion of 20 taxa. The community was fairly represented by model-relevant EPT taxa (40% to 50% relative abundance), but like a majority of the organisms at the site, they were short-lived. Only one to two semivoltine taxa were observed in the community, which is well below the regional reference condition of eight. Although several of the expected taxa were present at 'Below Gravel Pits', they were low in abundance and consisted mostly of organisms tolerant to the prevailing environmental conditions which were apparently inhospitable to sensitive, long-lived taxa. The 'partial/non-support' rating assigned by the WSII to the community at 'Below Gravel Pits', indicated that the assemblage of benthic macroinvertebrates was not a balanced, structurally functional community representative of the expected biological reference condition for the

Wyoming Basin. The indeterminate WSII ratings assigned to the benthic communities at the other Laramie River sites were attributed to the same biological changes at 'Below Gravel Pits', but the magnitude of change at those sites was not as great as what occurred at 'Below Gravel Pits'.

Inspection of a number of other relevant benthic macroinvertebrate metrics reflected the spatial and temporal patterns observed in the paired WY RIVPACS and WSII results. From the uppermost site to the lowermost site, there was an overall decline in total taxa richness, semivoltine taxa richness, and relative abundance of EPT sensitive taxa. Negative temporal shifts in community structure were apparent in taxa richness and composition measures at all sites, suggesting that existing water quality and/or physical channel conditions were altered appreciably from 2009 to 2010. Within all sites, the relative abundance of collector-gatherers increased from 2009 to 2010, whereas filterer densities fluctuated. The highly mobile bed conditions observed throughout the river were likely responsible for the compositional shifts in these two functional feeding groups. Several metrics suggested that environmental conditions favored organisms that were well-adapted to chronically unstable bed conditions and nutrient-enriched waters. Both stressors appeared to have a synergistic influence on the benthic community, particularly at the lowermost site.

The prevalence of short-lived, highly mobile collector-gatherer taxa at 'Below Gravel Pits' was indicative of a macroinvertebrate community adapted to a chronically unstable, depositional environment. The community was dominated by multivoltine (several life cycles per year) collector-gatherer taxa that included aquatic worms, midge-fly larvae and the relatively sediment-tolerant mayflies *Acentrella* and *Tricorythodes*. Temporal shifts observed in several compositional measures were diagnostic of the degree of bed instability at the site. From 2009 to 2010, the relative abundance of collector-gatherers increased from 50% to 91%. The increase in this metric was largely due to substantial increases in *Acentrella* and oligochaetes, which were the two most abundant taxa at 'Below Gravel Pits' in 2010. The sudden increase in the abundance of collector-gatherers suggested that the site received a large influx of both organics and fine sediment, conditions that would favor these organisms. However, this change was most likely almost entirely due to sedimentation (i.e., increases in sand and silt). Though the site received a high nutrient load, there was no excessive growth of filamentous algae and aquatic plants.

The decrease in filter feeders from 36% in 2009 to 3% in 2010 at 'Below Gravel Pits' provided further evidence that sediment had an overriding influence on the site's benthic macroinvertebrate community. *Simulium* and *Cheumatopsyche*, both filterers, were two of the top four dominant taxa found at the site in 2009, comprising 35% of the total community abundance. In 2010, *Cheumatopsyche* was eradicated from the community and *Simulium* densities were about 26% less than in 2009. Though both taxa are relatively tolerant to increases in fine sediment and nutrient enrichment, they require stable coarse bed material for attachment and filter feeding (Relyea et al. 2000, Voshell 2002, Ward 1992). Barbour et al. (1999) noted that *Cheumatopsyche* generally increases in response to environmental stressors and is usually one of the last EPT taxa found in abundance as water quality declines. Given the propensity of both *Simulium* and *Cheumatopsyche* to thrive in organically-enriched conditions, a case could be made that organic enrichment played a large role in their high relative abundance in the community in 2009. But in 2010, excess sedimentation and high bed mobility appeared to have a greater influence on their success in the community than organic enrichment. The large temporal decline in *Simulium*, an early

colonizer of disturbed habitat, and the disappearance of *Cheumatopsyche* in 2010 most likely reflects the degree of bed instability that occurred at the site. Though the site received an ample supply of nutrients in 2010 (Appendix 1) to support an abundant crop of filamentous algae and macrophytes, physical stressors associated with sedimentation and bed scour appeared to limit that growth. These findings suggested that the benthic macroinvertebrate community at 'Below Gravel Pits' was largely influenced by nutrient enrichment in 2009, whereas in 2010 sedimentation and bed scour had a greater influence on community structure and function.

Based on the available chemical, physical and biological information and the aquatic life other than fish use-support decision matrix (WDEQ/WQD 2014a), overall biological condition ratings of 'indeterminate' were assigned to the benthic macroinvertebrate communities at the three upper sites on the Laramie River for the 2009-2010 study period. The community at 'Below Gravel Pits' received consistent 'partial/non-support' assignments each year. An abrupt temporal change in the macroinvertebrate assemblage occurred at 'Above UPRR Tie Plant' which received aquatic life use assignments of 'full-support' in 2009 and 'partial/non-support' in 2010. In this case, the scouring flows and subsequent sedimentation observed in 2010 at the site most likely contributed to the temporal decline in biological condition. Biological condition at 'Below Spring Creek' however improved from 'indeterminate' in 2009 to 'full support' in 2010, primarily due to a 10% increase in expected taxa (measured by the WY RIVPACS model) and 30% increase in the model-relevant EPT taxa evaluated by the WSII. The favorable temporal response in the WSII score at 'Below Spring Creek' was attributed entirely to a 6-fold increase in the relative abundance of *Acentrella*. As described previously, *Acentrella* appeared to have been favored by the sedimentation and mobile bed conditions that occurred throughout the river. From this information it was apparent that biological condition at the two upper sites was largely dependent on prevailing bed conditions, which proved neither optimal nor severely detrimental to the benthos during the two year study. Given this line of reasoning, an overall biological condition rating of 'indeterminate' was deemed appropriate for the two uppermost sites. The benthic macroinvertebrate community at 'Above Laramie WWTF' was assigned consistent 'indeterminate' ratings each year.

Spatial and temporal changes in several diatom indices also provided evidence that the degree of environmental stress on the benthos in the Laramie River increased with distance downstream, particularly below 'Above Laramie WWTF'. Sediment and nutrient enrichment (organic and inorganic forms) were consistently singled-out as major stressors of concern in both years, but excess sediment and the physical stressors that accompany it (deposition and scour) appeared to have a greater influence on the composition of periphyton communities in 2010. Stevenson et al. (1996) reported that the type, diversity and stability of channel substrate are variables that have the greatest influence on diatom community structure. Nonetheless, nutrients appeared to play an influential role in the changes observed in periphyton communities with distance downstream.

Downstream decreases in the relative abundances of diatom taxa intolerant of organic nutrient enrichment (*Epithemia)* and corresponding increases in nutrient-tolerant taxa (*Cocconeis, R. abbreviata*, *Navicula*, and *Nitzschia*) and provided evidence of increasing nutrient inputs to the Laramie River. Marked increases in the densities of eutraphentic taxa and in *Cocconeis* and *R. abbreviata*, both of which are tolerant to heavy organic pollution and to bed scour, from 'Above Laramie WWTF' to 'Below Gravel

Pits' suggested that a substantial increase in nutrient loading (particularly inorganic nitrogen) and bed instability occurred downstream of the City of Laramie. Concentrations of total nitrogen and total phosphorus increased several fold between these sites, confirming that there was indeed an ample supply of nutrients available to algae and aquatic plants. Though a substantially greater degree of nutrient enrichment occurs at 'Below Gravel Pits', episodic pulses of inorganic nitrogen may enter the river upstream of the city, based on the relatively high densities of eutraphentic and hypereutraphentic diatoms observed at 'Above UPRR Tie Plant'. Despite inferences of possible nutrient enrichment, associated episodes of low dissolved oxygen concentrations appeared to be uncommon in the river during the 2009-2010 study period.

Progressive downstream increases in the relative abundance of *A. minutissimum* from 'Above UPRR Tie Plant' to 'Above Laramie WWTF' provided a strong indication that this reach of the river experienced bed scour and increases in nutrient enrichment, both stressors to which *A. minutissimum* responds favorably. Though relatively tolerant to these stressors, *A. minutissimum* exhibits a lag time response in colonizing recently disturbed substrate. The marked decline in its densities from 'Above Laramie WWTF' to 'Below Gravel Pits', accompanied by corresponding increases in the densities of *Cocconeis* and *Rhoicosphenia,* indicated an obvious change in environmental conditions occurred between the sites. Increases in both nutrient concentrations (particularly phosphorus) and chronically unstable sand bed conditions between these sites presumably contributed to the proliferation of *Cocconeis* and *Rhoicosphenia* and competitive exclusion of *A. minutissimum* at 'Below Gravel Pits. Combined, *Cocconeis* and *R. abbreviata* accounted for about 50% of the total diatom abundance at 'Below Gravel Pits' during the 2009-2010 study. By comparison, mean relative abundances of these diatoms combined were less than 15% at each of the three upper sites where more stable bed conditions and much lower levels of phosphorus were observed.

CONCLUSIONS

Excess sediment is considered the most important single pollutant in streams and rivers in the United States (Waters 1995). In the latest USEPA summary of the Nation's water quality, excess sediment is recognized as one of the top four stressors to streams and rivers and poses the greatest risk to the biological condition of the Nation's waters (USEPA 2009). Sediment transports other pollutants including nutrients and heavy metals that if produced in excess amounts can severely impact the growth, reproduction, recruitment and survival of aquatic organisms. Excess sediment impairs desirable river functions that are critical for the maintenance of channel stability and biological integrity. Excess sediment can also obstruct surface water diversion intakes and reduce channel capacity; raise channel bed elevations and potentially increase flood stage and flood hazards; increase reservoir sedimentation rates and reduce water storage; and accelerate stream bank erosion and lateral channel migration rates which can cause substantial loss of agricultural land, buildings and road infrastructure.

Several lines of evidence collected at sites on the Laramie River from 2009 to 2010 indicate that excess sediment and nutrient enrichment contribute to observed departures in the river's biological condition from regional reference expectations. The influence of excess sediment on both the benthic macroinvertebrate and periphyton communities is evident throughout the evaluation reach. The

resident benthos are well-adapted to chronic bed scour, sedimentation and highly mobile bed conditions. Episodic inputs of excess nutrients (nitrogen and phosphorus) to the river may influence benthic organisms to a certain degree in reaches upstream and within Laramie's city limits, but stressors associated with excess sediment appear to "mask" the biological responses typically associated with excess nutrient enrichment. However, both excess nutrients and excess sediment are considered responsible for the marked changes observed in the structure and function of the benthos downstream of the city.

Depressed biological conditions are observed throughout the Laramie River, but the greatest impacts to the river's benthic biota occur downstream of the City of Laramie (below 'Above Laramie WWTF'). A combination of excess sedimentation, bed scour, high bed mobility and nutrient enrichment are considered the principal stressors responsible for the marked downstream decline in the river's biological condition from the uppermost site at 'Above Laramie WWTF' to the lowermost site at 'Below Gravel Pits'. Macroinvertebrate richness, compositional and functional measures evaluated at 'Below Gravel Pits' differed appreciably from regional reference expectations and from corresponding measures at sites upstream. The same stressors were also singled out as those responsible for the compositional shifts in diatom communities with distance downstream.

Though channel survey results indicate that bankfull flows in the Laramie River are capable of mobilizing a majority of the sediment stored in-channel, the total amount of sediment supplied to the river on an annual basis is in excess of what can be effectively conveyed without causing aggradation. Having neither the competence nor capacity to transport the total sediment load supplied annually, the channel enlarges through the growth and expansion of point bar and mid-channel bar features, which accelerates lateral channel migration rates through bank erosion processes. The urbanized reach of the river appears to have a greater capacity for transporting excess sediment than reaches upstream and downstream of the city, but nevertheless, shows signs of aggradation. Among all sites, the most prevalent indicators of aggradation (enlarged channel, accelerated lateral channel migration, accelerated bar development, increases in fine sediment deposition, and highly bed mobility) are expressed at 'Below Gravel Pits'.

Downstream changes in bed substrate composition likely has the greatest influence on benthic macroinvertebrate and periphyton communities throughout the Laramie River evaluation reach. In the seven miles between the uppermost and lowermost sites, the reachwide percentage of sand and silt (<2 mm) during the study doubled from 30% to 60%. Mean riffle and reachwide D_{84} particle sizes (an index of bed roughness and interstitial living space for benthic organisms) steadily declined with distance downstream from coarse gravel-sized (15 to 23 mm) particles at the three upper sites to fine gravel (4-8 mm) at the lowermost site. These spatial and temporal changes in bed substrate culminate at 'Below Gravel Pits', resulting in a dynamically unstable and homogenous environment suited primarily to a biological community adapted to such conditions.

Relative to sites upstream, 'Below Gravel Pits' supports a much less diverse, predominantly short-lived assemblage of benthic macroinvertebrate taxa that thrive in nutrient-rich (collector-gatherers), highly mobile, fine sediment-dominated depositional environments (burrowers and swimmers, including

aquatic worms and the mayflies *Acentrella* and *Tricorythodes*). From 2009 to 2010, benthic taxa that subsist on stable, coarse-sized bed material for feeding, shelter and attachment (filterer, scraper, clinger and sprawler taxa), were nearly eradicated at the site. Compositional measures of the diatom community between 'Above Laramie WWTF' and 'Below Gravel Pits' (in particular, spatial shifts in dominance between *A. minutissimum* and *Cocconeis* and *R. abbreviata*) mirrored downstream changes observed in the macroinvertebrate community. Combined, this biological evidence provides a persuasive argument that the river downstream of the City of Laramie experiences a greater degree of sediment deposition and bed instability than sites upstream.

Channel survey results and qualitative observations of bank erosion and depositional patterns indicate that a vast majority of the excess sediment appears to originate from in-channel sources within unstable reaches of the Laramie River upstream of the City of Laramie and continuing downstream for several miles. Accelerated bank erosion and lateral channel migration is more prevalent in reaches upstream and downstream of the city. Incision processes are considered responsible for the channel instability in reaches upstream of the city, whereas instability in reaches within and downstream of the city is attributed to aggradation processes. Bank erosion within the urban reaches is mitigated by both a dense growth of riparian vegetation and the installation of bank/channel treatments intended to reduce bank erosion. The presence of delta bar features in the river below the city's stormwater drainage outlets suggest that excess sediment is contributed to the river from urban sources, though this sediment is considered secondary to those attributed to the river's in-channel sources. Spring Creek, a major tributary that receives most of the city's stormwater runoff, showed minor signs of channel instability and no signs of accelerated bar development. No evidence in this study demonstrates that sediment delivered to the Laramie River through the urban stormwater drainage system has a measurable degree of influence on the river's biological condition compared to sediment produced from in-channel sources. However, urban-produced sediment does contribute to the river's excess sediment load. Conrad (1996) reported that fine sediment (organic and inorganic matter) delivered to the Laramie River from the city's stormwater drainage system could contribute to alterations in the community structure of the river's aquatic biota, favoring organisms adapted to fine bed substrate.

One of the suspected underlying causes of the channel instability in the Laramie River is the urban and industrial development which confined and channelized the river since the city was founded in the 1860's. The confinement resulted in reductions in sinuosity, which translated to increases in channel gradient, ultimately increasing the erosive power of the river's flows. Bed incision processes initiated by the gradient increases were projected upstream for several miles. Aerial photography taken of the river upstream of the city shows extensive lateral and down-valley channel migration, old channel avulsions and enlarged depositional features, all of which are indicators typically associated with incision. Other historic landscape disturbances (i.e., decades of channel-scouring railroad tie drives and removal of riparian vegetation) and flow manipulations in the watershed also likely played a large role in altering the morphology of the river and contributing to the present channel instability.

Hydrologic information presented in this report indicates that the natural flow regime of the Laramie River has been altered over the last 100+ years by flow withdrawals in Colorado and Wyoming. This raises the question as to whether flow alterations have influenced the river's sediment competency and

capacity. Though the magnitude and duration of peak flows have been reduced by long-term water withdrawals, the available evidence reviewed in this report suggests that the channel forming or bankfull flow has not been appreciably altered within the evaluation reach. Bankfull flows appear to be achieved at the naturally expected magnitude and frequency. Flow regulation information further suggests that bankfull flows are likely maintained in most years. Thus, past changes in flow regime do not appear to have substantially altered the existing sediment transport and channel maintenance functions of river flows.

Though there are no numeric aquatic life use criteria currently established for nitrogen and phosphorus, they have long been recognized as pollutants that can alter the structure and function of biological communities and can be harmful to fish and other aquatic organisms. Water quality stressors associated with nutrient enrichment include large diurnal swings in pH and dissolved oxygen concentrations, both of which are driven by the photosynthetic processes that accompany abundant algae and aquatic plant growth. Applicable narrative criteria used to evaluate the influence of nutrients on water quality and aquatic biota include Sections 24, 26, 28 and 32 in Chapter 1 of the Wyoming Water Quality Rules and Regulations (WDEQ/WQD 2013a). The abrupt downstream increases in the relative abundance of diatoms tolerant to high and very high concentrations of inorganic nutrients (eutrophic and hypereutrophic taxa), and corresponding decreases in the density of diatoms that are intolerant to nutrient enrichment (e.g., *Epithemia*) correlate well with the abrupt downstream increases in nitrogen and phosphorous concentrations in the Laramie River.

Primary sources of excess nutrients to the Laramie River evaluation reach include the City of Laramie WWTF point source discharges and urban stormwater drainage. Excess nutrient inputs from non-point sources (i.e., fertilized croplands, livestock feedlots, rural septic systems) are considered minor relative to point sources. During this study, concentrations of total nitrogen (2,700 and 5,174 µg/L) and total phosphorus (420 and 714 µg/L) at 'Below Gravel Pits' were 10 to 20 times greater than expected regional reference levels, and more than 10 times greater than levels measured upstream of the city. Concentrations of both nutrients upstream of 'Below Gravel Pits' were within the range of regional reference concentrations. Greater than 80% of the total nitrogen at 'Below Gravel Pits' is composed of inorganic nitrogen, a form readily assimilated by algae and aquatic plants, especially if there is an available supply of phosphorus. By comparison, 65% to 100% of the total nitrogen in the river upstream of 'Below Gravel Pits' is bound in organic forms. Total phosphorus concentrations at 'Below Gravel Pits' were about 40 to 50 times greater than levels measured at sites upstream. Spring Creek contributes excess nutrients to the Laramie River in accordance with its prevailing nutrient load, which may account for less than 5% of the river's total nutrient load during baseflow. Relative to regional reference values, concentrations of total phosphorus in Spring Creek were comparable, but nitrate+nitrite-N concentrations were 30 times greater. Conrad (1996) found that nutrient concentrations in Laramie's stormwater drainage were elevated compared to average concentrations observed in urban stormwater samples collected in a nationwide study. However, nutrient inputs to the Laramie River from the urban stormwater system were considered minor relative to nutrient contributions from the city's WWTF effluent (Conrad 1996)

The evaluation of the 2009-2010 chemical, physical and biological information presented in this report indicates that the Laramie River, starting from lower extent of the 'Above Laramie WWTF' study site and extending downstream 14 stream miles to the Little Laramie River confluence ('*altered reach*' depicted in red on Figure 16), receives an excess supply of sediment and nutrients. The biological evidence indicates that both excess sediment and nutrient enrichment within this *altered reach* are the principal stressors responsible for the marked departure in its biological condition from the expected regional reference condition. Based on the aquatic life other than fish use-support decision matrix (WDEQ/WQD 2014a), an overall biological condition rating of 'partial/non-support' was assigned to the benthic macroinvertebrate community within the *altered reach* in both years. In addition to a departure in the regional biological expectation, an appreciable decline in biological condition is observed with distance downstream of 'Above Laramie WWTF'. The conclusion drawn from the combined weight of evidence indicates that excess sedimentation and nutrient enrichment are responsible for causing an adverse alteration to the structure and function of the aquatic biological community within the *altered reach* of the Laramie River, which translates to non-attainment of the narrative criteria described in Section 15 (Settleable Solids) and Section 32 (Biological Criteria) of WDEQ/WQD's Chapter 1 Water Quality Rules and Regulations.

Though several lines of physical evidence indicate that the river's benthos upstream of the *altered reach* are subjected to a high degree of physical stress associated with excess sedimentation and high bed mobility, there is not a sufficient weight of biological evidence to conclude that the structure and function of the aquatic community in this reach of the river is adversely altered by these stressors. Excess nutrients may also influence the benthos upstream of the *altered reach* to a limited degree, but the available weight of evidence suggests there is no appreciable alteration to the resident benthos by excess nutrient inputs.

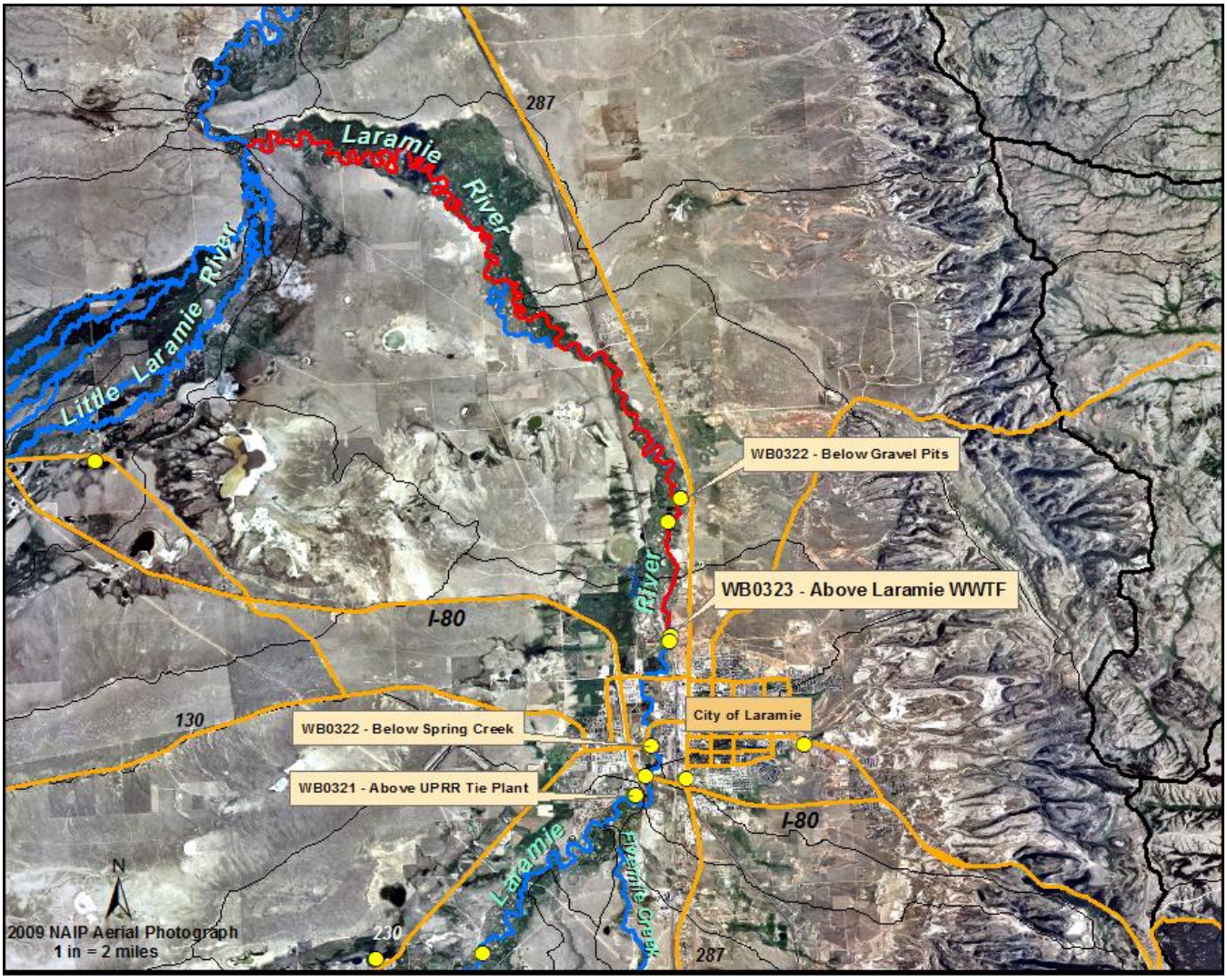
No exceedances of applicable numeric criteria for priority or non-priority pollutants were identified in the water quality data evaluated during this study. Furthermore, no indications of heavy metal toxicity, high salinity or episodes of depressed oxygen levels were inferred from relevant benthic macroinvertebrate and diatom metric results. Other water quality measurements either met applicable numeric and narrative criteria, or were comparable to regional expectations given the existing climate, flow regime, soils, geology and other basin characteristics.

