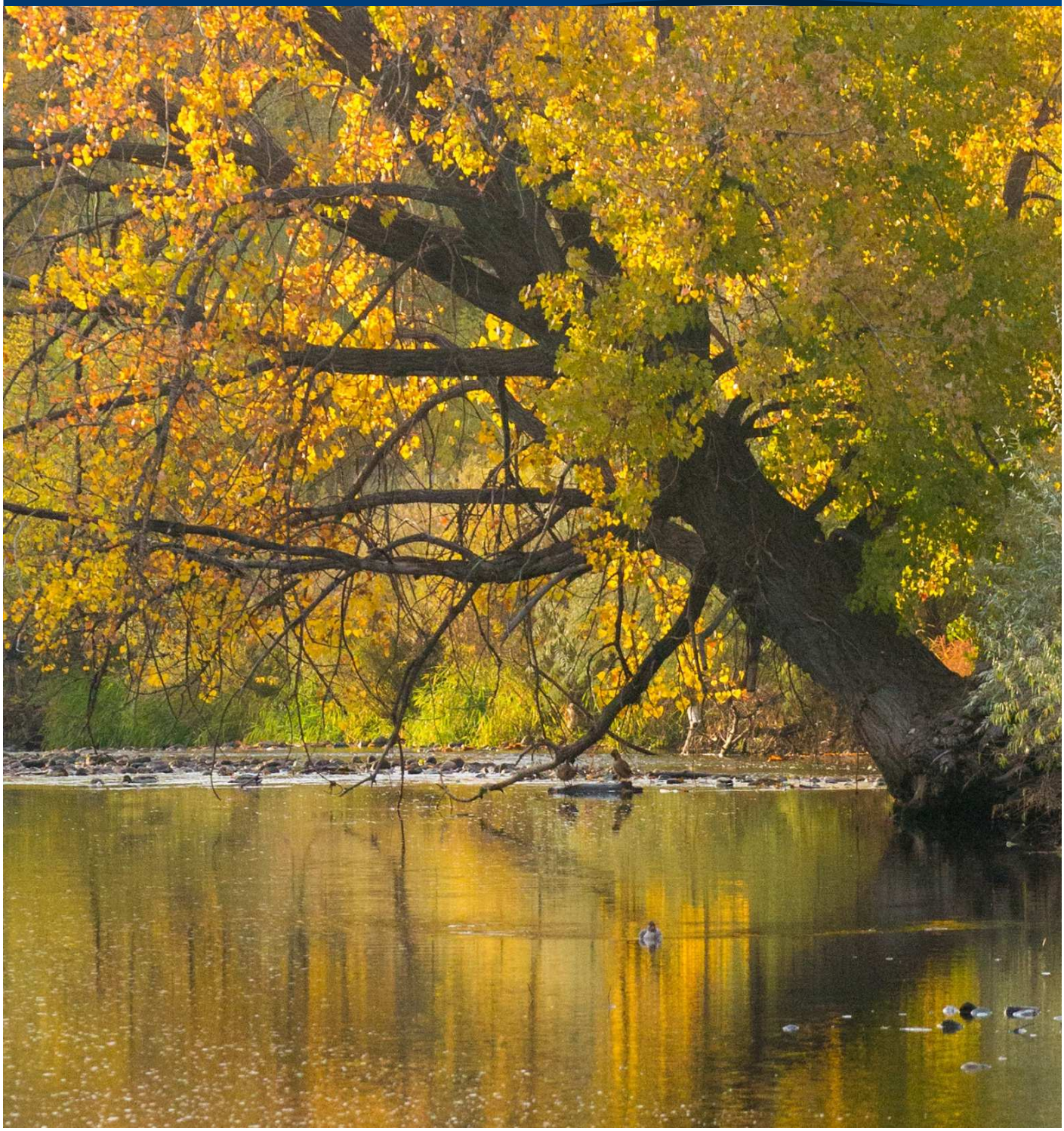
City of Fort Collins Natural Areas

An **Ecological Response Model** for the Cache la Poudre River through Fort Collins

EXECUTIVE SUMMARY

DECEMBER 2014



INTRODUCTION

The Cache la Poudre River (hereafter Poudre River or "river") is a treasured community asset. The City of Fort Collins recognizes that the Poudre River provides the community with a broad set of ecological, agricultural, municipal, industrial, and recreational benefits that are greatly valued by the public. Ecosystem benefits include a high quality water supply, flood conveyance, habitat in the river and its adjacent forest, and a variety of opportunities for recreation and enjoyment.

In 2011, the City of Fort Collins Natural Areas Department initiated a collaborative project with scientists to develop the Ecological Response Model (ERM) for the Poudre River through Fort Collins. The ERM effort supports a community-driven quest to manage for an ecologically healthy and resilient Poudre River.

The core purpose of the model is to identify probable ecological responses to a range of potential future changing conditions related to streamflows and important secondary factors affecting the river system. Nine separate model scenarios were developed to provide a lens through which the past, present, and potential future conditions of the river may be examined. The ERM findings, not surprisingly, confirm that the urban Fort Collins reach has been fundamentally altered from its native condition (for the purpose of this model defined as prior to the development of the past 150 years). More importantly, the Poudre continues on a trajectory of change that is difficult for the casual observer to perceive – and is likely to be headed towards a different future than what we see today.

The ERM is an integrated model designed to improve our overall understanding of the Poudre River ecosystem and the many factors that influence it, and to model the status and trends of its key resources. As a tool, the model contributes to the City's evaluation of a variety of interacting questions, such as:

- How do increasing societal demands for water, an altered floodplain, and a highly modified river channel intersect with the native ecological system to result in today's conditions?
- Does the river retain some characteristics of what is considered to be healthy river, and will it be able to retain or improve those characteristics in the future?
- What will it take to achieve a future river condition that our community desires?

The ERM demonstrates there is no single answer to these complicated questions. Yet, it provides a clearer understanding of key issues, potential management actions, and strategies that may help the City achieve the community's long term vision for the Poudre River.

What Is the Community's Vision?

Numerous City and community-adopted planning documents reflect broad support and vision for a ***healthy and resilient Poudre River***.

The ERM can help quantify conditions necessary to realize the integrated vision of clean water; vibrant plant and animal communities; and, a river that provides for the economy and the community's lifestyle. While this long-term goal is challenging, its attainment is made more likely if the community is able to make well-informed choices and strategic investments today.

By exploring the relationship between streamflow and the interdependent components of the river ecosystem, the ERM helps provide an understanding of the condition and potential trajectories of key ecological indicators such as fish, aquatic insects, and riverside vegetation. In turn, this assists in informing the projects' ***two overarching goals***:

1. To provide a broad and integrated evaluation of future river conditions given past, present, and potential future flow scenarios and multiple interacting ecological factors; and,

2. To inform flow and management scenarios and actions that help the community attain its vision of a healthy river.

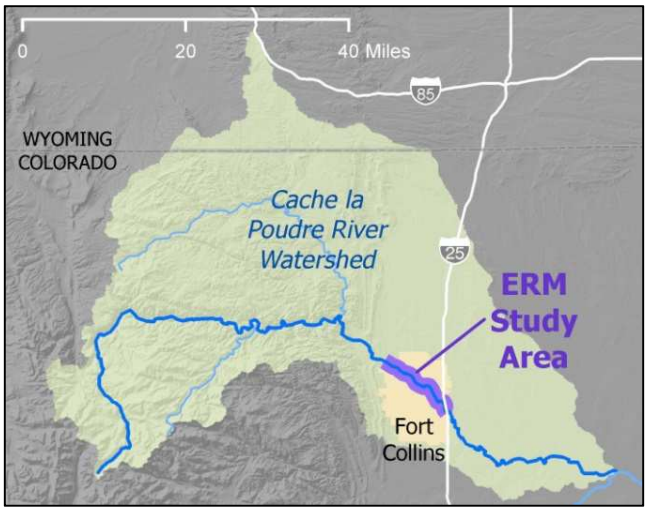
Who Created the ERM?

In the fall of 2011, the City of Fort Collins Natural Areas Department convened an interdisciplinary team of river scientists, planners and engineers to develop the ERM. This collaboration of nine team members brought together expertise in a variety of river science disciplines from organizations including Colorado State University, U.S. Forest Service, The Nature Conservancy, the U.S. Geological Survey, and the City of Fort Collins. Collectively the team has contributed to a broad spectrum of river science and management issues through the collective publication of more than 370 peer-reviewed articles.

Study Area

The ERM study area covers a 13-mile segment of the Poudre River. This study area lies along the Front Range of northern Colorado Rocky Mountains and runs through the City of Fort Collins from Overland Trail to Interstate 25 (Figure 1). For the purpose of the ERM this largely urban stretch of the Poudre was segmented into eight reaches as determined by the location of major diversion structures and changes in channel form. Three of the eight reaches were chosen as representative of the range of physical conditions across other reaches and thus were included in the model.

FIGURE 1 – ERM STUDY AREA



HOW WAS THE ERM BUILT?

The ERM team developed an integrated model to explore how river flow patterns interact with physical and biotic systems to influence several indicators of ecosystem condition.

The general structure of the model is depicted in Figure 2. Long term daily flow patterns are the primary input. A series of secondary inputs and ecological interactions are built into the intermediate nodes of the model. The ERM output is key ecological indicators of river condition.

FIGURE 2 OVERVIEW OF ERM STRUCTURE

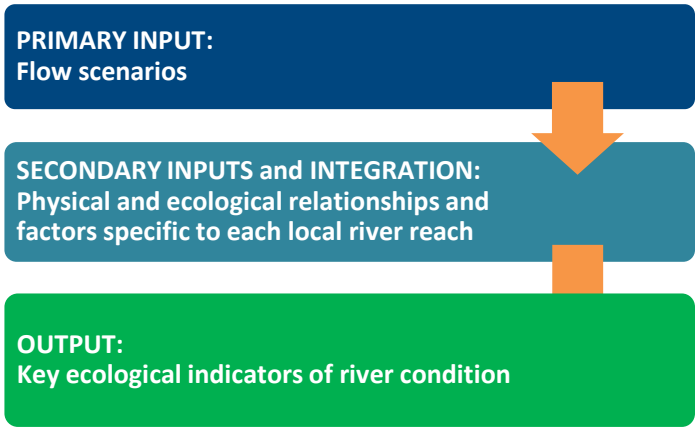


TABLE 1 – ERM INPUT: IMPORTANT ATTRIBUTES OF THE NINE FLOW SCENARIOS*

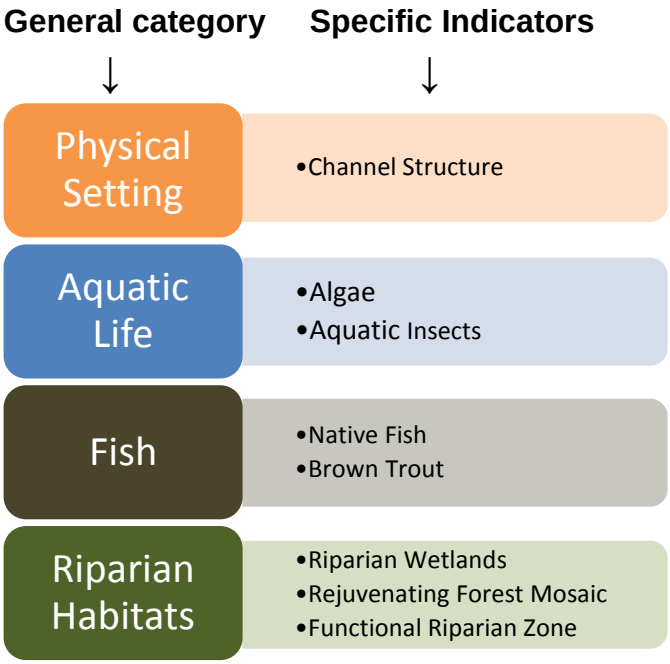
General Group↓	Attribute → / Flow scenario ↓	Average annual peak flow	Average summer base flow	Average winter base flow
Past and Present	Reconstructed Native	3287	347	70
	Recent Past (1969-2010)	1947	126	24
	Present Operations	1094	81	12
Possible Futures with Less Water	Additional Water Development	524	52	5
	Driest Climate	472	13	4
Environmental Flow Test Scenarios	StableBase - HighPeak	2535	61	35
	HighBase - ModeratePeak	1900	188	55
	DryBase - HighPeak	2555	67	21
	StableBase - LowPeak	1000	59	24

*flow values are reported in cubic feet per second (cfs)

For the model input, nine flow scenarios were developed and are best described in three general groups (Table 1). The first group (past and present) is based on considerable data. These scenarios model the flows running through the Poudre prior to and during the past 150 years of agriculture and urban development. The second group represents two possible futures with less water. While there are numerous reasons why the Poudre may have less water in the future, there remains a great amount of uncertainty regarding the specific details. It is important to interpret model output for this group of scenarios within this context of uncertainty. The third group, the environmental flow test scenarios, was developed to explore the response of the system to a very specific set of flow attributes (such as those represented in Table 1). These test scenarios inform the City's ongoing efforts at matching management actions with river health goals.

The model output provides a representation of the response of the key ecological indicators to various flow scenarios. Indicators were selected based on their role in ecosystem function, their regulatory implications, or their social value. Eight indicators were selected to meet these criteria and are presented in four general categories (Figure 3).

FIGURE 3. ERM OUTPUT: KEY ECOLOGICAL INDICATORS OF RIVER CONDITION



The ERM modeling framework allows for the integration of physical and biological factors and many relationships important to the resilience of the river ecosystem. This provides results that provide a broad perspective of system-wide trends.

MODEL OUTPUT: RESULTS AND DISCUSSION FOR THE KEY ECOLOGICAL INDICATORS

The nine flow scenarios evaluated by the ERM include a combination of flow increases and decreases throughout the seasons. The nine flow scenarios were applied to three physically distinct river reaches. With flow scenarios and physical setting combined the ERM provides 27 unique responses for the potential condition of the each of the indicators. The following discussion provides an overview and synthesis of the extensive set of ERM results. Please refer to the ERM report for the full set of results associated with all the model runs.

Physical Setting

Context: The physical setting (also called channel structure) includes the shape of the river and its floodplain and the composition of the riverbed. It is the central factor that interacts with flows to determine aquatic and riparian habitat potential. The physical setting of the Fort Collins reach of the Poudre River is affected and fundamentally altered by man-made structures such as bridges, bank stabilization, and floodplain development.

ERM Results and Discussion: Results for channel structure demonstrate the net benefit when important functions of both flows and the physical setting are intact. In those reaches with lower banks and less infrastructure the scenarios with higher and longer spring peak flows (such as the recent past, reconstructed native, and the two “High Peak” test flow scenarios) lead to a better predicted condition for channel structure. This condition is characterized by mobility of the riverbed and diversity of habitats, which in turn, benefits all other river indicators.

The results also indicate today’s flows (as represented by the Present Operations scenario) sometimes approach but rarely exceed thresholds necessary to maintain a channel structure that functionally supports habitat creation and maintenance. Thus, further declines will likely reduce sediment flushing and riverbed rejuvenation to frequencies and durations that preclude a flushed, clean and physically diverse channel.

Additionally, widespread bank stabilization to limit meandering of the channel in urban or agricultural landscapes reduces the potential of the channel to function naturally in building and maintaining habitats. Hence, further reductions of high flows are likely in to interact with extensive channel modifications, armoring, and levee construction to substantially limit the ecological potential of the riparian corridor and the biota supported in the stream channel.

Reconnecting the river with its floodplain through removing or widening the distance between stable banks in carefully targeted safe zones (away from human infrastructure) could positively impact the biological indicators of the system. Given extensive changes to the landscape and the variety of human alterations along the river, it is important to identify local physical conditions, constraints, opportunities, and associated flushing flow needs to ensure that the channel structure functionally supports the biological indicators of the system.

Aquatic Life

***Context**:* Algae are an important base of the aquatic food web. However, excessive amounts of algae can have negative ecological consequences and are not aesthetically desirable. Elevated nutrient levels, reduced frequency of scouring flows, and low summer base flows resulting in higher water temperatures create very favorable conditions for excessive algae growth. This in turn can reduce aquatic insect habitat and species diversity.

Aquatic insects play an intermediate role in the stream food web by consuming algae and providing a main source of food for fishes and wildlife such as birds in the riparian corridor. The distribution, abundance, and species diversity of aquatic insects can be used as an indicator of Poudre River water quality.

Photo: David Rees

ERM Results and Discussion: The ERM test scenarios demonstrate aquatic life benefits in all modeled river reaches from improved base flows as well as peak flows that meet thresholds necessary to scour and turn over the riverbed. ERM results for the present and recent flow scenarios match observations of an increase in undesirable levels of algae which is likely contributing to depressed aquatic insect diversity and abundance. Further reductions of flushing flows and increased concentrations of nutrient pollution will likely increase algae blooms and further stress aquatic insects.

Fish

***Context**:* Fishes lie near the top of the food chain and depend upon nutrients, algae, and aquatic insects. Abundance, size, and numbers of species are also influenced by the physical habitat which is controlled by patterns of streamflow, particularly spring peak and base-flow levels. Extreme low flows during the base-flow periods can negatively affect fish through a combination of reduced habitat volume and low water quality. These issues are amplified when channel structure and habitat are simplified (see Physical Setting above). Therefore, native fishes and trout are sensitive indicators of various river conditions and may be viewed as barometers of river health. In addition, trout are a valued recreational asset.

ERM Results and Discussion: ERM results suggest the number of native fish species and their abundance has declined over time under recent and current flow conditions. This is due mainly to reduced base flows and lack of diverse habitat created by peak flows. The ERM indicates the potential for declines for trout under recent and current flow scenarios. However, fish populations can change rapidly and observations from the past few years indicate trout abundance has increased, perhaps due to higher river flows, particularly in winter.

The ERM indicates reductions in base or peak flows would likely reduce fish populations from present conditions. The model indicates that habitat for native fish would improve most with higher base-flows combined with improvements to channel structure which is directly dependent on peak flows that cleanse and refresh the riverbed. ERM results show limited potential improvement for native fish because many sensitive species are already locally extinct, and others may be additionally limited by predation from trout and river fragmentation caused by irrigation dams that prevent downstream-upstream movements. Based on these

conditions, a multi-faceted management approach that addresses issues related to habitat limitations and connectivity, siltation, and invasive species as well as high and low flow restoration is needed to ensure self-sustaining and abundant populations of native and sport fishes.

Riparian Habitats (Riverside Forests)

Context: Riparian forests and the mosaic of habitat types commonly found within them, provide critical habitat and resources needed by wildlife in semiarid landscapes. In urban settings riparian corridors are a valued recreational asset and provide a range of important ecological services such as pollutant filtration and floodwater attenuation. The health of riparian habitats is supported by, and dependent on, the river's flow regime.

High flows seasonally saturate and connect the floodplain to the river and provide opportunities for seedling establishment. Stable base flows serve to maintain riverside wetlands and floodplain vegetation that is connected to shallow groundwater. Floodplain groundwater levels are also influenced by many factors in the surrounding uplands which are highly altered in urban and agricultural environments compared to undeveloped landscapes.

Natural streamflow has been changed substantially over the past 150 years resulting in shifts in vegetation through Fort Collins. Changes to flow patterns along with channel confinement, bank stabilization, land clearing and development in the floodplain have resulted in a narrow and simplified riparian zone that is characteristic of the Poudre River through central Fort Collins.

ERM Results and Discussion: ERM results indicate today's flows still support wetlands and many important ecological functions necessary for sustaining a productive diverse riverside forest (but to a lesser extent than historically). These functions include: nutrient cycling, decomposition, saturation of the soil, recharging groundwater within the floodplain and maintaining areas with shallow water tables to support wetlands within the forest. Results of the ERM that simulate a decrease in frequency and volume of overbank flows indicate a future narrowing of riparian forests and reductions in the extent of streamside wetlands.

Conversely, ERM results indicate riparian wetlands, functional riparian areas, and the riparian mosaic further from the channel would respond positively to an increase in peak flows that flood overbank for at least two weeks during the growing season in most years. The best areas for potential flow-related restoration of riparian forests are along less confined reaches and those that have been widened and physically reconnected to the channel.

Management actions that reconnect the river to its floodplain, allow the river channel to move across the floodplain in safe and feasible locations, and provide adequate streamflow will lead to the most favorable riparian outcomes.

PUTTING IT ALL TOGETHER: WHAT HAVE WE LEARNED?

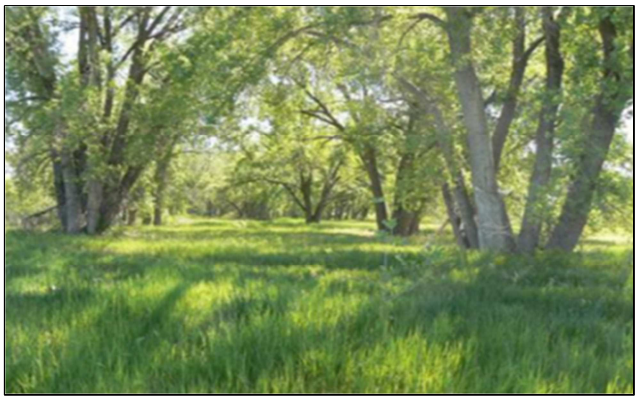
How Has the River Changed in the Past 150 Years and What is its Current Condition?

Although the Poudre River continues to support remnants of native riparian and aquatic communities, this contemporary urban ecosystem has experienced significant changes over the last 150 years. Land use and water management have substantially modified native aquatic and riparian communities, in turn altering the ecological function of the Poudre River. Indicators of this altered function include lost or diminished populations of sensitive native fishes and aquatic insects, narrowing of the riparian forest in some reaches, and limited ability of high-value native plants along the river, especially native plains cottonwood trees, to reproduce and replace declining stands of mature trees.

Despite these changes, the system still exhibits important, albeit diminished, ecological functions. These include; occasional flushing flows that have the potential to refresh riverbed habitat in some locations, overbank inundation of riparian areas that support important ecological services such as nutrient storage and processing, flood peak attenuation, provision of seasonal habitats, and maintenance of productive vegetative communities.

How Long Do Changes Take to Manifest in This System?