Considering that the record peak flow event for the Laramie River was broken in 2010, there was reason to expect that the rivers' benthic community would experience a considerable degree of alteration in response to physical stressors associated with bed scour and sedimentation. Yet the biological evidence gathered after the flood indicated that the communities at each site did not differ appreciably from the corresponding communities observed in 2009, which was considered a relatively normal runoff year. In both years, the community within the *altered reach* consistently exhibited less similarity to the regional reference expectation than communities at sites upstream of the *altered reach*. Though these findings indicate that the river's biological condition declines precipitously with distance downstream of the City of Laramie, it is also recognized that these observations were made during a time period in which annual peak flow conditions varied widely. With this recognition, it may be assumed that the environmental

stressors to which the river's aquatic life are subjected during other times or flow conditions may differ from those observed during this study.

Improvements in the river's biological condition may occur in the future as a result of channel restoration and enhancement efforts initiated in 2009 and completed in 2011 within the urban reaches of the Laramie River by HabiTech, Inc. and WWC Engineering, Laramie Rivers Conservation District (LRCD) staff and community volunteer groups. This work was implemented on behalf of the Beautification Committee of the Laramie Economic Development Corporation, LRCD, Wyoming Game and Fish Department, and several financial supporters. Much of the restoration work was intended to protect valuable public and private property in areas threatened by accelerated bank erosion, and to improve aquatic and riparian habitat through localized hydraulic controls. Evidence gathered during this study indicates that bank erosion potential within the urban reach was reduced appreciably by these efforts, which may ultimately reduce the river's total sediment load, increase sediment transport capacity and improve channel habitat and biological condition in the long-term.

Figure 16 – Recommended extent of the '*altered reach*' (shown in red) on the Laramie River that does not meet the narrative standards described in Sections 15 and 32 of Chapter 1 of the Wyoming Water Quality Rules and Regulations based on the 2009-2010 water quality condition evaluation.



CHAPTER 1 STANDARDS ATTAINMENT/NON-ATTAINMENT

Based on a weight-of-evidence evaluation of the chemical, physical and biological information collected at sites on the Laramie River from 2009 to 2011, and in accordance with Wyoming's Methods for Determining Surface Water Quality Condition and TMDL Prioritization (WDEQ/WQD 2014a), the following conclusions on attainment/non-attainment of standards in Chapter 1 of the Wyoming Water Quality Rules and Regulations are provided for the evaluated reach of river starting from the confluence with Fivemile Creek downstream approximately 23 stream miles to the Little Laramie River confluence (Figure 16):

1) **Attainment of the following numeric criteria for the full extent of the Laramie River evaluation reach (Figure 16):**
   - nitrate, arsenic, cadmium, copper and selenium for the protection of human health (Section 18); and
   - chloride, arsenic, selenium and dissolved cadmium and copper (Section 21), dissolved oxygen (Section 24), temperature (Section 25) and pH (Section 26) for the protection of aquatic life.

2) **Indeterminate attainment of narrative criteria described in Sections 15 (Settleable Solids) and 32 (Biological Criteria) of Chapter 1 from the confluence with Fivemile Creek, downstream nine stream miles to the lower extent of the 'Above Laramie WWTF' study site (Figure 16).** Though several lines of physical evidence indicate that the river's resident benthic biota throughout this reach are subjected to a high degree of stress associated with excess sedimentation and high bed mobility, there is not a sufficient weight of biological evidence to conclude that the structure and function of the aquatic biological community has been adversely altered to constitute non-attainment of Section 32 (Biological Criteria), nor is there a significant degradation of the habitat used by aquatic life as stated in Section 15 (Settleable Solids) of WDEQ/WQD's Chapter 1 Water Quality Rules and Regulations. Nonetheless, the available evidence indicates that the benthic aquatic life within this reach are subject to a high degree of physical stress, resulting in an overall depressed biological condition relative to regional reference expectations.

3) **Non-attainment of narrative criteria described in Section 15 (Settleable Solids) and Section 32 (Biological Criteria) of Chapter 1 starting from lower extent of the 'Above Laramie WWTF' study site, downstream 14 stream miles to the Little Laramie River confluence (Figure 16).** Several lines of evidence indicate that excess sediment and nutrient enrichment within this reach of the Laramie River (*altered reach*) cause both marked departures in biological condition relative to the regional reference condition and to corresponding conditions observed in upstream reaches. The resident benthic biota are well-adapted to nutrient-rich, chronically unstable, fine sediment-dominated depositional environments. The major source of excess sediment, consisting mostly of sand and fine gravels, originates from in-channel sources within unstable reaches of the Laramie River, both upstream and within the *altered reach*. The City of Laramie WWTF point source discharge is considered the primary source of excess nutrients to the *altered reach*. Urban stormwater drainage and other potential non-point sources in the upstream watershed are considered secondary contributors of excess sediment and nutrients.

The combined evidence of excess sediment coupled with nutrient enrichment and an adverse alteration to the structure and function of the aquatic biological community within this reach translates to non-attainment of narrative criteria described in Section 15 (Settleable Solids) and Section 32 (Biological Criteria) of WDEQ/WQD's Chapter 1 Water Quality Rules and Regulations.

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APPENDICES

Appendix 1 – Physicochemical results at WDEQ/WQD stations on the Laramie River and Spring Creek, Albany County, WY (2009–2010).

	Laramie River								Spring Creek			
	Above UPRR Tie Plant		Below Spring Creek		Above Laramie WWTF		Below Gravel Pits		Below Grand Avenue		Above Third Street	
Parameters	WB0321		WB0322		WB0323		WB0321		WB0319		WB0320	
Collection Date	8/24/2009	9/3/2010	8/24/2009	9/3/2010	8/24/2009	9/3/2010	8/24/2009	9/3/2010	8/24/2009	9/3/2010	8/24/2009	9/3/2010
Collection Time	1635	1110	1430	1055	1215	1040	1045	1015	1810	1150	1730	1130
pH (S.U.)	8.47	7.81	8.33	7.86	8.19	7.83	8.37	7.49	8.24	8.02	8.48	8.03
Temperature (°C)	20.4	13.4	19.8	12.6	18.4	12.0	17.5	12.2	11.6	11.3	17.4	10.5
Specific Conductivity (µS/cm)	701	1421	814	1552	882	1568	996	1749	453	451	1613	1665
Dissolved Oxygen (mg/L)	8.41	7.86	9.29	7.91	8.11	7.35	9.51	7.11	8.90	8.59	9.15	10.61
Dissolved Oxygen (% saturation)	122	96	132	95	113	87	130	84	106	100	147	122
Turbidity (NTU)	2.9	2.3	2.3	2.5	2.3	3.0	3.0	5.6	1.2	0.5	0.7	0.3
Total Suspended Solids (mg/L)	9	4	7	5	12	5	8	8	4	6	8	4
Total Alkalinity (mg/L)	127	172	135	180	142	188	150	201	221	219	156	218
Calcium (mg/L)	58	88	68	108	70	102	80	122	57	59	180	209
Chloride (mg/L)	8	19	11	23	13	27	26	43	5	5	21	20
Magnesium (mg/L)	24	61	32	71	32	67	39	79	18	17	92	82
Sulfate (mg/L)	218	538	262	593	292	590	317	642	13	12	740	688
Total Kjeldahl Nitrogen (µg/L)	200	341	200	336	200	593	500	844	ND (<100)	ND (<100)	100	219
Nitrate+Nitrite-N (µg/L)	ND (<10)	ND (<10)	110	184	90	207	2220	4330	2570	2100	1690	2310
Total Nitrogen (µg/L)	200	341	300	520	300	800	2700	5174	2600	2100	1800	2529
Total Phosphorus (µg/L)	10	13	8	14	10	15	420	714	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Total Hardness (mg/L as $CaCO_3$)	244	472	299	562	309	532	361	631	216	217	827	859
Dissolved Arsenic (µg/L)	NM	ND (<1.0)	NM	ND (<1.0)	NM	ND (<1.0)	NM	1.2	NM	1.8	NM	1.7
Dissolved Cadmium (µg/L)	ND (<10)	NM	ND (<10)	NM	ND (<10)	NM	ND (<10)	NM	ND (<10)	NM	ND (<10)	NM
Dissolved Copper (µg/L)	ND (<10)	NM	ND (<10)	NM	ND (<10)	NM	ND (<10)	NM	ND (<10)	NM	ND (<10)	NM
Total Arsenic (µg/L)	ND (<1)	NM	ND (<1)	NM	ND (<1)	NM	ND (<1)	NM	2	NM	2	NM
Total Cadmium (µg/L)	ND (<0.1)	NM	ND (<0.1)	NM	ND (<0.1)	NM	ND (<0.1)	NM	ND (<0.1)	NM	ND (<0.1)	NM
Total Copper (µg/L)	0.6	NM	0.6	NM	0.6	NM	0.9	NM	1.4	NM	1.0	NM
Total Selenium (µg/L)	ND (<1)	(<1.0)	ND (<1)	1.5	ND (<1)	1.7	ND (<1)	1.7	ND (<1)	1.3	2	2.5
SVOCs - 64 analytes	Note 1	NM	Note 1	NM	Note 1	NM	Note 1	NM	NM	NM	NM	NM
Discharge (cfs)	18.5	13.2	17.8	17.2	20.8	16.7	22.7	26.2	0.15	NM	0.55	NM
Sheen	None	None	Note 2	Note 2	None	None	None	None	None	None	None	None
Color	None	None	None	None	None	None	None	None	None	None	None	None
Odor	None	None	Note 2	Note 2	None	None	None	None	None	None	None	None
Aerial Coverage (%) of Aquatic Macrophytes in Riffle [Reachwide]	0 [10-40]	0 [10-40]	0 [10-40]	0 [10-40]	1 [10-40]	1 [10-40]	<1 [10-40]	<1 [10-40]	NM	NM	NM	NM
Aerial Coverage (%) of Filamentous Algae in Riffle [Reachwide]	48 [40-75]	52 [40-75]	21 [10-40]	6 [10-40]	21 [10-40]	22 [40-75]	4 [40-75]	11 [10-40]	NM	NM	NM	NM

ND = Not Detected at reporting limit; NM = Not Measured
Values in parentheses ( ) represent analytical reporting limits.
SVOC = Semi-Volatile Organic Compound
Note 1: Results for all 64 SVOC analytes and their corresponding analytical reporting limits are provided in Appendix 1-A below.
Note 2: Intermittent sheen and weak hydrocarbon odor observed on water surface after disturbing sediment deposits in a backwater pool habitat and locally along left bank within the reach.

Appendix 1-A. Results of semi-volatile organic compounds (SVOCs) analyzed from water samples collected at WDEQ/WQD stations on the Laramie River in 2009.

	Above UPRR Tie Plant	Below Spring Creek		Above Laramie WWTF	Below Gravel Pits
Parameters	**WB0321**	**WB0322**		**WB0323**	**WB0321**
Collection Date	8/24/2009	8/24/2009	8/31/2009	8/24/2009	8/24/2009
Collection Time	1635	1430	1220	1215	1045
1,2,4-Trichlorobenzene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
1,2-Dichlorobenzene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
1,3-Dichlorobenzene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
1,4-Dichlorobenzene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
1-Methylnaphthalene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
2,4,5-Trichlorophenol	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
2,4,6-Trichlorophenol	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
2,4-Dichlorophenol	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
2,4-Dimethylphenol	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
2,4-Dinitrophenol	ND (<50)	ND (<50)	ND (<50)	ND (<50)	ND (<50)
2,4-Dinitrotoluene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
2,6-Dinitrotoluene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
2-Chloronaphthalene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
2-Chlorophenol	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
2-Methylnaphthalene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
2-Nitrophenol	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
3,3´-Dichlorobenzidine	ND (<20)	ND (<20)	ND (<20)	ND (<20)	ND (<20)
4,6-Dinitro-2-methylphenol	ND (<50)	ND (<50)	ND (<50)	ND (<50)	ND (<50)
4-Bromophenyl phenyl ether	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
4-Chloro-3-methylphenol	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
4-Chlorophenol	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
4-Chlorophenyl phenyl ether	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
4-Nitrophenol	ND (<50)	ND (<50)	ND (<50)	ND (<50)	ND (<50)
Acenaphthene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Acenaphthylene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Anthracene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Azobenzene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Benzidine	ND (<20)	ND (<20)	ND (<20)	ND (<20)	ND (<20)
Benzo(a)anthracene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Benzo(a)pyrene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Benzo(b)fluoranthene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Benzo(g,h,i)perylene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Benzo(k)fluoranthene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
bis(-2-chloroethoxy)Methane	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
bis(-2-chloroethyl)Ether	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
bis(2-chloroisopropyl)Ether	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
bis(2-ethylhexyl)Phthalate	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Butylbenzylphthalate	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Chrysene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Dibenzo(a,h)anthracene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Diethyl phthalate	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Dimethyl phthalate	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Di-n-butyl phthalate	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Di-n-octyl phthalate	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Fluoranthene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Fluorene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Hexachlorobenzene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Hexachlorobutadiene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Hexachlorocyclopentadiene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Hexachloroethane	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Indeno(1,2,3-cd)pyrene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Isophorone	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
m+p-Cresols	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Naphthalene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Nitrobenzene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
n-Nitrosodimethylamine	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
n-Nitroso-di-n-propylamine	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
n-Nitrosodiphenylamine	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
o-Cresol	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Pentachlorophenol	ND (<50)	ND (<50)	ND (<50)	ND (<50)	ND (<50)
Phenanthrene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Phenol	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Pyrene	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)
Pyridine	ND (<10)	ND (<10)	ND (<10)	ND (<10)	ND (<10)

Appendix 2 – Channel dimension, pattern and profile attributes and dimensionless ratios at sites on the Laramie River (2009–2010).

	Site Name	Above UPRR Tie Plant		Below Spring Creek		Above Laramie WWTF		Below Gravel Pits	
	Site ID	WB0321		WB0322		WB0323		WB0324	
	Year	2009	2010	2009	2010	2009	2010	2009	2010
	Rosgen Stream Classification	C4/1c-	C4/1c-	C4/5/1c-	C5/1c-	C4/1c-	C4/1c-	C5c-	C5c-
	Bankfull Channel Slope - Sbkf (ft/ft)	0.0011	0.00091	0.00046	0.00039	0.00079	0.00080	0.00037	0.00040
	Valley Slope = Sinousity x Sbkf (ft/ft)	0.0012	0.0010	0.00053	0.00045	0.00085	0.00086	0.00048	0.00052
	[a]Valley Slope - measured (ft/ft)	0.0013		0.00047		0.00094		0.00046	
	Reach Length (ft)	1150		1196		1500		2154	
	Watershed Area (mi^2)	1005		1060		1070		1109	
	Rosgen Valley Type	VIII		VIII		VIII		VIII	
[b]Channel Dimension	Mean Riffle Depth - d (ft)	2.20	2.15	1.95	2.30	1.97	1.97	2.30	2.26
	Maximum Riffle Depth - dmbkf (ft)	2.79	3.01	3.68	3.44	2.59	2.75	3.70	3.67
	Riffle Width - W (ft)	50.6	51.2	88.5	87.6	67.1	66.8	79.9	80.5
	Riffle Area - A (ft^2)	111	110	173	201	133	132	184	182
	Riffle W/d	23.0	23.8	45.4	38.1	34.1	33.9	34.7	35.6
	Riffle dmbkf/d	1.27	1.40	1.89	1.50	1.31	1.40	1.61	1.62
	Mean Pool Depth (ft)	1.78	1.93	2.74	2.89	2.35	3.77	2.08	2.26
	Maximum Pool Depth (ft)	3.87	4.33	4.09	4.26	4.70	5.06	5.32	4.78
	Pool Width (ft)	81.0	73.8	53.3	53.7	49.1	51.2	58.9	55.4
	Pool Area (ft^2)	144	143	146	155	115	193	122	125
	Mean Pool Depth / d	0.81	0.90	1.41	1.26	1.19	1.91	0.90	1.00
	Maximum Pool Depth / d	1.76	2.01	2.10	1.85	2.39	2.57	2.31	2.12
	Pool Width / W	1.60	1.44	0.60	0.61	0.73	0.77	0.74	0.69
	Pool Area / A	1.30	1.30	0.85	0.77	1.09	1.47	0.67	0.69
	Flood-prone Area Width - Wfpa (ft)	180		280		150		1000	
	Entrenchment Ratio (Wfpa / W)	3.56	3.52	3.16	3.20	2.23	2.24	12.52	12.43
[c]Channel Pattern	Channel Sinuosity - stream length/valley length (ft/ft)	1.10		1.16		1.08		1.30	
	Mean Meander Wavelength - Lm (ft)	375		274		305		258	
	Mean Radius of Curvature - Rc (ft)	162		143		158		151	
	Mean Belt Width - Wblt (ft)	117		127		177		263	
	Meander Length Ratio (Lm / W)	7.4	7.3	3.1	3.1	4.5	4.6	3.2	3.2
	Radius of Curvature (Rc / W)	3.2	3.2	1.6	1.6	2.4	2.4	1.9	1.9
	Meander Width Ratio (Wblt / W)	2.3	2.3	1.4	1.4	2.6	2.6	3.3	3.3
	Percentage (%) of Pool Habitat Reachwide	49	47	70	75	44	60	26	63
	Mean Individual Pool Length (ft)	186	169	282	282	192	304	212	341
	Mean Pool to Pool Spacing (ft)	331	235	524	367	489	279	860	431
	Mean Riffle Length (ft)	54.0	31.7	14.0	23.2	119	129[f]	347[f]	73
	Pool Length / W	3.7	3.3	3.2	3.2	2.9	4.5	2.6	4.2
	Pool to Pool Spacing / W	6.5	4.6	5.9	4.2	7.3	4.2	10.8	5.4
	Riffle Length / W	1.1	0.62	0.16	0.26	1.8	1.9	4.3	0.91

Appendix 2 (cont.) – Channel dimension, pattern and profile attributes and dimensionless ratios at sites on the Laramie River (2009–2010).

	Site Name	Above UPRR Tie Plant		Below Spring Creek		Above Laramie WWTF		Below Gravel Pits	
	Site ID	WB0321		WB0322		WB0323		WB0324	
	Year	2009	2010	2009	2010	2009	2010	2009	2010
	Rosgen Stream Classification	C4/1c-	C4/1c-	C4/5/1c-	C5/1c-	C4/1c-	C4/1c-	C5c-	C5c-
	Bankfull Channel Slope - Sbkf (ft/ft)	0.0011	0.00091	0.00046	0.00039	0.00079	0.00080	0.00037	0.00040
	Valley Slope = Sinousity x Sbkf (ft/ft)	0.0012	0.0010	0.00053	0.00045	0.00085	0.00086	0.00048	0.00052
	[a]Valley Slope - measured (ft/ft)	0.0013		0.00047		0.00094		0.00046	
	Reach Length (ft)	1150		1196		1500		2154	
	Watershed Area (mi^2)	1005		1060		1070		1109	
	Rosgen Valley Type	VIII		VIII		VIII		VIII	
[d]Facet Slopes	Mean Riffle/Run Slope (ft/ft)	0.00214f	0.00393[f]	0.00096[f]	0.00292[f]	0.00130[f]	0.00171[f]	0.00079[f]	0.00097[f]
	Riffle/Run Slope / Sbkf	1.95	4.32	2.09	7.49	1.65	2.14	2.14	2.43
	Mean Pool Slope (ft/ft)	0.00043	0.00019	0.00013	0.00009	0.00004	0.00002	0.00032	0.00015
	Pool Slope / Sbkf	0.39	0.21	0.28	0.23	0.05	0.03	0.86	0.38
	Mean Glide Slope (ft/ft)	0.00167	0.00090	0.00027	0.00031	0.00094	0.00144	0.00164	0.00014
	Glide Slope / Sbkf	1.52	0.99	0.59	0.79	1.19	1.80	4.43	0.35
[e]BHR	Low est Bank Height (LBH) - u/s to d/s	3.54 - 3.80	3.68 - 3.85	3.19 - 3.32	4.13 - 3.24	3.11 - 3.40	3.09 - 3.41	3.42 - 3.62	3.47 - 3.76
	Riffle-run Depth (dbkf) - u/s to d/s	2.94 - 2.67	3.08 - 2.72	2.67 - 2.91	3.62 - 2.83	2.80 - 3.00	2.80 - 3.01	2.57 - 2.91	2.71 - 3.15
	Bank Height Ratio (LBH/dbkf) - u/s to d/s	1.20 - 1.42	1.20 - 1.42	1.19 - 1.14	1.14 - 1.14	1.11 - 1.13	1.10 - 1.13	1.33 - 1.24	1.28 - 1.19
[d,g]Facet Depths	Mean Riffle/Run Depth (ft)	2.75[f]	2.84[f]	3.26[f]	3.16[f]	2.83[f]	2.78[f]	3.14[f]	3.31[f]
	Riffle/Run Depth / d	1.25	1.32	1.67	1.37	1.44	1.41	1.37	1.46
	Mean Maximum Pool Depth (ft)	4.53	4.37	5.53	5.57	3.79	3.72	5.31	4.73
	Pool Depth / d	2.06	2.03	2.84	2.42	1.92	1.89	2.31	2.09
	Mean Glide Depth (ft)	2.57	2.68	3.06	2.84	2.67	2.38	3.26	2.90
	Glide Depth / d	1.17	1.25	1.57	1.23	1.36	1.21	1.42	1.28

NOTE: All w idths and depths measured from bankfull elevations, excluding low bank heights.

[a] Field-measured value derived from surveyed elevations on abandoned terraces or past floodplain features.

[b] Measurements derived from cross-section survey data.

[c] Measurements derived from 2009 aerial photography and longitudinal survey data.

[d] Statistic derived from multiple measurements made at bed features (facets) of the same type identified in the longitudinal profile.

[e] BHR= Bank-Height Ratio (degree of channel incision). Low bank height (LBH) measurements made at mid-point of riffle/run bed features at upstream (u/s) and dow nstream (d/s) stations of reach.

[f] Because of the difficulty in differentiating riffle and run facets, measurements from both w ere used to derive one value reported as a riffle/run attribute.

[g] Riffle/run depths measured at midpoint of feature. Glide depths measured at the tail-out or head of riffle. Pool depths measured at deepest point of feature.

Appendix 3 – Estimated bankfull discharge and associated velocity and shear stress values derived from baseflow channel dimensions (measured) and scour-adjusted channel dimensions (estimated from bed scour survey results) for sites on the Laramie River (2009–2010).

Bankfull channel attributes derived from baseflow survey data.

										Velocity & Bankfull Discharge (Qbkf) Estimation Methods										
										Mannings "n" (Limerinos 1970)		Darcy-Weisbach (Leopold et al. 1964)		Darcy-Weisbach (Hey 1979)		U/U* (Rosgen 1996)				
Reach	Year	Cross-Section	Channel Slope (ft/ft)	Cross-Sectional Area (ft^2)	Mean Depth (ft)	Hydraulic Radius (ft)	Max Depth (ft)	Riffle D_{84} (mm)	Wetted Perimeter (ft)	Velocity (ft/sec)	Qbkf (cfs)	Velocity (ft/sec)	Qbkf (cfs)	Velocity (ft/sec)	Qbkf (cfs)	Velocity (ft/sec)	Qbkf (cfs)	Mean Velocity (ft/sec)	Mean Qbkf (cfs)	Qbkf Shear Stress (lbs/ft^2)
Above UPRR Tie Plant	2009	Riffle 1+79	0.0011	111	2.20	2.11	2.79	32	52.6	2.92	325	2.82	313	2.89	321	2.79	310	2.86	318	0.14
(WB0321)	2010	Riffle 1+79	0.00091	110	2.15	2.08	3.01	17	53.1	3.00	331	2.93	322	3.01	332	2.89	318	2.96	326	0.12
																	Mean Values	**2.91**	**322**	**0.13**
Below Spring Creek	2009	Riffle 10+66	0.00046	173	1.95	1.88	3.68	21	91.6	1.91	330	1.85	319	1.94	336	1.83	316	1.88	325	0.054
(WB0322)	2010	Riffle 10+66	0.00039	201	2.30	2.21	3.44	31	91.0	1.81	364	1.75	352	1.82	366	1.73	349	1.78	358	0.054
																	Mean Values	**1.83**	**342**	**0.054**
Above Laramie WWTF	2009	Riffle 5+90	0.00079	133	1.97	1.92	2.59	15	69.0	2.71	359	2.64	351	2.71	359	2.62	347	2.67	354	0.095
(WB0323)	2010	Riffle 5+90	0.00080	132	1.97	1.82	2.75	15[a]	72.4	2.63	346	2.56	337	2.64	347	2.53	333	2.59	341	0.091
																	Mean Values	**2.63**	**347**	**0.093**
Below Gravel Pits	2009	Riffle 7+87	0.00037	184	2.30	2.23	3.70	15[a]	82.5	2.06	379	2.01	370	2.08	384	1.99	366	2.04	375	0.051
(WB0324)	2010	Riffle 7+87	0.00040	182	2.26	2.20	3.67	15[a]	82.6	2.12	385	2.07	376	2.15	390	2.05	372	2.10	381	0.055
																	Mean Values	**2.07**	**378**	**0.053**

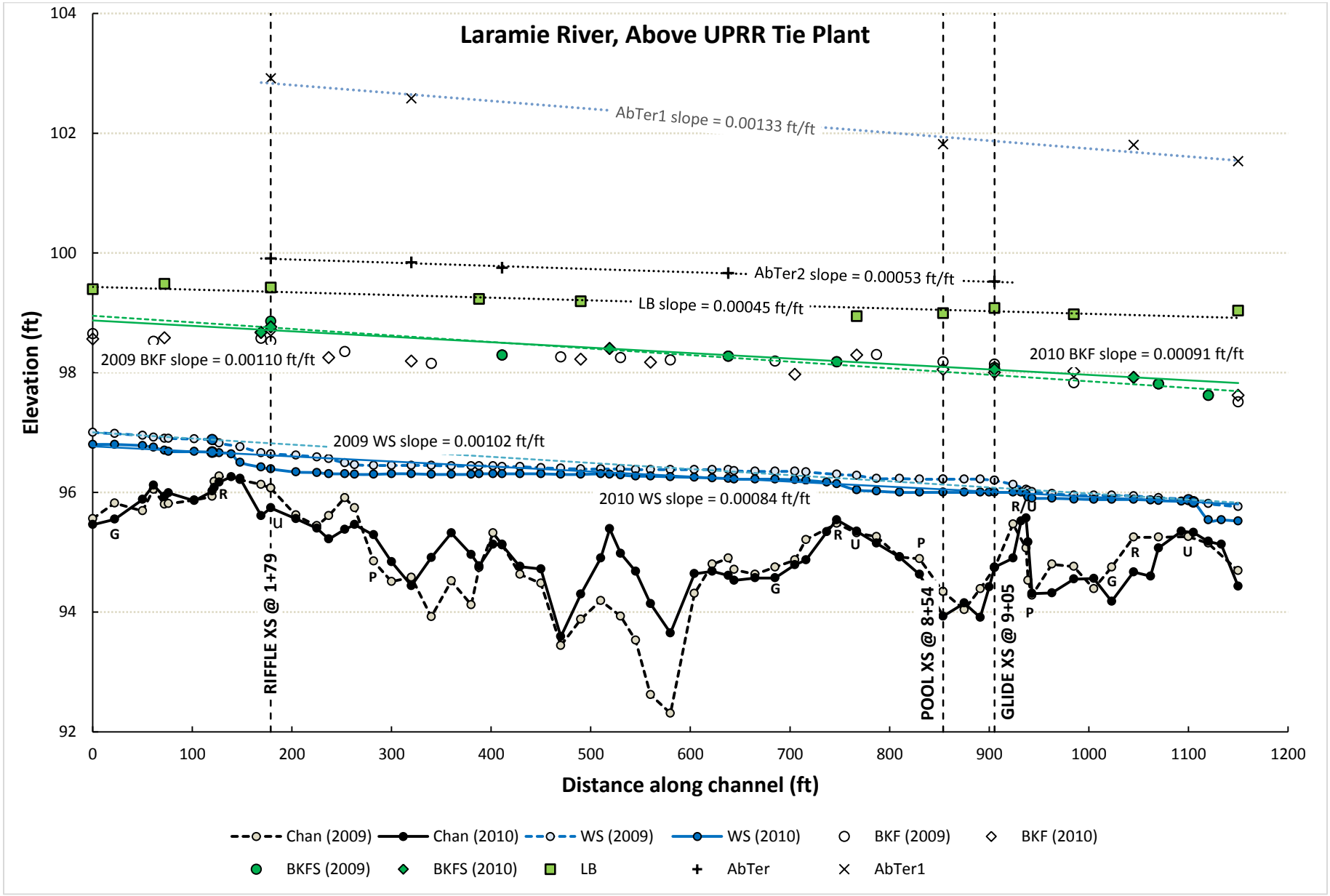
[a] Estimated sand/fine gravel dune protrusion height. Measured riffle D_{84} values ranged from 10 to 15 mm.

Bankfull channel attributes estimated from bed scour results.

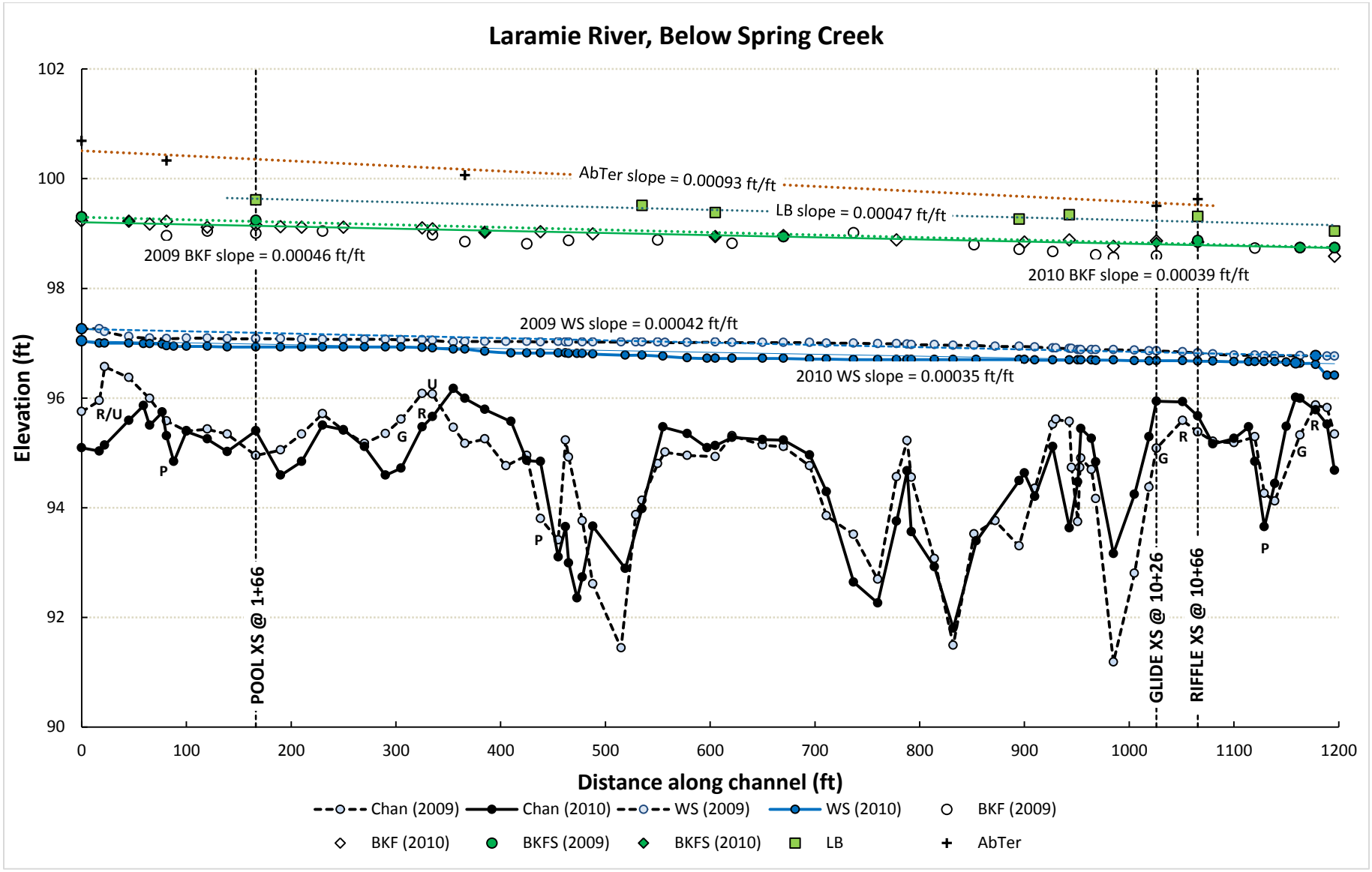
										Velocity & Bankfull Discharge (Qbkf) Estimation Methods										
										Mannings "n" (Limerinos 1970)		Darcy-Weisbach (Leopold et al. 1964)		Darcy-Weisbach (Hey 1979)		U/U* (Rosgen 1996)				
Reach	Year	Cross-Section	Channel Slope (ft/ft)	Cross-Sectional Area (ft^2)	Mean Depth (ft)	Hydraulic Radius (ft)	Max Depth (ft)	Riffle D_{84} (mm)	Wetted Perimeter (ft)	Velocity (ft/sec)	Qbkf (cfs)	Velocity (ft/sec)	Qbkf (cfs)	Velocity (ft/sec)	Qbkf (cfs)	Velocity (ft/sec)	Qbkf (cfs)	Mean Velocity (ft/sec)	Mean Qbkf (cfs)	Qbkf Shear Stress (lbs/ft^2)
Above UPRR Tie Plant	2010	Riffle 1+79	0.0011	141	2.37	2.32	3.39	17	60.7	3.57	503	3.48	490	3.57	503	3.44	484	3.52	495	0.16
Below Spring Creek	2010	Riffle 10+66	0.00046	226	2.56	2.46	3.86	21	92.2	2.30	520	2.24	507	2.38	538	2.21	501	2.28	517	0.071
Above Laramie WWTF	2010	Riffle 5+90	0.00080	172	2.55	2.40	3.33	15	71.6	3.20	550	3.11	535	3.19	549	3.08	530	3.15	541	0.120
Below Gravel Pits	2010	Riffle 7+87	0.00040	243	2.96	2.87	3.88	15[a]	84.6	2.56	622	2.49	606	2.55	619	2.47	599	2.52	612	0.072

[a] Estimated sand/fine gravel dune protrusion height. Measured riffle D_{84} values ranged from 10 to 15 mm.

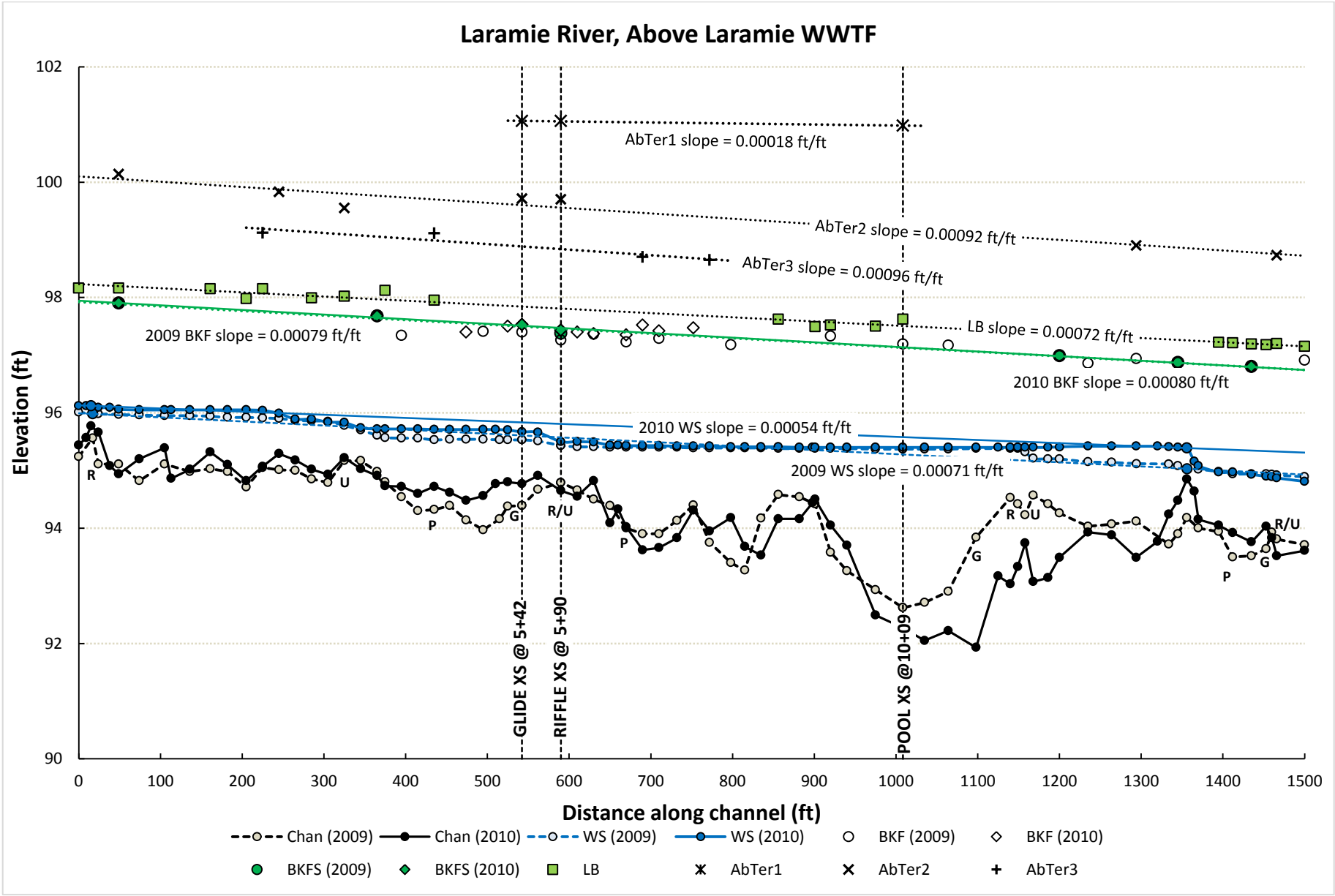
Appendix 4 – Overlays of 2009 and 2010 longitudinal profiles at WDEQ/WQD sites on the Laramie River that illustrate cross-section (XS) locations and annual changes in channel bed thalweg (Chan) and water surface (WS) elevations. Riffle (R), Run (U), Pool (P), and Glide (G) bed features are associated with 2009 profile survey. BKF= bankfull elevation, BKFS= bankfull slope, LB= Low Bank, LBS= Low Bank Slope, AbTer= Abandoned Terrace.



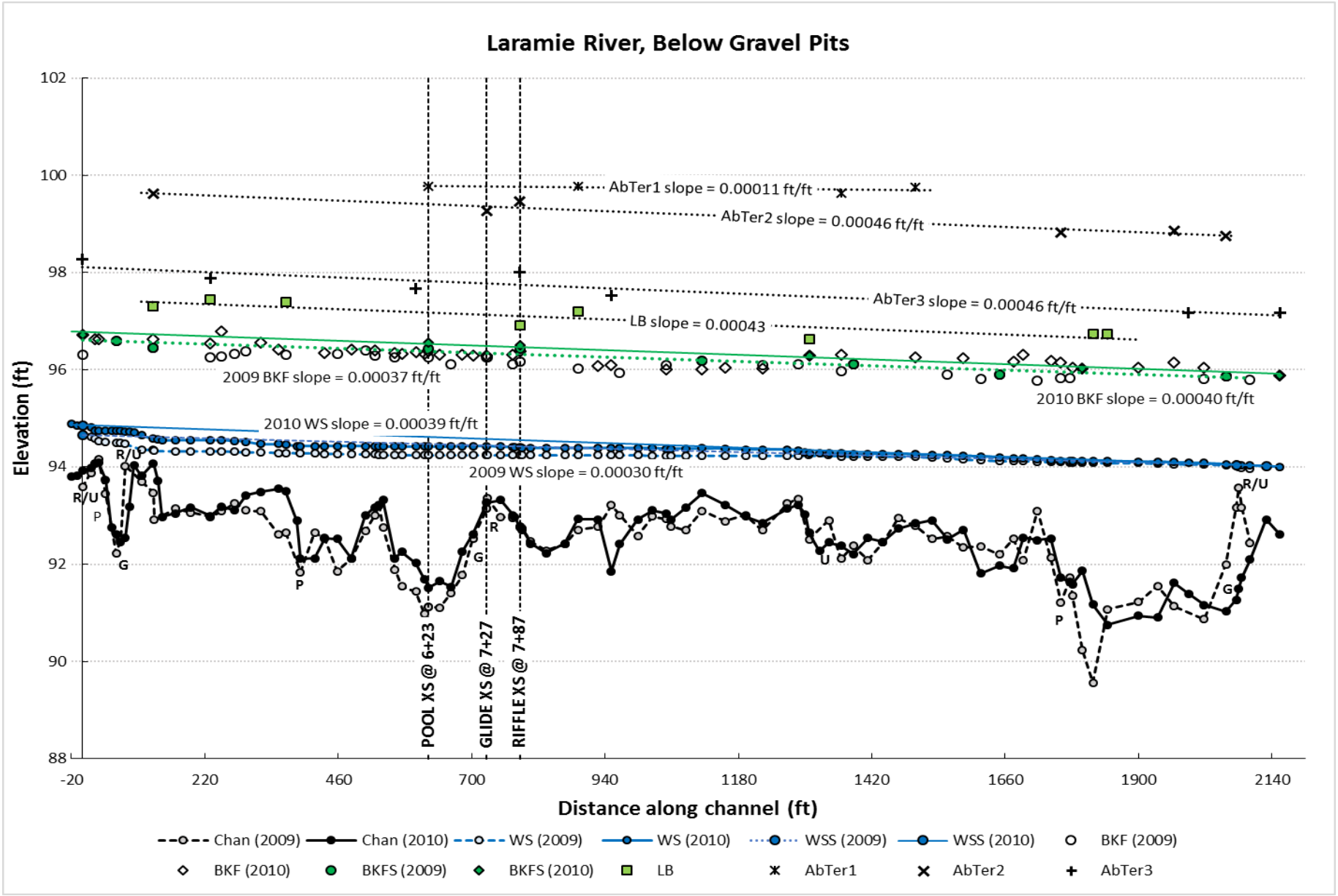
Appendix 4 (cont.) – Overlays of 2009 and 2010 longitudinal profiles at WDEQ/WQD sites on the Laramie River that illustrate cross-section (XS) locations and annual changes in channel bed thalweg (Chan) and water surface (WS) elevations. Riffle (R), Run (U), Pool (P), and Glide (G) bed features are associated with 2009 profile survey. BKF= bankfull elevation, BKFS= bankfull slope, LB= Low Bank, LBS= Low Bank Slope, AbTer= Abandoned Terrace.



Appendix 4 (cont.) – Overlays of 2009 and 2010 longitudinal profiles at WDEQ/WQD sites on the Laramie River that illustrate cross-section (XS) locations and annual changes in channel bed thalweg (Chan) and water surface (WS) elevations. Riffle (R), Run (U), Pool (P), and Glide (G) bed features are associated with 2009 profile survey. BKF= bankfull elevation, BKFS= bankfull slope, LB= Low Bank, LBS= Low Bank Slope, AbTer= Abandoned Terrace.



Appendix 4 (cont.) – Overlays of 2009 and 2010 longitudinal profiles at WDEQ/WQD sites on the Laramie River that illustrate cross-section (XS) locations and annual changes in channel bed thalweg (Chan) and water surface (WS) elevations. Riffle (R), Run (U), Pool (P), and Glide (G) bed features are associated with 2009 profile survey. BKF= bankfull elevation, BKFS= bankfull slope, LB= Low Bank, LBS= Low Bank Slope, AbTer= Abandoned Terrace.



Appendix 5 – Percent streambank stability and cover estimates at sites on the Laramie River (2009–2010).

	Above UPRR Tie Plant		Below Spring Creek		Above Laramie WWTF		Below Gravel Pits	
	2009	2010	2009	2010	2009	2010	2009	2010
% Stable	30	59	67	63	88	75	52	55
% Covered	48	31	62	68	67	86	48	46

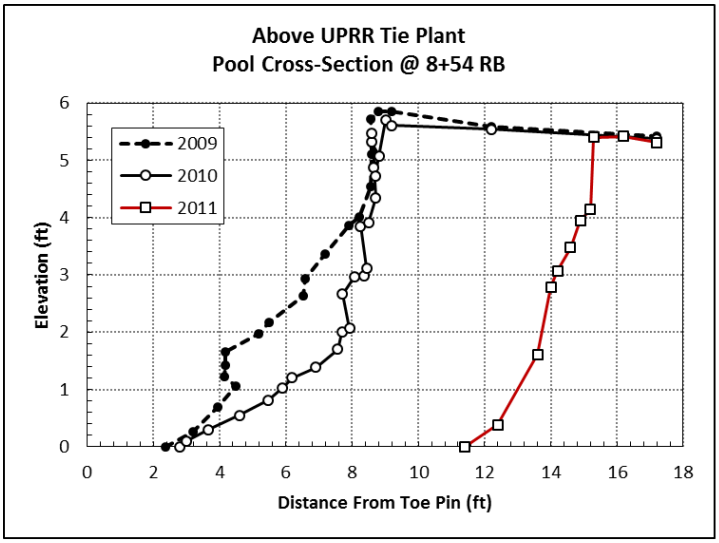
Appendix 6 – Observed and predicted average annual stream bank erosion rates and associated BEHI/NBS ratings at permanent cross-sections at Laramie River sites (2009–2010). LB and RB equate to left bank and right bank, respectively. Negative values under bank erosion rate columns represent the rate of bank retreat (lateral accretion).