Changes to the river's ecosystem can occur slowly over decades or even centuries, or rapidly over shorter time scales ranging from hours to a few years. Of the indicators examined in this report, the riparian forest is the slowest to respond as cottonwood trees have the longest lifespan and can reflect ecological conditions present 100 years ago or more. Alternatively, the shape of the channel may appear to change slowly in dry periods and then be altered quickly and significantly by a single flood or fire. This underscores the importance of thinking over the long term when planning river management activities.



The model input scenario representing today's flows ("Present Operations") helps provide an understanding of conditions that are likely to occur if today's water management practices continue over the coming decades. Because of the lag time in ecosystem response, such as for cottonwood regeneration, the results from the ERM may surprise the reader because they indicate that current river management practices are likely to yield ongoing changes and decline in ecological condition in the future compared to the present.

What Does The ERM Indicate about the Future Poudre River?

Given the potential for future water development and climate change, the possibility of a future urban Poudre River with less water must be considered. River science over the last several decades has clearly established that declining flows can cause both gradual and abrupt shifts in ecosystem condition. Several ERM flow scenarios allow us to look at changes that may occur with lower flows and, as might be anticipated, the condition of ecological indicators will likely decline.

The current and likely future flow scenarios of the ERM paint a future of changing river conditions that represent a substantial departure from the City of Fort Collins' goal of a healthy and resilient river. Despite this possibility, model test runs have revealed that this departure from a biologically thriving river is not a foregone conclusion and that carefully designed environmental flows could improve the state of the Poudre River ecosystem.

Why are Environmental Flows Important?

Environmental flows define specific patterns of flow (volume, timing, frequency, and duration) necessary to meet desired ecological and societal objectives for a river. The ERM is a first step in identifying environmental flows specific to the Fort Collins segment of Poudre River. These environmental flows are a key element to reach the community's vision of a healthy and resilient river.

The ERM demonstrates that environmental flows which combine adequate base flows during the majority of the year with late spring/early summer high flows are likely to synergistically improve all biological indicators across the system. One of the test scenarios indicates substantial improvements in the river ecosystem can be achieved with flow volumes similar to (but delivered more strategically) those observed in the river over the last half century of intensive water development. These results underscore how the river ecosystem can be sustained and improved through active management while still maintaining the economic benefits and the Poudre's role as a working river.

Flow management alone is not a panacea given the extent of river modifications that have already occurred. Significant ecological benefits from environmental flows are most likely to occur if flow management is strategically combined with other management actions that promote upstream-downstream and channel-floodplain connectivity along the river corridor. This includes reconnecting side arms and oxbow lakes, removing or modifying diversion structures, widening the distance between stabilized features and creating gradients of habitat rather than abrupt steep banks.

What will the 21st Century Poudre River Ecosystem Look Like?

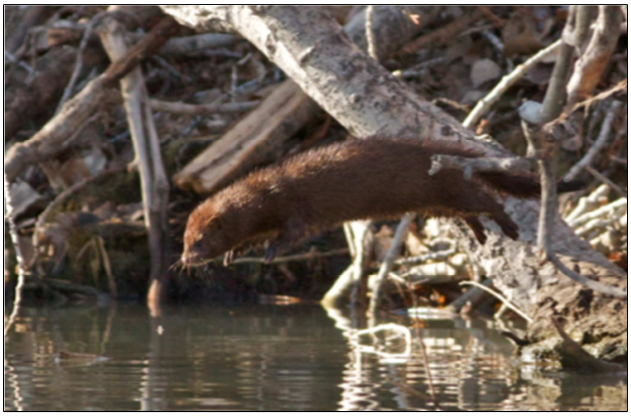
Through the in-depth exploration of specific Poudre River reaches, it became evident this river has a complex history of development and a legacy of change that should be considered in future management scenarios. The contemporary Poudre River ecosystem is characterized by a patchwork-like set of physical conditions and an evolving biological composition. It is likely to have reduced ecological resilience to both human and natural stressors. However, while the ERM provides important insight, but as a simplified ecosystem representation, it does not precisely predict the Poudre River's future. It does, however, provide a suite of potential conditions and options to consider in the future management of the river.

How Can the ERM Help Direct Future Management of the Poudre River?

The ERM was designed to represent the multi-dimensional character of this urban river. It provides a scientific foundation that can serve as a decision support tool and foster a more informed community discussion about the future of the river. It can assist managers in identifying specific and potentially obtainable goals for key indicators of river health and help to link them to management actions based on the understanding of the likely response of the Poudre River ecosystem to environmental flow management and other stewardship activities.

The model evaluates probable ecological responses to the range of potential future changes, with little restraint as to what is affordable, or administratively possible. Accordingly, the ERM team recognizes the challenge of integrating the model results with legal, jurisdictional, fiscal, and managerial constraints. Decision-makers must ultimately weigh a variety of stakeholder interests and the ecological, economic, and societal consequences associated with all policy options in an atmosphere of uncertainty.

Probability-based assessments like the ERM can provide a rational, scientific and transparent basis for prediction and decision-making by explicitly recognizing uncertainty and helping clarify the likely consequences of policy choices and management activities.



Final Thoughts

The ERM provides valuable new insight on the effects of changing flow patterns, the relative magnitude of changes expected for ecological indicators, and other landscape factors uniquely influencing the Fort Collins portion of the Poudre River. Despite the challenges identified through the ERM, it has also identified opportunities. For example, aquatic and riparian habitats are likely to respond in relatively short time frames to favorable physical conditions and management actions. These actions, as well as policy initiatives, provide options that will help build a sustainable river ecosystem that supports wildlife, recreation, and economic activity as well as great natural beauty.

An Ecological Response Model for the Cache la Poudre River through Fort Collins

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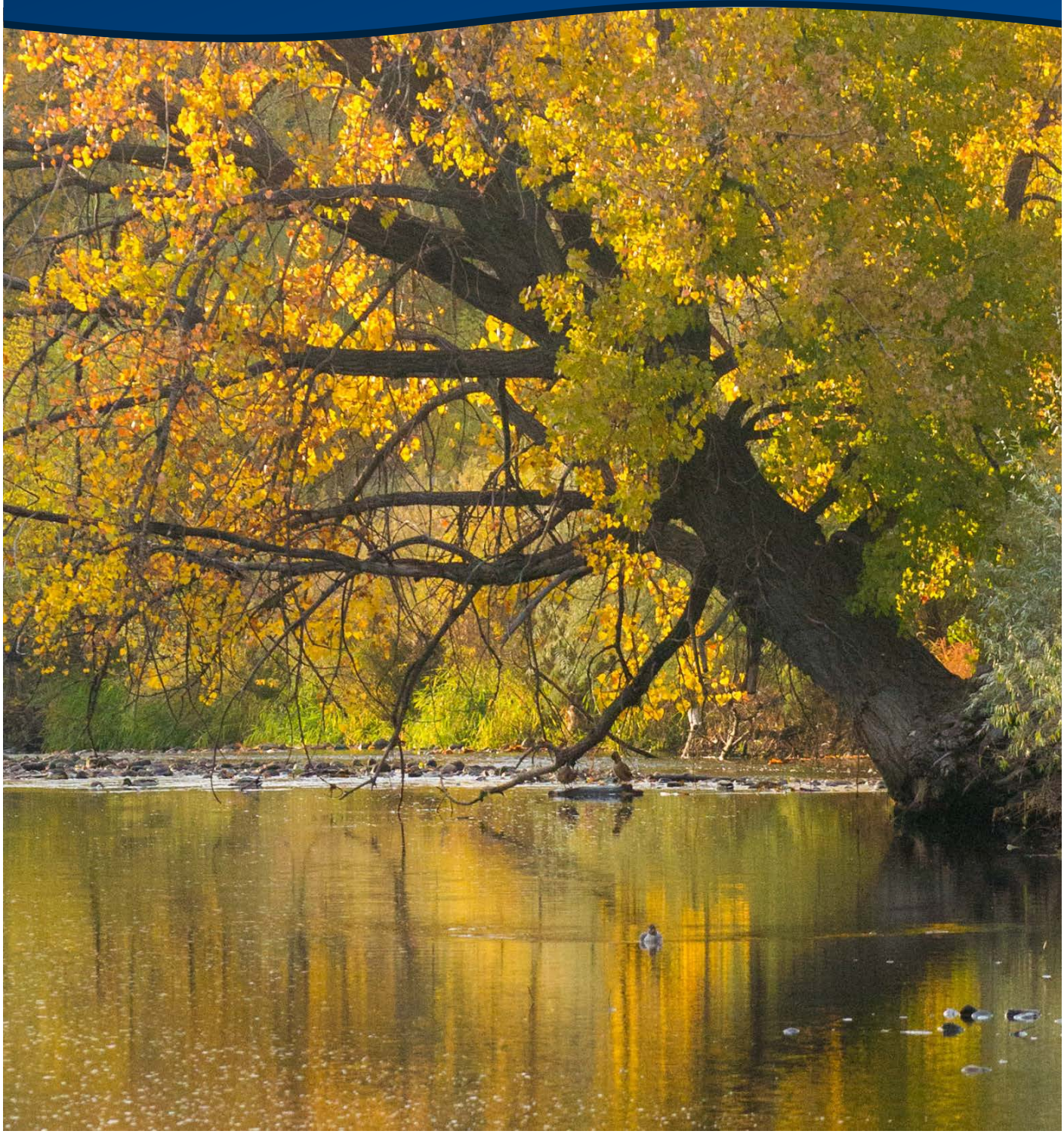

An Ecological Response Model for the Cache la Poudre River through Fort Collins

Ecological Response Modeling Team

THE ECOLOGICAL RESPONSE MODELING TEAM

The development of the Ecological Response Model (ERM) has been a collaborative team effort that includes watershed scientists, policy analysts, and environmental planners. The ERM Team members include (listed alphabetically):

- **Dr. Gregor Auble**, *Riparian Ecologist*, U.S. Geological Survey, contributed to development and application of riparian model components
- **Dr. Daniel Baker**, *Hydrologist*, *Research Scientist*, Department of Civil and Environmental Engineering, Colorado State University
- **Dr. Kevin Bestgen**, *Biologist*, *Director* and *Research Scientist* in Larval Fish Laboratory, Department of Fish, Wildlife, and Conservation Biology, Colorado State University
- **Dr. Brian Bledsoe**, *Hydrologist*, Department of Civil and Environmental Engineering and Graduate Degree Program in Ecology, Colorado State University
- **Dr. Boris Kondratieff**, *Entomologist*, Department of Bioagricultural Sciences and Pest Management, Colorado State University
- **Mark Lorie**, *Policy Analyst*, independent consultant specializing in water resources planning
- **Dr. David Merritt**, *Riparian Ecologist*, National Stream and Aquatic Ecology Center, U.S. Forest Service
- **Dr. LeRoy Poff**, *Aquatic Biologist*, Department of Biology and Director of the Graduate Degree Program in Ecology, Colorado State University
- **Dr. John Sanderson**, *Co-director* for Colorado's Center of Science and Strategy, Freshwater Biologist, The Nature Conservancy
- **Jennifer Shanahan**, *Environmental Planner* for the City of Fort Collins, Natural Areas Department
- **John Stokes**, *Natural Areas Department Director* and *City of Fort Collins* point person for Poudre River issues

Abbreviated biographical information for each Team member can be found in Appendix A

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ABSTRACT

The Poudre River Ecological Response Model (ERM) is a collaborative effort initiated by the City of Fort Collins and a team of nine river scientists to provide the City with a tool to improve its understanding of the past, present, and likely future conditions of the Cache la Poudre River ecosystem. The overall ecosystem condition is described through the measurement of key ecological indicators such as shape and character of the stream channel and banks, streamside plant communities and floodplain wetlands, aquatic vegetation and insects, and fishes, both coolwater trout and warmwater native species. The 13-mile-long study area of the Poudre River flows through Fort Collins, Colorado, and is located in an ecological transition zone between the upstream, cold-water, steep-gradient system in the Front Range of the Southern Rocky Mountains and the downstream, warm-water, low-gradient reach in the Colorado high plains.

The City wanted to better understand the ecological response of the Poudre River ecosystem to potential changes in stream flow and other physical parameters through the conceptual framework of a multi-variable integrated model. This goal was met through the use of a probabilistic model based on Bayesian concepts. This construct allowed the integration of a wide range of data and expert opinion (as informed by local data) to predict potential changes to ecosystem conditions under various flow scenarios. Nine flow scenarios representing past, present, and possible future hydrology were developed as the primary model input. Both reach-scale drivers such as stream channel conditions and pollutant loads, as well as ecological conditions, including species composition, interactions, and habitat requirements influenced model-predicted ecosystem outcomes. Model output consisted of probability distributions for eight ecological indicators collectively representing the physical setting, aquatic life, and riparian habitats of the river ecosystem.

We are confident in model predictions related to probable trends, relative magnitude of changes and potential ecosystem responses to changing flow conditions, though data availability and the process of converting diverse data types into a common unit (probabilities) limit precision of individual results. Key findings suggest that:

- The present ecological function of the Poudre River is altered as a result of more than 150 years of human influences that include highly managed flows, urbanization, gravel mining, channelization and urban and industrial encroachment in the floodplain, underscoring the vulnerable and complex character of the Poudre River;
- A continuation of today's flow management will lead to ongoing changes in ecosystem condition, and additional water depletions will compromise ecological conditions;
- High flows play an essential role in maintaining and improving the aquatic and riparian condition of the river;
- Adequate flows in base-flow periods are critical to desirable water quality, and thriving fish and insect populations; Improvement of native aquatic life is possible if issues related to channel modifications, siltation, invasive species, and base and high flow conditions are managed properly;
- The present confined river channel and modified flows has reduced the potential for a keystone and iconic species, plains cottonwood, to be self-sustaining in the study area;
- The streamside corridor retains the potential to support a functioning riparian forest that provides important ecological services if periodic floodplain inundation occurs.

Environmental flows that combine stable and adequate flows in base-flow periods with occasional rejuvenating high flows that meet target levels defined in this study are likely improve all biological indicators across the system. ERM test scenarios that include both stable base flows and rejuvenating high flows indicate that substantial improvements in the river ecosystem can be achieved with improved management of flow volumes similar to those observed in the river during the last half century of intensive water development. These results underscore the possibility of improving the river ecosystem through active management while still maintaining the Poudre's diverse economic benefits and role as a working river.

The ERM was designed to represent the multi-dimensional ecological character of the contemporary urban Poudre River. It provides a scientific foundation that can serve as a decision support tool and foster a more informed community discussion about the future of the river as it provides a better understanding of the likely response of the Poudre River ecosystem to environmental flow management and other stewardship activities. In particular, model results can assist managers in developing specific management actions to achieve desirable goals for key indicators of river health.

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LIST OF SYMBOLS, CHEMICALS, UNITS OF MEASURE, AND ABBREVIATIONS

Symbols

d	grain diameter
d_i	geometric average grain diameter of fraction *i*
D	hydraulic depth
D_{50}	median sediment size
f_i	number between 0 and 1 representing the fraction of sediments in grain-size class *i*
F_s	fraction of sand on the bed surface
g	acceleration due to gravity
G	specific gravity of sediment
n	Manning roughness value
N	number
p	probability
q_{bvi}	volumetric bedload transport per time per channel width for a given bed-material size fraction
Q	discharge (flow)
R	hydraulic radius
R^2	statistic term for coefficient of determination
S	slope
S_e	energy slope
S_f	friction slope
w	width
γ	specific weight of fluid mixture
τ	channel shear stress
τ^*	dimensionless shear stress

Chemicals

N	nitrogen
NH_3	ammonia
NO_2	nitrite
NO_3	nitrate
NO_3+NO_2+TKN	total nitrogen
P	phosphorus
PO_4	phosphate
TKN	total Kjeldahl nitrogen

Units of Measure

cfs	cubic feet per second
cms	cubic meter(s) per second
ºC	degree(s) Celsius
ha	hectares
kg	kilogram(s)
kg/year	kilogram(s) per year
km	kilometer(s)

l	liter(s)
m	meter(s)
m^2	square meter(s)
m^3/s	cubic meter(s) per second
mg	milligram(s)
mg/L	milligram(s) per liter
mm	millimeter(s)
Pa	Pascal(s)
µm	micrometer(s)
%	percent
#	number

Abbreviations

+, 0, -, --	probability category or state definitions
1, 2, 3a, 3b, 4, 5, 6, 7	Poudre River reaches
3a, 3b, 6	Poudre River reaches modeled with ERM
ACE	Anderson Consulting Engineers, Inc.
ASCE	American Society of Civil Engineers
BAGS	Bedload Assessment in Gravel-bedded Streams; U.S. Forest Service software package
BMP	best management practice
BN	Bayesian network
BNR	Biological Nutrient Removal
BOR	Bureau of Reclamation
CDPHE	Colorado Department of Public Health and Environment
CFC	City of Fort Collins
CSU	Colorado State University
CTP	Common Technical Platform
D5, D16, D35, D50, D65, D84, D95	diameter of sediment percentiles (e.g., D5 is 5th percentile diameter)
DEM	digital elevation model
DWRF	Drake Water Reclamation Facility
EIS	Environmental Impact Statement
ELC	Environmental Learning Center, Colorado State University
EMAP	Environmental Monitoring and Assessment Program
ENV	environment
EPA	U.S. Environmental Protection Agency
EPT	Sensitive macroinvertebrate taxa (*Ephemeroptera*, *Plecoptera*, and *Trichoptera*)
%EPT	Percent of sample consisting of orders *Ephemeroptera*, *Plecoptera*, and *Trichoptera*
ERM	Ecological Response Model
FORTRAN	programming language
GCM	global circulation model
GIS	geographic information system
GPS	global positioning system
H	Historic gage record ERM hydrologic scenario
HEC-RAS	1-dimensional hydraulic model from the Hydrologic Engineering Center of U.S. Army Corps of Engineers

HEC-2	1-dimensional hydraulic model from the Hydrologic Engineering Center of U.S. Army Corps of Engineers (precursor to HEC-RAS)
HL	Hosmer-Lemeshow goodness of fit tests
HSWMP	Halligan-Seaman Water Management Project
LL	-2 log likelihood
MFA	Magnitude-Frequency Analysis
MODSIM	River Basin Management Decision Support System
MWRF	Mulberry Water Reclamation Facility
N	Reconstructed Native ERM hydrologic scenario
NAD	Natural Areas Department of the City of Fort Collins
NCWCD	Northern Colorado Water Conservancy District
NISP	Northern Integrated Supply Project
NSF	National Science Foundation
P1, P2, P5	sampling sites
PBOX	measurement from Boxelder Creek
pers. comm.	personal communication
PDF	probability density function
Poudre River	Cache la Poudre River
TIN	triangulated irregular network
TL	total length
TMDL	total maximum daily load
TNC	The Nature Conservancy
U.S.	United States
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WCRP CMIP3	World Climate Research Programme's Coupled Model Intercomparison Project Phase 3
WY	water year(s); for the purposes of this report the water year is from November 1 to October 31
x, y	axes
y/n	yes/no
YOY	young-of-year

Reported Units

In this report, both metric and English units are used to describe methodology and preliminary results; this maintains the original form of a wide array of analyses. However, all final results are expressed as dimensionless metrics (percentages) for ease and clarity of comparison.

SECTION I: THE FOUNDATION

INTRODUCTION

The Cache la Poudre River (hereafter Poudre River, or Poudre) is a treasured community resource and asset. The City of Fort Collins recognizes that a healthy Cache la Poudre River provides the community with a broad set of ecological, municipal, industrial, and agricultural benefits that are highly valued by the public. Ecosystem benefits include providing a high quality water supply, flood conveyance, and native flora and fauna. Associated benefits include recreation and aesthetic appeal. Healthy and diverse river ecosystems are more resilient to extreme weather events such as floods and fires and community's resilience is intricately tied to the condition of the rivers and watersheds in which they live.

The quantity and timing of flow in the river, known as its hydrologic or flow regime, is of fundamental importance in the provision and maintenance of these benefits. The Poudre River ecosystem has many existing and anticipated future demands on its water. These demands and other stresses on the river (such as non-point source pollution) have caused fundamental changes to its ecosystem. The ecosystem will likely experience additional stresses and changes over the coming decades, as demands increase with a growing population and changes in water delivery from the Poudre River watershed. During the next decade, the City of Fort Collins and the region will be faced with the challenge of determining local and regional priorities for consumptive use of water, while also providing for non-consumptive benefits and amenities, such as ecological health and recreation.

The goal of achieving consumptive and non-consumptive uses has been embraced by statewide, regional, and local planning and management agencies in Colorado. In 2013, Governor Hickenlooper issued an executive order directing the Colorado Water Conservation Board to develop a Colorado Water Plan that, among other objectives, provides for "a strong environment that includes healthy watersheds, rivers and streams, and wildlife" (Hickenlooper, 2013).

There are numerous local entities focused on the future of the Poudre River, including The Poudre Runs Through It Study/Action Group, a collaborative group convened by the Colorado Water Institute at Colorado State University. This group reflects a diversity of stakeholder values, including municipal water suppliers, farmers, and environmental interests. In their recent progress report (Colorado State University, 2013), the group conveys agreement that "we all want a river that meets our human needs AND is a healthy river in its own right." This sentiment provokes a number of questions:

- How is a healthy Poudre River defined?
- What is the current state of river health?
- What are possible future states of the river?
- What can be done to achieve and sustain river health in balance with the provision of consumptive and ecosystem services?

In September 2011, the City of Fort Collins Natural Areas Department initiated a science-based collaborative project by convening a team of scientists to help quantify long-term environmental trends and opportunities for improvement on the Poudre River. The product of that effort, the Poudre River Ecological Response Model (ERM), is presented in this report and was conceived and developed to help the City's leaders and citizens better understand the changes that would likely occur in the Poudre River ecosystem under a range of plausible hydrologic futures that reflect increasing human demand and climate change. This information is critical to helping the City and public forge a vision for the long-term

health and resilience for the Poudre River ecosystem. It identifies possible alternative actions to pursue that vision.