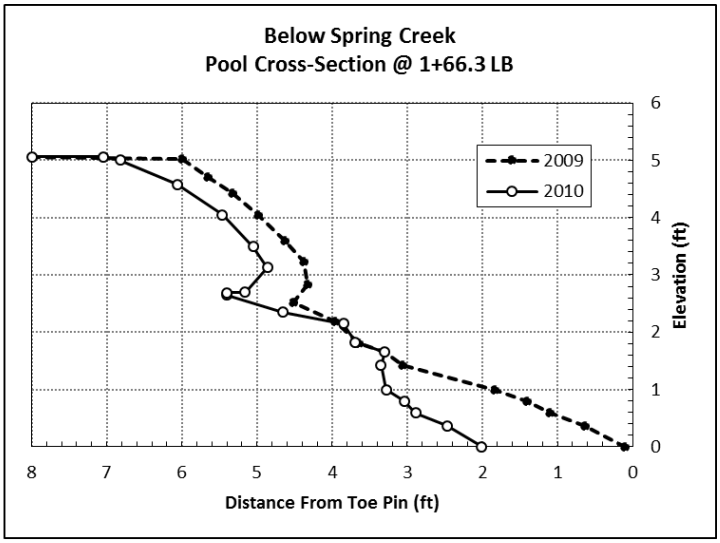
Study Site	Year	Study Bank Height (ft)	BEHI	NBS (d_{nb}/d_{bkf})	Toe Pin Area (ft^2)	Bank Erosion Rate (ft/yr) 2009 - 2010 Predicted[a]	2009 - 2010 Observed	2010 - 2011 Predicted[a]	2010 - 2011 Observed	Total Observed Bank Erosion (ft) 2009 - 2011
Above UPRR Tie Plant 8+54 RB	**2009**	5.86	Extreme	High	39.47	-2.75				
	2010	5.70	Extreme	High	43.92		-0.76	-2.75		
	2011[b]	5.42	-	-	76.02				-5.63	-6.24
Below Spring Creek 1+66 LB	**2009**	5.06	High	Low	18.60	-0.25				
	2010	5.06	Very High	Low	22.35		-0.74	-0.25	-	-
Above Laramie WWTF 10+09 LB	**2009**	6.01	High	High	18.09	-2.75				
	2010	6.01	Very High	Low	18.72		-0.10	-0.25		
	2011[b]	5.78	-	-	33.17				-2.40	-2.51
Below Gravel Pits 6+23 RB	**2009**	7.21	Extreme	High	27.40	-2.75				
	2010	7.21	Extreme	High	45.05		-2.45	-2.75	-	-

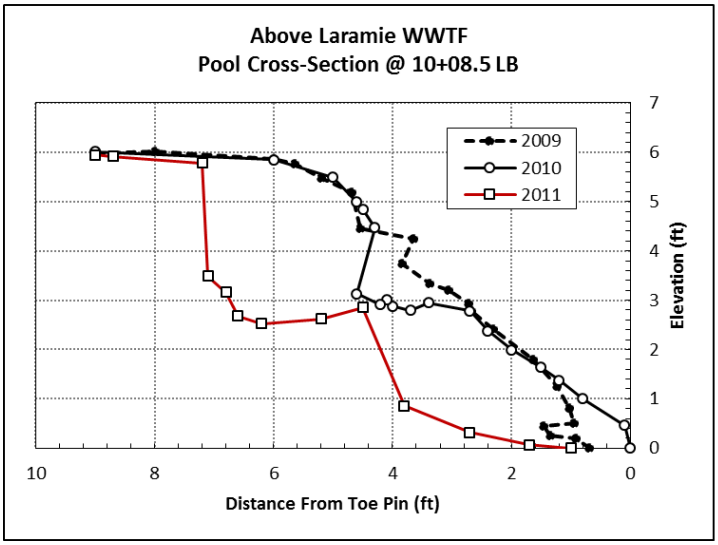
[a] Derived from streambank erosion rate relationships developed by (Rosgen 2006a) using Colorado USDA Forest Service data for streams found in sedimentary and/or metamorphic geology and corresponding annual BEHI/NBS ratings.

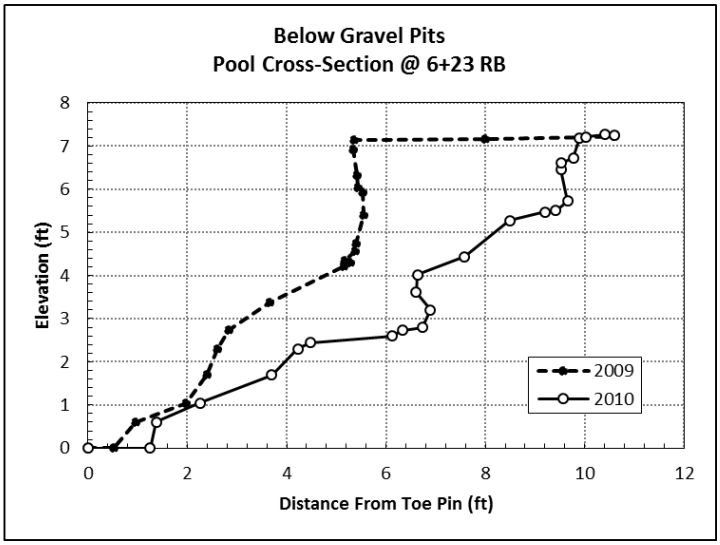
[b] Study bank height and toe pin area obtained from 2011 cross-section survey data. Estimates of BEHI and NBS were not made in 2011.

Appendix 7 – Bank profile plots generated from survey data collected at permanent cross-sections at Laramie River sites (2009–2010). LB and RB represent left bank and right bank, respectively. A bank profile survey could not be completed at 'Below Spring Creek' in 2011 because the bank was reshaped to install bank and channel treatments that year, resulting in the loss of reference elevation pins.









Appendix 8 – Predicted annual stream bank erosion rates at Laramie River sites. Predictions derived from BANCS model developed from stream data collected in sedimentary/metamorphic geographic regions in Colorado (Rosgen 2006a).

Above UPRR Tie Plant (2009)

Bank	Start Station (ft)	End Station (ft)	BEHI	NBS	Predicted Bank Erosion Rate (ft/yr)	Length of Bank (ft)	Bank Height (ft)	Erosion Subtotal (ft^3/yr)
Left	375	428	High	Low	0.2504	53	4.7	62.38
Left	428	454	Very High	Low	0.2504	26	4.5	29.30
Left	454	461	Very High	High	0.5753	7	5.3	21.34
Left	461	477	Moderate	High	0.4203	16	4.4	29.59
Left	477	528	Extreme	High	2.7474	51	4.6	644.54
Left	528	547	Moderate	Low	0.1529	19	4.7	13.65
Left	547	557	High	High	0.5753	10	5.5	31.64
Left	937	945	Low	Very Low	0.0171	8	4.4	0.60
Left	945	969	Extreme	High	2.7474	24	5.8	382.44
Left	969	1020	High	Low	0.2504	51	5.2	66.41
Left	1020	1058	Extreme	Moderate	1.0742	38	5.3	216.34
Left	1058	1085	Low	Very Low	0.0171	27	5.4	2.49
Left	1085	1113	Moderate	Very Low	0.0922	28	5.4	13.94
Left	1113	1150	High	Low	0.2504	37	5.3	49.11
Right	20	137	Extreme	Very Low	0.1642	117	6.1	117.19
Right	137	160	High	Very Low	0.1652	23	5.8	22.04
Right	160	255	Extreme	Very Low	0.1642	95	6.1	95.16
Right	255	281	Extreme	Low	0.4200	26	6.0	65.52
Right	281	314	High	High	0.5753	33	4.5	85.44
Right	314	360	Very High	Low	0.2504	46	4.2	48.38
Right	360	385	Moderate	Moderate	0.2535	25	4.2	26.62
Right	606	720	Extreme	Very Low	0.1642	114	6.5	121.67
Right	720	780	Very High	Low	0.2504	60	5.4	81.14
Right	780	832	Extreme	Low	0.4200	52	5.4	117.93
Right	832	837	Moderate	Moderate	0.2535	5	5.6	7.10
Right	837	881	Extreme	Low	0.4200	44	5.6	103.48
Right	881	895	Low	Moderate	0.0744	14	5.0	5.20

Dominant BEHI/NBS Rating for Reach = Extreme/Very Low		**Total Predicted Erosion (ft^3/yr)**	**2460.6**
		Total Predicted Erosion (yds^3/yr)	**91.1**
		Total Predicted Erosion (tons/yr)	**118.5**
Total Reach Length ft) =	1,150	**Total Erosion (tons/yr/ft)**	**0.103**

Above UPRR Tie Plant (2010)

Bank	Start Station (ft)	End Station (ft)	BEHI	NBS	Predicted Bank Erosion Rate (ft/yr)	Length of Bank (ft)	Bank Height (ft)	Erosion Subtotal (ft^3/yr)
Left	382	460	High	Low	0.2504	78	4.6	89.85
Left	460	500	High	Moderate	0.3796	40	5.4	81.99
Left	500	555	Extreme	Low	0.4200	55	5.0	115.49
Left	555	585	High	High	0.5753	30	4.4	75.94
Left	940	1050	Extreme	Low	0.4200	110	5.9	272.57
Left	1050	1100	Moderate	Low	0.1529	50	2.7	20.64
Left	1100	1150	High	Low	0.2504	50	6.0	75.13
Right	0	15	Moderate	Low	0.1529	15	6.5	14.90
Right	15	138	Extreme	Low	0.4200	123	6.6	340.94
Right	138	160	Moderate	Low	0.1529	22	6.6	22.20
Right	160	290	Extreme	Low	0.4200	130	5.9	322.12
Right	290	315	Very High	Moderate	0.3796	25	4.6	43.65
Right	315	340	High	Low	0.2504	25	4.2	26.29
Right	340	362	Very High	Low	0.2504	22	4.5	24.79
Right	362	382	Moderate	Low	0.1529	20	4.5	13.76
Right	620	765	Extreme	Low	0.4200	145	6.4	389.74
Right	765	880	Extreme	Low	0.4200	115	6.5	313.93
Right	880	900	Very High	High	0.5753	20	3.2	36.82

Dominant BEHI/NBS Rating for Reach = Extreme/Low		**Total Predicted Erosion (ft^3/yr)**	**2280.8**
		Total Predicted Erosion (yds^3/yr)	**84.5**
		Total Predicted Erosion (tons/yr)	**109.8**
Total Reach Length ft) =	1,150	**Total Erosion (tons/yr/ft)**	**0.095**

Appendix 8 (cont.) – Predicted annual stream bank erosion rates at Laramie River sites. Predictions derived from BANCS model developed from stream data collected in sedimentary/metamorphic geographic regions in Colorado (Rosgen 2006a).

Above UPRR Tie Plant (2011)

Bank	Start Station (ft)	End Station (ft)	BEHI	NBS	Predicted Bank Erosion Rate (ft/yr)	Length of Bank (ft)	Bank Height (ft)	Erosion Subtotal (ft3/yr)
Left	380	425	High	Low	0.2504	45	4.8	54.09
Left	425	457	High	High	0.5753	32	3.8	69.96
Left	457	493	Moderate	High	0.4203	36	4.0	60.52
Left	493	530	High	Moderate	0.3796	37	4.2	58.99
Left	530	572	Moderate	Moderate	0.2535	42	4.5	47.91
Left	572	620	Moderate	Low	0.1529	48	2.9	21.28
Left	945	1000	High	Low	0.2504	55	5.0	68.87
Left	1000	1056	Extreme	Moderate	1.0742	56	4.8	288.74
Left	1056	1078	Very High	High	0.5753	22	5.1	64.55
Left	1078	1150	Very High	Low	0.2504	72	5.0	90.15
Right	0	18	Moderate	Low	0.1529	18	5.7	15.68
Right	18	143	Very High	Low	0.2504	125	5.9	184.69
Right	143	160	Moderate	Low	0.1529	17	6.1	15.85
Right	160	235	Very High	Low	0.2504	75	5.6	105.18
Right	235	295	Very High	Moderate	0.3796	60	5.6	127.54
Right	295	340	High	High	0.5753	45	3.8	98.38
Right	340	370	High	Moderate	0.3796	30	3.8	43.27
Right	370	395	Moderate	Moderate	0.2535	25	3.0	19.01
Right	610	712	Very High	Low	0.2504	102	5.4	137.93
Right	712	785	High	Low	0.2504	73	5.0	91.40
Right	785	810	High	Moderate	0.3796	25	4.3	40.80
Right	810	845	Very High	Moderate	0.3796	35	4.5	59.78
Right	845	890	Extreme	Moderate	1.0742	45	5.0	241.69
Right	890	915	Moderate	Moderate	0.2535	25	3.5	22.18

Dominant BEHI/NBS Rating for Reach = Very High/Low		**Total Predicted Erosion (ft3/yr)**	**2028.4**
		Total Predicted Erosion (yds3/yr)	**75.1**
		Total Predicted Erosion (tons/yr)	**97.7**
Total Reach Length ft) =	1,150	**Total Predicted Erosion (tons/yr/ft)**	**0.085**

Appendix 8 (cont.) – Predicted annual stream bank erosion rates at Laramie River sites. Predictions derived from BANCS model developed from stream data collected in sedimentary/metamorphic geographic regions in Colorado (Rosgen 2006a).

Below Spring Creek (2009)

Bank	Start Station (ft)	End Station (ft)	BEHI	NBS	Predicted Bank Erosion Rate (ft/yr)	Length of Bank (ft)	Bank Height (ft)	Erosion Subtotal (ft^3/yr)
Left	66	112	Moderate	Low	0.1529	46	5.0	35.16
Left	112	127	Very High	Very Low	0.1652	15	4.8	11.90
Left	127	157	High	Very Low	0.1652	30	4.5	22.30
Left	157	174	Very High	Low	0.2504	17	5.2	22.14
Left	174	256	High	Low	0.2504	82	5.0	102.67
Left	256	281	High	Moderate	0.3796	25	4.8	45.55
Left	281	300	High	Low	0.2504	19	5.1	24.27
Left	574	618	Moderate	Low	0.1529	44	3.7	24.89
Left	618	714	Very High	Low	0.2504	96	4.3	103.37
Left	714	730	High	Very High	0.8721	16	5.5	76.74
Left	730	895	Very High	High	0.5753	165	5.5	522.11
Left	895	920	High	High	0.5753	25	5.0	71.92
Left	1120	1140	High	High	0.5753	20	3.2	36.82
Left	1140	1155	Moderate	Low	0.1529	15	3.2	7.34
Right	0	20	Moderate	Very Low	0.0922	20	4.0	7.38
Right	320	388	High	Very Low	0.1652	68	4.1	46.06
Right	388	425	High	Low	0.2504	37	5.0	46.33
Right	425	443	High	High	0.5753	18	5.5	56.96
Right	443	455	High	Very High	0.8721	12	4.6	48.14
Right	455	465	High	Moderate	0.3796	10	4.5	17.08
Right	465	475	Very High	Low	0.2504	10	4.5	11.27
Right	475	520	Low	Very Low	0.0171	45	5.0	3.85
Right	940	946	Moderate	High	0.4203	6	4.0	10.09
Right	946	985	Very Low	High	0.1550	39	5.5	33.26
Right	985	1005	High	High	0.5753	20	5.0	57.53
Right	1005	1057	Low	Very Low	0.0171	52	3.0	2.67
Right	1057	1065	Moderate	Low	0.1529	8	3.5	4.28
Right	1065	1160	Very High	Low	0.2504	95	3.8	90.40
Right	1160	1200	Low	Moderate	0.0744	40	4.5	13.38

Dominant BEHI/NBS Rating for Reach = Very High/Low		**Total Predicted Erosion (ft^3/yr)**	**1555.8**
		Total Predicted Erosion (yds^3/yr)	**57.6**
		Total Predicted Erosion (tons/yr)	**74.9**
Total Reach Length ft) =	1,200	**Total Erosion (tons/yr/ft)**	**0.062**

Below Spring Creek (2010)

Bank	Start Station (ft)	End Station (ft)	BEHI	NBS	Predicted Bank Erosion Rate (ft/yr)	Length of Bank (ft)	Bank Height (ft)	Erosion Subtotal (ft^3/yr)
Left	78	110	Moderate	Low	0.1529	32	5.5	26.90
Left	110	178	Extreme	Low	0.4200	68	5.2	148.50
Left	178	205	Moderate	Moderate	0.2535	27	4.7	32.17
Left	205	245	Moderate	Low	0.1529	40	4.9	29.96
Left	245	310	Very High	Moderate	0.3796	65	5.5	135.70
Left	600	620	Moderate	Low	0.1529	20	3.4	10.40
Left	620	715	Extreme	Low	0.4200	95	4.6	183.53
Left	715	775	Extreme	High	2.7474	60	5.3	873.67
Left	775	820	Extreme	Very High	7.0269	45	5.5	1739.16
Left	820	850	Extreme	High	2.7474	30	4.4	362.65
Left	850	905	Extreme	Moderate	1.0742	55	5.6	330.84
Left	905	915	Very High	High	0.5753	10	5.3	30.49
Right	337	410	Moderate	Low	0.1529	73	4.6	51.33
Right	410	479	Very High	Moderate	0.3796	69	5.4	141.43
Right	479	520	Very High	High	0.5753	41	6.0	141.53
Right	915	975	Low	Low	0.0357	60	4.5	9.63
Right	975	1005	Moderate	High	0.4203	30	3.8	47.91
Right	1075	1176	Very High	Low	0.2504	101	4.5	113.82

Dominant BEHI/NBS Rating for Reach = Extreme/Low		**Total Predicted Erosion (ft^3/yr)**	**4409.6**
		Total Predicted Erosion (yds^3/yr)	**163.3**
		Total Predicted Erosion (tons/yr)	**212.3**
Total Reach Length ft) =	1,200	**Total Erosion (tons/yr/ft)**	**0.177**

Appendix 8 (cont.) – Predicted annual stream bank erosion rates at Laramie River sites. Predictions derived from BANCS model developed from stream data collected in sedimentary/metamorphic geographic regions in Colorado (Rosgen 2006a).

Below Spring Creek (2011)

Bank	Start Station (ft)	End Station (ft)	BEHI	NBS	Predicted Bank Erosion Rate (ft/yr)	Length of Bank (ft)	Bank Height (ft)	Erosion Subtotal (ft^3/yr)
Left	45	70	Low	Low	0.0357	25	3.5	3.12
Left	70	78	Low	Low	0.0357	8	4.4	1.26
Left	78	112	Moderate	Low	0.1529	34	4.5	23.39
Left	112	131	Low	Low	0.0357	19	4.5	3.05
Left	131	148	High	Low	0.2504	17	4.1	17.45
Left	148	156	Low	Low	0.0357	8	4.2	1.20
Left	156	166	High	Low	0.2504	10	4.6	11.52
Left	166	179	Low	Low	0.0357	13	4.2	1.95
Left	179	216	Moderate	Low	0.1529	37	4.6	26.02
Left	216	226	Low	Low	0.0357	10	3.4	1.21
Left	226	260	High	Moderate	0.3796	34	3.4	43.88
Left	260	275	Low	Low	0.0357	15	3.6	1.93
Left	275	309	Moderate	Low	0.1529	34	3.4	17.67
Left	309	320	Low	Low	0.0357	11	3.1	1.22
Left	320	328	Low	Low	0.0357	8	3.6	1.03
Left	552	595	Low	Low	0.0357	43	2.6	3.99
Left	595	793	Low	Low	0.0357	198	4.0	28.24
Left	793	892	Low	Moderate	0.0744	99	4.0	29.44
Left	892	910	Low	Low	0.0357	18	3.7	2.37
Left	910	923	Moderate	Low	0.1529	13	2.7	5.37
Left	923	941	Moderate	Moderate	0.2535	18	4.0	18.25
Left	1050	1091	Low	Moderate	0.0744	41	3.8	11.58
Left	1091	1119	Moderate	Moderate	0.2535	28	2.5	17.74
Right	328	362	Moderate	Low	0.1529	34	2.5	12.99
Right	362	382	Low	Low	0.0357	20	3.0	2.14
Right	382	414	Low	Low	0.0357	32	3.7	4.22
Right	414	430	Low	Low	0.0357	16	3.8	2.17
Right	430	440	Low	Low	0.0357	10	3.4	1.21
Right	440	453	Low	Low	0.0357	13	1.7	0.79
Right	453	496	Low	Low	0.0357	43	3.6	5.52
Right	496	540	Moderate	Moderate	0.2535	44	4.0	44.61
Right	540	567	Moderate	Low	0.1529	27	3.5	14.45
Right	941	952	Low	Low	0.0357	11	2.3	0.90
Right	952	972	Low	Moderate	0.0744	20	2.5	3.72
Right	972	989	Low	Low	0.0357	17	3.0	1.82
Right	1023	1055	Moderate	Moderate	0.2535	32	3.2	25.96
Right	1055	1102	Low	Moderate	0.0744	47	5.0	17.47
Right	1102	1138	Low	Low	0.0357	36	3.8	4.88
Right	1138	1175	Low	Low	0.0357	37	2.5	3.30
Right	1175	1200	Low	Moderate	0.0744	25	4.0	7.44

Dominant BEHI/NBS Rating for Reach = Low/Low		**Total Predicted Erosion (ft^3/yr)**	**426.5**
		Total Predicted Erosion (yds^3/yr)	**15.8**
		Total Predicted Erosion (tons/yr)	**20.5**
Total Reach Length ft) =	1,200	**Total Erosion (tons/yr/ft)**	**0.017**

Below Spring Creek (2013)

Bank	Start Station (ft)	End Station (ft)	BEHI	NBS	Predicted Bank Erosion Rate (ft/yr)	Length of Bank (ft)	Bank Height (ft)	Erosion Subtotal (ft^3/yr)
Left	45	70	Low	Very Low	0.0171	25	4.1	1.75
Left	70	78	Low	Low	0.0357	8	4.5	1.28
Left	78	112	Low	Very Low	0.0171	34	4.5	2.62
Left	112	131	Low	Low	0.0357	19	4.3	2.91
Left	131	148	High	Low	0.2504	17	4.6	19.58
Left	148	156	Low	Very Low	0.0171	8	4.2	0.57
Left	156	166	High	Low	0.2504	10	5.4	13.52
Left	166	179	Low	Low	0.0357	13	4.2	1.95
Left	179	216	Low	Low	0.0357	37	3.8	5.01
Left	216	226	Low	Low	0.0357	10	3.6	1.28
Left	226	260	Moderate	Moderate	0.2535	34	3.7	31.89
Left	260	275	Low	Low	0.0357	15	3.8	2.03
Left	275	309	Low	Very Low	0.0171	34	3.6	2.09
Left	309	320	Low	Very Low	0.0171	11	3.1	0.58
Left	552	595	Low	Very Low	0.0171	43	2.3	1.69
Left	595	680	Low	Low	0.0357	85	3.3	10.00
Left	680	738	Low	Moderate	0.0744	58	4.0	17.25
Left	738	892	Low	Very High	0.3233	154	4.0	199.16
Left	892	910	Low	Low	0.0357	18	3.2	2.05
Left	910	923	Low	Very Low	0.0171	13	2.0	0.44
Right	0	20	Low	Very Low	0.0171	20	3.5	1.20
Right	320	328	Low	Very Low	0.0171	8	3.5	0.48
Right	328	348	Moderate	Very Low	0.0922	20	2.7	4.98
Right	348	362	Low	Low	0.0357	14	2.6	1.30
Right	362	382	Low	Low	0.0357	20	3.0	2.14
Right	382	414	Low	Very Low	0.0171	32	3.2	1.75
Right	414	430	Low	Very Low	0.0171	16	2.6	0.71
Right	430	440	Low	Low	0.0357	10	2.2	0.78
Right	440	453	Low	Very Low	0.0171	13	1.5	0.33
Right	453	496	Low	Low	0.0357	43	3.6	5.52
Right	496	540	Low	Moderate	0.0744	44	3.1	10.14
Right	540	567	Low	Very Low	0.0171	27	3.4	1.57
Right	941	972	Low	Moderate	0.0744	31	2.3	5.30
Right	972	989	Low	Very Low	0.0171	17	2.5	0.73
Right	1023	1055	Low	Moderate	0.0744	32	3.2	7.61
Right	1055	1102	Low	Moderate	0.0744	47	5.0	17.47
Right	1102	1200	Low	Low	0.0357	98	3.0	10.48

Dominant BEHI/NBS Rating for Reach = Low/Low		**Total Predicted Erosion (ft^3/yr)**	**390.2**
		Total Predicted Erosion (yds^3/yr)	**14.5**
		Total Predicted Erosion (tons/yr)	**18.8**
Total Reach Length ft) =	1,200	**Total Erosion (tons/yr/ft)**	**0.016**

Appendix 8 (cont.) – Predicted annual stream bank erosion rates at Laramie River sites. Predictions derived from BANCS model developed from stream data collected in sedimentary/metamorphic geographic regions in Colorado (Rosgen 2006a).