The ERM is one of many tools and approaches that have been developed and applied during the past two decades to understand the relationship between streamflow and the condition of fish, plants, and other species residing in and along the Poudre River and elsewhere in Colorado. Some examples of other tools include the Indicators of Hydrologic Alteration (descriptions of ecologically relevant streamflow conditions relative to pre-flow altered conditions); R2Cross (estimates of minimum flows for sustaining fish); River2D (modeling of available fish habitat at various flow levels); HEC-RAS (modeling flows required for sediment movement and the elevation of the water surface at various flow volumes); and the Watershed Flow Evaluation Tool (estimates potential risks to fish and streamside vegetation based on current or potential future streamflow conditions). The ERM fills a particular niche among these tools because it is specific to a 13-mile reach of the Poudre River, and it addresses and integrates multiple physical and ecological aspects of the river system. Like the other tools, the ERM was developed and is applied primarily to understand how streamflow sustains species and ecosystems, and to define the streamflow conditions necessary to maintain certain ecosystem conditions in the Poudre River.

The ERM project has two overarching goals:

1. To provide a broad and integrated evaluation of future river conditions given past, present, and potential future flow scenarios and multiple interacting ecological drivers and
2. To inform flow and management scenarios that help the community attain its vision of a healthy river.

To achieve these goals, the team developed an integrated model that could be used to explore how the hydrologic regime of the Poudre River influences several different ecosystem responses. This requires a framework to explicitly define connections between different ecosystem components and their relationship to key environmental drivers (such as the magnitude, duration, and timing of river flows) with known geomorphic or ecological functions (such as flushing fine sediment and inundating floodplains that control habitat structure). The ERM makes it possible to perform what-if analyses and to examine ecosystem responses to a number of plausible scenarios of future hydrologic regimes.

Scope of this Project and Report

This report provides a comprehensive description of the ERM. Section I describes the background, scope and general approach used to develop the overall model. Section II provides a more detailed description of the overall strength of the model and its methods, followed by a description of the unique analytical approach used for each model component or node. Section III presents and discusses the results of the ERM, as well as some limitations of the model in its current form and recommendations for its further improvement and application. Section IV presents conclusions from the model and new insights gained from the ERM process.

The ERM offers objective science-based insight into how the Poudre River ecosystem will respond to water resources development and various forms of management activity. As such it can be used to help inform decisions about improving and sustaining river health. The ERM project does not evaluate the legal, technical, and administrative feasibility of attaining specific flow conditions or enacting specific floodplain or in-channel management actions. The model also does not directly generate decisions or determine priorities; however, the scientific results of the model may be able to help inform managers' decision making and prioritization.

This project covers the reach of the Poudre River through Fort Collins, specifically from Overland Trail Road to Interstate 25. Hydrologic data for the model come from the past 60 years of flow records at multiple gages upstream of and within Fort Collins and simulations of river flow (described in Section II). By applying contemporary and proposed operations (diversion extraction, transbasin augmentation, and storage) to this historical flow record, the model provides a comprehensive view of current and possible future river conditions based on currently available data.

BACKGROUND

The Poudre River Ecosystem

Prior to agricultural and urban development that began in the mid-1800s, the river ecosystems of Colorado's Front Range (an area located between the Great Plains to the east and the foothills of the Rocky Mountains to the west) evolved with periodic high flows driven by spring snowmelt. These high flows provided scour, deposition, and associated movement of the river channel back and forth across the floodplain. Native animals and plants in the river ecosystem became adapted to and/or dependent on these predictable patterns of flood disturbance, as well as on late summer and fall base flows that were typically low and extended through the winter. The native Poudre River through Fort Collins was highly sinuous, oftentimes with multiple channels, and bordered by riparian forests of plains cottonwood and other water-dependent plant, animal and insect species. The patterns of growth, reproduction and survival of the aquatic and riparian life (aquatic insects, native fishes, and riparian vegetation) closely followed the seasonal pattern of flows and disturbance.

These patterns of natural flow and disturbance varied from year to year in terms of magnitude and duration, creating a heterogeneous river corridor with a spatial mosaic of habitats in which the cover, species, composition, and establishment of aquatic and riparian species also varied. In wet years, high flows inundated the floodplain, physically altering the structure of the channel and creating complex off-channel habitats that supported a range of habitats and supporting diverse aquatic and riparian communities. Recruitment and establishment (successful reproduction) among riparian species also depended on the intensity and lateral extent of annual floodplain inundation. High flows, and the associated scouring and burial, could cause some immediate mortality of aquatic species. However, the complex channel structure and off-channel habitats created and maintained by high flows provided refuges, such as cleansed beds for insects and spawning native fishes. These contributed to a shifting mosaic of habitat types that favored different species in different years, and thus maintained the potential for high biodiversity and for rapid recovery from extreme events.

The stretch of the Poudre River running through the City of Fort Collins is characterized as a transitional zone (an ecotone in ecological terms). The Poudre originates in the high-elevation mountains of the Front Range as a fast-flowing, steep, physically confined cold montane river. As the Poudre emerges from the foothills to the wider, lower gradient valley reaches of the transition zone (approximately 1,600-1,900m altitude), it changes to a river that is less confined and begins to meander across a wide floodplain. Prior to development of the area that began in the mid-1800s, the composition of the plant and wildlife communities was characteristic of the unique conditions found in a transitional zone. For example, upper reaches of the river were almost entirely dominated by narrowleaf cottonwood, whereas downstream reaches were dominated by plains cottonwood. A similar shift occurred in shrubs and herbaceous plant communities, as well as in aquatic species, such as native fish and insects; cold-water species dominated the upper reaches and warm-water species the lower reaches. Additionally, several native fishes were restricted in their occurrence to only this transition zone.

The Contemporary, Urban Poudre River

A common local saying is that "the Poudre River is the hardest-working river in Colorado." Existing diversions from the river for agriculture, municipal water supply, and return flow, including sewage effluent and other uses, have significantly altered its flow regime and water quality compared to the period prior to water development. Figure I.1 compares the typical pattern of the Poudre's monthly average flows (expected under native conditions) with the pattern of flows that has actually occurred over the last 40 years. The change from the native condition is substantial; on average the spring peak monthly flow is reduced by nearly 1,200 cfs (59%), while the lowest monthly flow, typically in February, is 57% lower. Because of the strong and direct link between flow quantity, timing, and ecosystem condition, these changes in flow patterns have substantially impacted the character of the river. Furthermore, it is apparent from multiple lines of evidence that changes are ongoing. Future demands for water are likely to increase the degree of flow alteration, resulting in additional changes to river condition. To conserve a healthy working river, it is important to understand the consequences and possibilities of alternative water management actions.

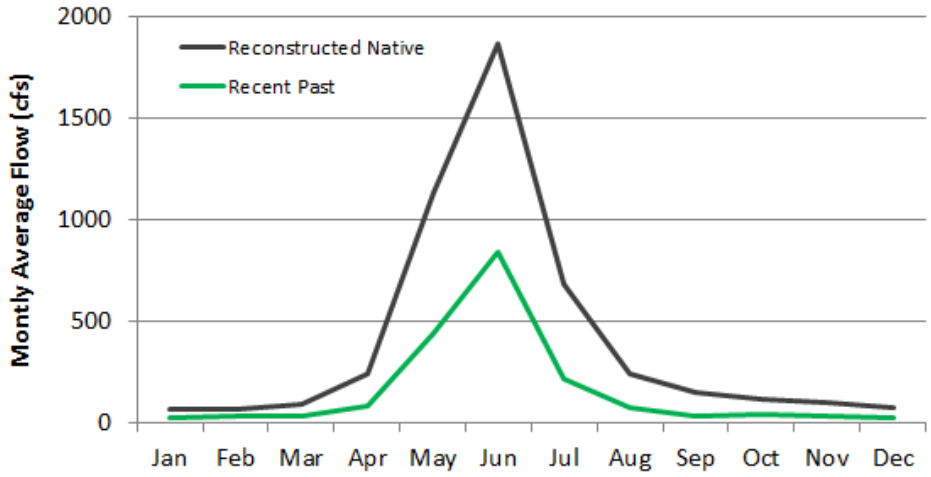


Figure I.1: Comparison of the monthly average flows at the Lincoln Gage in downtown Fort Collins for Water Years 1970-2005 between the recent past and reconstructed native hydrologic scenarios.

Note: Both scenarios are discussed in detail later in Section II.

In addition to the numerous water diversions from the river, urbanization surrounding this reach of the Poudre River has physically constrained its ability to expand and migrate laterally within the floodplain during high runoff periods. This confinement limits the available habitat for both plants and aquatic animals, and reduces the ability of the river to create and maintain habitats over time.

Data-Based Understanding of the Poudre River

Scientific knowledge of the Poudre River ecosystem comes from studies specifically focused on the Poudre River and from numerous studies about similar snowmelt-driven rivers in the western United States. Some of the most comprehensive research relevant to the urban reach of the river includes an analysis of flushing flow needs of the lower Poudre River (Milhous, 2007); an effort to determine a flow regime necessary to maintain overall health of the river (Bartholow, 2010); a management plan of natural areas within the floodplain (City of Fort Collins, 2011); and, most recently, extensive studies related to multiple Environmental Impact Statements (EISs) supporting federal permitting of proposed expansion or creation of reservoirs in the basin (U.S. Army Corps of Engineers (COE), 2008).

Applied research currently being conducted on the Poudre includes periodic sampling of fish populations, investigations into the effects of the High Park fire runoff on aquatic invertebrates, and collection of data on sediment movement, water quality, and vegetation along the river. These disparate projects provide valuable insight into individual components and reaches of the Poudre River ecosystem.

Models used in the regulatory processes, such as the EISs currently being conducted for both the Northern Integrated Supply Project (NISP) and the Halligan-Seaman Water Management Plan (HSWMP) under the National Environmental Policy Act, typically address a fairly broad range of important river resources such as fish, sediment, and wetlands. They can provide valuable new information and understanding. However, the EISs are being developed for the specific purpose of evaluating and describing the impacts of the proposed projects and possible alternatives under Section 404 of the Clean Water Act (U.S. Environmental Protection Agency, 2012). The City has different interests: What is the range of possible futures and under what conditions can a desirable healthy future river system be achieved? The ERM is not intended to replace the models used in the HSWMP and NISP regulatory processes. Furthermore, because of the different modeling framework used across these studies, ERM outputs should not be viewed as directly comparable with outputs from the EIS models. Failure to recognize that the ERM was developed with a different modeling approach than EIS models risks drawing inaccurate conclusions when comparing outputs between the models.

The ERM was built as a probability-based model known as a Bayesian network. A graphical representation of the relationship between variables, this powerful platform allows incorporation of a range of data inputs – from collected field data, to simulated outputs from sub models, to expert opinion. All these different types of data can have different degrees of associated certainty. The ERM's flexibility is required to build an integrated ecosystem model that can paint a broad picture of ecosystem responses even when some aspects of the ecosystems are less well understood than others. The greatest value of the Bayesian model is that it captures known and inferred relationships among hydrology, sediment/geomorphology and ecology to investigate ecosystem-level responses to a range of plausible hydrologic futures. Comparison of ecosystem responses across the hydrologic futures provides insight into the relative impacts to the overall Poudre River ecosystem under different runoff scenarios, both directly through management interventions and indirectly through climate change.

A series of water storage and supply projects have been proposed in recent years that may have a direct effect on the Poudre River. These include HSWMP on the North Fork of the Poudre as well as implementation of NISP. Initially, these two projects were being evaluated independently, but the U.S. Army Corps of Engineers (COE) realized that a Common Technical Platform (CTP) for hydrologic analysis (as well as other analyses) would be merited to better analyze the effects of all proposed projects. The continuing development of EISs for both projects has improved the understanding of the Poudre River ecosystem. At the time of publication, a draft EIS for HSWMP and supplemental draft EIS for NISP are under development. Future rounds of EISs will likely include the following:

1. Detailed hydrologic modeling that captures how current and proposed future operations affect river flow patterns
2. Two-dimensional modeling of the hydraulics of the river under different flow regimes
3. Modeling of how flows and hydraulics will affect available fish habitat during low flows
4. Modeling of sediment movement during high-flow events and the resulting impact on the structure and character of the channel
5. Modeling of water quality as it depends on flow patterns and other factors
6. Modeling of floodplain inundation and its impact on riparian vegetation

Despite the improved understanding of the Poudre River that is being derived from the EIS analyses, several important questions about relationships and tradeoffs in river management will likely remain, such as:

1. Is it better to restore high flows or low flows for native fishes and introduced species such as brown trout?
2. If conditions for brown trout are improved, how will that impact native fishes?
3. What impact does the legacy of channelization and stabilization have on the ecosystem condition, and is this system-wide or reach-specific?
4. If the City of Fort Collins wants to manage against the growth of filamentous algae, would it be more effective to increase low flows, reduce pollutant loads, or promote high scouring flows?

These types of questions are important for the City, but may fall largely outside the scope of EIS development and may not be easily answered with the sort of models and analyses generated for that purpose. Thus, City staff recognized the need for a model designed to support proactive investigations into the long-term drivers of and requirements for ecosystem health. The ERM offers progress on this range of questions, with the understanding that no single model will answer all questions conclusively.

Developing the ERM Team

In September 2011, the City of Fort Collins Natural Areas Department convened a team of scientists to develop the ERM. The nine members of the team, recognized at the beginning of this report, represent top expertise in their respective sub-disciplines of river science. Collectively this group has more than 370 peer-reviewed publications, many of which have contributed to cross-disciplinary and applied river science. The level of experience and expertise across the team is important to note because developing the ERM was a novel and challenging undertaking. Team members have extensive knowledge of river science (from both practical experience and peer-reviewed published literature) and they applied empirical data for the Poudre River to create the current integrated modeling framework.

The team met regularly, including several day-long workshops, from September 2011 to June 2013 to conceptualize, design, test, and improve the model and to review outputs. It reviewed available data and models that could support development of the ERM and devised methods to fill in knowledge gaps. Members conducted independent research and analysis to develop each component, or node, of the ERM (described in Section II). After implementation of the individual components, the team discussed, reviewed and interpreted results of this holistic model of the Poudre River ecosystem.

The model as presented includes an evaluation of a range of flow scenarios over multiple key ecosystem elements. It provides results that support broad, integrated investigations into long-term ecosystem drivers. The ERM was developed using the best available input data, with the appreciation that any new data could be used to potentially improve model performance. For example, data from the current EIS processes and from the post-2013 flooding and High Park fire research could be incorporated into the model to update it.

STUDY AREA

The geographic scope is a 13-mile stretch of the Poudre River (Figure I.2). This river reach sits at the base of the Front Range of the northern Colorado Rocky Mountains and runs through the City of Fort Collins from Overland Trail Road to Interstate 25. This largely urban stretch of the Poudre was segmented into eight reaches as determined by the location of major diversion structures. A more detailed description of the study area is provided in Section II.

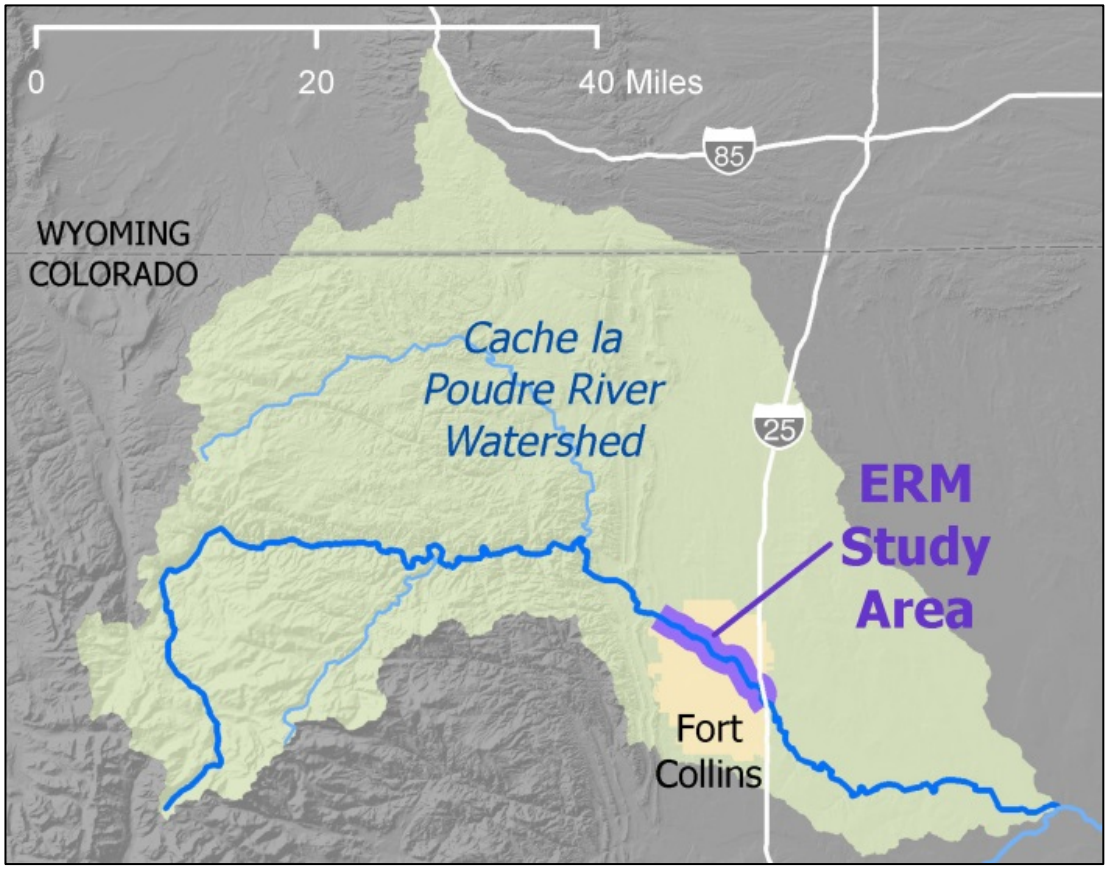


Figure I.2: ERM study area within the Poudre watershed

Like any large-scale, natural riverine ecosystem that has been altered by decades of engineering activities, the Poudre River ecosystem is highly complex. Because the underlying factors that drive the ecosystem processes and states that we observe consist of complicated and often unknown interactions between both natural processes and human activities, building a highly detailed model of the entire system is pragmatically impossible. For purposes of regional planning, any model of the Poudre River ecosystem with an appropriate scale and prediction accuracy requires that the ecosystem be simplified to key drivers and components. Ecosystem output variables can be averaged over space (river segments) and time (response periods of decades) to provide insight into the consequences of different management actions on the necessarily simplified version of the river ecosystem.

The ERM was first conceived as a conceptual framework and then refined into more distinct relationships in a Bayesian network. Nine hydrologic scenarios were compiled for analysis, using the best field and modeling data available.

ERM Overview

The model considers the impacts of water use and development, changes in climate, and pollutant loading on the Poudre River ecosystem. The general structure of the model is depicted in Figure I.3. Water use and development, climate, degree of riverbank armoring (and hence potential for channel migration), and pollutant loading are characterized as drivers that act as inputs to force ecosystem responses. The model itself incorporates variables and relationships that describe how these factors affect physical and ecological processes such as sediment movement and riparian vegetation regeneration, which themselves are then represented by indicators of river condition.

The ERM is built and used to predict potential future states of the Poudre River. The primary input is a series of hydrologic scenarios that represent variations in operations, water use/demand, and climate. (Section I provides only a broad structural overview; additional detail on the model is provided in Section II.)

Indicators of River Condition

Prior to selection of the indicators of river condition, multiple criteria for inclusion in the model were adopted. First, the team decided to include variables that are key components of ecosystem function and thus indicate ecosystem condition. The team then included variables that have regulatory implications, such as Clean Water Act nutrient thresholds and water temperatures. Indicators of social value were also included. The following eight indicators were selected to meet these criteria:

1. Channel Structure – the combined influence of substrate conditions and channel geometry as the physical template for physical and ecological processes
2. Algae – a basal resource in the aquatic food web, but which, under conditions of excessive nutrients, is viewed as unaesthetic by the public
3. Aquatic Insects – the abundance and species distribution of aquatic insects, both as an indicator of water quality and as a crucial link in the aquatic food web
4. Native Fish – reflecting the relative health and condition of the system
5. Brown Trout – an introduced species that is a valued recreational component of the ecosystem and indicator of the thermal and hydrologic regime
6. Rejuvenating Mosaic – a multi-stage forest dominated by those riparian species adapted to disturbance-prone environments, such as the plains cottonwood that dominates the Poudre River ecosystem
7. Functional Riparian Zone – a riparian zone that is hydrologically connected to the river and thus has the potential to support ecosystem functions including biogeochemical processing, flood peak attenuation, sediment trapping and exchange, episodic expansion of aquatic habitat, as well as supporting a productive vegetative community
8. Riverine Wetlands – the area where inundation from the river is sufficient to support plant communities dominated by wetland species

A further description and extensive explanation of the probabilities for each of these eight indicators is discussed in further detail in Section II and Appendix B of this report.