Above Laramie WWTF (2009)

Bank	Start Station (ft)	End Station (ft)	BEHI	NBS	Predicted Bank Erosion Rate (ft/yr)	Length of Bank (ft)	Bank Height (ft)	Erosion Subtotal (ft^3/yr)
Left	0	195	Low	Very Low	0.0171	195	3.6	12.00
Left	195	360	Low	Low	0.0357	165	4.4	25.89
Left	360	433	Moderate	Low	0.1529	73	4.2	46.87
Left	433	505	High	Low	0.2504	72	4.4	79.33
Left	505	571	Moderate	Low	0.1529	66	4.0	40.36
Left	940	980	Low	Moderate	0.0744	40	3.4	10.11
Left	980	1017	High	Low	0.2504	37	5.2	48.18
Left	1017	1070	Very High	Low	0.2504	53	5.5	73.00
Left	1070	1105	High	Low	0.2504	35	4.4	38.57
Left	1105	1165	Low	Low	0.0357	60	3.4	7.27
Left	1165	1185	Low	Very Low	0.0171	20	3.0	1.03
Left	1277	1340	Low	Low	0.0357	63	3.2	7.19
Left	1340	1428	Very High	Low	0.2504	88	5.4	119.00
Left	1428	1500	High	Moderate	0.3796	72	4.2	114.78
Right	657	688	Moderate	Moderate	0.2535	31	3.4	26.72
Right	688	740	Moderate	Low	0.1529	52	4.6	36.57
Right	740	776	High	Low	0.2504	36	4.0	36.06
Right	776	837	High	Moderate	0.3796	61	4.1	94.93
Right	837	865	High	Low	0.2504	28	3.8	26.64
Right	1238	1277	Low	Low	0.0357	39	3.6	5.01

Dominant BEHI/NBS Rating for Reach = Low/Low		**Total Predicted Erosion (ft^3/yr)**	**849.5**
		Total Predicted Erosion (yds^3/yr)	**31.5**
		Total Predicted Erosion (tons/yr)	**40.9**
Total Reach Length ft) =	1,500	**Total Erosion (tons/yr/ft)**	**0.027**

Above Laramie WWTF (2010)

Bank	Start Station (ft)	End Station (ft)	BEHI	NBS	Predicted Bank Erosion Rate (ft/yr)	Length of Bank (ft)	Bank Height (ft)	Erosion Subtotal (ft^3/yr)
Left	269	387	Moderate	Low	0.1529	118	5.3	95.60
Left	387	475	High	High	0.5753	88	5.0	253.15
Left	475	522	Moderate	Low	0.1529	47	4.3	30.89
Left	522	610	Low	Low	0.0357	88	4.7	14.75
Left	980	996	Low	Low	0.0357	16	5.2	2.97
Left	996	1035	Very High	Low	0.2504	39	5.9	57.62
Left	1035	1071	Very High	High	0.5753	36	5.7	118.06
Left	1071	1100	Very High	Moderate	0.3796	29	5.4	59.44
Left	1100	1150	Very High	Low	0.2504	50	5.0	62.61
Left	1289	1341	Low	Low	0.0357	52	4.3	7.97
Left	1341	1475	High	Low	0.2504	134	2.5	83.89
Left	1475	1500	Very High	Low	0.2504	25	5.5	34.43
Right	679	717	Low	Low	0.0357	38	4.3	5.83
Right	754	823	High	Moderate	0.3796	69	4.5	117.86
Right	823	880	High	High	0.5753	57	4.9	160.69

Dominant BEHI/NBS Rating for Reach = High/High		**Total Predicted Erosion (ft^3/yr)**	**1105.8**
		Total Predicted Erosion (yds^3/yr)	**41.0**
		Total Predicted Erosion (tons/yr)	**53.2**
Total Reach Length ft) =	1,500	**Total Erosion (tons/yr/ft)**	**0.035**

Appendix 8 (cont.) – Predicted annual stream bank erosion rates at Laramie River sites. Predictions derived from BANCS model developed from stream data collected in sedimentary/metamorphic geographic regions in Colorado (Rosgen 2006a).

Above Laramie WWTF (2011)

Bank	Start Station (ft)	End Station (ft)	BEHI	NBS	Predicted Bank Erosion Rate (ft/yr)	Length of Bank (ft)	Bank Height (ft)	Erosion Subtotal (ft3/yr)
Left	269	350	Moderate	Low	0.1529	81	3.5	43.34
Left	350	405	High	Moderate	0.3796	55	3.9	81.42
Left	405	480	High	High	0.5753	75	4.5	194.17
Left	480	517	Moderate	Moderate	0.2535	37	4.4	41.27
Left	517	610	Low	Low	0.0357	93	3.2	10.61
Left	970	990	High	Low	0.2504	20	5.0	25.04
Left	990	1035	Extreme	Low	0.4200	45	5.3	100.16
Left	1035	1085	Very High	Moderate	0.3796	50	4.0	75.91
Left	1085	1150	Very High	Low	0.2504	65	4.5	73.25
Left	1275	1355	High	Low	0.2504	80	4.8	96.16
Left	1355	1390	Very High	Moderate	0.3796	35	4.0	53.14
Left	1390	1430	Very High	High	0.5753	40	4.0	92.05
Left	1430	1500	High	High	0.5753	70	4.0	161.09
Right	625	660	Moderate	Low	0.1529	35	4.2	22.47
Right	660	727	Moderate	Moderate	0.2535	67	3.8	64.54
Right	727	880	High	Moderate	0.3796	153	3.2	185.84

Dominant BEHI/NBS Rating for Reach = High/Moderate		**Total Predicted Erosion (ft3/yr)**	**1320.5**
		Total Predicted Erosion (yds3/yr)	**48.9**
		Total Predicted Erosion (tons/yr)	**63.6**
Total Reach Length ft) =	1,500	**Total Predicted Erosion (tons/yr/ft)**	**0.042**

Appendix 8 (cont.) – Predicted annual stream bank erosion rates at Laramie River sites. Predictions derived from BANCS model developed from stream data collected in sedimentary/metamorphic geographic regions in Colorado (Rosgen 2006a).

Below Gravel Pits (2009)

Bank	Start Station (ft)	End Station (ft)	BEHI	NBS	Predicted Bank Erosion Rate (ft/yr)	Length of Bank (ft)	Bank Height (ft)	Erosion Subtotal (ft^3/yr)
Right	0	48	High	Very Low	0.1652	48	6.0	47.58
Right	48	65	Moderate	Moderate	0.2535	17	5.0	21.55
Right	87	261	Moderate	Very Low	0.0922	174	6.5	104.27
Right	261	305	High	Low	0.2504	44	6.0	66.11
Right	305	344	High	Moderate	0.3796	39	7.0	103.62
Right	344	368	Low	Moderate	0.0744	24	4.5	8.03
Right	368	389	High	Moderate	0.3796	21	6.0	47.83
Right	389	419	High	High	0.5753	30	3.5	60.41
Right	419	567	Extreme	Low	0.4200	148	7.0	435.10
Right	567	618	Extreme	Moderate	1.0742	51	7.0	383.48
Right	618	737	Extreme	Low	0.4200	119	7.0	349.84
Right	737	783	Very High	Very Low	0.1652	46	6.0	45.60
Right	1920	1952	Moderate	Very Low	0.0922	32	5.5	16.23
Right	1952	1982	Moderate	Low	0.1529	30	5.5	25.22
Right	1982	2100	High	Low	0.2504	118	6.0	177.30
Left	783	1082	Moderate	Low	0.1529	299	4.5	205.69
Left	1082	1102	High	Low	0.2504	20	6.0	30.05
Left	1102	1165	Moderate	Low	0.1529	63	6.0	57.78
Left	1165	1292	High	Low	0.2504	127	6.5	206.72
Left	1292	1332	Moderate	Low	0.1529	40	3.5	21.40
Left	1332	1461	Extreme	Low	0.4200	129	7.0	379.24
Left	1461	1540	Very High	Low	0.2504	79	7.0	138.48
Left	1540	1648	Extreme	Low	0.4200	108	7.0	317.50
Left	1648	1743	Extreme	Very Low	0.1642	95	7.0	109.19
Left	1743	1766	Extreme	High	2.7474	23	6.5	410.73
Left	1766	1800	High	High	0.5753	34	4.0	78.25
Left	1800	1826	Moderate	Moderate	0.2535	26	5.0	32.95
Left	1826	1853	High	Moderate	0.3796	27	6.0	61.49
Left	1853	1892	Moderate	Low	0.1529	39	5.0	29.81

Dominant BEHI/NBS Rating for Reach = Extreme/Low		**Total Predicted Erosion (ft^3/yr)**	**3971.5**
		Total Predicted Erosion (yds^3/yr)	**147.1**
		Total Predicted Erosion (tons/yr)	**191.2**
Total Reach Length ft) =	2,100	**Total Erosion (tons/yr/ft)**	**0.091**

Below Gravel Pits (2010)

Bank	Start Station (ft)	End Station (ft)	BEHI	NBS	Predicted Bank Erosion Rate (ft/yr)	Length of Bank (ft)	Bank Height (ft)	Erosion Subtotal (ft^3/yr)
Right	0	44	Very High	Low	0.2504	44	6.00	66.11
Right	44	64	High	Moderate	0.3796	20	4.80	36.44
Right	233	300	Very High	Very Low	0.1652	67	6.00	66.42
Right	300	357	Moderate	Low	0.1529	57	4.90	42.70
Right	357	385	Low	Moderate	0.0744	28	5.30	11.03
Right	385	415	High	Moderate	0.3796	30	3.00	34.16
Right	415	502	Extreme	Low	0.1642	87	6.00	85.71
Right	502	621	Very High	Low	0.2504	119	6.50	193.70
Right	621	651	Moderate	Low	0.1529	30	6.20	28.43
Right	651	673	Moderate	Moderate	0.2535	22	6.50	36.25
Right	673	795	Moderate	Low	0.1529	122	6.00	111.90
Right	1990	2060	Very High	Low	0.2504	70	6.00	105.18
Right	2060	2100	High	Low	0.2504	40	6.00	60.10
Left	801	948	Moderate	Low	0.1529	147	3.50	78.65
Left	948	1016	Moderate	Moderate	0.2535	68	4.00	68.95
Left	1016	1080	Low	Low	0.0171	64	4.00	4.38
Left	1080	1122	Moderate	Low	0.1529	42	5.50	35.31
Left	1122	1151	Moderate	Very Low	0.0922	29	5.30	14.17
Left	1151	1183	Very High	Low	0.2504	32	6.00	48.08
Left	1183	1251	High	Low	0.2504	68	6.50	110.69
Left	1251	1294	High	Very Low	0.1652	43	6.00	42.63
Left	1294	1334	Low	Low	0.0171	40	4.50	3.08
Left	1334	1758	Very High	Low	0.2504	424	7.00	743.25
Left	1758	1793	Very High	Moderate	0.3796	35	7.90	104.95
Left	1793	1820	High	Low	0.2504	27	3.50	23.66
Left	1820	1990	Moderate	Moderate	0.2535	170	6.80	293.02

Dominant BEHI/NBS Rating for Reach = Very High/Low		**Total Predicted Erosion (ft^3/yr)**	**2449.0**
		Total Predicted Erosion (yds^3/yr)	**90.7**
		Total Predicted Erosion (tons/yr)	**117.9**
Total Reach Length ft) =	2,100	**Total Erosion (tons/yr/ft)**	**0.056**

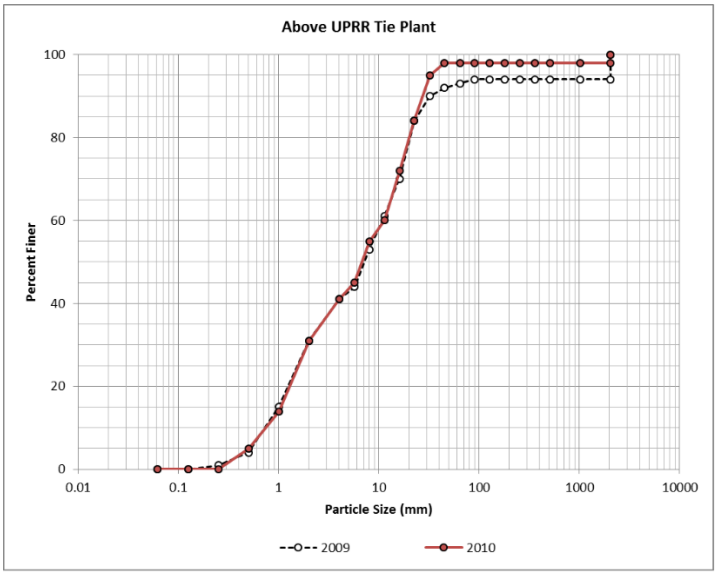
Appendix 9 – Channel bed material composition at WDEQ/WQD sites on the Laramie River (2009–2010).

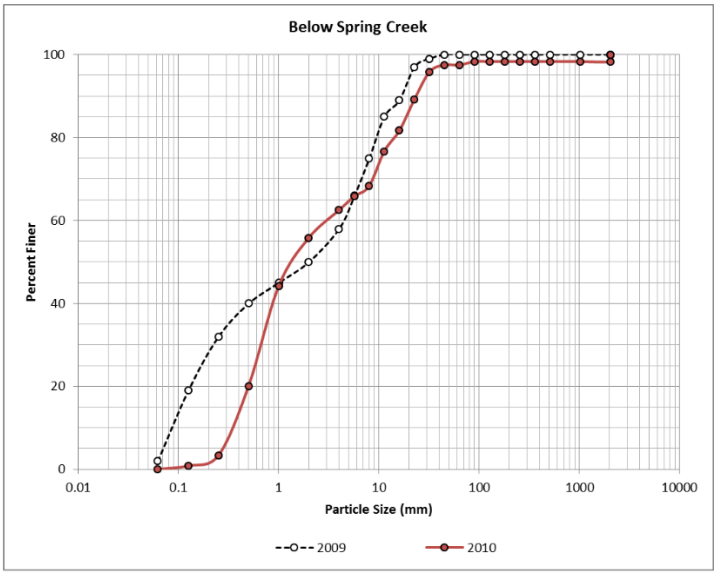
		Above UPRR Tie Plant WB0321		Below Spring Creek WB0322		Above Laramie WWTF WB0323		Below Gravel Pits WB0324	
	Year	2009	2010	2009	2010	2009	2010	2009	2010
	Rosgen Stream Classification	C4/1c-	C4/1c-	C4/5/1c-	C5/1c-	C4/1c-	C4/1c-	C5c-	C5c-
	Bankfull Channel Slope (ft/ft)	0.00103	0.00084	0.00044	0.00034	0.00078	0.00072	0.00033	0.00035
	Reach Length (ft)	1150		1196		1500		2154	
	Watershed Area (mi^2)	1005		1060		1070		1109	
	Rosgen Valley Type	VIII		VIII		VIII		VIII	
Reachwide	% Silt/Clay	0	0	2	0	0	2	2	0
	% Sand	31	31	48	56	26	43	56	61
	% Gravel	62	67	50	42	72	53	42	39
	% Cobble	1	0	0	1	2	1	0	0
	% Boulder	0	0	0	0	0	0	0	0
	% Bedrock	6	2	0	2	0	1	0	0
	D16 (mm)	1.1	1.1	0.1	0.4	1.0	0.5	0.4	0.4
	D35 (mm)	2.8	2.8	0.3	0.8	4.6	1.2	0.9	0.9
	D50 (mm)	7.2	6.9	2.0	1.5	8.3	3.7	1.6	1.5
	D84 (mm)	22.6	22.6	11.0	18.1	25.0	18.2	8.2	6.9
	D95 (mm)	Bedrock	32.0	21.0	30.8	38.5	27.3	13.0	13.7
	D100 (mm)	Bedrock	Bedrock	45[a]	Bedrock	90[a]	Bedrock	32.0	22.6
Riffle Cross-Section	% Silt/Clay	0	0	0	0	1	2	1	9
	% Sand	5	25	3	22	27	21	37	30
	% Gravel	90	74	97	78	72	77	62	61
	% Cobble	4	0	0	0	0	0	0	0
	% Boulder	0	0	0	0	0	0	0	0
	% Bedrock	1	1	0	0	0	0	0	0
	D16 (mm)	6.7	1.2	11.0	1.7	0.6	1.4	0.2	0.2
	D35 (mm)	10.4	4.6	18.0	4.7	4.3	4.0	1.7	1.6
	D50 (mm)	16.4	7.4	22.3	9.0	5.5	6.8	4.6	4.0
	D84 (mm)	32.0	16.7	31.2	20.7	13.0	15.1	9.5	10.4
	D95 (mm)	64.0	28.2	40.0	27.8	16.0	21.3	12.0	14.0
	D100 (mm)	Bedrock	Bedrock	45.0	45.0	64.0	32.0	16.0	16.0
Glide Cross-Section	% Silt/Clay	0	0	2	0	2	1	6	10
	% Sand	37	36	51	46	41	22	57	62
	% Gravel	63	64	47	54	57	77	37	28
	% Cobble	0	0	0	0	0	0	0	0
	% Boulder	0	0	0	0	0	0	0	0
	% Bedrock	0	0	0	0	0	0	0	0
	D16 (mm)	0.5	1.2	0.4	1.2	0.2	1.4	0.2	0.1
	D35 (mm)	1.8	2.0	0.7	1.7	1.4	4.2	0.4	0.3
	D50 (mm)	5.7	3.8	1.8	2.7	3.6	6.7	0.9	0.5
	D84 (mm)	15.5	15.8	10.8	15.0	8.3	16.5	7.7	5.1
	D95 (mm)	28.9	30.3	18.7	22.6	13.2	21.7	13.2	14.4
	D100 (mm)	64.0	45.0	32.0	45.0	32.0	45.0	22.6	32.0
Pool Cross-Section	% Silt/Clay	0	0	0	0	0	8	2	7
	% Sand	62	44	60	51	58	48	87	78
	% Gravel	38	56	40	49	42	17	11	15
	% Cobble	0	0	0	0	0	1	0	0
	% Boulder	0	0	0	0	0	0	0	0
	% Bedrock	0[a]	0[a]	0[a]	0[a]	0	26	0	0
	D16 (mm)	0.4	1.0	0.4	0.8	0.3	0.2	0.3	0.2
	D35 (mm)	0.7	1.7	1.0	1.5	0.6	1.2	0.4	0.3
	D50 (mm)	1.3	2.8	1.6	2.0	1.5	1.8	0.6	0.4
	D84 (mm)	8.0	8.9	5.7	21.9	6.9	Bedrock	1.7	1.8
	D95 (mm)	25.3	18.6	10.2	31.2	18.2	Bedrock	5.7	9.0
	D100 (mm)	32.0	45.0	32.0	64.0	32.0	Bedrock	22.6	22.6
Bar Sample	% Silt/Clay	0	0	0	0	0	0	0	0
	% Sand	30	31	39	35	55	32	44	48
	% Gravel	70	69	61	65	45	68	56	52
	% Cobble	0	0	0	0	0	0	0	0
	% Boulder	0	0	0	0	0	0	0	0
	% Bedrock	0	0	0	0	0	0	0	0
	D16 (mm)	0	0	0	0	0	0	0	0
	D35 (mm)	2.9	2.6	0	0	0	2.4	0	0
	D50 (mm)	6.0	5.2	4.4	6.7	0	5.3	2.5	2.2
	D84 (mm)	19.9	15.7	14.8	23.4	11.9	20.5	6.4	7.0
	D95 (mm)	29.5	28.4	31.2	31.1	23.5	30.2	10.8	16.2
	D100 (mm)	52.0	48.0	41.0	46.0	37.0	47.0	20.0	24.0

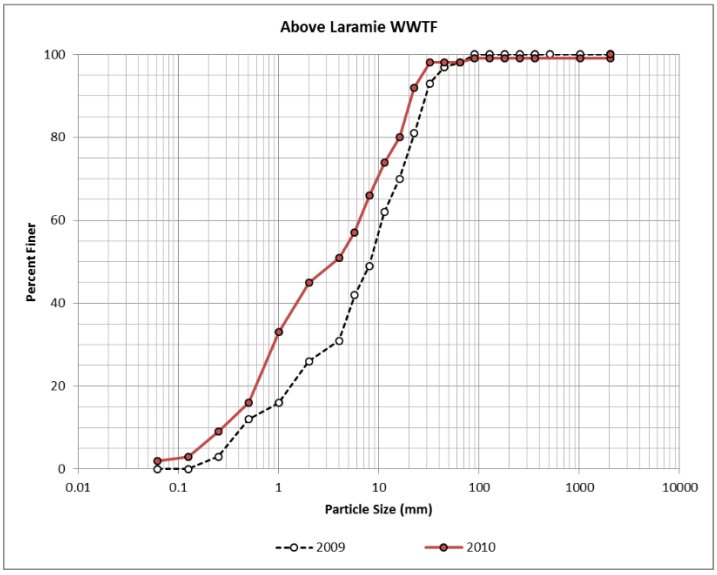
Note: Percentages of all particle size categories for pool cross-section counts may not always sum to 100% due to rounding.