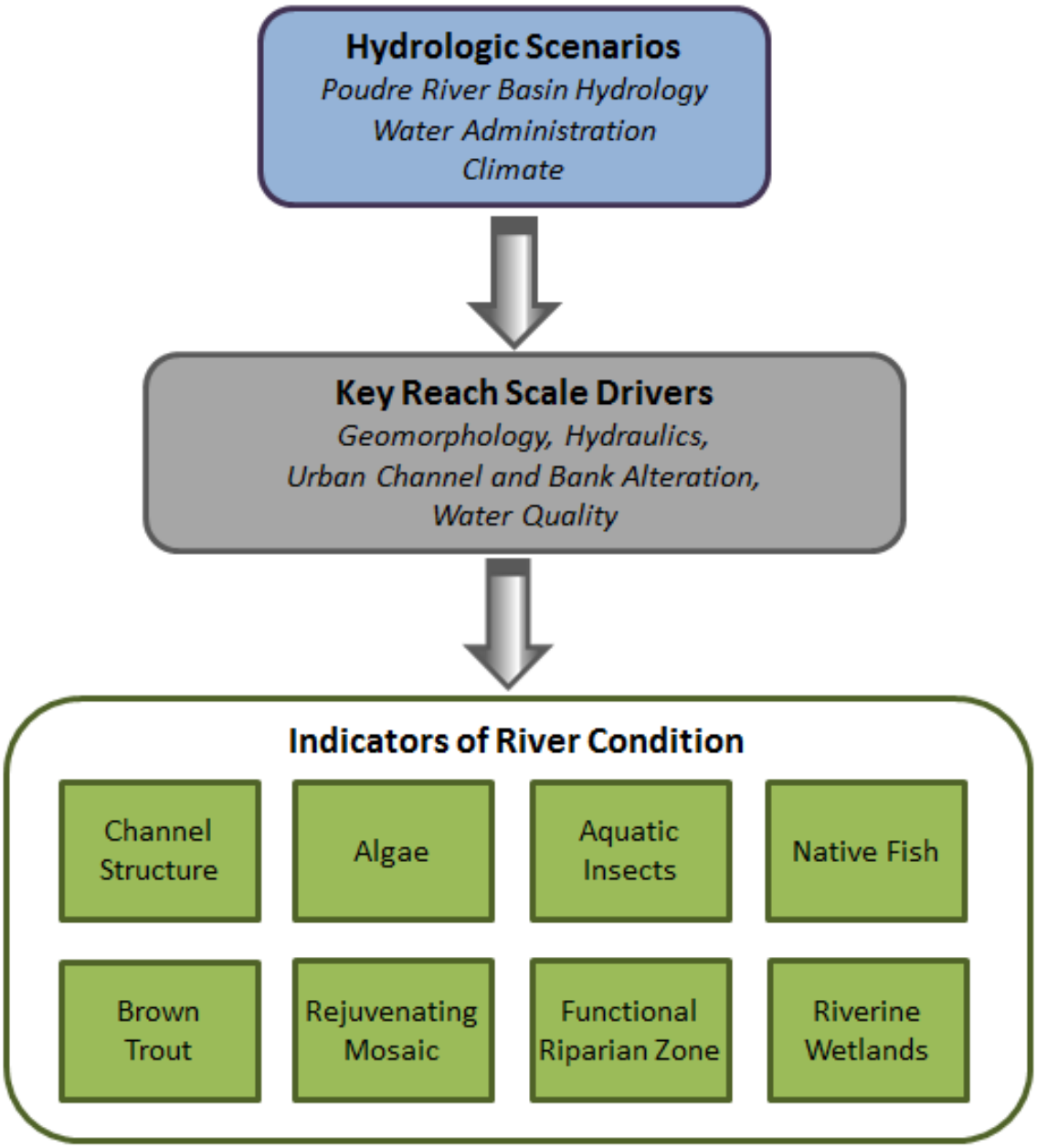


Figure I.3: The overall structure of the Poudre River ERM.

Final Bayesian Network Structure

The ERM team mapped the linkages that determine the condition of these indicators (see Figure I.4) for the final Bayesian network structure. First, the key aspects of flow regime on the physical and ecological systems were identified and represented by a set of universally important flow metrics that would have differential influence depending on the specific nature of the imposed flow scenario. Next, non-hydrologic environmental drivers such as water temperature, nutrient loads and bank stabilization were included as important drivers that interact with flow regime metrics to influence aquatic and riparian ecological outputs.

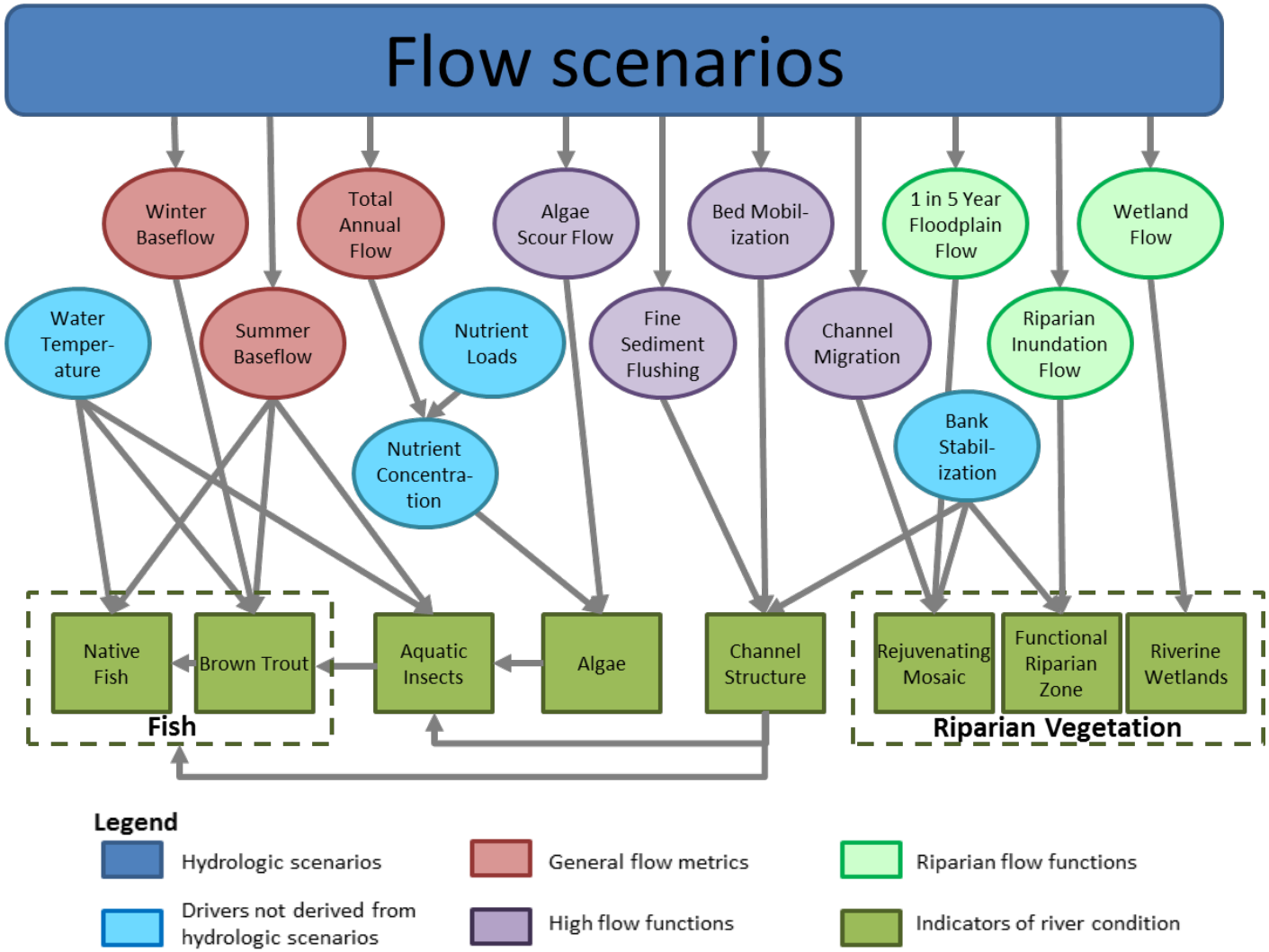


Figure I.4: Overall structure of the Bayesian network for the Poudre ERM.

Note: Arrows between nodes indicate a causal relationship between the linked variables in the final model.

The final model structure was developed after several months of extensive debate and the evaluation of a wide array of potential influence diagrams. Given the breadth of expertise and experience of the modeling team, there is high confidence that a comprehensive set of elements and causal linkages are included in the model. The linkages explicitly included represent the most important and dominant processes, connections, and interactions that control ecosystem condition and functioning as judged by the team of experts. Although this is not a comprehensive representation of ecosystem structure and function, the model adopted has an appropriate balance of including those key drivers and response variables of interest on the one hand, and of the ability to confidently quantify the hydro-ecological relationships between the drivers and responses on the other hand. A more highly detailed model would suffer from lack of driver-response specification. As described further in Section II of this report, the selected nodes and linkages are based upon the best data and understanding currently available, yet the underlying sub-models vary substantially in terms of approach. Empirical data relied upon to construct the conditional probability tables are presented in Appendix C.

Hydrologic Scenarios

Following establishment of the final influence diagram, the next step of model development was to develop input data. This consisted primarily of the development of nine hydrologic scenarios (Table I.1). Statistics derived from these hydrologic scenarios (such as the frequency of a high flow threshold or the duration of low flows) characterize their effects on the ecosystem. Nine hydrologic scenarios were developed for this project, allowing a better understanding of the past, current and future possible conditions. The nine scenarios are divided into two groups, based coarsely on the method upon which they were developed:

1. Core Hydrologic Scenarios – based upon the past, present, and plausible future flow conditions on the Poudre River and derived from gage and operations data for the system.
2. Test Hydrologic Scenarios – synthetically derived hydrographs designed to test what-if scenarios of base flow magnitude, base flow consistency, and peak flow magnitude, duration and frequency.

Table I.1: Hydrology scenarios for the Poudre ERM.

Name	General description
Core hydrologic scenarios	
Reconstructed Native	This scenario represents flows for the Poudre River with all human influences of the past 150 years removed. Flow alterations from operations are accounted for, leaving just the native flow conditions.
Recent Past	This scenario is derived from the historical gage data and includes historical climate variability and operations[a] evolving over time.
Present Operations	This scenario represents the river as though current operations are imposed on the period of record. It is different from the Recent Past scenario because operations have evolved and more water is being diverted today than in the 1950s.
Additional Water Development	This scenario builds on present conditions and, additionally, includes preliminary estimates of potential flow alteration based on construction and operation of three proposed water development projects: 1) expansion of Halligan Reservoir, 2) expansion of Seaman Reservoir, and 3) construction of the Northern Integrated Supply Project. It also factors in an anticipated increase in municipal demand. It does not include all possible changes to flow based on new uses of existing water rights, nor does it consider possible mitigation flows associated with these projects. This scenario was modeled by City of Fort Collins staff and may differ from the final hydrology determined in the project EISs, which will likely have more refined low flows and daily disaggregation.
Driest Climate	This scenario also builds on present conditions. It maintains the inclusion of present conditions, but then superimposes the driest conditions forecasted from a collection of climate models.
Test hydrologic scenarios	
StableBase-LowPeak	This scenario is similar in condition to the Additional Water Development scenario (reduced peak flows and minimum base flows), with the exception that the base flows remain consistent.
HighBase-ModeratePeak	Based upon Bartholow (2010), this scenario uses the 25th percentile of monthly averages from native flows and recommendations for managed changes in streamflow in all months, including a moderate level peak flow magnitude.
DryBase-HighPeak	This scenario is designed to test the question "Even if the peak flows are ample, what is the ecological effect of intermittent periods of no flow?" The percent of dry days were patterned on the Present Operations scenario and the high flows were based on the StableBase-HighPeak scenario below.
StableBase-HighPeak	This scenario is designed to use the *minimum* amount of flow necessary to elevate most of the ERM indicators of river condition to their highest levels.

[a] *Operations* refers to all trans-basin basin diversions, diversion withdrawals, and reservoir storage

This concludes an overview of the background, scope and development of the Poudre River ERM. In Section II, considerably greater scientific detail is provided on the study methods and components.

SECTION II: METHODS AND MODEL COMPONENTS

OVERVIEW

Section II first provides a deeper look into the methods for the overall model. A description of the study area and three selected focus sites is followed by some brief background and an explanation of the basic steps of the Bayesian network approach. Next, the development of nine hydrologic scenarios is described in greater detail. The strengths, limitations and elements not included in the ERM are then explained.

Following the methods for the overall model, the methods for each of the components is provided. Each model component, or indicator, is summarized in three parts.

1. The **background** of the component is discussed with regard to how it functions and connects with other elements in the system, as well as the controls and constraints on its ecological condition. Special attention was given to the local condition of the indicators for the study reach, which is influenced by both the transitory nature of the system as it moves from the mountains to the plains and the substantial alteration of the system to meet human demands.
2. Next, the **data sources** for each component (from a wide variety of sources and expert opinion) are summarized, falling across the spectrum from quantitative to qualitative.
3. Finally, an overview description of the methods of empirical analysis that justify the development of the **probability tables** for each component is provided. This included the merging of new analysis with both published thresholds and expert opinion to form probabilities for each variable.

The foundation of the integrative Bayesian model requires converting continuous empirical data into categorical probabilities, making this element of the project distinctive, challenging, and complex. The narrative and data in Section II is augmented with a more comprehensive description of the empirical basis for the development of probabilities in Appendix B.

METHODS FOR THE OVERALL ERM

Site Selection

The geographic scope for the Poudre ERM is the stretch of the Poudre River in Fort Collins, running 13 river miles from Overland Trail Road to Interstate 25. This largely urban stretch of the Poudre was segmented into seven reaches as determined by the location of major diversion structures. In addition, one of the resulting reaches (Reach 3) was split into two segments. The upper and lower portions of this reach differ significantly in that the upper portion (Reach 3a) is characterized by more bank stabilization and confinement than is the lower (Reach 3b). Figure II.1 shows the resulting reaches of the river. Table II.1 describes the physical character and break points of the reaches.

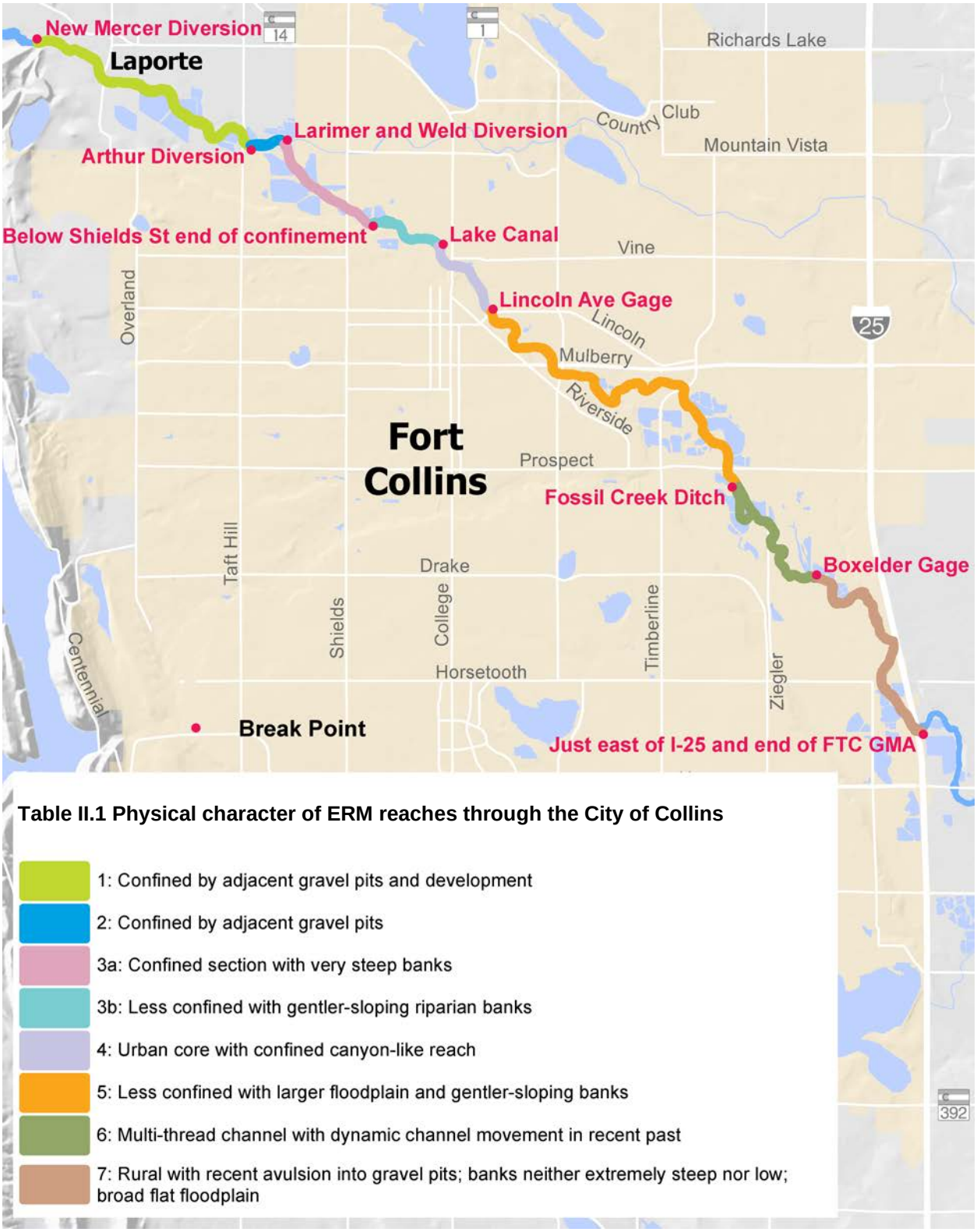


Figure II.1: Designated ERM reaches through the City of Fort Collins, starting near the town of Laporte and flowing downstream to just east of Interstate 25.

Three of the eight reaches of the river corridor were selected to be modeled in the ERM, and represent the range of variability in channel form, floodplain connectivity, and boundary conditions (such as substrate composition and lateral armoring) that occur in the urban river corridor. Those reaches, from upstream to downstream, are as follows:

- **Reach 3a:** Begins at the Larimer & Weld Irrigation Canal, about 0.5 miles below Taft Hill Road, and ends at a point about 0.25 miles below Shields Street. Reach 3a is a highly confined stretch of river with a high degree of bank stabilization.
- **Reach 3b:** Starts at the downstream terminus of Reach 3a and continues to Lake Canal, just upstream of College Avenue. Reach 3b is less confined and represents an intermediate stretch of river where there might be opportunities to restore natural riverine and riparian functions.
- **Reach 7:** Begins at the U.S. Geological Survey (USGS) stream gage just above Boxelder Creek and ends just downstream of Interstate 25. Reach 7 has a mix of armored banks and open floodplain and is the least confined of the three reaches modeled in the ERM.

Not only does the character of the Poudre River vary among its reaches, its discharge varies as well. While most natural rivers in this region increase in flow in the downstream direction, the Poudre's flow generally decreases downstream through Fort Collins due to extractions for municipal and agricultural uses. This is evident by a decreasing trend in both the median and mean values in Table II.2. Additionally, flow variability appears to increase (as evidenced by the increasing coefficient of variation) in the downstream direction, particularly in the reaches covered by this report (Reaches 3a, 3b, and 7).

Table II.2: Flow statistics for reaches of the Poudre River moving in an upstream to downstream direction.*

	Canyon Gage	Below Greeley Diversion	Below Hansen Canal	Below Pleasant Valley Pipeline	Below Jackson Ditch	Below New Mercer Diversion	Below Arthur Ditch	Below Larimer & Weld Diversion	Below Lake Canal	Lincoln Gage	Boxelder Ditch	Boxelder Gage
ERM reaches						1	2	3a+3b	4	5	6	7
Median (cfs)	67	50	70	64	58	45	49	31	29	30	36	13
Mean (cfs)	324	308	403	386	296	257	259	164	153	154	158	133
Standard deviation (cfs)	581	582	628	613	528	495	494	430	423	425	420	408
Coefficient of variation (cfs)	1.8	1.9	1.6	1.6	1.8	1.9	1.9	2.6	2.8	2.8	2.7	3.1
Number of zero flow days	0	449	0	164	29	884	5	1848	70	27	66	0
Percent zero flow days	0.0%	3.0%	0.0%	1.1%	0.2%	5.9%	0.0%	12.3%	0.5%	0.2%	0.4%	0.0%

* Based upon a Recent Past scenario, which is a daily point flow model using 40 years of historic gage data and operations records as developed by the Northern Colorado Water Conservancy District (NCWCD).

Bayesian Network

Background

Bayesian, or *probabilistic*, networks are a graphical representation of the relationships among a series of independent variables (see Borsuk *et al*., 2004, and Uusitalo, 2007, for more general information). Bayesian networks are becoming a more commonly used tool in the environmental sciences because the modeled systems are complex, interactive, and non-linear, and they require an integrated framework that can incorporate a range of data and model types. As an example, Bayesian networks have been used by the USACE to examine risk levels of dredging operations (Schultz *et al*., 2011) by combining a range of highly quantitative and qualitative information. Additionally, Bayesian modeling has been used for a wide variety of riverine topics including modeling estuary eutrophication (Borsuk *et al*., 2004), fish population dynamics (Marcot*et al*., 2001), and watershed restoration (Stewart-Koster *et al*., 2010). For a comprehensive list of Bayesian network application in watershed studies, see Schultz *et al*. (2011).

The Bayesian network developed for this study included a series of seven general steps, described below, similar to other ecological models using a Bayesian approach. These steps are illustrated in detail for the ERM in the remainder of this report.

1. **Define conceptual model** – Translate a conceptual model of the system into a top-to-bottom influence diagram with variables as nodes and with arrows between nodes indicating influence of one variable on another (Figure II.2). The top are input data and the bottom indicate results.
2. **Define states of each variable** – Explicitly define the states (or classes) for each variable in the model.
3. **Use data to populate input variables** – All input variables (those nodes having arrows from them but not to them) must be populated from available data or simulated data (for example, the hydrologic time series described immediately following this subsection and all additional variables described in Section II).
4. **Compute conditional probabilities** – Use the best available data and scientific knowledge to compute conditional probabilities that define the interactions among the causal variables and the response variables.
5. **Run model** – Run the model using a range of input data to compute the expected values of the response variables.
6. **Synthesize and interpret data** – The model computes the probability that the response variables will fall into each of their pre-defined states. Additionally, a single expected value (the mean of the full probability distribution scaled from 0-1) is computed to enable a summation of a wide range of outputs into a single figure (Section III).
7. **Refine model** – As better data become available adjust conditional probabilities for each variable so that the results most closely fit actual data.

Building the Bayesian ERM

After the team determined the eight ecological indicators, they worked to map the linkages that determine the condition of these indicators (see Figure II.2, reproduced below from Section I, for the final Bayesian network structure). First, the influence of general flow metrics, high-flow functions, and riparian functions from each flow scenario were derived. Next, the influence of water temperature and nutrient loads were included in addition to the hydrologic scenarios. Finally, the effects of bank stabilization on lateral channel mobility were included.

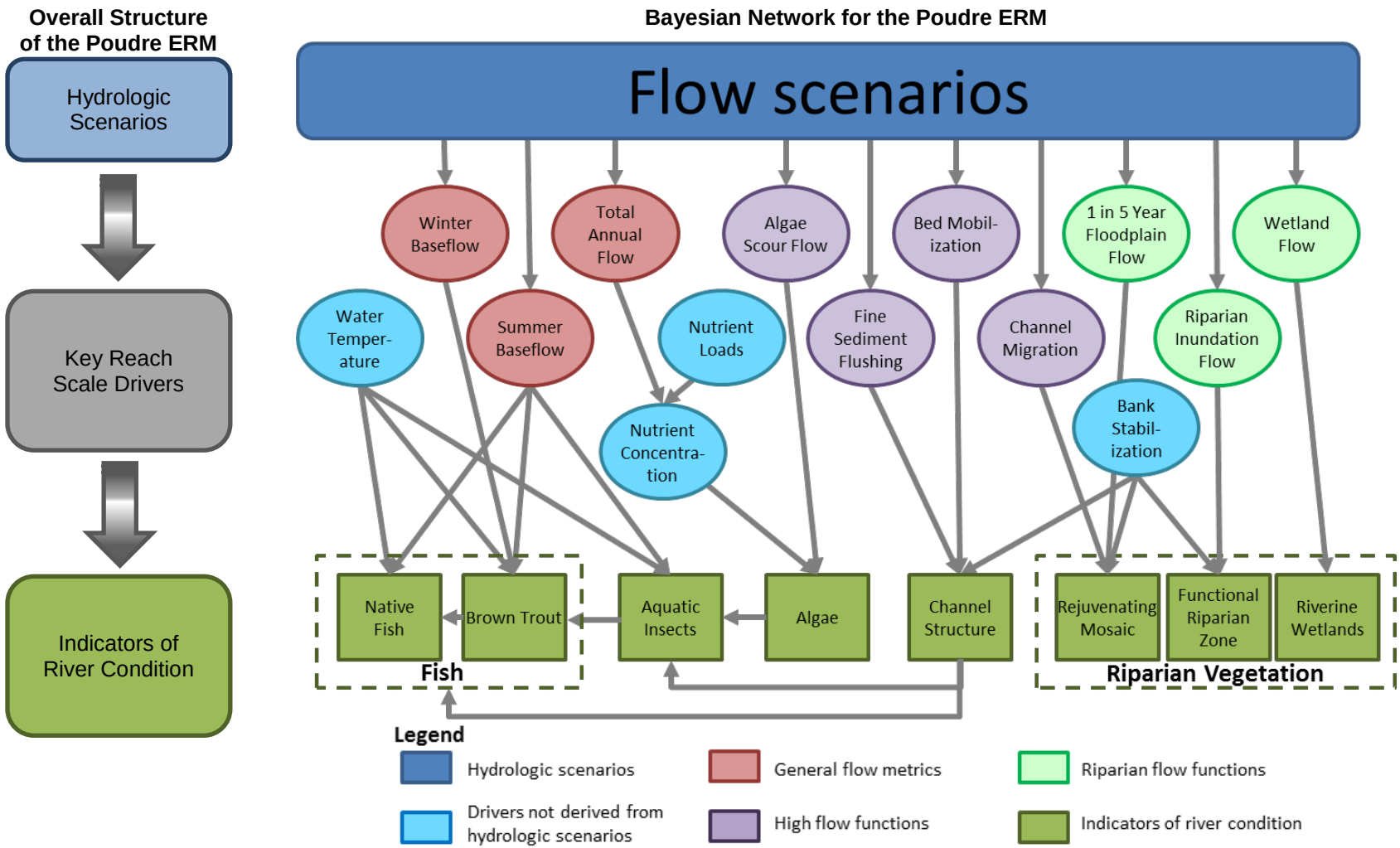


Figure II.2: Overall structure of the Bayesian network for the Poudre ERM as reproduced from Section I.

Note: Arrows between nodes indicate a causal relationship between the linked variables in the final model

A refined model structure was developed over a period of several months through extensive debate and the evaluation of a wide array of potential influence diagrams. Given the breadth of expertise and experience of the modeling team, there is high confidence that a comprehensive set of elements and causal linkages were included in the model. The linkages explicitly included in the model represent the most important and dominant processes, connections, and interactions that control ecosystem condition and functioning, as judged by the ERM's team of experts. As described later in this report, the selected nodes and linkages are based upon the best data and understanding currently available, yet the underlying sub-models vary substantially in terms of approach. Empirical data relied upon to construct the conditional probability tables are presented in Appendix B.

The ERM model runs the software SMILE (Structural Modeling, Inference, and Learning Engine) running within the GeNIe (Graphical Network Interface). Both are found at http://genie.sis.pitt.edu/ (Decision Systems Laboratory (2014). The model computes resulting conditional probabilities of input data through each step of the model, using the general form:

$$P(A_i|B) = \frac{P(B|A_i)P(A_i)}{P(B)} = \frac{P(B|A_i)P(A_i)}{\sum_{i=1}^{n} P(B|A_i)P(A_i)}$$

Where A and B are possible outcomes and $P(A_i|B)$ is interpreted the conditional probability of A_i given B.

Hydrologic Scenarios

The second step of development for the ERM, developing input data, consisted primarily of analyzing probable hydrologic scenarios. Statistics derived from these hydrologic scenarios (such as frequency of a high flow threshold, or the duration of low flows) characterize the effects of scenarios on the ecosystem. Nine hydrologic scenarios were developed for this project to allow a better understanding of past, current and plausible-future conditions. These nine scenarios can be divided into two groups, based coarsely on the method upon which they were developed:

1. Core hydrologic scenarios – based upon the past, present, and plausible future flow conditions on the Poudre River and derived from gage and operations data for the system
2. Test hydrologic scenarios – synthetically-derived hydrographs designed to test what-if scenarios of peak flow magnitude, base flow magnitude, and base flow consistency.

Core Hydrologic Scenario Development

The core hydrologic scenarios originate from a series of models used by Fort Collins Utilities and other regional water users and managers (see Table II.3 for more details). These models simulate the native hydrology and all the operations of diversions and reservoirs within the Poudre River Basin. Together, these models produce time series of simulated flow at a daily or monthly time step. Additionally, a hydrologic metric summary for all the hydrologic scenarios can be found at the end of this subsection in Table II.5.

Table II.3: Core Hydrologic Scenarios for the Poudre ERM.

Name	Period of record	General description	Source
Reconstructed Native	11/1/1949 to 10/31/2005	This scenario represents flows for the Poudre River with all human influences of the past 150 years removed. Flow alterations from operations are accounted for, leaving just the native flow conditions.	Monthly[b] model that factors in water diversions, trans-basin augmentation (water added to the Poudre from other watersheds), return flows, and retimes the water held back in reservoirs to the historic hydrologic record. Developed in a MODSIM model by the City of Fort Collins.
Recent Past	11/1/1969 to 10/31/2010	This scenario is derived from the historical gage data and includes historical climate variability and operations[a] evolving over time.	Historic daily point flow model based on historic gage data (Canyon Mouth, Lincoln Street, and Boxelder) and operation records of diversion structures as developed by the Northern Colorado Water Conservancy District (NCWCD) (Andy Pineda, 2012, pers. comm.)
Present Operations	11/1/1949 to 10/31/2005	This scenario represents the river as though current operations are imposed on the period of record. It is different from the Recent Past scenario because operations have evolved and more water is being diverted today than in the 1950s.	Monthly[b] model that applies 2010 operations to the Reconstructed Native scenario. Developed in a MODSIM model by the City of Fort Collins as part of the HSWMP draft EIS process.
Additional Water Development	11/1/1949 to 10/31/2005	This scenario builds on present conditions and additionally includes preliminary estimates of potential flow alteration based on construction and operation of three proposed water development projects: 1) expansion of Halligan Reservoir, 2) expansion of Seaman Reservoir, and 3) construction of the Northern Integrated Supply Project. It additionally factors in an anticipated increase in municipal demand. It does not include all possible changes to flow based on new uses of existing water rights, nor does it consider possible mitigation flows associated with these projects.	Monthly[b] model that applies projected 2050 operations to the Reconstructed Native scenario. Developed in a MODSIM model by the City of Fort Collins. Data and models used for this scenario were preliminary, and may differ from the final hydrology determined in the HSWMP and NISP EISs, which will likely have more refined low flows and daily disaggregation
Driest Climate	11/1/1949 to 10/31/2005	This scenario also builds on present conditions. It maintains the inclusion of present conditions, but then superimposes the driest conditions forecasted from a collection of climate models.	Present Operations scenario data as modified using the driest climate projection available using the Bias Corrected and Downscaled WCRP CMIP3 Climate and Hydrology Projections[c]

[a] *Operations* refers to all trans-basin basin diversions, diversion withdrawals, and reservoir storage.

[b] Later disaggregated to daily using historic data from the USGS Poudre Canyon Mouth gage: http://www.dwr.state.co.us/SurfaceWater/data/detail_graph.aspx?ID=CLAFTCCO.

[c] http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html.

The current core hydrologic scenarios provide a reasonable starting point for model testing using hypothetical future conditions based on currently available data; however, the ERM team recognizes that upon public release of the Common Technical Platform (linking the hydrologic analysis of the Halligan and Seaman expansions with the NISP), all four modeled scenarios (Reconstructed Native, Recent Past,

Additional Water Development, and Driest Climate) will likely be updated. At that time the newly modified scenarios may be incorporated into the ERM model.

To incorporate the impacts of climate changes in the ERM, the Present Operations scenario was modified into a plausible Driest Climate scenario (see Bureau of Reclamation (BOR, 2011) for details). Climate change data from the BOR includes output from a number of global circulation models (GCMs) and emissions scenarios. Together, the different GCMs and emissions scenarios create 112 possible climate projections. The data for each climate projection were spatially downscaled (to the extents of the Poudre watershed) and used to create projections of unit runoff at a resolution of 1/8 degree latitude-longitude (12 km x 12 km). The model run selected for use as the Driest Climate scenario in the Poudre ERM was the overall driest GCM (Diansk and Volodin, 2002). As the spatial scale of the GCM models was so much greater than the spatial scale of the model that the Present Operations scenario was based upon, it was necessary to calculate a percent change between the driest climate GCM and the average runoff under all available GCMs for the Poudre River watershed. This ratio was then multiplied by the monthly average of the Present Operations scenario to arrive at the Driest Climate scenario.

Monthly to Daily Disaggregation

All hydrologic scenarios based on the monthly time step MODSIM models were disaggregated to a daily time step using the patterning of the Recent Past daily data. This use of analog years helps reproduce hydrologic patterns from similar years (wet years, dry years, etc.). This was done to support the shorter time scale ecological functions captured by the ERM, as it is easier to predict ecosystem responses to changes in patterns of daily average flow than to changes in patterns of monthly average flow. The following disaggregation procedure was used:

1. Identify analog year – The annual average for each year in the monthly time-step scenarios was first matched to an analog water year in the Recent Past scenario.
2. Calculate daily-to-monthly ratios – For each month of the Recent Past scenario (42yr x 12mo = 492 total months) a daily-to-monthly ratio (each day's flow divided by the average flow for that month) was calculated, such that each month of the record has a unique set of daily ratios.
3. Disaggregate monthly data – The daily record from the analog water year was then used to pattern the daily flows for the other scenarios. Computationally the daily-to-monthly ratios from the selected analog year were multiplied by the monthly averaged model data to produce a daily record with the same monthly and annual averages as the original model data.

This disaggregation approach does not provide a precise calculation of daily flows under a given scenario, but it does provide a reasonable distribution and seasonal pattern of daily flow while preserving the average flow in each month of a given time series. As all flow scenarios are inherently based upon the Recent Past scenario, the pattern of inter-annual variability is the same for all scenarios.

Test Hydrologic Scenarios

In addition to the base set of five core hydrologic scenarios, the team wanted to be able to use the ERM to test some additional what-if scenarios. These test scenarios are related to the influence of future water use and management decisions aimed at improving specific parameters of the flow regime. The test hydrologic scenarios vary across the following characteristics.

- Base flow magnitude – Base flows provide habitat for fish and aquatic insects during the majority of the year and are related to aquatic habitat volume and quality as well as water temperature and nutrient levels.

- Base flow consistency – Low base flows, combined with flow extraction from the series of diversion structures along the Poudre, can cause sections of the river to be reduced to disconnected pools that are very detrimental to both fish and aquatic insects.
- Peak flow magnitude and duration – Peak flows flush algae, flush deposits of fine sediments, rejuvenate the river bed, connect the river to its riparian forests, and control the overall form of a gravel bed river. While peak flows largely depend on annual snowpack levels, proposed water projects may reduce the peak flows below current levels.

Using parameters from the various indicators of river condition, the team developed four additional scenarios across the gradient of characteristics in Table II.4. These are further described below. Additionally, a hydrologic metric summary for all the Hydrologic Scenarios can be found in Table II.5.

Table II.4: Summary of characteristics of each test hydrologic scenario.

Name (baseflow-peakflow)	Base flow magnitude	Base flow consistency	Peak flow magnitude	General description
StableBase-LowPeak	Minimum	Consistent	Low	This scenario is similar in condition to the Additional Water Development scenario (reduced peak flows and minimum base flows) with the exception that the base flows remain consistent in the StableBase-LowPeak scenario.
HighBase-ModeratePeak	High	Consistent	Moderate	Based upon Bartholow (2010), this uses the 25th percentile of monthly averages from native flows and recommendations for managed changes in streamflow in all months, including a moderate level peak flow magnitude.
DryBase-HighPeak	Variable	Intermittent	High	This scenario is designed to test the question: "Even if the peak flows are ample, what is the ecological effect of intermittent periods of no flow?" The percent of dry days were patterned on the Present Operations scenario and the high flows were based on the StableBase-HighPeak scenario below.
StableBase-HighPeak	Minimum	Consistent	High	This scenario is designed to use the minimum amount of flow necessary to elevate most of the ERM indicators of river condition to their highest levels.

These test scenarios were evaluated using the same analysis technique as the core flow scenarios. Test scenarios generally preserve snowmelt hydrograph patterns observed on the Poudre River; however, these scenarios have not been constructed by explicitly simulating the combined effects of climate variability, reservoir storage, and decentralized operations. Hence, the test scenarios are designed to evaluate the effects of hypothetical flow patterns on the Poudre River ecosystem. See Figures II.4 and II.5 for an annual median hydrograph of the four test scenarios.

Each scenario is comprised of separate low (0 to < 25%), average (25% to < 75%), and high (75% to100%) flow years to account for inter-annual climate variability. The sequential pattern of low, average, and high years for the test scenarios are based upon the corresponding low, average, and high flow years in the Recent Past scenario.

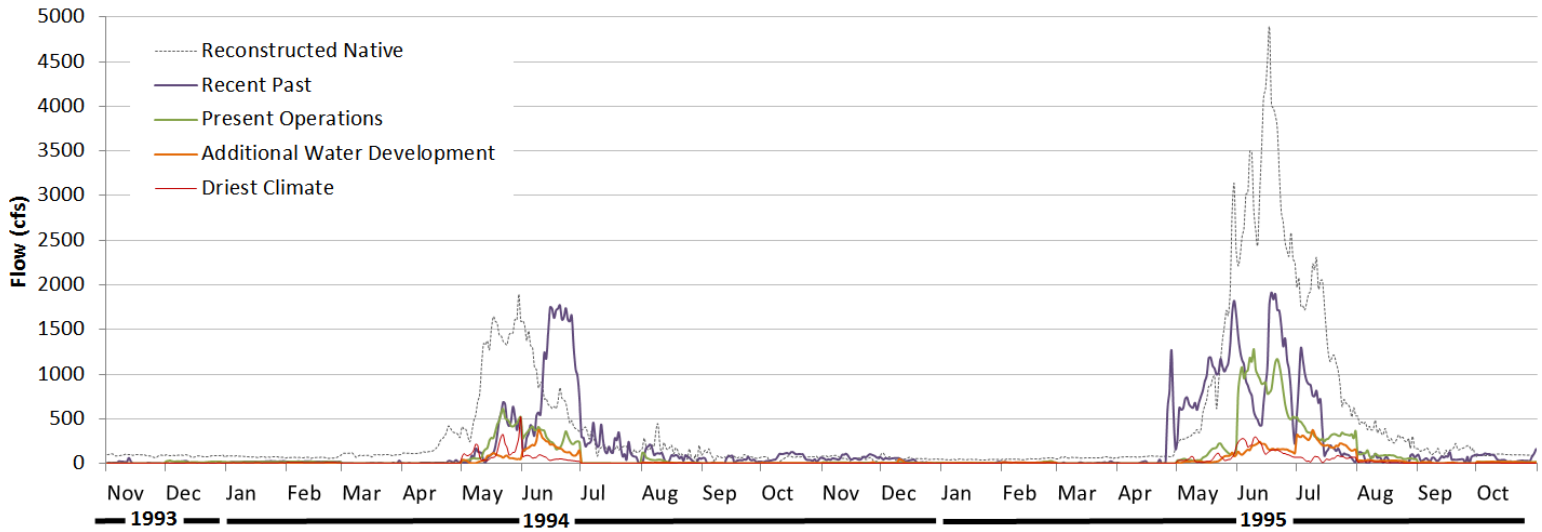


Figure II.3: Hydrographs of Water Years 1994 and 1995 across the five core hydrologic scenarios.

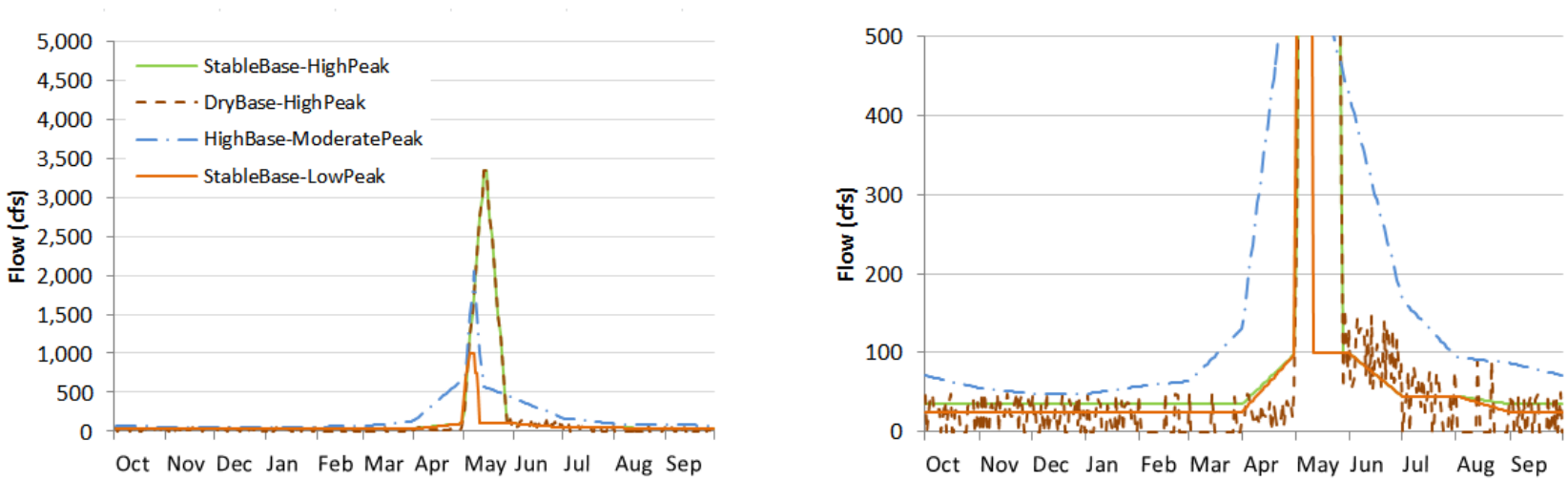


Figure II.4: Comparison of median (25% to < 75%) annual hydrographs of the four test hydrologic Scenarios.

Note: Right side of figure is zoomed into the baseflow portion (0–500 cfs).

Table II.5: Hydrologic metric summary for core and test scenarios for the location below the Larimer & Weld Canal.

	Core hydrologic scenarios					Test hydrologic scenarios			
Hydrologic Metric	**Reconstructed Native**	**Recent Past**	**Present Operations**	**Additional Water Development**	**Driest Climate**	**StableBase-LowPeak**	**HighBase-ModeratePeak**	**DryBase-HighPeak**	**StableBase-HighPeak**
Period of record (WY)	1950–2005	1970–2010	1950–2005	1950–2005	1950–2005				
Average daily flow (cfs)	383	164	99	48	27				
Average summer (July–September) base flow (cfs)	347	126	81	52	13				
Average winter base flow (cfs)	70	24	12	5	4				
Average peak daily flow (cfs)	3,287	1,947	1,094	524	472				
Wetland flow (cfs)[a]	2,645	1,638	1,007	424	246				
Functioning riparian zone flow (cfs)[b]	4,172	3,832	2,190	1,488	793				
5-year return period flow	4,210	2,795	1,582	521	575				
Percent zero flow days	0.0%	12.3%	30.7%	40.0%	30.7%				
Annual volumetric discharge (acre-ft)	277,634	118,685	71,996	35,533	19,309				

[a] Flow occurring two weeks of the growing season, May–September, every other year (later described in more detail in the Riparian Vegetation section).

[b] Flow occurring one day per year (later described in more detail in the Riparian Vegetation section).

Strengths and Limitations of the Bayesian Approach

A challenge confronting the assembly of any model that represents a complex system (such as the Poudre River ecosystem) is deciding which system elements to include and how to represent their relationships in time and space. The saying goes that all models are wrong, but some are useful (Box, 1976). The ERM was constructed as a Bayesian network model that could serve the useful purpose of accurately representing ecosystem complexity, but in an intentionally simplified manner that nonetheless allows major system components to be incorporated and their interactions modeled. Of course, no model is perfect and no modeling effort is able to comprehensively capture every ecological interaction of a complex system with feedback loops, additive impacts over time and unknown future changes to the system. Both the strengths and weaknesses of the ERM lie in its Bayesian approach and efforts to develop an integrated model.