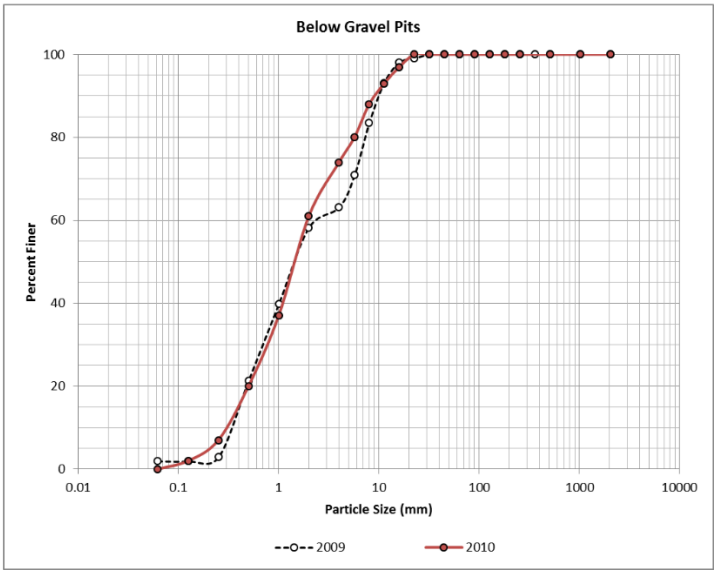
[a] Bedrock observed, but not enumerated in particle count.

Appendix 10 – Reachwide cumulative particle size distribution plots for WDEQ/WQD sites on Laramie River (2009–2010).

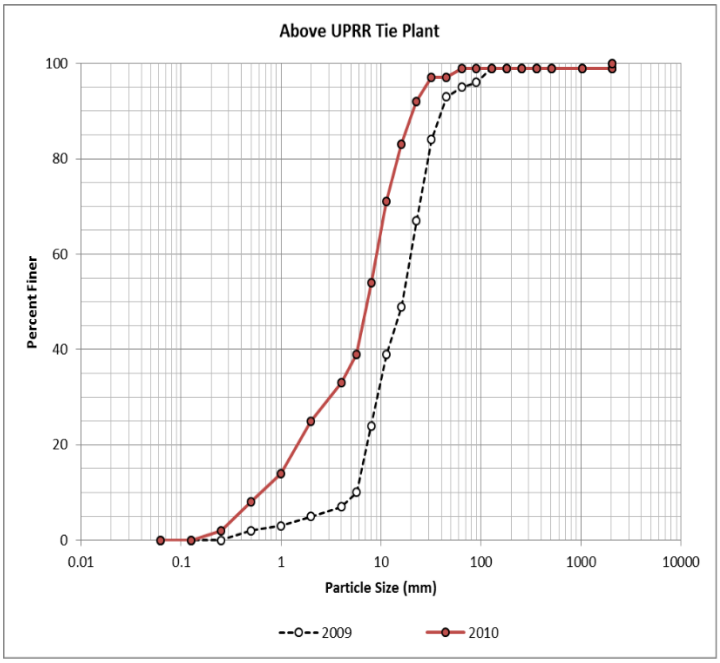


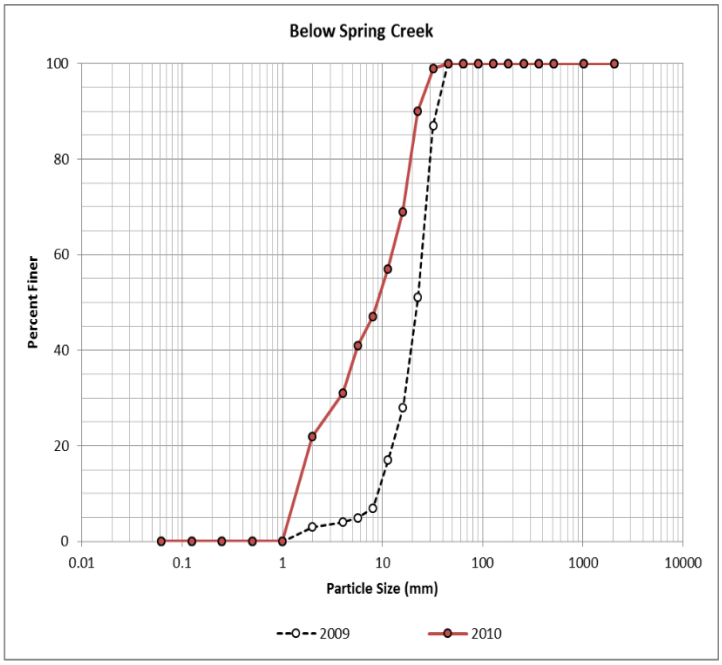


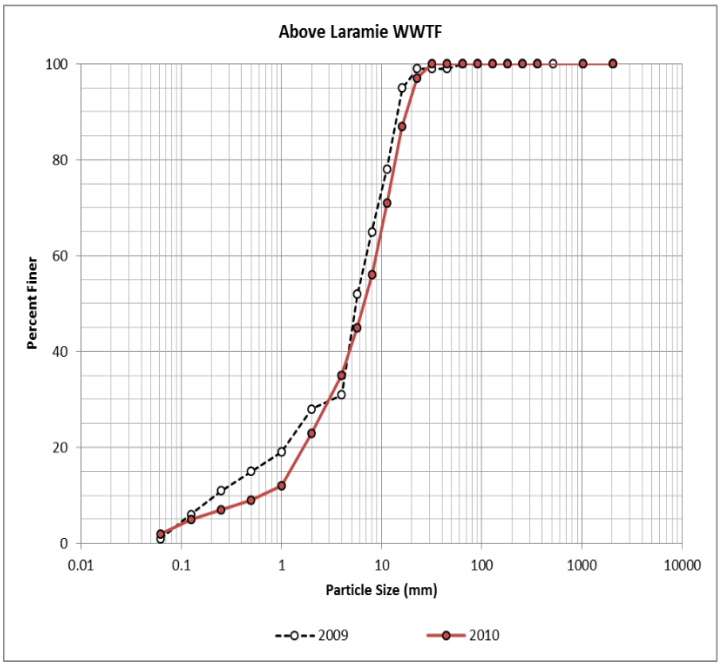


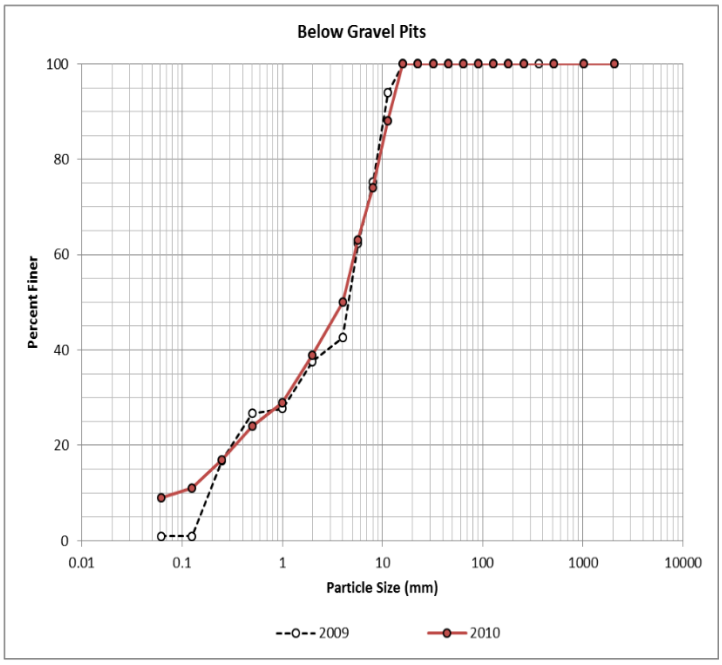


Appendix 11 – Riffle cumulative particle size distribution plots for WDEQ/WQD sites on the Laramie River (2009–2010).









Appendix 12 – Annual change in bankfull cross-sectional areas and reachwide thalweg bed elevations at WDEQ/WQD sites on the Laramie River (2009-2010). A negative change in area or positive change in average bed elevation indicates aggradation, whereas a positive change in area or negative change in average bed elevation indicates degradation.

		2009		2010				
Study Reach	Cross-Section	Area (ft^2)	Width (ft)	Area (ft^2)	Width (ft)	Change in Area (ft^2) from 2009	Change in Average Bed Elevation (ft) from 2009	Change in Average Reachwide Thalweg Elevation (ft) from 2009
Above UPRR Tie Plant	Riffle 1+79	111	50.6	110	51.2	-1	0.02	0.07
	Pool 8+54	144	81.0	143	73.8	-2	0.02	
	Glide 9+05	146	81.7	144	77.0	-2	0.03	
Below Spring Creek	Pool 1+66	146	53.3	155	53.7	9	-0.17	-0.10
	Glide 10+26	224	102.0	231	100.3	7	-0.07	
	Riffle 10+66	173	88.5	201	87.6	29	-0.33	
Above Laramie WWTF	Glide 5+42	144	72.2	128	71.8	-16	0.22	-0.08
	Riffle 5+90	133	67.1	132	66.8	-1	0.02	
	Pool 10+09	115	49.1	193	51.2	78	-1.52	
Below Gravel Pits	Pool 6+23	122	58.9	125	55.4	3	-0.05	0.05
	Glide 7+27	153	66.5	143	67.2	-10	0.14	
	Riffle 7+87	184	79.9	182	80.5	-2	0.03	

Appendix 13 – Scour chain survey data collected at WDEQ/WQD sites on the Laramie River, (2009-2010).

		Scour Chain Installation					Scour Chain Recovery							
					Particles near chain					Particles near chain				
Study Reach	Cross-Section	Chain No. (length in ft)	Date	Bed Elevation (ft)	Largest (mm)	2nd Largest (mm)	Date	Bed Elevation (ft)	Scour Depth Elevation (ft)	Largest (mm)	2nd Largest (mm)	Change in Bed Elevation (ft) 2009-2010	Depth of Scour (ft)	Net Deposition (ft)
Above UPRR Tie Plant	Riffle 1+79	1 (2.2)[a]	8/28/2009	96.14	92	61	9/2/2010	95.83	95.74	30	27	-0.31	0.40	0.09
	Riffle 1+79	2 (1.8)[a]		96.16	100	60		96.02	96.06	50	34	-0.14	0.14	0.00
	Glide 9+05	3 (1.4)[a]		94.92	80	37		94.87	94.87	35	34	-0.05	0.05	0.00
	Glide 9+05	4 (1.0)[a]		94.84	32	23		94.86	94.64	9	8	0.02	0.20	0.22
Below Spring Creek	Riffle 10+66	1 (1.8)	8/27/2009	95.45	41	35	9/1/2010	95.70	95.01	2	1	0.25	0.44	0.69
	Riffle 10+66	2 (1.9)		95.61	52	42		95.79	No Scour	11	10	0.18	No Scour	0.18
	Glide 10+26	3 (1.0)		95.26	31	30		96.25	94.26	13	12	0.99	1.00[b]	1.99
	Glide 10+26	4 (1.6)		95.47	38	29		96.23	94.23	14	12	0.76	1.24[c]	2.00
Above Laramie WWTF	Riffle 5+90	1 (1.0)[a]	8/26/2009	87.35	58	56	8/31/2010	87.91	87.18	23	22	0.56	0.17	0.73
	Riffle 5+90	2 (2.0)[a]		87.42	52	37		87.98	87.38	22	18	0.56	0.04	0.60
	Glide 5+42	3 (1.3)[a]		87.46	21	18		87.48	86.95	25	20	0.02	0.51	0.53
	Glide 5+42	4 (1.5)[a]		87.24	31	22		88.30	86.30[c]	27	25	1.06	0.94[c]	2.00
Below Gravel Pits	Riffle 7+87	1 (1.9)	8/25/2009	92.73	29	20	8/30/2010	92.83	No Scour	17	15	0.10	No Scour	0.10
	Riffle 7+87	2 (1.7)		92.93	37	27		93.17	92.83	11	7	0.24	0.10	0.34
	Glide 7+27	3 (1.7)		93.21	20	23		93.51	No Scour	0.5	0.5	0.30	No Scour	0.30
	Glide 7+27	4 (1.6)		93.31	30	25		93.40	No Scour	8	6	0.09	No Scour	0.09

[a] Anchor secured firmly into sandstone bedrock.

[b] Chain was not found after excavating to a depth approximately 2 ft below the 2010 bed surface. Depth of scour was at least equivalent to chain length.

[c] Chain was not found after excavating to a depth approximately 2 ft below the 2010 bed surface. Depth of scour was greater than measured value.

Appendix 14 – Sediment competence calculations used to evaluate channel bed stability at bankfull stage at WDEQ/WQD sites on the Laramie River (2009-2010). With the exception of bar sample particle sizes, all measurements were obtained from the riffle cross-section.

Sediment competence calculations used to assess channel bed stability at bankfull stage at WDEQ/WQD study sites on the Laramie River (2009-2010). With the exception of bar sample particle sizes, all measurements were obtained from the riffle cross-section.

Competence to mobilize existing Dmax within study reach.

									[a] Sediment Competence Predictions					
Reach	Year	Riffle D50 (mm)	Bar Sample D^50 (mm)	[b]Bar sample Dmax (mm)	Slope (ft/ft)	Hydraulic Radius (ft)	Mean Depth (ft)	Existing Shear Stress (lbs/ft^2)	Predicted Dmax at existing shear stress (mm)	Predicted shear stress to mobilize existing Dmax (lbs/ft^2)	Predicted mean depth to mobilize existing Dmax (ft)	Predicted slope to mobilize existing Dmax (ft/ft)	Ratio of Existing to Predicted Shear Stress	Competence Evaluation
Above UPRR Tie Plant	2009	16.4	6.0	52	0.00110	2.11	2.20	0.15	38	0.23	3.39	0.0017	**0.65**	Aggrading
	2010	7.4	5.2	48	0.00091	2.08	2.15	0.12	32	0.21	3.67	0.0016	**0.59**	Aggrading
Below Spring Creek	2009	22.3	4.4	41	0.00046	1.88	1.95	0.056	18	0.17	5.87	0.0014	**0.33**	Aggrading
	2010	9.0	6.7	46	0.00039	2.21	2.30	0.056	18	0.20	8.09	0.0014	**0.28**	Aggrading
Above Laramie WWTF	2009	5.5	<2	37	0.00079	1.92	1.97	0.097	27	0.15	2.97	0.0012	**0.66**	Aggrading
	2010	6.8	5.3	47	0.00080	1.82	1.97	0.098	28	0.20	4.06	0.0016	**0.49**	Aggrading
[c] Below Gravel Pits	2009	4.6	2.5	20	0.00037	2.23	2.30	0.053	18	0.063	2.75	0.00044	**0.84**	Aggrading
	2010	4.0	2.2	24	0.00040	2.20	2.26	0.056	18	0.081	3.26	0.00058	**0.69**	Aggrading

[a] Predicted Dmax, shear stress, depth and slope values were computed from a modified version of Shield's critical shear stress relation for gravel bed streams (Rosgen 2006a). Only data collected at 'Below Spring Creek' and 'Above Laramie WWTF' in 2009 were appropriate for applying dimensionless shear stress relations - predictions generated from those data sets were less accurate compared to those derived from dimensional relations.

[b] Dmax represents the largest existing particle (D100) in the reach mobilized at bankfull stage.

[c] Sediment competence predictions are normally not made for sand-bed streams as the existing Dmax is assumed mobile at flows ≤ bankfull discharge. The predictions shown are based on the expectation that the bed should be dominated by gravel-sized particles. Based on this premise, the existing Dmax was used to approximate the size of particle made available from the immediate upstream reach which exhibited a gravel-dominated bed.

Competence to mobilize Dmax made available from immediate upstream sediment supply (i.e., upstream study reach).

									[a] Sediment Competence Predictions					
Reach	Year	Riffle D50	Bar Sample D^50	[b]Upstream Dmax (mm)	Slope (ft/ft)	Hydraulic Radius (ft)	Mean Depth (ft)	Existing shear stress (lbs/ft^2)	Predicted Dmax at existing shear stress (mm)	Predicted shear stress to mobilize upstream Dmax (lbs/ft^2)	Predicted mean depth to mobilize upstream Dmax (ft)	Predicted slope to mobilize upstream Dmax (ft/ft)	Ratio of Existing to Predicted Shear Stress	Competence Evaluation
Above UPRR Tie Plant	2009	16.4	-	56	0.00110	2.11	2.20	0.15	38	0.26	3.75	0.0019	**0.59**	Aggrading
	2010	7.4	-	50	0.00091	2.08	2.15	0.12	32	0.22	3.88	0.0016	**0.55**	Aggrading
Below Spring Creek	2009	22.3	6.6	52	0.00046	1.88	1.95	0.056	18	0.23	8.10	0.0019	**0.24**	Aggrading
	2010	9.0	5.2	48	0.00039	2.21	2.30	0.056	18	0.21	8.57	0.0015	**0.27**	Aggrading
Above Laramie WWTF	2009	5.5	4.4	41	0.00079	1.92	1.97	0.097	27	0.17	3.42	0.0014	**0.58**	Aggrading
	2010	6.8	6.7	46	0.00080	1.82	1.97	0.098	28	0.20	3.94	0.0016	**0.50**	Aggrading
[c] Below Gravel Pits	2009	4.6	<2	37	0.00037	2.23	2.30	0.053	18	0.15	6.34	0.0010	**0.36**	Aggrading
	2010	4.0	5.3	47	0.00040	2.20	2.26	0.056	18	0.20	8.12	0.0014	**0.28**	Aggrading

[a] Predicted Dmax, shear stress, depth and slope values were computed from a modified version of Shield's critical shear stress relation for gravel bed streams (Rosgen 2006a). Only data collected at 'Below Spring Creek' in 2009 were appropriate for applying dimensionless shear stress relations - predictions generated from that data set were less accurate compared to those derived from dimensional relations.

[b] Upstream Dmax is the largest particle (D100) measured from the bar sample collected in the immediate upstream study reach. Dmax for 'Above UPRR Tie Plant' is represented by the largest particles measured at scour chains, which are considered the size of particles mobilized at bankfull stage.

[c] Sediment competence predictions are normally not made for sand-bed streams as the existing Dmax is assumed mobile at flows ≤ bankfull discharge. The predictions shown are based on the expectation that the bed should be dominated by gravel-sized particles. Based on this premise, the existing Dmax was used to approximate the size of particle made available from the immediate upstream reach which exhibited a gravel-dominated bed.

Appendix 15 – Categorical scores and narrative ratings from the WARSSS River Prediction Assessment Procedure applied at WDEQ/WQD sites on the Laramie River (2009-2010).

Above UPRR Tie Plant

Lateral Stability	
Criteria	Narrative Category (total points)
[a]W/d Ratio State	Unstable - relative to C4 reference W/d (6)
Depositional Pattern	Highly Unstable - side and mid-channel bars w / lengths exceeding 2-3 times channel W (4)
Meander Pattern	Unstable - unconfined abandoned meander scrolls and oxbow cutoffs (3)
Dominant BEHI / NBS	Unstable - Extreme/Very Low , Extreme/Low (7)
[a]Degree of Confinement (MWR / MWRref)	Unstable - confined relative to reference MWR for C stream-type (3)
Overall narrative category and score	**Highly Unstable (23)**

Vertical Stability for Excess Deposition/Aggradation	
Criteria	Narrative Category (total points)
[b]Sediment Competence	Excess Deposition - cannot move D_{100} of bar material, but capable of moving riffle D_{95} based on scour chain results (6)
[c]Sediment Capacity	Aggradation - insufficient depth and slope to mobilize existing D_{100} of bar material, presence of side and mid-channel bars w ith lengths exceeding 2-3 times channel W (8)
[a]W/d Ratio State	Excess Deposition - 2010 W/d relative to C4 reference W/d = 15 (6)
Stream Succession State	Excess Deposition - transition to higher W/d C (6)
Depositional Pattern	Aggradation - side and mid-channel bars w / lengths exceeding 2-3 times channel W (4)
Debris / Blockage	No Deposition - minimal amount (1)
Overall narrative category and score	**Aggradation (31)**

Vertical Stability for Channel Incision/Degradation	
Criteria	Narrative Category (total points)
[b]Sediment Competence	Slightly Incised - cannot move D_{100} of bar, but capable of moving >D_{84} of bed based on scour chain results (4)
[c]Sediment Capacity	Slightly Incised - Indication of excess energy at upper end of reach and increased potential to increase sediment load (6)
Degree of Channel Incision (BHR)	Slightly Incised - BHR 1.2-1.5, increased exposure of bedrock locally from 2009 to 2010 (5)
Stream Type / Succession State	Not Incised - past incision evident but aggrading to a fill terrace, W/d >20, transition to higher W/d C (2)
[a]Degree of Confinement (MWR / MWRref)	Moderately Incised - confined relative to reference MWR for C stream-type (3)
Overall narrative category and score	**Moderately Incised (20)**

Channel Enlargement	
Criteria	Narrative Category (total points)
Stream Succession State	Slight Increase - transition from C→High W/d C (4)
Lateral Stability	Extensive - Highly Unstable (8)
Vertical Stability for Excess Deposition / Aggradation	Extensive - Aggradation (8)
Vertical Stability for Channel Incision / Degradation	Moderate Increase - Moderately Incised (6)
Overall narrative category and score	**Extensive (26)**

Overall Sediment Supply Prediction	
Criteria	Narrative Category (total points)
Lateral Stability	Highly Unstable (4)
Vertical Stability for Excess Deposition / Aggradation	Aggradation (4)
Vertical Stability for Channel Incision / Degradation	Moerately Incised (3)
Channel Enlargement	Extensive (4)
Pfankuch Channel Stability Rating	Unstable - Poor rating scores relative to C4 potential for 2009 & 2010 (4)
Overall narrative category and score	**Very High (19)**

[a]Degree of confinement and W/d ratio state are normally derived from a comparison to a geomorphic reference reach (Rosgen 2006a), w hich w as not available for the Laramie River. In lieu of a reference reach, existing geomorphic data, field observations, literature and professional judgement w ere used to select an appropriate conservative narrative category.

[b]Sand-bed streams are considered competent as the entire bed is assumed to be mobile at bankfull discharge or less (i.e., the D_{100} of the bed material is entrained at bankfull flow) (Rosgen 2006a).

[c]Sediment capacity is normally derived using the FLOWSED and POWERSED models (Rosgen 2006a) w hich require quantitative estimates of suspended and bed loads. These data are not available for the Laramie River. In lieu of using these models, existing geomorphic data, field observations and professional judgement w ere used to select an appropriate conservative narrative category.

Appendix 15 (cont.) – Categorical scores and narrative ratings from the WARSSS River Prediction Assessment Procedure applied at WDEQ/WQD sites on the Laramie River (2009-2010).