For purposes of this project, the Bayesian network approach has several advantages (Uusitalo, 2007):

1. It uses an established methodology to integrate across various ecosystem functions that are typically modeled as independent with little interaction. A Bayesian network is intended to capture most or all of the dominant functions in a system, which allows for a systematic, integrated evaluation of cause, effect and response among different elements of the ecosystem.
2. A Bayesian network can incorporate different and distinct sources of data, ranging from quantitative output from other models and databases to qualitative, expert judgment.
3. A Bayesian network is explicit about uncertainty, because causal relationships between variables are described probabilistically and the outcomes are described in terms of their combined probabilities.
4. Finally, this kind of model is very flexible; it can be used to test various kinds of scenarios and the sensitivity of outcomes to individual factors in those scenarios. For example, the model will allow the testing of how various restoration projects might function under different flow conditions.

This approach also has some limitations. The limits on the complexity of the Bayesian network arise from the degree to which causal relationships can be expressed between all the causal and response nodes in the network and the amount of information needed to populate the probability and conditional probability tables. As noted above, the model is built with a mixture of data and data-informed expert judgment. Expert judgment, which is based on research experience and broad knowledge of ecological and hydro-geomorphic principles published in peer-reviewed literature, was used to create parts of the model for which scant site-specific empirical data exist. Use of expert judgment in modeling and decision analysis is a well-established practice, but not without pitfalls (von Winterfeldt and Edwards, 1986; Otway and von Winterfeldt, 1992). One way to account for uncertainty associated with expert judgment is to be more conservative with the assignment of conditional probabilities based upon expert judgment informed by empirical data, and that principle was followed in this study. As new data become available, this expert judgment can be refined and/or replaced to continually improve the ERM as a tool.

The subsections that follow provide in-depth information on the eight biological indicators used as model components in the ERM.

CHANNEL STRUCTURE

This focus of the ERM was led by and is reported on by the following experts:

- *Daniel Baker, Ph.D., Hydrologist, Research Scientist, Department of Civil and Environmental Engineering, Colorado State University*
- *Brian Bledsoe, Ph.D., Hydrologist, Department of Civil and Environmental Engineering and Graduate Degree Program in Ecology, Colorado State University*

Background

Moderate to high flows in the Poudre River support many amenities including water quality, fisheries and their food base, riparian habitats, recreational opportunities, and aesthetic benefits. High flows can prevent excessive accumulation of fine sediments and algae, and maintain habitats, channels, riparian corridors, and groundwater connections that moderate stream temperatures (Whiting, 2002). Excessive deposition of fine sediment can impair aquatic life in a variety of ways. For example, trout and aquatic insects (invertebrates), such as mayflies and stoneflies, depend on clean interstitial spaces between gravels and cobbles in the river bed to carry out their life cycles (Waters, 1995). These effects can also propagate out of the channel to the riparian ecosystem as birds and other animals depend on aquatic insects as a food source.

Reductions of moderate to high flows over the 20th century have altered the capacity of the Poudre River to maintain physical habitat for fishes and aquatic invertebrates by reducing the number of days that flows exceed the thresholds necessary to flush fine sediment and clean the river bed. The period of years between flushing events is now longer than what river biota are adapted to in terms of habitat availability and reproduction. In addition to being critical components of the river ecosystem, fishes and aquatic invertebrates are standard indicators used for water-quality assessment performed under the auspices of the *Clean Water Act*, because they integrate many physical and chemical factors. Furthermore, the Colorado Water Quality Commission has promulgated a narrative water quality standard for protecting aquatic life uses against excessive deposition (5 CR 1002-31, Section 31.11). Thus, the maintenance of flows that periodically cleanse the river bed is directly linked to the attainment of aquatic life uses.

The Poudre has been affected by a combination of flow alterations and directly imposed channel changes such as straightening, levee building, aggregate mining, and extensive bank stabilization with *riprap* (large angular stones) placed to protect river banks from scour. Because the quality and quantity of habitat is determined by the interaction between streamflow and the structure of the river channel, the effects of flow changes on the ecosystem must be considered in the context of the current channel structure and its variability along the river. Because of these changes to the structure of the river channel a return to pre-settlement levels of streamflow would not yield pre-settlement habitat, given the relatively simplified and static form of the present-day river channel in some segments of the urban corridor. Therefore, the ERM had to be designed to account for the unique characteristics of each river segment in terms of its flows, channel forms, and boundary materials (i.e., sizes of rocks on the bed and extent of riprap along the banks).

Hydraulic and geomorphic analyses are important for understanding the linkages between flow patterns, instream habitat quality, and river biota. Such analyses inform river stewardship by providing physically-based, quantitative targets for the flows that maintain habitat quality. To quantify the effects of moderate to high flows on Native Fish, Brown Trout, Aquatic Insects, and three riparian vegetation indicators in the ERM, a shear stress analysis and an effective discharge analyses were performed at representative locations in each of the three reaches modeled in the ERM along the Fort Collins river corridor. Hydraulic modeling was performed to identify the discharges at which critical thresholds of shear stress, associated

with river bed flushing and rejuvenation, are met based on the unique flow characteristics, channel geometry, and substrate composition at each site.

Frequency and Duration of Flushing Flows

Implementation of flushing flows necessitates specification of a target frequency and duration. Two interrelated lines of evidence were considered with respect to frequency: return periods of high flows to which regional river biota are adapted, and the reproductive cycles of trout and aquatic insects. Previous studies of numerous Colorado snowmelt rivers with gravel beds (Andrews, 1984), as well as similar systems in the western U.S. (Emmett and Wolman, 2001), indicate that events that transport appreciable amounts of coarse bed material tend to occur with a return period of less than two years in the annual maximum series. Regional river biota have adapted over long time scales to this inter-annual pattern of high flow. Numerous studies also indicate that the non-native trout species that dominate the Poudre River (upstream from College Avenue) and its tributaries depend on high flows that provide suitable habitat conditions as in their native range (Waters, 1995). Recent research conducted in comparable river segments downstream of the ERM study area has clearly documented habitat degradation and degradation of aquatic insect communities in the absence of flushing flows (Nehring et al., 2011).

Given that trout are a highly valued amenity and primary indicator of aquatic ecological health in the Poudre River, maintenance of their food base is an important consideration. Trout depend on aquatic insects at all life stages from rearing to death, and production of aquatic insects depends on the quantity and quality of habitat available in the river substrate. Most of the aquatic insects that support the trout fishery in the Poudre River reproduce one or more times per year (Ward and Kondratieff, 1992). Current scientific understanding of the ecology of these systems therefore indicates that providing an annual high flow pulse capable of at least flushing surface deposits of fine sediment is a logical precautionary measure.

Widespread mobilization of the coarse fractions of the river bed is a somewhat less-frequent occurrence (approximately two out of three years to three out of four years) in low-gradient segments of undepleted Rocky Mountain streams and rivers (Emmett and Wolman, 2001). Coarse substrate mobilization may occur much less frequently in high gradient channels (> 2%), (Grant et al.,1990 and Wohl, 2010). From a biological standpoint, trout reproduction varies considerably from year to year and population maintenance does not require high levels of recruitment every year. However, brown trout populations in the Poudre River do depend on recruitment events approximately every three years. Although substrate quality is a critical limiting factor in trout reproduction, other factors, such as late summer temperatures, can limit recruitment even when other habitat characteristics are adequate. It follows that a high flow that at least partially cleans interstices in the river bed every two years on average will increase the likelihood that the multiple factors supporting reproduction of both brown trout and aquatic insects are synchronized and maintained over decadal and longer time scales. In practice, an effective flushing event on a strict interval of every other year is not likely to be feasible under the current management infrastructure, given inter-annual variability and the inevitability of multi-year dry spells. Accordingly, an average return period of two years is a reasonable target over time.

Data Sources

Existing data on cross-sectional geometry available from previous studies (USACE, 2008; Brad Anderson, 2011, pers. comm.) were used to perform shear stress and effective discharge analyses at three locations on the Poudre River mainstem. As described earlier, these locations were selected to represent three relatively distinct geomorphic contexts:

1. Reach 3a, a highly entrenched and laterally armored upstream reach
2. Reach 3b, a partially entrenched and armored intermediate reach
3. Reach 7, a moderately labile reach that is better connected with its floodplain than Reach 3, though still bounded by a number of historical gravel pits (Figure II.1)

The USACE's Hydrologic Engineering Centers River Analysis System (HEC-RAS) hydraulic model used in these analyses was provided by Anderson Consulting Engineers, Inc. (USACE, 2008; Brad Anderson, 2011, pers. comm.), using cross sections measured by King Surveyors in 2007, as well as additional cross-sections added by Anderson Consulting using other means (such as interpolation, repeated cross sections, and photogrammetry). The discharge-shear stress rating curves for Reaches 3a and 3b were taken as an average of a multiple representative curves for those specific reaches. The discharge-shear stress rating curve for Reach 7 was taken from a single representative cross section (after comparing the rating curves of multiple cross sections). Median grain size (d_{50}) for each reach was estimated from a report by Ayres Associates (2001) as well as recent monitoring data (Daniel W. Baker, personal communication). The effective discharge analyses were based on a flow record representing flow conditions at the USGS gage 06752260, Cache la Poudre River at Fort Collins, Colorado, with flow adjusted through the city based on operations of diversions and additions (Andy Pineda, NCWCD, 2012, pers. comm.). The Boxelder gage (USGS gage 06752280), located at the head of the reach, was used for Reach 7.

Methods and Probability Tables

The key to evaluating whether sediment deposition and river habitat are likely to be exacerbated by an alteration of streamflow patterns is to examine changes in frequencies and durations of the hydraulic conditions that most influence sediment flushing, habitat rejuvenation, and channel maintenance. This range of flows is typically identified by performing shear stress and effective discharge analyses. To assess potential changes in sediment processes and physical habitat and improve understanding of the potential long-term effects of different patterns of flow alteration on aquatic habitat, three primary lines of evidence were examined in developing the geomorphic/physical habitat components of the ERM (See Appendix B1 for more details on all three):
:

1. Shear stress analyses that quantify the frequency and duration of flows that perform sediment flushing, river bed rejuvenation, and channel maintenance
2. Effective discharge analysis of cumulative sediment transport capacity over the full spectrum of streamflows under historical conditions
3. Historical analysis of aerial images of the river planform and evidence of lateral migration
4. Channel maintenance flow index

In the shear stress analysis, the ERM team modeled 53 different river flows ranging from 50 cfs up to 9,000 cfs using HEC-RAS to develop piecewise, at-a-station hydraulic geometry relationships for hydraulic radius, friction slope, shear stress, and dimensionless shear stress as functions of discharge for representative cross sections in each reach. Spreadsheet tools were used to quantify the frequency and average number of days per year that hydraulic conditions exceed ecologically-relevant values of dimensionless shear stress referenced to the median grain size on the river bed (τ_*) for any input streamflow series.

Thresholds of dimensionless shear stress referenced to the median grain size of the river bed (τ_*) are associated with important geomorphic and ecological processes (American Society of Civil Engineers (ASCE), 1992; Milhous, 2000, 2003). These processes include the following.

- Algae scour/disturbance
- Sand/fine sediment flushing
- Partial transport of bedload
- Limiting encroaching vegetation
- Armor breakup and full transport of bedload

States of Channel Structure in the ERM

Sediment movement in gravel-bed rivers can be described in terms of five general states (Table II.6), (Milhous, 2000, 2003).

Table II.6: Interpretation of dimensionless shear stress values in terms of states of fine sediment flushing and coarse substrate mobilization.

	Dimensionless shear stress (τ_*) referenced to d_{50}	
Sediment movement state	**Lower bound**	**Upper bound**
Fines and sand are stored		0.009
Fines and sand in motion	0.009	0.021
Surface cleaning and removal of fines	0.021	0.035
Initial movement of armor and substrate cleaning	0.035	0.06
General movement of and cleaning of substrate	0.06–0.084	–

Source: Adapted from Milhous, 2000, 2003.

The main channel hydraulic radii and friction slopes from HEC-RAS, were used in conjunction with site-specific, grain-size distributions to calculate estimates of the discharges that correspond to ecologically relevant thresholds of dimensionless shear stress for each reach (Table II.7).

Table II.7: Discharge (cfs) corresponding to three thresholds of dimensionless shear stress at the three study locations.

Location	$\tau_* = 0.021$	$\tau_* = 0.03$	$\tau_* = 0.035$	$\tau_* = 0.06$
Reach 3a: Taft to Shields	1,750	2,700	3,300	6,900
Reach 3b: Shields to College	1,400	2,500	3,200	8,000
Reach 7: Boxelder Gage to I-25	900	1,550	2,100	9,200

Channel Structure is ultimately defined by three flow indices in the ERM, and these flows can be quantified based on the site-specific hydraulic modeling, shear stress analysis, and effective discharge analysis (Appendix B):

1. Flushing of algae (explained in detail later in the Algae portion of Section II) and surface flushing of fine sediment
2. Bed mobilization/substrate rejuvenation with the potential for some scour of encroaching seedlings

3. Channel migration habitat diversity flow with effectiveness that depends on categorical states of bank stabilization along a particular reach (as described in the Riparian Vegetation portion of Section II)

The surface flushing of fine sediment and bed mobilization were addressed using a channel maintenance flow approach that incorporates flow magnitude, duration, and frequency. This approach has been formulated in the context of this project; however, the intent of the methodology outlined here is to be readily adaptable to other rivers as well. First, a flow magnitude and duration metric, called the channel maintenance flow index (CMFI), was developed in the form of:

$$CMFI = \sum_{i=1,n} \left(\frac{\tau_{*i}}{\tau_{*R}}\right)^{1.5} \left(\frac{D}{D_c}\right)$$

Wherein:

τ_* = $Dimensionless\ shear\ stress$

τ_{*R} = $Reference\ shear\ stress\ capable\ of\ initiating\ geomorphic\ process\ of\ interest$

D = $Duration\ (days)$

D_c = $Duration\ ceiling\ above\ which\ no\ additional\ geomorphic\ benefit\ is\ calculated$

n = $Number\ of\ days\ during\ a\ year\ of\ record\ in\ which\ \tau_{*R}\ is\ exceeded$

This index provides a continuous metric of flushing effectiveness based on excess shear stress and its duration; therefore, it avoids issues associated with discretization approaches based on categorical thresholds of shear stress that are relatively insensitive to differences among similar scenarios. This metric was calculated for each year of the flow record for both flushing and bed mobilization using the reference shear and duration ceiling values found in Table II.8. An annual average CMFI was then computed for each flow scenario.

Table II.8: Summary of the reference shear (τ_{*R}) and duration ceiling (D_c) for the computation of CMFI-F and CMFI-M.

Function	τ_{*R}	D_c
Fine sediment flushing (CMFI-F)	0.021	5
Bed mobility (CMFI-M)	0.030	5

The end product is a physically-based and intuitive equation for quantifying flows associated with sedimentation such as surface flushing of fine sediments and coarse substrate mobilization.

Next, the two CMFI metrics were combined with information on flood flow frequency and site-specific bank stabilization to produce a single channel condition metric for the ERM biological metrics. This single channel condition metric is based on the likely channel condition from 0.0 (poorest condition) to 1.0 (ideal condition for fish and aquatic insects). Upon investigating CMFI-F and CMFI-M values for a range of flushing and mobility conditions suggested by available literature (e.g., Kondolf and Wilcock, 1996, Milhous, 2009; Milhous, 2012), a linear value function was developed between the channel condition probability and the two CMFI metrics. The combined channel condition metric was assumed to have a normal distribution; thus, a mean and standard deviation were computed and, before distribution, binned into the states described in Table II.9 (see Appendix B1 for more information):

Table II.9: Description of four states of Channel Structure that depend on the combined status of flushing flows, coarse substrate mobilization, channel migration flows, and extent of bank stabilization.

State	Description
Clean and diverse	Flushing and bed mobility flow functions intact, substrate clean on surface, interstitial space open, vegetation encroachment not advancing, channel has wide variety of depth, velocity, substrate combinations with morphologically diverse features such as side channels, chutes, bars owing to substantial removal of lateral bank stabilization.
Partially mobile and diverse	All three flow functions at least partially intact, flushing occurs at least every few years, interstitial space open in high-stress zones such as riffles, vegetation encroachment slowly advancing in low-stress zones, habitat diversity flows may be intact but bank stabilization partially limiting channel complexity.
Largely immobile and homogeneous	Bed mobilization and/or channel migration flows not intact, flushing partially or not intact, vegetation encroachment likely advancing, river increasingly canal-like with homogeneous habitat until partially reset by an extreme event that overcomes bank stabilization in isolated locations, substrate flushing at least partially intact, habitat diversity flows could be intact but stabilization present.
Entrenched	Partial to no substrate cleaning, channel maintenance absent, interstitial space not opened > 3–5 years, extensive bank stabilization, canal-like homogeneous channel.

Additional details on the entire hydraulic and geomorphic modeling approach are provided in Appendix B (Subsection B1).

ALGAE

This focus on the ERM was led by and is reported on by the following experts:

- *Daniel Baker, Ph.D., Hydrologist, Research Scientist, Department of Civil and Environmental Engineering, Colorado State University*
- *Mark Lorie, independent consultant specializing in water resources planning*
- *LeRoy Poff, Ph.D., Aquatic Biologist, Department of Biology, and Director, Graduate Degree Program in Ecology, Colorado State University*

The Impact of Nutrients on Algae

This subsection begins with a discussion of how nutrients affect the Algae indicator in the Poudre River. Both nitrogen and phosphorus are critical elements for supporting algal growth in aquatic ecosystems. However, excessive nutrients in these waters can also lead to reduced water quality and violations of regulatory standards. The City of Fort Collins' wastewater treatment plants on the Poudre River are also working to limit their nutrient loading to the river.

The State of Colorado has established new nutrient criteria for the state's surface waters, including the Poudre River (Keith Elmund, 2011, pers. comm.). There is concern that the Poudre will be in violation of these new criteria under a changing climate, and with further abstraction of water from the river, unless management practices that reduce point and nonpoint sources of nutrient loading to the river are implemented.

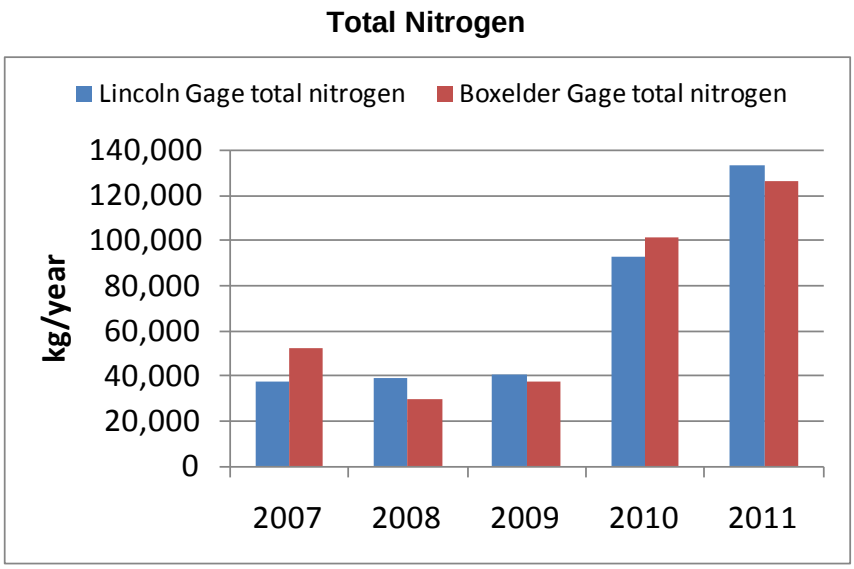
The analysis of the available nutrient data is included due to its importance, both ecologically and for the regulatory impacts described above. However, there is not a final endpoint in the Bayesian model for nutrients. Nutrient data offered here is to inform probabilities that influence algal response.

Data Sources

The City of Fort Collins Utilities measure and record nutrient levels in the Poudre River on a weekly basis at several locations throughout the City, including three sites within the ERM project reach. The ERM team was able to match measurements from Lincoln Street to Reaches 3a and 3b, and from Boxelder Creek (PBOX) to Reach 7. Analysis includes concentrations of nitrite (NO_2), nitrate (NO_3), ammonia (NH_3), total Kjeldahl nitrogen (TKN), and total orthophosphate (PO_4) (see Appendix B).

Methods and Probability Tables

For the ERM, a standard approach was used to amass the daily single nutrient measurements into average annual loads as a function of daily average discharge (Cohn *et al*., 1989; Preston *et al*., 1989; Etchells *et al*., 2005). This was done by first converting each weekly concentration measurement into a load rate (units of mass per time) by multiplying the concentration (mg/L) and the daily average flow on the day of sampling in cubic meters per second (cms), and converting the result to units of kilograms per year (kg/year). For sample data less than the detection limit, a concentration of half the detection limit was assumed (Cohn *et al*., 1989; Etchells *et al*., 2005). Next, using these estimated 2007–2011 nutrient loads, a plausible range of nutrient concentrations was estimated using the flow rates of the Core and Test hydrologic scenarios. By assuming no change in nutrient loading, the load was then divided by the projected average annual flow of a given scenario to estimate the distribution of Total N and Total orthophosphate concentrations, and the likelihood of exceeding the proposed new concentration standards (see Appendix B2). Figure II.5 shows the resulting estimates of annual load for total nitrogen and total orthophosphate for 2007–2011.



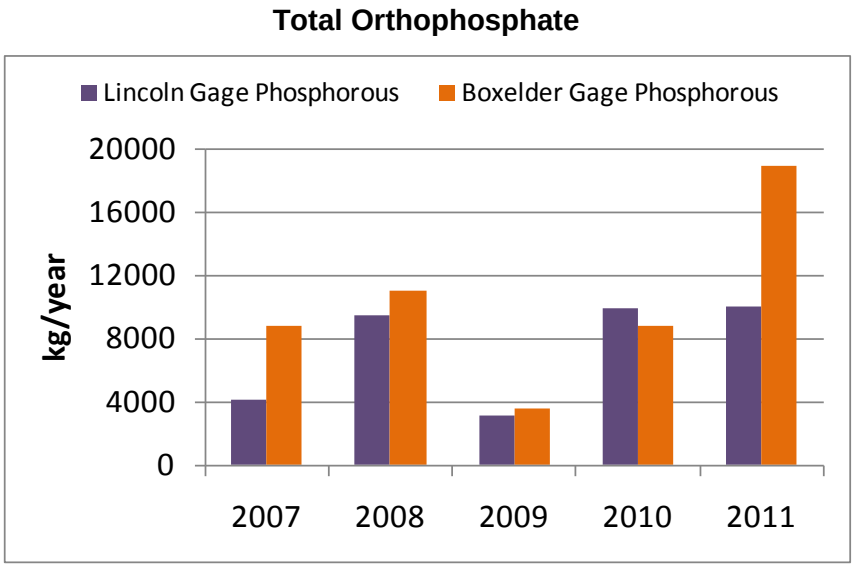


Figure II.5: Annual load rates.

All three reaches are subject to nutrient standards under Nutrient Control Regulations (also referred to as Reg85) from the Colorado Department of Public Health and Environment (CDPHE). These standards were changed in March 2013 to 1.25 mg/L in a cold-water reach and 2.01 mg/L in a warm-water reach for total nitrogen and to 0.11 mg/L for phosphorus in a cold-water reach and 0.17 mg/L in a warm-water reach (CDPHE, 2012). Along with the standard changes, the three reaches modeled for this study were also reclassified by the CDPHE as warm water as of May 2013. The cold-water threshold is also relevant because, above Shields Street, the Poudre River is classified as a cold-water stream.

Exceedance probabilities for each hydrology flow scenario were calculated and graphs of these data are presented in Appendix B.

Finally, the exceedance probabilities were used to calculate a state variable representing the degree of enrichment as compared to threshold concentrations for the nuisance growth of algae. These threshold concentrations were 0.4 mg/L for total nitrogen (Dodds *et al*., 1997, 2002) and 0.11 mg/L for total phosphorous (representing the cold-water limit) (CDPHE, 2012; Elmund *et al*., 2011). The exceedance was then converted to a state variable (quantifying changes in overall algae abundance compared to recent conditions) as input to the Algae component of the model. Thus, each exceedance probability was normalized to that of the Recent Past hydrologic scenario. Finally, the enrichment was categorized into three enrichments (Table II.10). Thus, the state for a given scenario is determined by calculating the difference in frequency of exceedance of the thresholds between that scenario and the Recent Past scenario. An example, using total Nitrogen at Lincoln Street: If under the Recent Past scenario the standard is exceeded 65% of the time, and under Present Operations the standard is exceeded 67% of the time, the difference of 2% would land the state of nutrients in Present Operations into the 0 (about the same) category.

Table II.10: Enrichment states for nutrient concentrations.

State	Definition
Significant improvement	At least 25% less frequent exceedance of the threshold than under Recent Past conditions.
About the same	Within ±25% of the frequency of exceedance under Recent Past conditions.
Significant enrichment	At least 25% more frequent exceedance of the threshold than under Recent Past conditions.

Background

Benthic, or attached, algae play two roles in the ERM.

First, algae are a component of the food web, providing a source of food for many aquatic insects (Allan and Castillo, 2007). Algal production is a direct response to several factors, including the positive effects of nutrients as discussed above (primarily orthophosphate, nitrate and ammonium) and the reducing effects of consumption by aquatic insects and scouring by high flows (Biggs, 1996).

In late summer, extensive algal mats can form in the slow-flowing parts of the river. Observation of the Poudre over the last several years by members of the ERM team strongly suggest that years with low summer base flows are much more likely to support high densities of late-summer algal mats than high-flow years, such as N. L. Poff's personal observation with CSU Stream Ecology class on several late-summer field trips to the Poudre River. As another example, in 2011, with its high runoff into late summer, there was very little algal mat production observed in the river near Martinez Park compared to previous years and 2012.

These benthic algal mats are comprised of filamentous green and bluegreen algae, which are often not palatable to most aquatic insects and which can be difficult for many insects to eat because of the algae's large filament size. During the daytime, thick mats can become supersaturated with oxygen due to high algal productivity; at night the oxygen demand of the algal mat can create unfavorable dissolved oxygen availability for aquatic insects that live in close association with the mat.

The second role of algae in the model is as an ecological endpoint of aesthetic concern. Thick mats of filamentous algae are viewed by many as undesirable (nuisance algae). Therefore, the Algae indicator in the ERM is considered as a socially-relevant indicator of ecosystem health, as well as a more basic ecological indicator.

Data Sources

Estimates of benthic algae in relation to flow conditions in the Poudre River were based on the combined influences of nutrient enrichment (as defined above) and algae-flushing flows (see Table II.11). As nutrient data were limited to the Lincoln and Boxelder gages, Reaches 3a and 3b were calculated with the Lincoln Street data and Reach 7 with the Boxelder data.

Table II.11: Definition of states for algae-flushing flows.[1]

State	Definition
Intact	*Q* exceeds 1,500 cfs for 14+ days 1 out of 2 years
Partially intact	*Q* exceeds 1,000 cfs for 7+ days 1 out of 2 years
Absent	Less than above

[1] Based upon field observations and the expert judgment of the ERM team.

Historical levels of algae in the river are poorly documented. However, it is reasonable to expect that the abundance of algae has been increasing over time as more nutrients are added to the river from land use and agricultural runoff, perhaps ameliorated by nutrient reductions associated with water treatment plants.

The nutrient states (Table II.10) and the states for algae flushing flow (Table II.11) were both used as inputs to estimate algal production in the Poudre River.

Methods and Probability Tables

Estimates of benthic algae in relation to flow conditions in the Poudre are based on expert knowledge and observation by members of the ERM team. These estimates are applied uniformly to all three reaches of the model.

The ERM includes three possible states for Algae, defined in Table II.12. Given the lack of monitoring data, the states for the Algae indicator are defined in very general terms and are defined relative to the general algae conditions in recent years.

Table II.12: Description of three states of Algae that depend on dilution flows, temperature, and flushing flows.

State	Definition
Less than today	Less frequent and/or less severe algal blooms than have been typical in recent years.
About the same as today	About the same frequency and severity of algal blooms as have been typical in recent years.
More than today	More frequent and/or more severe algal blooms than have been typical in recent years.

The probability tables for the impacts of nutrient enrichment (total nitrogen and dissolved phosphorus) and scouring flows are based on general observations by experts of river conditions in recent years. The probabilities are presented in Appendix B and are derived from the following logic: Significant improvement in both sources of nutrients leads to the greatest chances of reduced Algae, especially in conjunction with sustained high flows that scour the streambed. Probability of algal abundance increases if either nutrient source does not improve or as scouring flows are reduced. Under possible significant enrichment of nutrients and reduction of scouring flows, algal abundance is very likely to increase greatly.

AQUATIC INSECTS

This focus of the ERM was led by and is reported on by the following expert:

- *Boris Kondratieff, Ph.D., Entomologist, Department of Bioagricultural Sciences and Pest Management, Colorado State University*

Background

Stream biotas reflect the chemical, physical, and biological conditions in which they evolved. Biological community changes and, therefore, biological evaluation, reflect many environmental conditions and anthropogenic impacts. Surveillance of aquatic and habitat quality using macroinvertebrate species or communities as indicators of biotic integrity has become common practice (Rosenberg and Resh, 1993; Rosenberg *et al*., 2008). Benthic macroinvertebrates, or *aquatic insects* for the purposes of this report, are especially useful for this purpose because they are:

- Common in most streams
- Readily collected
- Relatively easily identified
- Not very mobile
- Expected to have life cycles of a year or more

Benthic macroinvertebrates are defined as those aquatic insects that are retained by a 500-µm net or sieve (Hauer and Lamberti, 2006). They have been used to assess water quality in a number of ways including toxicological assays, bioaccumulation, indicator species, and community measures that include biotic indices, diversity indices, similarity indices, description of community structure, and function (Rosenberg *et al*., 2008).

In 1842 and 1843, John C. Frémont crossed the Poudre River near present-day Fort Collins in early summer and noted a river that was clear and running across clean gravel (Jackson and Spence, 1970). At that time native greenback cutthroat trout occurred throughout the river, even as far east as Greeley, depending on the magnitude of the water year or sequence of years (Fausch and Bestgen, 1997). No doubt dynamic, diverse aquatic insect communities also existed throughout the length in the Poudre River, transitioning from typical higher elevation southern Rocky Mountain taxa in the upper canyon reaches to perhaps a unique mix of taxa and more typical High Plains Steppe taxa along the Front Range. Unfortunately, no surveys or collections of these taxa were apparently made before the substantial impacts of irrigated agriculture, gravel mining, logging, channelization, and establishment of settlements by the 1860s (Wohl, 2001). It is known that several species of mayflies (*Ephemeroptera*) and stoneflies (*Plecoptera*) were extirpated from the lower Poudre River by the late 1880s (Zuellig *et al*., 2011).

Currently, the aquatic insect communities are composed of relatively resilient species that can vary in diversity and abundance depending on the yearly flow regime and biotic condition of the river (Grotheer *et al*., 1994; Shieh *et al*., 1999, 2002; Voelz *et al*., 2000, 2005; USGS, 2003; Rice and Bestgen, 2006; Douglas Rice, 2011, pers. comm.).

Data Sources

Many of the sampling sites on the Poudre River have been described by various authors (Grotheer et al., 1994; Shieh et al., 1999, 2002; Voelz et al., 2000, 2005; USGS, 2003; Rice and Bestgen, 2006). Aquatic insect data for the years 2000–2010 for several sites in Fort Collins (Martinez Park, Lincoln Bridge,

Prospect Street Bridge, Mulberry Street, and Moore Farm) were provided by Douglas A. Rice, Environmental Health Services, Colorado State University. These samples were collected using a standard square foot Surber sampler (0.09 m2) (Merritt et al., 2008). Three replicates were taken at each site and the three samples composited. Sampling at three sites (at Lee Martinez Park above the bike path and foot bridge between College and Shields, near Fort Collins Nursery on Mulberry, and on the east side of the river at the CSU Environmental Learning Center) was terminated in 2007. Aquatic invertebrates were identified to the lowest practical taxonomic level, usually genus, but in the case of non-insect taxa higher categories were identified. In some of the above studies, individual samples were subsampled to determine the number of organisms of each taxon for the entire sample.

Methods and Probability Tables

The biological health of the aquatic insect community of the Poudre River was evaluated for the ERM by using a standard approach of calculating the percentage of all species in the collected samples that are comprised of species from three sensitive orders (hereafter referred to as the EPT): *Ephemeroptera* (mayflies), *Plecoptera* (stoneflies), and *Trichoptera* (caddisflies). These insect orders are generally regarded as sensitive and loss of taxa in these groups is an indication of potential perturbation (Wallace *et al*., 1996). The percent EPT (%EPT) is a universal metric applicable in many stream systems (Plafkin *et al*., 1989). Percent EPT was computed for the genera identified for the months of April and August in the years provided. A master list for the taxa of Aquatic Insects used as an indicator in the ERM is given in Appendix B (Subsection B3).

Based on the above studies, other unpublished data, the known life cycles of the aquatic insects, available environmental tolerance values (e.g., Platts et al., 1983; Hilsenhoff, 1987), and known substrate preferences, three states for Aquatic Insect abundance and diversity were defined for the ERM. Table II.13 reports these states and definitions.

Table II.13: Description of three states of Aquatic Insects that depend on scouring flows that cleanse streambed and check algal proliferation, and on summer baseflows.

State	Definition
+	Presence of species that take one (univoltine) to two (semivoltine) years to complete life cycles; semivoltine species present in all size classes, indicating successful annual reproduction and similar abundance to upstream/canyon areas; similar overall diversity to upstream/canyon reaches.
0	Mostly univoltine taxa present; reproduction during favorable conditions; less abundant than upstream/canyon areas; low diversity compared to upstream/canyon reaches.
-	Mostly univoltine taxa present; low abundance or high abundance dominated by tolerant taxa such as oligochaete worms, Turbellaria (flatworms), and chironomid worms.

It is anticipated that there would be little change in aquatic invertebrate community composition due to the resiliency of the existing, relatively non-sensitive taxa (as most sensitive taxa have been largely extirpated from the lower Poudre River). The remaining communities are generally composed of species that can survive and reproduce in the lower Poudre River in the City of Fort Collins, where short-term hydrologic and temperature fluctuations exceed what was typical under Recent Past scenario conditions.

For purposes of the ERM, three important drivers of Aquatic Insect abundance and diversity were modeled:

1. Channel Structure
2. Summer base flow and water temperature (as one combined variable)
3. Algae

Tables II.15 through II.17 provide the probabilities for each individual driver. The individual tables were combined using a weighted average calculation.

Channel Structure

This driving variable is the state of the channel in a given reach, which is impacted by high flows and bank stabilization (Table II.14). More detail on Channel Structure is presented in a previous subsection.

Table II.14: Probabilities for impact of Channel Structure on Aquatic Insect states.

	Invertebrate states		
Channel Structure	**-**	**0**	**+**
Clean and diverse	0	0.5	0.5
Partially mobile and diverse	0.5	0.5	0
Largely immobile and homogeneous	0.5	0.5	0
Entrenched	0.5	0.5	0

Summer Base Flow and Water Temperature

This driving variable is a combination of summer base flow and water temperature (Table II.15). To meet the summer base flow criterion, average flow from July 1–September 30 must be greater than 35 cfs and daily flow must stay above 20 cfs. Meeting both of these is designated as “adequate flow” in the table. Little historical water temperature was available but temperature is recognized as a key driver and thus included as a placeholder if better data becomes available, therefor summer water temperature was set to a 50/50 probability of being above or below 20C. In general, %EPT and stream Aquatic Insect diversity will decline with lower flows and higher temperatures that create physiological stress. (The cutoff of 23°C was used to match the typical upper limit used for the Brown Trout indicator, see below).

Table II.15: Probabilities for the impact of summer base flow and water temperature on Aquatic Insect states.

	Invertebrate states		
Flow and temperature states	**-**	**0**	**+**
Adequate flow and cool water (< 23ºC)	0	0.5	0.5
Adequate flow and warm water (> 23ºC)	0.5	0.5	0
Inadequate flow and cool water (< 23ºC)	0.5	0.5	0
Inadequate flow and warm water (> 23ºC)	1	0	0

Algae

The impact of algae abundance as the primary food source of aquatic insects is generally well understood, though the specifics in the Poudre River have not been well documented. Thus, the general relationship between algae and aquatic insects was represented using the simple states and probabilities presented below (Table II.16).

Table II.16: Probabilities for impact of Algae on Aquatic Insect states.

	Aquatic Insect states		
Algae	**-**	**0**	**+**
Less than today	0	0.5	0.5
About the same as today	0	1	0
More than today	0.5	0.5	0

NATIVE FISH AND BROWN TROUT

This focus of the ERM was led by and is reported on by the following experts:

- *Kevin Bestgen, Ph.D., Director and Senior Research Scientist, Larval Fish Laboratory, Department of Fish, Wildlife and Conservation Biology, Colorado State University*
- *LeRoy Poff, Ph.D., Aquatic Biologist, Department of Biology, and Director, Graduate Degree Program in Ecology, Colorado State University*

Background

Fish communities integrate a host of watershed conditions (including the individual and combined effects of stressors) that are manifest as population responses over time. Changes in native fish communities and the Poudre River trout fishery are of interest because they reflect the relative health and condition of the system. Data that describe the biota and water chemistry of the Poudre River from Fort Collins to near Greeley have been collected over relatively long periods with a goal to monitor water quality of the Poudre River. Therefore, some of those data are used to describe the fish communities of the Poudre River near Fort Collins to understand trends in species richness and abundance of native fishes and salmonids (mostly brown trout) related to stream flow patterns and habitat changes over time. These patterns will be used to project changes in the ERM's Native Fish and Brown Trout indicators in the section of the Poudre River under a range of simulated future flow conditions from just west of College Avenue downstream to the Environmental Learning Center (ELC). (For more information on Brown Trout and Native Fish and environmental conditions in the Poudre River generally, see Appendix B (Subsection B4)).

For this study, patterns of native fishes and total fish species richness were examined (number of each species at a site), fish abundance (number of all individuals collected), and fish community biomass at the McMurry Natural Area (ERM Reach 3b) and ELC (ERM Reach 7) sites relative to various flow metrics and relative to year (time effect) in an attempt to discern meaningful patterns. Environmental variables examined included average winter flow (November–February), average annual flow, maximum annual flow, and minimum annual flow.

In general, there are more species, all taxa as well as native kinds, downstream compared to upstream. This is because the cooler water upstream supports fewer taxa that are cool-water tolerant than the warm water downstream. Persistence of native fishes upstream may also be inhibited by the occasional high abundances of brown trout, which are predators and may limit the diversity and abundance of native fishes at the McMurry Natural Area site. Few other meaningful patterns relative to environmental variables were apparent, except for those associated with species richness and biomass relative to time. Species richness, both for native species and all taxa, declined over time from 1982–2011. This pattern reflects the generally reduced state of native fishes and habitat in the Poudre River study area, historically and now. Many sensitive species, especially those that require clean spawning gravel for reproduction have disappeared from the Poudre River entirely. Gravel spawning species include common shiner (*Luxilus cornutus*), central stoneroller (*Campostoma anomalum*), and creek chub (*Semotlius atromaculatus*); brassy minnow (*Hybognathus hankinsoni*) is a habitat specialist that has largely disappeared. The fish community that remains is a relatively low percentage of what likely occurred historically, and is represented by an array of species that are tolerant to moderate or high levels of degradation.

Reductions in biomass over time may reflect the relatively simplified state of habitat at sites in the study area and efforts to maintain that state. For example, periodic channelization of the ELC site reduced the deep pool habitat (and large trees that acted as cover) that held many fish, particularly large-bodied

suckers and common carp that constituted much of the biomass present. At the McMurry Natural Area site, deep pools and cover were reduced when flows were low and when riparian trees that had fallen into the river were removed, again reducing habitat for suckers and trout. The lower habitat diversity may also explain the low abundance or near extirpation of cover-seeking species such as creek chub at those sites.

Because few patterns were evident for trends within the Native Fish indicator relative to flow or other river or environmental conditions, the ERM team used expert judgment to assign probability states for Native Fish related to driving variables that are thought to influence populations. Information used included knowledge of the habitat types used and preferred, the processes and river functions that create such habitats, sensitivity of species to toxicants or siltation, relative diet specialization, and other information about river conditions where such species exist in Colorado.

Data Sources

Data were collected in these reaches from 1993–present. Data from an upstream site, which was adjacent to McMurry Natural Area and Martinez Park (Site #1 in Bestgen and Fausch, 1993), were used to draw inferences about Brown Trout abundance and dynamics. The second site, near the ELC (Site #3 in Bestgen and Fausch, 1993) provided data on Native Fish (Brown Trout were rare there). More details on these sites and the sampling methods used to collect fish are provided in Appendix B (Subsection B4).

Methods and Probability Tables for Brown Trout

The number of age-0 (young) brown trout captured in autumn samples at the McMurry Natural Area site was used as an index of reproductive success the prior winter. Brown trout spawn in autumn and winter, so an age-0 fish captured in autumn (a fish ≤ 160 mm total length (TL), about six inches total length or less) was produced about nine to ten months earlier, and hatched the same winter. For example, a fish captured in autumn 2000 was produced from an embryo that was fertilized in late autumn 1999, hatched in winter of 2000, and grew during the spring and summer before being captured in autumn.

It was reasoned that numbers of young trout should be reflective of the conditions leading up to and during the incubation period (defined as November 1–March 1) and that, in order to have a productive trout fishery, reproduction must be relatively high in most or all years. Production of young brown trout is also a function of the number of adult brown trout in general, so those metrics were correlated with each other, but numbers of young fish were used in ERM calculations because that was likely a more sensitive metric of winter habitat conditions. Such data were available at the McMurry Natural Area site for the period 1990–2006, except for 1997 and 1999. The empirical data show that the number of young brown trout are correlated to average winter streamflow (November 1–March 1), with a higher probability of observing more trout with years with higher winter base flows (Figure II.6).

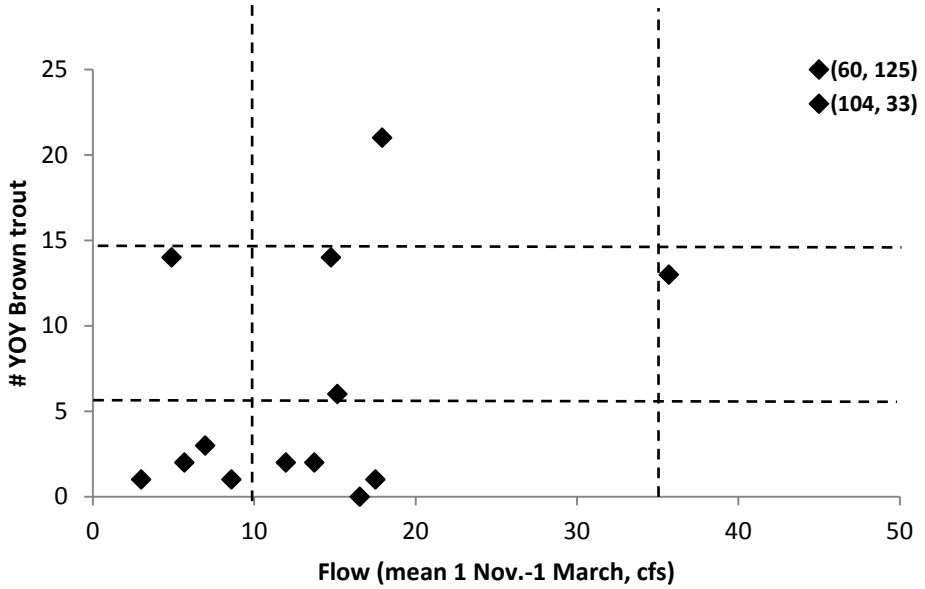


Figure II.6: Number of young Brown Trout (< 160 mm total length, about six inches) captured with electrofishing in the Poudre River at McMurry Park, 1990–2006 (except 1997 and 1999) in autumn samples as a function of flow level (cfs) in the prior winter (1 November-1 March) during incubation.

Note: There is a positive statistical trend between volume of winter base flow and number of young-of-year (YOY) Brown Trout (not shown). The vertical and horizontal dashed lines indicate breaks in the data that are used to define the probability table for young Brown Trout as a function of winter base flows (see text). Higher flow level data (> 50 cfs) were not graphed so lower flow data detail was evident. Higher flow data (flow (cfs), number of fish captured) are shown parenthetically.