Below Spring Creek

Lateral Stability	
Criteria	Narrative Category (total points)
[a]W/d Ratio State	Highly Unstable - relative to C4 reference W/d (8)
Depositional Pattern	Highly Unstable - side and mid-channel bars w / lengths exceeding 2-3 times channel W, delta bars below mouth of Spring Creek (4)
Meander Pattern	Moderately Unstable - distorted and truncated meanders (2)
Dominant BEHI / NBS	Unstable - Very High/Low , Extreme/Low (7)
[a]Degree of Confinement (MWR / MWRref)	Unstable - confined relative to reference MWR for C stream-type (3)
Overall narrative category and score	**Highly Unstable (24)**

Vertical Stability for Excess Deposition/Aggradation	
Criteria	Narrative Category (total points)
[b]Sediment Competence	Excess Deposition - cannot move D_{100} of bar material, capable of moving riffle D_{50} but not D_{84} based on scour chain results (6)
[c]Sediment Capacity	Aggradation - insufficient depth and slope to mobilize existing D_{100} of bar material, increase in percentage of sand reachw ide from 2009 to 2010, presence of side and mid-channel bars w ith lengths exceeding 2-3 times channel W (8)
[a]W/d Ratio State	Aggradation - 2010 W/d relative to C4 reference W/d = 15 (8)
Stream Succession State	Excess Deposition - transition to low er W/d C (5)
Depositional Pattern	Aggradation - side and mid-channel bars w / lengths exceeding 2-3 times channel W, delta bars below mouth of Spring Creek (4)
Debris / Blockage	No Deposition - minimal amount (1)
Overall narrative category and score	**Aggradation (32)**

Vertical Stability for Channel Incision/Degradation	
Criteria	Narrative Category (total points)
[b]Sediment Competence	Not Incised - no indication of excess competence - incapable of moving D_{100} of bar or D_{84} of bed based on scour chain results (2)
[c]Sediment Capacity	Not Incised - no indication of excess energy (2)
Degree of Channel Incision (BHR)	Not Incised - past incision evident, but decreases in BHR w ith distance dow nstream indicate aggradation (2)
Stream Type / Succession State	Not Incised - past incision evident, but channel aggrading to a fill terrace, W/d >45 but transition to low er W/d C (2)
[a]Degree of Confinement (MWR / MWRref)	Moderately Incised - confined relative to reference MWR for C stream-type (3)
Overall narrative category and score	**Not Incised (11)**

Channel Enlargement	
Criteria	Narrative Category (total points)
Stream Succession State	No increase - transition from High W/d C to low er W/d C (3)
Lateral Stability	Extensive - Highly Unstable (8)
Vertical Stability for Excess Deposition / Aggradation	Extensive - Aggradation (8)
Vertical Stability for Channel Incision / Degradation	No Increase - high end of Not Incised scale (3)
Overall narrative category and score	**Moderate Increase (22)**

Overall Sediment Supply Prediction	
Criteria	Narrative Category (total points)
Lateral Stability	Highly Unstable (4)
Vertical Stability for Excess Deposition / Aggradation	Aggradation (4)
Vertical Stability for Channel Incision / Degradation	Not Incised (1)
Channel Enlargement	Moderate Increase (3)
Pfankuch Channel Stability Rating	Moderately Unstable - Fair rating scores relative to C4 potential for 2009 & 2010 (3)
Overall narrative category and score	**High (15)**

[a]Degree of confinement and W/d ratio state are normally derived from a comparison to a geomorphic reference reach (Rosgen 2006a), w hich w as not available for the Laramie River. In lieu of a reference reach, existing geomorphic data, field observations, literature and professional judgement w ere used to select an appropriate conservative narrative category.

[b]Sand-bed streams are considered competent as the entire bed is assumed to be mobile at bankfull discharge or less (i.e., the D_{100} of the bed material is entrained at bankfull flow) (Rosgen 2006a).

[c]Sediment capacity is normally derived using the FLOWSED and POWERSED models (Rosgen 2006a) w hich require quantitative estimates of suspended and bed loads. These data are not available for the Laramie River. In lieu of using these models, existing geomorphic data, field observations and professional judgement w ere used to select an appropriate conservative narrative category.

Appendix 15 (cont.) – Categorical scores and narrative ratings from the WARSSS River Prediction Assessment Procedure applied at WDEQ/WQD sites on the Laramie River (2009-2010).

Above Laramie WWTF

Lateral Stability	
Criteria	Narrative Category (total points)
[a]W/d Ratio State	Highly Unstable - relative to C4 reference W/d (8)
Depositional Pattern	Highly Unstable - delta bars below mouth of storm drainage outlet, main channel branching with numerous mid-channel bars and islands, transverse bars, side and mid-channel bars with lengths exceeding 2-3 times channel width (4)
Meander Pattern	Moderately Unstable - distorted and truncated meanders (2)
Dominant BEHI / NBS	Moderately Unstable - Low/Low, High/High (4)
[a]Degree of Confinement (MWR / MWRref)	Unstable - confined relative to reference MWR for C stream-type (3)
Overall narrative category and score	**Unstable (21)**

Vertical Stability for Excess Deposition/Aggradation	
Criteria	Narrative Category (total points)
[b]Sediment Competence	Excess Deposition - cannot move D_{100} of bar material, but capable of moving riffle D_{84} and D_{95} based on scour chain results (6)
[c]Sediment Capacity	Excess Deposition - insufficient depth and slope to mobilize existing D_{100} of bar material, reachwide decreases in all size fractions < D_{98}, increase in % sand reachwide from 2009 to 2010, side and mid-channel bars with lengths exceeding 2-3 times channel W (7)
[a]W/d Ratio State	Aggradation - 2010 W/d relative to C4 reference W/d = 15 (8)
Stream Succession State	Excess Deposition - transition to lower W/d C (5)
Depositional Pattern	Aggradation - delta bars below mouth of storm drainage outlet, main channel branching with numerous mid-channel bars and islands, transverse bars, side and mid-channel bars with lengths exceeding 2-3 times channel width (4)
Debris / Blockage	No Deposition - minimal amount (1)
Overall narrative category and score	**Aggradation (31)**

Vertical Stability for Channel Incision/Degradation	
Criteria	Narrative Category (total points)
[b]Sediment Competence	Slightly Incised - cannot move D_{100} of bar, but capable of moving >D_{84} of bed based on scour chain results (3)
[c]Sediment Capacity	Not Incised - no indication of excess energy (2)
Degree of Channel Incision (BHR)	Not Incised - past incision evident, but decreases in BHR with distance downstream indicates aggradation (2)
Stream Type / Succession State	Not Incised - past incision evident, but channel aggrading to a fill terrace, W/d >30 but transition to lower W/d C (2)
[a]Degree of Confinement (MWR / MWRref)	Moderately Incised - confined relative to reference MWR for C stream-type (3)
Overall narrative category and score	**Slightly Incised (12)**

Channel Enlargement	
Criteria	Narrative Category (total points)
Stream Succession State	No increase - transition from High W/d C to lower W/d C (3)
Lateral Stability	Moderate Increase - high end of Unstable scale (7)
Vertical Stability for Excess Deposition / Aggradation	Extensive - Aggradation (8)
Vertical Stability for Channel Incision / Degradation	No Increase - low end of Slightly Incised scale (3)
Overall narrative category and score	**Moderate Increase (21)**

Overall Sediment Supply Prediction	
Criteria	Narrative Category (total points)
Lateral Stability	Unstable (3)
Vertical Stability for Excess Deposition / Aggradation	Aggradation (4)
Vertical Stability for Channel Incision / Degradation	Slightly Incised (2)
Channel Enlargement	Moderate Increase(3)
Pfankuch Channel Stability Rating	Moderately Unstable - Fair rating scores relative to C4 potential for 2009 & 2010 (3)
Overall narrative category and score	**High (15)**

[a]Degree of confinement and W/d ratio state are normally derived from a comparison to a geomorphic reference reach (Rosgen 2006a), which was not available for the Laramie River. In lieu of a reference reach, existing geomorphic data, field observations, literature and professional judgement were used to select an appropriate conservative narrative category.

[b]Sand-bed streams are considered competent as the entire bed is assumed to be mobile at bankfull discharge or less (i.e., the D_{100} of the bed material is entrained at bankfull flow) (Rosgen 2006a).

[c]Sediment capacity is normally derived using the FLOWSED and POWERSED models (Rosgen 2006a) which require quantitative estimates of suspended and bed loads. These data are not available for the Laramie River. In lieu of using these models, existing geomorphic data, field observations and professional judgement were used to select an appropriate conservative narrative category.

Appendix 15 (cont.) – Categorical scores and narrative ratings from the WARSSS River Prediction Assessment Procedure applied at WDEQ/WQD sites on the Laramie River (2009-2010).

Below Gravel Pits

Lateral Stability	
Criteria	Narrative Category (total points)
[a]W/d Ratio State	Highly Unstable - relative to C4 reference W/d (8)
Depositional Pattern	Highly Unstable - main channel branching with some mid-channel bars, side and mid-channel bars with lengths exceeding 2-3 times channel width (4)
Meander Pattern	Unstable - unconfined abandoned meander scrolls and oxbow cutoffs (3)
Dominant BEHI / NBS	Unstable - Extreme/Low, Very High/Low (7)
[a]Degree of Confinement (MWR / MWRref)	Unstable - confined relative to reference MWR for C stream-type (3)
Overall narrative category and score	**Highly Unstable (25)**

Vertical Stability for Excess Deposition/Aggradation	
Criteria	Narrative Category (total points)
[b]Sediment Competence	Excess Deposition - competent to mobilize entire sand-dominated bed at bankfull discharge, but cannot move D_{100} (coarse gravel) of bar sample, capable of moving riffle D_{95} based on scour chain results (7)
[c]Sediment Capacity	Aggradation - insufficient depth and slope to mobilize existing D_{100} of bar material, increase in percentage of sand reachwide from 2009 to 2010, side and mid-channel bars with lengths exceeding 2-3 times channel W (8)
[a]W/d Ratio State	Aggradation - 2010 W/d relative to C4 reference W/d = 15 (8)
Stream Succession State	Excess Deposition - transition to higher W/d C (6)
Depositional Pattern	Aggradation - main channel branching with some mid-channel bars, side and mid-channel bars with lengths exceeding 2-3 times channel width (4)
Debris / Blockage	No Deposition - minimal amount (1)
Overall narrative category and score	**Aggradation (34)**

Vertical Stability for Channel Incision/Degradation	
Criteria	Narrative Category (total points)
[b]Sediment Competence	Not Incised - cannot move D_{100} of bar, capable of moving >D_{84} of bed based on scour chain results (2)
[c]Sediment Capacity	Not Incised - no indication of excess energy (2)
Degree of Channel Incision (BHR)	Not Incised - past incision evident, but decreases in BHR with distance downstream indicates aggradation (2)
Stream Type / Succession State	Not Incised - past incision evident but aggrading to a fill terrace, W/d >35 and increasing, transition to higher W/d C (2)
[a]Degree of Confinement (MWR / MWRref)	Slightly Incised - confined relative to reference MWR for C stream-type (3)
Overall narrative category and score	**Not Incised (11)**

Channel Enlargement	
Criteria	Narrative Category (total points)
Stream Succession State	Slight Increase - transition from C→High W/d C (4)
Lateral Stability	Extensive - Highly Unstable (8)
Vertical Stability for Excess Deposition / Aggradation	Extensive - Aggradation (8)
Vertical Stability for Channel Incision / Degradation	No increase - Not Incised (2)
Overall narrative category and score	**Moderate Increase (22)**

Overall Sediment Supply Prediction	
Criteria	Narrative Category (total points)
Lateral Stability	Highly Unstable (4)
Vertical Stability for Excess Deposition / Aggradation	Aggradation (4)
Vertical Stability for Channel Incision / Degradation	Not Incised (1)
Channel Enlargement	Moderate Increase (3)
Pfankuch Channel Stability Rating	Unstable - Poor rating scores relative to C4 potential for 2009 & 2010 (4)
Overall narrative category and score	**Very High (16)**

[a]Degree of confinement and W/d ratio state are normally derived from a comparison to a geomorphic reference reach (Rosgen 2006a), which was not available for the Laramie River. In lieu of a reference reach, existing geomorphic data, field observations, literature and professional judgement were used to select an appropriate conservative narrative category.

[b]Sand-bed streams are considered competent as the entire bed is assumed to be mobile at bankfull discharge or less (i.e., the D_{100} of the bed material is entrained at bankfull flow) (Rosgen 2006a).

[c]Sediment capacity is normally derived using the FLOWSED and POWERSED models (Rosgen 2006a) which require quantitative estimates of suspended and bed loads. These data are not available for the Laramie River. In lieu of using these models, existing geomorphic data, field observations and professional judgement were used to select an appropriate conservative narrative category.

Appendix 16 – WSII and WY RIVPACS scores and associated aquatic life use narrative assignments for WDEQ/WQD sites on the Laramie River (2009-2010). F = Full-Support, I = Indeterminate, P/N = Partial/Non-Support.

	Above UPRR Tie Plant		Below Spring Creek		Above Laramie WWTF		Below Gravel Pits	
	WB0321		WB0322		WB0323		WB0324	
Wyoming Basin WSII Metrics	8/28/2009	9/2/2010	8/27/2009	9/1/2010	8/26/2009	8/31/2010	8/25/2009	8/30/2010
Number of EPT Taxa (less Baetidae, Arctopsychidae, Hydropsychidae and Tricorythodes)	7	3	5	3	2	2	1	1
% EPT (less Arctopsychidae and Hydropsychidae)	35.4	39.5	29.4	60.0	56.1	74.4	39.6	46.5
Number of Semivoltine Taxa	3	3	4	3	3	0	2	1
BCICTQa	95.3	93.2	98.6	98.5	102.3	99.8	106.1	105.2
WSII Score	**29.5**	**25.8**	**28.2**	**32.4**	**29.9**	**26.4**	**20.2**	**19.3**
WSII Narrative Assignment	**I**	**P/N or I[b]**	**I**	**I**	**I**	**I or P/N[b]**	**P/N**	**P/N**
WY RIVPACS Score	**1.008**	**0.784**	**0.784**	**0.896**	**0.784**	**0.672**	**0.784**	**0.672**
WY RIVPACS Narrative Assignment	**F**	**I**	**I**	**F**	**I**	**I**	**I**	**I**
Aquatic Life Use-Support Narrative Assignment[a]	**F**	**P/N**	**I**	**F**	**I**	**I**	**P/N**	**P/N**

[a] Aquatic Life Use Decision Matrix (WDEQ/WQD 2014a)

[b] Either aquatic life-use narrative rating may apply based on ± 1.6 unit allowance (90% C.I.).

Appendix 17 – Benthic macroinvertebrate sample results (riffle habitat) at WDEQ/WQD sites on the Laramie River (2009-2010). Count = Number of Individuals/m^2, PRA = Percent Relative Abundance.

				Above UPRR Tie Plant - WB0321				Below Spring Creek - WB0322				Above Laramie WWTF - WB0323				Below Gravel Pits - WB0324			
				8/28/2009		9/2/2010		8/27/2009		9/1/2010		8/26/2009		8/31/2010		8/25/2009		8/30/2010	
	Taxa Group	Taxon	FFG	Count	PRA	Count	PRA	Count	PRA	Count	PRA	Count	PRA	Count	PRA	Count	PRA	Count	PRA
NON - INSECTS	Nematoda (roundworms)	Nematoda	PA			27	0.76	2	0.19	56	1.24	148	1.62					23	0.77
	Oligochaeta (aquatic worms)	Naididae (Tubificinae) - w/ capillary setae	CG					5	0.58									81	2.69
		Naididae (Tubificinae) - w/out capillary setae	CG	34	0.90			12	1.34	24	0.53	256	2.81	4	0.19	10	0.19	392	13.08
		Nais	CG	215	5.77	20	0.57	64	7.29	65	1.42	54	0.59	16	0.75			161	5.37
		Ophidonais serpentina	CG	20	0.54			35	4.03			175	1.92	8	0.37				
	Veneroida (clams)	Sphaeriidae	CG	13	0.35							40	0.44	4	0.19			6	0.19
	Basommatophora (snails)	Ancylidae	SC	20	0.54	13	0.38	208	23.80			161	1.77	8	0.37	50	0.97		
		Lymnaeidae	CG															17	0.58
		Physidae	SC					3	0.38			161	1.77	12	0.56	202	3.86	35	1.15
		Planorbidae	SC	7	0.18			2	0.19										
	Hyrudinea (leeches)	Erpobdellidae	PR											1	0.05				
	Amphipoda (shrimp)	*Hyalella*	CG	34	0.91														
	Acari (water mites)	Acari	CG	195	5.23	208	5.92	13	1.54	97	2.12	256	2.81	28	1.31	242	4.63	12	0.38
	Decapoda (crayfish)	Cambaridae	CG											1	0.05				
		Decapoda	SH	1	0.03														
		Orconectes	UN			1	0.03												
INSECTS	Odonata (dragonflies + damselflies)	Gomphidae	PR	7	0.18	13	0.38	2	0.19										
		Ophiogomphus	PR	20	0.54					1	0.02	27	0.30			10	0.19	12	0.38
	Ephemeroptera (mayflies)	*Acentrella*	CG	276	7.40	928	26.33	82	9.40	2558	56.10	4761	52.29	1360	62.83	1271	24.32	1251	41.73
		Acerpenna pygmaea	UN	27	0.72	7	0.19	2	0.19							10	0.19		
		Baetidae	CG			40	1.14			40	0.88							17	0.58
		Baetisca	CG	7	0.18			8	0.96										
		Caenis	CG	7	0.18			7	0.77					4	0.19				
		Cinygmula	SC			13	0.38												
		Ephemera	CG	40	1.08														
		Fallceon quilleri	CG			7	0.19			16	0.35			4	0.19				
		Heptageniidae	SC			87	2.48			8	0.18								
		Leptophlebiidae	CG	20	0.54	54	1.53												
		Paraleptophlebia	CG					2	0.19										
		Stenonema	SC	7	0.18														
		Tricorythodes	CG	625	16.78	229	6.49	98	11.13	56	1.24	81	0.89	133	6.15	696	13.32	104	3.46
	Trichoptera (caddisflies)	*Cheumatopsyche*	F	377	10.11	47	1.34	8	0.96	129	2.83	229	2.51	81	3.73	363	6.95		
		Hydropsyche	F	87	2.35	168	4.77	8	0.96	97	2.12			20	0.93			12	0.38
		Hydropsychidae	F	34	0.90	27	0.76			32	0.70								
		Hydroptila	PH	175	4.69	27	0.76	27	3.07	48	1.06	256	2.81	24	1.12	81	1.54	12	0.38
		Hydroptilidae	PH	81	2.17			3	0.38					85	3.92	10	0.19	12	0.38
		Leptoceridae	CG					2	0.19	8	0.18								
		Nectopsyche	OM	54	1.44			27	3.07			13	0.15						
	Coleoptera (beetles)	*Dubiraphia*	CG	20	0.54	7	0.19	8	0.96	8	0.18								
		Optioservus	SC	7	0.18			10	1.15	8	0.18	27	0.30			10	0.19		
		Zaitzevia	CG			13	0.38	2	0.19			13	0.15						

Appendix 17 (cont.) – Benthic macroinvertebrate sample results (riffle habitat) at WDEQ/WQD sites on the Laramie River (2009-2010). Count = Number of Individuals/m^2, PRA = Percent Relative Abundance.

				Above UPRR Tie Plant - WB0321				Below Spring Creek - WB0322				Above Laramie WWTF - WB0323				Below Gravel Pits - WB0324			
				8/28/2009		9/2/2010		8/27/2009		9/1/2010		8/26/2009		8/31/2010		8/25/2009		8/30/2010	
	Taxa Group	Taxon	FFG	Count	PRA	Count	PRA	Count	PRA	Count	PRA	Count	PRA	Count	PRA	Count	PRA	Count	PRA
INSECTS	Non-midge Diptera	*Dicranota*	PR					2	0.19										
		Diptera	UN									135	1.48			20	0.39		
		Hexatoma	PR	114	3.07	296	8.40	13	1.54	113	2.48	13	0.15	8	0.37				
		Simulium	F	7	0.18	20	0.57			654	14.33	901	9.90	113	5.22	1483	28.38	75	2.50
		Tipulidae	UN			47	1.34												
	Chironomidae (midge flies)	*Ablabesmyia*	CG					5	0.58										
		Chironomini	CG					2	0.19										
		Chironomus	CG					7	0.77										
		Cladotanytarsus	CG			54	1.53	5	0.58									467	15.58
		Conchapelopia	PR									13	0.15						
		Corynoneura	CG					2	0.19	16	0.35								
		Cricotopus	CG	47	1.26	13	0.38	2	0.19			242	2.66	28	1.31	40	0.77	12	0.38
		Cricotopus (Cricotopus)	SH	7	0.18	20	0.57			8	0.18	67	0.74			30	0.58		
		Cricotopus bicinctus	OM	94	2.53	161	4.58	17	1.92	65	1.42	161	1.77	12	0.56	50	0.97	6	0.19
		Cricotopus trifascia	OM	155	4.15	753	21.37	8	0.96	97	2.12	430	4.73	129	5.97	161	3.09	23	0.77
		Cryptochironomus	PR					3	0.38			27	0.30	16	0.74	10	0.19	29	0.97
		Dicranota	PR					2	0.19										
		Dicrotendipes	CG					10	1.15			13	0.15			81	1.54	6	0.19
		Epoicocladius	CG	13	0.36														
		Eukiefferiella	OM	20	0.54	7	0.19												
		Lopescladius	CG			13	0.37			8	0.18								
		Micropsectra	CG			13	0.38	5	0.58										
		Microtendipes	CG					2	0.19										
		Nanocladius	CG					3	0.38										
		Orthocladius	CG	13	0.36			8	0.96	65	1.43	67	0.74	12	0.56	81	1.54		
		Parakiefferiella	CG					15	1.73			27	0.30			30	0.58	12	0.38
		Parametriocnemus	CG	155	4.15	27	0.76	3	0.38	8	0.18	54	0.59			111	2.12		
		Phaenopsectra	SC					17	1.92			13	0.15						
		Polypedilum	OM	13	0.36			18	2.11			67	0.74			20	0.39	6	0.19
		Rheotanytarsus	F	148	3.97	47	1.33	5	0.58	178	3.89	40	0.44	44	2.03			6	0.19
		Saetheria	CG			13	0.38	2	0.19	56	1.23	121	1.33	4	0.19	40	0.77	179	5.97
		Tanytarsini	UN							8	0.18								
		Tanytarsus	F	511	13.71	40	1.14	77	8.83			27	0.30			20	0.39		
		Thienemanniella	CG	7	0.18	47	1.34	2	0.19	32	0.71							17	0.57
		Thienemannimyia Gr.	PR	13	0.36							27	0.30	4	0.19	81	1.54	17	0.58
		Tvetenia Vitracies group	CG			13	0.38									10	0.19		
		Total Count (# individuals/m^2)		**3727**	**100**	**3524**	**100**	**876**	**100**	**4560**	**100**	**9106**	**100**	**2164**	**100**	**5225**	**100**	**2997**	**100**

[a] **FFG = Functional Feeding Group:** CG = Collector-Gatherer, F = Filterer, MH = Macrophyte Herbivore, OM = Omnivore, PA = Parasite, PH = Piercing Herbivore, PR = Predator, SC = Scraper, SH = Shredder, UN = Unspecified

Appendix 18 – Selected benthic macroinvertebrate metric results for WDEQ/WQD sites on the Laramie River (2009-2010).

	Above UPRR Tie Plant (WB0321)		Below Spring Creek (WB0322)		Above Laramie WWTF (WB0323)		Below Gravel Pits (WB0324)	
Metric	8/28/2009	9/2/2010	8/27/2009	9/1/2010	8/26/2009	8/31/2010	8/25/2009	8/30/2010
Density (individuals/m^2)	3727	3524	876	4560	9106	2164	5225	2997
Biotic Index BCICTQa	95.3	93.2	98.6	98.5	102.3	99.8	106.1	105.2
Hilsenhoff Biotic Index	6.0	5.0	6.0	4.7	5.1	4.9	5.8	5.8
WSII-Shannon Diversity	3.0	2.6	3.0	1.9	2.1	1.7	2.3	2.1
WSII-Shannon Diversity (E)	2.9	2.6	2.9	1.8	2.1	1.6	2.2	2.1
# of Taxa	35	30	44	26	31	23	24	24
# of EPT Taxa (Epemeroptera + Plecoptera + Trichoptera)	12	9	10	8	5	7	5	4
# of Ephemeroptera Taxa	8	6	6	4	2	4	3	2
# of Plecoptera Taxa	0	0	0	0	0	0	0	0
# of Trichoptera Taxa	4	3	4	4	3	3	2	2
# of Scraper Taxa	4	2	5	2	4	2	3	1
# of Multivoltine Taxa/ (Semivoltine + Univoltine Taxa)	0.69	1.27	1.29	1.20	1.45	1.00	2.00	1.86
% 5 Dominant Taxa	55	69	62	80	73	84	78	88
% Chironomidae (midge fly larvae)	32	35	25	12	15	12	15	26
% Non-midge fly Diptera	3	10	2	17	12	6	29	3
% *Simulium*	0.2	1	0	14	10	5	28	3
% Ephemeroptera	23	20	14	15	6	17	13	8
% Ephemeroptera - Baetidae excluded	19	11	13	1	0.9	6	13	3
% Ephemeroptera - Baetidae and *Tricorythodes* excluded	24	12	11	7	5	10	9	1
% *Acentrella*	7	26	9	56	52	63	24	42
% *Tricorythodes*	17	6	11	1	0.9	6	13	3
% *Tricorythodes* (within Ephemeroptera)	62	17	49	2	2	9	35	8
% Trichoptera	22	8	9	7	5	10	9	1
% Trichoptera - Hydropsychidae excluded	8	0.8	7	1	3	5	2	0.8
% Trichoptera - Hydropsychidae excluded (within Trichoptera)	38	10	78	18	54	52	20	69
% *Cheumatopsyche + Hydropsyche*	12	6	2	5	3	5	7	0.4
% *Hydropsyche*	2	5	1	2	0	0.9	0	0.4
% Non-Insect	14	8	39	5	14	4	10	24
% Oligochaeta	7	0.6	13	2	5	1	0.2	21
% Collector-Gatherer	47	48	47	67	68	74	50	91
% Filterer	31	10	11	24	13	12	36	3
% Predator	4	9	2	2	1	1	2	2
% Scraper	1	3	27	0.4	4	0.9	5	1
% Burrower	11	11	15	4	3	1	2	6
% Clinger	43	22	23	28	20	14	42	4
% Sprawler	24	9	21	4	3	8	19	6
% Swimmer	7	27	10	57	52	63	24	42

Appendix 19 – Diatom metric results for WDEQ/WQD sites on the Laramie River (2009-2010).

	Above UPRR Tie Plant WB0321		Below Spring Creek WB0322		Above Laramie WWTF WB0323		Below Gravel Pits WB0324	
Metric	**8/28/2009**	**9/2/2010**	**8/27/2009**	**9/1/2010**	**8/26/2009**	**8/31/2010**	**8/25/2009**	**8/30/2010**
Taxa Richness	55	50	64	67	51	49	43	46
Taxonomic Composition								
% Dominant Species	32	23	20	18	25	17	19	34
% Amphora	5.0	5.3	4.7	5.0	11.8	14.3	2.3	3.8
% Cocconeis	8.3	7.7	3.5	10.7	6.1	4.0	21.8	34.0
% Cymbella	0	0	5.5	4.0	1.0	1.7	0.7	0.5
% Cymbella / (% Cymbella + % Navicula)	0	0	0.4	0.2	6.5	0.1	8.9	6.8
% Diatoma	36.7	24.0	12.0	18.2	3.8	7.5	3.3	1.0
% Epithemia	4.8	15.0	0.7	0.5	0.3	0.2	0	0
% Fragilaria	0	0	0	0	0	0	0.7	0.3
% Gomphonema	3.5	1.7	2.0	2.7	3.3	5.3	22.4	3.7
Number of *Gomphonema* species	5	4	4	6	3 (5)	4 (2)	5	4
% Navicula	4.7	2.8	7.0	13.8	14.4	11.0	6.8	6.8
% Nitzschia	5.8	13.5	10.5	9.3	12.1	12.3	7.8	7.0
% Rhoicosphenia	2.5	4.7	1.2	4.2	1.5	5.3	18.2	19.2
% Rhopalodiales *(Rhopalodia + Epithemia)*	5.2	15.3	0.7	0.5	0.3	0.2	0	0
% Synedra	2.2	3.5	2.3	2.5	1.3	0.7	0.2	0.2
Number of *Synedra* species	3	1	3	2	1 (2)	2 (2)	1	1
Pollution Tolerance								
% Sensitive Individuals	43.7	52.3	59.7	56.5	67.2	66.7	74.6	70.2
% Tolerant Individuals	52.3	44.8	35.8	38.0	26.9	25.8	20.5	15.2
% Most Tolerant Individuals	4.0	2.8	4.5	5.5	6.0	7.5	5.0	14.7
Pollution Tolerance Index	2.41	2.49	2.54	2.50	2.61	2.58	2.67	2.55
Disturbance Index (%)	1.2	4.2	19.7	16.3	25.4	17.0	6.8	2.3
Siltation Index	14.0	16.8	20.3	27.2	29.9	28.0	16.0	25.0
Stability Index	50.7	34.3	26.0	21.8	9.8	11.2	7.8	4.8
Heavy Metals Index	5.3	5.2	11.3	7.3	9.8	7.5	3.3	13.0
Trophic State								
% Eutraphentic	62.0	64.3	38.0	53.3	37.6	40.8	78.2	70.8
% Hypereutraphentic	0.3	1.5	3.0	2.3	3.2	2.0	1.5	9.5
Nitrogen Uptake Metabolism								
% Nitrogen Autotrophs (low organics)	8.8	17.2	14.8	6.8	4.0	3.5	4.8	1.3
% Nitrogen Autotrophs (high organics)	75.7	66.8	70.3	72.5	68.7	55.7	59.1	72.7
% Facultative Nitrogen Heterotrophs	5.5	2.8	3.8	3.7	4.5	9.7	8.9	5.7
% Obligate Nitrogen Heterotrophs	1.8	5.5	2.5	3.3	4.1	2.7	1.8	11.8
Oxygen Demand Tolerance								
% Continuously High (D.O. sat. 100%)	15.0	15.2	44.0	26.7	33.5	28.0	12.9	10.5
% High (D.O. sat. >75%)	26.5	32.2	15.0	17.5	19.7	15.3	23.9	29.8
% Moderate (D.O. sat. >50%)	45.7	42.5	28.0	36.8	22.4	20.2	32.0	42.8
% Low (D.O. sat. >30%)	4.7	2.3	5.0	5.7	6.3	8.0	5.4	8.0
% Very Low (D.O. sat. 10%)	0.7	0.3	0.3	0	0	0	0.3	0.7
Saprobity								
% Oligosaprobous (D.O. sat. >85%, BOD <2 mg/L)	5.0	0.7	4.8	2.0	1.7	0	0	0.3
% Beta Mesosaprobous (D.O. sat. 70-85%, BOD 2-4 mg/L)	41.5	53.2	58.5	54.2	62.2	54.0	74.1	69.3
% Alpha Mesosaprobous (D.O. sat. 25-70%, BOD 4-13 mg/L)	38.8	30.0	23.0	26.7	15.4	16.2	13.7	9.0
% Alpha Mesosaprobous/Polysaprobous (D.O. sat. 10-25%, BOD 13-22 mg/L)	9.2	8.0	7.3	5.0	4.8	6.7	6.4	12.2
% Polysaprobous (D.O. sat. <10%, BOD >22 mg/L)	0.3	1.3	1.7	1.7	3.2	2.0	0.3	3.0
Motility								
% Motile (Highly Motile + Moderately Motile)	25.0	41.3	28.7	35.5	43.4	47.8	19.6	32.5
% Non-Motile	75.0	57.3	56.3	57.7	49.1	46.3	79.2	66.8
Salinity Tolerance								
% Fresh-Brackish (Oligohalobous) (<0.9% salinity)	53.2	59.8	77.2	64.5	77.1	72.5	81.7	86.7
% Brackish-Fresh (Mesohalobous) (0.9 - 1.8% salinity)	41.7	34.2	17.0	24.8	12.6	17.3	13.4	9.2
% Brackish (Mesohalobous) (1.8 - 9.0% salinity)	0	0.3	2.0	1.3	0.7	0.3	0.8	0
Moisture Regime								
% Rarely Occur Outside Waterbodies	50.0	33.3	26.8	25.2	12.8	12.2	12.4	6.5
% Mainly Occur in Waterbodies; Sometimes Wet Places	21.3	33.3	18.8	24.3	16.1	15.2	39.3	55.3
% Mainly Occur in Waterbodies; Regularly Wet Places	17.7	19.3	47.2	37.0	54.2	44.7	22.6	23.2
% Mainly Occur in Wet Places; Sometimes in Water	0.8	0.2	0.3	0.8	0	0.3	0.8	6.8

Appendix 20 – Diatom sample results for WDEQ/WQD sites on the Laramie River (2009-2010). D = cells/cm^2, PRA = Percent Relative Abundance. Values shown in red font represent dominant taxa.

	Above UPRR Tie Plant - WB0321						Below Spring Creek - WB0322						Above Laramie WWTF - WB0323						Below Gravel Pits - WB0324					
	8/28/2009			9/2/2010			8/27/2009			9/1/2010			8/26/2009			8/31/2010			8/25/2009			8/30/2010		
Taxon	Count	D	PRA	Count	D	PRA	Count	D	PRA	Count	D	PRA	Count	D	PRA	Count	D	PRA	Count	D	PRA	Count	D	PRA
Achnanthes conspicua	1	1172	0.2				2	7102	0.3															
Achnanthes sp.																			3	7600	0.5			
Achnanthidium affine										1	277	0.2												
Achnanthidium exiguum																2	332	0.3						
Achnanthidium gracillimum										1	277	0.2												
Achnanthidium minutissimum	7	8201	1.2	25	16335	4.2	118	419034	**19.7**	98	27146	**16.3**	153	280845	**25.4**	102	16935	**17.0**	41	103873	**6.8**	14	1210	2.3
Achnanthidium pyrenaicum							2	7102	0.3															
Achnanthidium rivulare													1	1836	0.2	12	1992	2.0	2	5067	0.3	5	432	0.8
Adlafia minuscula										1	277	0.2				2	332	0.3						
Amphora copulata							1	3551	0.2	1	277	0.2	1	1836	0.2			0.0	4	10134	0.7	2	173	0.3
Amphora inariensis	3	3515	0.5							5	1385	0.8	17	31205	2.8	58	9630	**9.7**				5	432	0.8
Amphora ovalis	1	1172	0.2	4	2614	0.7	2	7102	0.3	2	554	0.3	2	3671	0.3			0.0						
Amphora pediculus	26	30463	**4.3**	28	18296	**4.7**	25	88778	4.2	22	6094	3.7	51	93615	**8.5**	28	4649	4.7	7	17734	1.2	16	1383	2.7
Amphora veneta																			3	7600	0.5			
Caloneis bacillum				1	653	0.2																		
Cocconeis pediculus	32	37492	**5.3**	13	8494	2.2	2	7102	0.3	4	1108	0.7	5	9178	0.8	4	664	0.7	18	45603	3.0	2	173	0.3
Cocconeis placentula	18	21089	3.0	33	21563	**5.5**	19	67472	3.2	60	16620	**10.0**	32	58739	**5.3**	20	3321	3.3	114	288819	**18.8**	202	17462	**33.7**
Cymbella excisa							33	117188	**5.5**	22	6094	3.7	6	11014	1.0	10	1660	1.7	4	10134	0.7	3	259	0.5
Cymbella tumida										2	554	0.3												
Denticula kuetzingii							3	10653	0.5							2	332	0.3						
Denticula subtilis							2	7102	0.3															
Diatoma moniliformis	193	226126	**32.2**	140	91478	**23.3**	65	230824	**10.8**	107	29640	**17.8**	21	38547	3.5	44	7305	**7.3**	20	50670	3.3	6	519	1.0
Diatoma tenuis				2	1307	0.3	1	3551	0.2															
Diatoma vulgaris	27	31634	**4.5**	2	1307	0.3	6	21307	1.0	2	554	0.3	2	3671	0.3	1	166	0.2						
Encyonema cespitosum										1	277	0.2												
Encyonema minutum							6	21307	1.0				6	11014	1.0									
Encyonema prostratum				2	1307	0.3																		
Encyonema reichardtii													22	40383	**3.6**	24	3985	4.0	2	5067	0.3			
Encyonema silesiacum							28	99432	4.7	3	831	0.5	7	12849	1.2	1	166	0.2				1	86	0.2
Encyonopsis microcephala							23	81676	3.8	8	2216	1.3	4	7342	0.7									
Encyonopsis subminuta										1	277	0.2												
Eolimna minima	14	16403	2.3				8	28409	1.3	10	2770	1.7	11	20191	1.8	24	3985	4.0				9	778	1.5
Epithemia adnata	18	21089	3.0	7	4574	1.2				1	277	0.2												
Epithemia sorex	11	12888	1.8	83	54233	**13.8**	4	14205	0.7	2	554	0.3	2	3671	0.3	1	166	0.2						
Eunotia bilunaris										1	277	0.2												
Fragilaria capucina v. gracilis																						2	173	0.3
Fragilaria elliptica																			4	10134	0.7			
Geissleria acceptata	5	5858	0.8	1	653	0.2				2	554	0.3										2	173	0.3
Geissleria decussis	1	1172	0.2																					
Gomphoneis eriense	8	9373	1.3				6	21307	1.0	6	1662	1.0												
Gomphoneis geitleri				6	3920	1.0																		
Gomphonema sp.										4	1108	0.7	2	3671	0.3							3	259	0.5
Gomphonema kobayasii	3	3515	0.5	5	3267	0.8	5	17756	0.8	4	1108	0.7				14	2324	2.3	8	20268	1.3	1	86	0.2
Gomphonema minutum	8	9373	1.3	1	653	0.2	2	7102	0.3	2	554	0.3	13	23863	2.2	13	2158	2.2	113	286285	**18.6**	10	864	1.7
Gomphonema olivaceum	2	2343	0.3	2	1307	0.3				2	554	0.3	5	9178	0.8	2	332	0.3	1	2533	0.2			
Gomphonema pala										2	554	0.3												
Gomphonema parvulum	6	7030	1.0	2	1307	0.3	4	14205	0.7	2	554	0.3				3	498	0.5	13	32935	2.1	8	692	1.3
Gomphonema parvulum v. lagenula																			1	2533	0.2			
Gomphonema truncatum	2	2343	0.3				1	3551	0.2															
Hippodonta capitata							2	7102	0.3				5	9178	0.8				4	10134	0.7	5	432	0.8
Hippodonta hungarica							1	3551	0.2							2	332	0.3						
Karayevia clevei	1	1172	0.2	1	653	0.2	2	7102	0.3	2	554	0.3												
Mayamaea agrestis																						8	692	1.3
Mayamaea atomus										2	554	0.3							3	7600	0.5	39	3371	**6.5**
Melosira varians	7	8201	1.2				3	10653	0.5				1	1836	0.2				1	2533	0.2			
Navicula antonii							4	14205	0.7	2	554	0.3				5	830	0.8						
Navicula canalis				1	653	0.2																		
Navicula capitatoradiata	5	5858	0.8	1	653	0.2	9	31960	1.5	15	4155	2.5	20	36712	3.3	9	1494	1.5	6	15201	1.0	14	1210	2.3
Navicula caterva	10	11716	1.7	11	7188	1.8	14	49716	2.3	34	9418	**5.7**	21	38547	3.5	12	1992	2.0	14	35469	2.3	11	951	1.8
Navicula cryptocephala										1	277	0.2	4	7342	0.7							1	86	0.2

Appendix 20 (cont.) – Diatom sample results for WDEQ/WQD sites on the Laramie River (2009-2010). D = cells/cm^2, PRA = Percent Relative Abundance. Values shown in red font represent dominant taxa.

	Above UPRR Tie Plant - WB0321						Below Spring Creek - WB0322						Above Laramie WWTF - WB0323						Below Gravel Pits - WB0324					
	8/28/2009			9/2/2010			8/27/2009			9/1/2010			8/26/2009			8/31/2010			8/25/2009			8/30/2010		
Taxon	Count	D	PRA	Count	D	PRA	Count	D	PRA	Count	D	PRA	Count	D	PRA	Count	D	PRA	Count	D	PRA	Count	D	PRA
Navicula cryptotenella	5	5858	0.8	3	1960	0.5	4	14205	0.7	9	2493	1.5	19	34876	3.2	22	3653	3.7	4	10134	0.7	2	173	0.3
Navicula cryptotenelloides										3	831	0.5				4	664	0.7				4	346	0.7
Navicula gregaria	6	7030	1.0	1	653	0.2	2	7102	0.3	9	2493	1.5	6	11014	1.0	4	664	0.7	9	22801	1.5	3	259	0.5
Navicula peregrina										1	277	0.2												
Navicula reichardtiana																2	332	0.3						
Navicula rostellata							2	7102	0.3	2	554	0.3	4	7342	0.7									
Navicula subminuscula																			5	12667	0.8	4	346	0.7
Navicula tripunctata	1	1172	0.2				3	10653	0.5	6	1662	1.0	11	20191	1.8	3	498	0.5				1	86	0.2
Navicula veneta							4	14205	0.7	1	277	0.2	2	3671	0.3	5	830	0.8	3	7600	0.5			
Navicula viridula	1	1172	0.2																			1	86	0.2
Nitzschia acicularis				3	1960	0.5	2	7102	0.3										1	2533	0.2	6	519	1.0
Nitzschia acidoclinata										1	277	0.2				4	664	0.7						
Nitzschia agnita													2	3671	0.3									
Nitzschia amphibia							2	7102	0.3										13	32935	2.1	1	86	0.2
Nitzschia archibaldii				6	3920	1.0	1	3551	0.2	2	554	0.3												
Nitzschia aurariae										2	554	0.3												
Nitzschia capitellata							8	28409	1.3	1	277	0.2							4	10134	0.7			
Nitzschia desertorum																2	332	0.3						
Nitzschia dissipata	12	14060	2.0	14	9148	2.3	29	102983	**4.8**	24	6648	4.0	27	49561	**4.5**	18	2989	3.0				1	86	0.2
Nitzschia fonticola																2	332	0.3						
Nitzschia frustulum				2	1307	0.3							2	3671	0.3							2	173	0.3
Nitzschia inconspicua	2	2343	0.3	12	7841	2.0	4	14205	0.7	7	1939	1.2	15	27534	2.5	31	5147	**5.2**	23	58270	**3.8**	12	1037	2.0
Nitzschia liebetruthii	2	2343	0.3	8	5227	1.3				1	277	0.2												
Nitzschia linearis	3	3515	0.5				1	3551	0.2															
Nitzschia microcephala				4	2614	0.7	1	3551	0.2	6	1662	1.0	2	3671	0.3	1	166	0.2						
Nitzschia palea	2	2343	0.3	8	5227	1.3	10	35511	1.7	10	2770	1.7	19	34876	3.2	12	1992	2.0	2	5067	0.3	18	1556	**3.0**
Nitzschia paleacea	9	10545	1.5	16	10455	2.7	2	7102	0.3	2	554	0.3	2	3671	0.3	3	498	0.5				2	173	0.3
Nitzschia pumila				4	2614	0.7																		
Nitzschia recta	2	2343	0.3	2	1307	0.3																		
Nitzschia sigmoidea	1	1172	0.2				2	7102	0.3															
Nitzschia sociabilis							1	3551	0.2							1	166	0.2						
Nitzschia sp.	2	2343	0.3	2	1307	0.3							2	3671	0.3				2	5067	0.3			
Nitzschia supralitorea																			2	5067	0.3			
Nitzschia vermicularis													2	3671	0.3									
Pinnularia sp.													2	3671	0.3									
Placoneis clementis										2	554	0.3												
Placoneis pseudanglica	1	1172	0.2																					
Planothidium sp.																			1	2533	0.2			
Planothidium daui	1	1172	0.2							1	277	0.2												
Planothidium delicatulum				2	1307	0.3				1	277	0.2												
Planothidium dubium													8	14685	1.3									
Planothidium frequentissimum	21	24604	3.5	23	15028	3.8	6	21307	1.0				8	14685	1.3	5	830	0.8	5	12667	0.8	8	692	1.3
Planothidium granum	2	2343	0.3																					
Planothidium lanceolatum										2	554	0.3							1	2533	0.2			
Planothidium rostratum	8	9373	1.3				1	3551	0.2							2	332	0.3						
Pseudostaurosira brevistriata	11	12888	1.8	4	2614	0.7	2	7102	0.3				6	11014	1.0									
Pseudostaurosira parasitica v. subconstricta							18	63920	3.0															
Reimeria sinuata	4	4687	0.7	10	6534	1.7	13	46165	2.2	14	3878	2.3	3	5507	0.5	16	2657	2.7	8	20268	1.3	22	1902	**3.7**
Reimeria uniseriata	1	1172	0.2	12	7841	2.0				3	831	0.5	4	7342	0.7	14	2324	2.3						
Rhoicosphenia abbreviata	15	17575	2.5	28	18296	**4.7**	7	24858	1.2	25	6925	**4.2**	9	16520	1.5	32	5313	**5.3**	110	278685	**18.2**	115	9941	**19.2**
Rhopalodia acuminata				2	1307	0.3																		
Rhopalodia brebissonii	2	2343	0.3																					
Sellaphora bacillum				2	1307	0.3				4	1108	0.7												
Sellaphora pupula																			2	5067	0.3	2	173	0.3
Simonsenia delognei							5	17756	0.8				2	3671	0.3									
Staurosira construens	6	7030	1.0	4	2614	0.7	1	3551	0.2				6	11014	1.0	4	664	0.7	21	53203	3.5	3	259	0.5
Staurosira construens v. binodis	14	16403	2.3																					
Staurosira construens v. venter	28	32806	**4.7**	19	12415	3.2	32	113636	**5.3**	3	831	0.5				4	664	0.7				4	346	0.7
Staurosirella pinnata	12	14060	2.0	14	9148	2.3	14	49716	2.3	4	1108	0.7	16	29369	2.7	10	1660	1.7				13	1124	2.2
Stephanocyclus meneghiniana	4	4687	0.7	2	1307	0.3	2	7102	0.3										2	5067	0.3	4	346	0.7
Surirella angusta																						2	173	0.3
Synedra acus	2	2343	0.3				1	3551	0.2	1	277	0.2												
Synedra ulna	10	11716	1.7	21	13722	3.5	12	42614	2.0	14	3878	2.3	8	14685	1.3	3	498	0.5	1	2533	0.2	1	86	0.2
Synedra ulna v. biceps	1	1172	0.2				1	3551	0.2															
Synedra ulna v. spathulifera																1	166	0.2						
Tabularia fasciculata							3	10653	0.5										1	2533	0.2			
Thalassiosira weissflogii				1	653	0.2				1	277	0.2												
Tryblionella apiculata							1	3551	0.2	3	831	0.5	2	3671	0.3									
Total Cell Density		**702983**	**100**		**392048**	**100**		**2130678**	**100**		**166201**	**100**		**1106859**	**100**		**99615**	**100**		**1535290**	**100**		**51864**	**100**