This relationship suggests that numbers of young brown trout are consistently high (more than 20, in two out of three years) when Poudre River flows average 35 cfs or higher in the 1 November– 1 March period, reflecting good conditions for incubation of embryos (i.e., adequate flow of water through sediment-free gravel riffles where eggs are deposited), and a subsequent relatively high survival to autumn. Flows in the 10–35 cfs range were associated with variable and moderate numbers of young brown trout (6–20), and winters with flows < 10 cfs were nearly always associated with low numbers of young brown trout (0–5, in four out of five years). Using these breakpoints, the probability table (Table II.17) can be constructed.

Table II.17: Empirical (observed) relationship between winter base flow and young Brown Trout collected the following autumn in the Poudre River upstream of College Avenue bridge, Fort Collins, Colorado.

	Number of young Brown Trout collected		
Average winter base flow (cfs)	**0–5**	**6–14**	**> 20**
0–10 (five years of observation)	0.8	0.2	0.0
10–35 (seven years of observation)	0.57	0.29	0.14
> 35 (three years of observation)	0.0	0.33	0.67

These flow categories were used to describe the probabilities of having a trout fishery in four categories, or states, identified and defined in Table II.18.

Table II.18: Description of four states of Brown Trout that depend on summer temperature, summer baseflow, winter baseflow, Aquatic Insects, and Channel Structure.

State	Definition
+	Multiple (3–4 or more) age classes; successful annual reproduction; high total biomass; resilient to multiple detrimental events/years; viable recreational fishery, many adult fish.
0	Three age classes; more variability across years in terms of biomass and reproduction; variable as a recreational fishery from year to year, occasional years with moderate numbers of adult fish.
-	Dominated by a single age class, others may be present; reproduction minimal; recovery from stressor events would take several years; generally poor fishery, inconsistent from to year to year.
- -	Single age class present; very sporadic reproduction; low abundance, population vulnerable to one detrimental event/year, the poor fishery is in danger of collapse; many years of good conditions for recovery.

The present status of the fishery in the Poudre River at the McMurray Natural Area site, and the Poudre River in the entire ERM study area, is viewed as somewhere between the “0” and “-“, not only reflecting variability in conditions over the 16 years of sampling, but also reflecting a generally depressed biological state relative to what could occur under more stable flow and improved channel structure conditions.

Based on the team’s understanding of the ecological needs of Brown Trout, four driving variables were derived:

1. Summer base flow and water temperature (combined into a single variable)
2. Channel Structure
3. Aquatic Insect abundance and diversity
4. Winter base flows

Understanding the trends in biota and their life history needs, the ERM team then assigned probabilities for Brown Trout as a function of these four driving variables, recognizing that the present state of the fishery is only moderate and in most years falls between “0” and “-“. The probabilities were set individually for each driving variable, and then combined using a weighted average (more below). For example, the table for young Brown Trout and winter flows reflects that in only a few years will young trout abundance be high, and only when flows are relatively high or moderately high, which is then associated with a relatively high probability of a substantial trout fishery (e.g., “0” or “+” state). Similarly, low winter flows are associated with high probabilities of moderate or low abundance of young trout, which, when taken over a series of years, would result in a diminished trout fishery (e.g., “-“ or “- -“ state), and never would we expect high trout abundance when winter flows were consistently low.

The respective tables relating one driving variable and outcomes for trout are presented as Tables II.19 through II.22.

Summer Base Flow, Water Temperature and Brown Trout States

It was assumed that cool water temperatures (brown trout can persist when water temperatures are consistently < 23ºC) would benefit trout and other cool-water fishes. It was also assumed that moderate to relatively high summer flows that are sufficient to maintain connections between pools, along with relatively deep riffles to support riffle-dependent fishes and aquatic insects and to maintain connections with backwaters and the main channel, would support a variety of life stages of trout. Observations

suggest this may be in the range of 35–50 cfs (minimum level), depending on the relative degree of channel confinement. Water temperatures that were potentially too warm (consistently > 23°C, which roughly corresponds with summer water temperature of the Poudre River downstream of the College Avenue bridge, near the downstream extent of brown trout persistence), particularly when induced by low flows, may stress trout and other cool-water fishes, and reduce or eliminate them from affected reaches.

To meet the summer base flow criterion, average flow from July 1–September 30 must be greater than 35 cfs and daily flow must also remain above 20 cfs. Meeting both of these is designated as adequate flow in the table. Temperature data are limited, but this factor is included as a categorical variable as shown in Table II.19.

Table II.19: Summer base flow and water temperature conditions, and the relative probabilities of achieving poor ("- -") to good ("+") populations of Brown Trout in the Poudre River upstream of College Avenue bridge.

	Brown Trout states			
Flow and water temperature states	**--**	**-**	**0**	**+**
Adequate flow and cool water (< 23°C)	0	0.15	0.15	0.7
Adequate flow and warm water (> 23°C)	0	0.25	0.5	0.25
Inadequate flow and cool water (< 23°C)	0.25	0.5	0.25	0
Inadequate flow and warm water (> 23°C)	0.7	0.15	0.15	0

Channel Structure and Brown Trout States

Channel Structure importantly reflects habitat diversity and subsequently the number of species and their abundance in the reach. For example, a clean and diverse channel has a variety of habitat types including pools, riffles, runs, and backwaters; among those there is variation in depths from deep to shallow, providing cover for all life stages of fishes. Further, a diverse and meandering channel may scour and undercut riparian trees that fall into the river and create deep-pool habitat and cover. A diverse channel would also support a variety of substrate types for reproduction, and those would typically be free of fine sediments that would allow for sufficient intra-gravel flow for egg incubation. Such may result in a relatively high probability of achieving a thriving Brown Trout community in the absence of other limiting stressors (e.g., high water temperatures), perhaps achieving a "0" or "+" state. Alternatively, a laterally constricted and entrenched canal-type habitat would have little diversity, consist mainly of runs (with few riffles or backwaters), have little or no cover, and substrate would be armored and homogeneous (which does not provide for reproduction). This is especially relevant for the Brown Trout indicator, as trout rely on clean gravel substrate for spawning in late autumn, well after scouring flows from springtime snowmelt runoff. A consequence of this type of channel for trout would be low abundance, with few age classes, and high probabilities of attaining "-" or "- - " states.

Such a range of channel conditions is created and maintained by geomorphically significant flow events, as described above. The effects of those flow events were not directly modeled on Brown Trout, therefore the model is not expected to have much direct sensitivity to high-flow metrics. However, the probability of Brown Trout population success was modeled to the state of Channel Structure at the whole reach scale, which is affected by high flows and bank stabilization (Table II.20). More detail on Channel Structure is presented above.

Table II.20: Channel Structure conditions, and the relative probabilities of achieving poor ("- -") to good ("+") populations of Brown Trout in the Poudre River upstream of College Avenue bridge.

	Brown Trout states			
Channel Structure states	**--**	**-**	**0**	**+**
Clean and diverse	0	0	0.25	0.75
Partially mobile and diverse	0	0.25	0.5	0.25
Largely immobile and homogeneous	0	0.5	0.5	0
Entrenched	0.75	0.25	0	0

Aquatic Insect Abundance and Brown Trout States

In terms of food resources, a high diversity of Aquatic Insect taxa that are available year-round and abundant would provide needed food resources for all life stages of Brown Trout. A low diversity of Aquatic Insect taxa, even when seasonally abundant, would provide less food for Brown Trout, or perhaps not enough of a certain size or life stage to support all life stages of fishes from larvae to large-bodied adults. Here, the state of the Aquatic Insect population at the whole-reach scale is considered in relation to Brown Trout states (Table II.21).

Table II.21: Aquatic Insect diversity and abundance and the relative probabilities of achieving poor ("- -") to good ("+") populations of Brown Trout in the Poudre River upstream of College Avenue bridge.

	Brown Trout states			
Aquatic Insect states	**--**	**-**	**0**	**+**
+	0	0	0.5	0.5
0	0	0.25	0.5	0.25
-	0.25	0.5	0.25	0

Winter Base Flow and Brown Trout States

Adequate Brown Trout habitat in winter requires submersion of spawning substrates that are free of fine sediments, and maintenance of inter-gravel flows to provide oxygenated and cool or cold water to developing embryos. Post-emergence, higher flows are needed to provide adequate habitat and escape cover for young fish, as larger brown trout are predaceous and cannibalistic. Observations of flow relative to habitat availability suggest that 35–50 cfs may be needed to maintain habitat diversity and connections, dependent upon channel complexity and width (Table II.22).

Table II.22: Winter base flow and the relative probabilities of achieving poor ("- -") to good ("+") populations of Brown Trout in the Poudre River upstream of College Avenue bridge.

	Brown Trout states			
Percent of years < 35 cfs	**--**	**-**	**0**	**+**
0–25%	0	0.1	0.2	0.7
25–50%	0.1	0.2	0.3	0.4
50–75%	0.2	0.3	0.3	0.2
75–90%	0.5	0.4	0.1	0
>90%	0.9	0.1	0	0

Methods and Probability Tables for Native Fish

States were assigned with designations ("+", "0", "-", and "- - ") to reflect the best to worst condition for Native Fish based on results of sampling at sites in the study area from 1982–2011. Those Native Fish community states are defined in Table II.23.

Table II.23: Description of four states of Native Fish that depend on summer baseflow, summer temperature, Brown Trout predation, Aquatic Insects, and Channel Structure.

State	Definition
+	High diversity (> 12 taxa in warm-water streams) and high abundance (> 1,000 individuals total), multiple life stages.
0	Moderate diversity (7–12 taxa in warm-water streams) and abundance (100–1,000 individuals total) in standard sampling effort, two or more life stages per species.
-	Low diversity (six or fewer taxa in warm-water streams) or abundance (< 100 individuals total) in standard sampling effort, single life stage for many species.
- -	Low diversity (four or fewer taxa in warm-water streams) and abundance (< 100 individuals total) in standard sampling effort, single life stages for most species.

It was assumed for Native Fish communities that the present state was between "0" and "-", but trending toward the "-" state. This is because of the declining state of native fishes in the Poudre River drainage and because many of the most sensitive taxa have already been extirpated (Bestgen and Fausch, 1993).

Main drivers for Native Fish states include:

1. Summer base flow and summer water temperature (a single variable with dual temperature limitations of potentially being too warm (> 30ºC, which may limit survival of some species) or too cool (<18ºC, which may limit reproduction by some species)
2. Channel Structure
3. Aquatic Insects
4. Brown Trout impact on Native Fish

It was assumed that water temperatures that were moderate (18–30ºC) and summer flows that were sufficient to maintain connections between pools—along with relatively deep riffles to support riffle-dependent fishes and aquatic insects and to maintain connections with backwaters and the main channel—would support a variety of reproductive styles and a diverse and abundant Native Fish community. Water temperatures that were potentially too warm (induced by low flows) or too cold (restricting reproduction by warm-water taxa) would negatively affect Native Fish, especially if flow conditions were altered and either very low or very high (possible but unlikely). That would be especially true if flows were low and induced heat stress or disconnected habitat in summer for some species with specialized reproductive styles (such as plains topminnow spawns in vegetation in backwaters).

Channel Structure importantly reflects habitat diversity and subsequently the number of species and their abundance in the reach. Channel Structure was treated for Native Fish similarly as to how it was treated for Brown Trout (see above).

In terms of food resources, a high diversity of Aquatic Insect taxa that are available year-round and that are abundant would provide needed food resources for all life stages of Native Fish in all seasons. A low diversity of Aquatic Insects, even when seasonally abundant, would provide less food for Native Fish, or perhaps not enough of a certain size or life stage to support all life stages of fishes from very small larvae to large-bodied adults.

The ERM team also included a variable regarding the impact of Brown Trout on Native Fish because, at high abundance levels, Brown Trout can suppress diversity and abundance of Native Fish via predation. Probability values for that metric reflect that even if physical habitat conditions are good for Native Fish, a healthy Brown Trout population has the ability to suppress Native Fish to a relatively low state. Conversely, if physical habitat conditions are good and Brown Trout abundance is low, the Native Fish community (at least the elements that now remain) has a moderate to high probability of achieving a "0" or "+" state.

The respective tables relating one driving variable and outcomes for Native Fish are presented in Tables II.24–II.27.

One key driving variable is a combination of summer base flow and summer water temperature (Table II.24). To meet the summer base-flow criterion, average flow from July 1–September 30 must be greater than 35 cfs and daily flow must remain above 20 cfs. Meeting both of these criteria is designated as adequate flow in the table. Temperature data are limited, but this factor is included as a categorical variable and associated with the flow driver.

Table II.24: Summer base flow and water temperature states and the relative probabilities of achieving poor ("- -") to good ("+") Native Fish populations in the Poudre River upstream and downstream of College Avenue bridge.

	Native Fish states			
Flow and temperature states	**--**	**-**	**0**	**+**
Adequate flow and water temperatures (18–30ºC)	0	0.15	0.15	0.7
Adequate flow and inadequate water temperatures (< 18ºC or > 30ºC)	0	0.25	0.5	0.25
Inadequate flow and adequate water temperatures (18–30ºC)	0.25	0.5	0.25	0
Inadequate flow and inadequate water temperatures (< 18ºC or > 30ºC)	0.7	0.15	0.15	0

Channel Structure is impacted by high flows and bank stabilization, and the effects of the different types of Channel Structure on Native Fish were estimated (Table II.25). More detail on Channel Structure is presented above in the Brown Trout section.

Table II.25: Channel Structure states and the relative probabilities of achieving poor ("- -") to good ("+") Native Fish populations in the Poudre River upstream and downstream of College Avenue bridge.

	Native Fish states			
Channel Structure states	**--**	**-**	**0**	**+**
Clean and diverse	0	0	0.25	0.75
Partially mobile and diverse	0	0.5	0.25	0.25
Largely immobile and homogeneous	0.25	0.5	0.25	0
Entrenched	0.75	0.25	0	0

For the driving variable of Aquatic Insect populations at the whole-reach scale, Table II.26 shows the estimated response of Native Fish to different levels of Aquatic Insect biomass and diversity. (More detail on Aquatic Insect modeling is provided above.)

Table II.26: Aquatic Insect states and the relative probabilities of achieving poor ("- -") to good ("+") Native Fish populations in the Poudre River upstream and downstream of College Avenue bridge.

	Native Fish states			
Aquatic Insect states	**--**	**-**	**0**	**+**
+	0	0	0.5	0.5
0	0	0.25	0.5	0.25
-	0.25	0.5	0.25	0

The Native Fish states, in response to Brown Trout predation at the whole reach scale, are shown in Table II.27.

Table II.27: Brown Trout population states and the relative probabilities of achieving poor ("- -") to good ("+") Native Fish populations in the Poudre River upstream and downstream of College Avenue bridge.

	Native Fish states			
Brown Trout states	**--**	**-**	**0**	**+**
--	0	0	0.25	0.75
-	0	0	0.5	0.5
0	0	0.25	0.5	0.25
+	0.75	0.25	0	0

RIPARIAN VEGETATION – REJUVENATING MOSAIC, FUNCTIONAL RIPARIAN ZONE AND RIVERINE WETLANDS

This focus of the ERM was led by and is reported on by the following experts:

- *Gregor Auble, Ph.D., Riparian Ecologist, United States Geological Survey*
- *David Merritt, Ph.D., Riparian Ecologist, United States Forest Service*

Background

The riparian zone is the portion of stream channel occurring between the low and high water marks and the adjacent terrestrial areas extending from the high water mark toward the uplands where vegetation may be influenced by elevated water tables or flooding. The riparian zone is an integral part of the overall river system in a number of important respects. Occasional inundation of this area:

1. Expands the physical habitat and food resources available to aquatic organisms
2. Enables transport and exchange of water-borne materials including sediment, nutrients, propagules, and contaminants
3. Influences the pattern of streamflow by storing and slowing water

In turn, the moisture and physical disturbance provided by the river produce terrestrial flora and fauna that are generally distinct from those in surrounding uplands.

Streamflow acting on the bottomland topography governs the characteristics and composition of these riparian zones and the nature of riparian vegetation. Species composition of vegetation varies across a gradient, from locations near the channel that are inundated for a long duration each growing season and subjected to intense physical disturbance, to locations further from the channel that are less frequently and intensely flooded. Plants growing along river margins typically have adaptations to flooding, scour, occasional burial, submergence, and seasonally varying water availability (Lytle and Poff, 2004).

The riparian portion of the Poudre River system in Fort Collins is set in an alluvial fan associated with the change from a steep canyon setting to the lower gradient plains. A number of physical variables change rapidly in the upstream-downstream direction with implications for the behavior of the riparian system. The change in gradient produces an unstable geomorphic setting that is naturally prone to channel movement. The steep gradients of temperature and elevation encompass the edges of distributional ranges for some species. One example is cottonwood. Narrow-leaved cottonwood *(Populus angustifolia*) occurs in the higher-elevation, cooler Poudre Canyon, shifting to plains cottonwood (*Populus deltoidies*) downstream in the lower-elevation, warmer plains. This transition occurs within Fort Collins with sites near the canyon mouth dominated by narrow-leaved cottonwood, which can exhibit substantial vegetative reproduction, and sites on the eastern edge of Fort Collins dominated by plains cottonwood, which is almost exclusively dependent on regeneration from seed.

The Poudre River riparian system in Fort Collins is heavily modified in several fundamental ways. Streamflow has been altered substantially. Topography and bank stability have been altered to restrict the extent of inundation and lateral channel movement. In combination with clearing and land development, this has narrowed the functional riparian zone (Figures II.7 and II.8). Furthermore, beaver are likely having a much smaller role in enhancing channel complexity today than in the 1800s. The combination of gravel mining, water conveyance and storage, and applied water (irrigation) has made the uplands adjacent to the river wetter. This tends to blur the vegetative transition, or boundary between riparian and upland, by allowing plants that might otherwise be restricted to a riparian zone (where

supplemental river moisture was available) to extend farther into the surrounding uplands. Finally, the species pool has changed dramatically in the last 150 years. For example, introduced species such as crack willow (*Salix fragilis*), Siberian elm (*Ulmus pumila*), Russian-olive (*Elaeagnus angustifolia*), and saltcedar (*Tamarix ramosissima*) are now important components of the woody riparian communities in Fort Collins and generally throughout the western U.S. (Friedman *et al*., 2005).

Figure II.7: Area between Overland Trail and Taft Hill roads in 1937.

Note: In this image, a wide zone of channel movement and cottonwood forests of various ages that have established along the former paths of the river may be seen.

Figure II.8: This shows the same area as Figure II.3 after a century of land use changes (including extensive gravel mining).

Note: In combination with bank stabilization, these land use and topographic changes have confined and simplified the channel, reduced channel migration and the associated rejuvenation of plant species (such as plains cottonwood) that require bare, moist sites for establishment. This transition to an urban geomorphology has effectively narrowed the riparian zone and mediates the biological responses to Poudre River streamflows.

Methods and Probability Tables

Approach

A number of procedures have been developed for quantifying relationships between streamflow and the distribution and abundance of riparian vegetation (Merritt *et al*., 2010). Many of these involve the following basic steps.

1. Estimate how streamflow determines physical conditions throughout the bottomland
2. Relate physical conditions to riparian vegetation through the use of modeling, empirical data, and expert judgment
3. Project the likely physical conditions (duration of inundation) at various locations associated with alternative streamflow regimes
4. Estimate new riparian vegetation from projected physical attributes (reflecting different future flow scenarios)

The ERM team implemented the steps listed above using existing data (from aforementioned sources) to produce three Bayesian network indicators:

1. Rejuvenating Mosaic, an index of the potential for floodplain turnover and creation of new bare, moist sites
2. Functional Riparian Zone, an indicator of the area providing general riparian functions
3. Riverine Wetlands, an indicator of riverine wetland area (width) based on surface water inundation from the river

Finally, a set of more-detailed geospatial probability of occurrence models were established for selected individual plant species and riparian guilds.

Data

The City of Fort Collins Natural Areas Department sampled riparian vegetation along the Poudre River along 55 transects in 2009 (Shanahan, 2009). The City provided a digital elevation model (DEM) for the Poudre River corridor in the form of a Triangulated Irregular Network (TIN) of elevations (±1 m). It also used a linear coverage of known riprap and hardened levee locations (J. Shanahan, 2011, pers. comm.). An ArcGIS shapefile of cross-sectional data and a HEC-RAS (1-dimensional hydraulic) model of the Poudre River were obtained from Anderson Consulting Engineers (USACE, 2008; Brad Anderson, 2011, pers. comm.). The HEC-RAS hydraulic model was used for the Poudre River from the town of Laporte to slightly downstream of Interstate 25. Finally, a flow partitioning algorithm was used to relate measured or predicted flows at gage locations to the pattern of flows in reaches of the river as influenced by locations of water withdrawals and accretions (Andy Pineda, 2012, pers. comm.).

Relationship of Streamflow to Physical Conditions in the Bottomland

From the elevational TIN data, the ERM team first created an ArcGIS grid coverage of the Poudre River bottomland from the town of Laporte to slightly below Interstate 25. It then created a channel center line of the main channel and, as described in the Overview subsection, subdivided the total area into eight reaches based on a combination of geomorphic characteristics (e.g., degree of confinement) and known flow changes due to major diversion structures.

The hydraulic model was run at a series of discharges: 200, 300, 400, 500, 600, 700, 800, 900, 1,000, 1,500, 2,000, 2,500, 3,000, 3,500, 4,000, 4,500, 5,000, 5,500, 6,000, 6,500, and 7,000 cfs. Water-surface

elevations were obtained for each discharge for all the grid cells within the study area by natural neighbor interpolation between the spatially referenced hydraulic cross sections. Within the limitations of accuracy and the discrete cells and given discharges, these calculations provide an estimate of the stream discharge required to inundate each cell (water surface at or higher than ground elevation) as well as the aggregate area inundated by various discharges. These calculations were then used to provide an estimate of the pattern of inundation associated with a given flow regime at the scales of both individual geospatial cells and aggregated areas along different reaches.

The riparian study area was restricted to cells above the river stage at 200 cfs (excluding the channel itself, where bathymetry was unavailable) and below the 7,000 cfs flow line. The area above 7,000 cfs was excluded because it was very rarely inundated, and it contained a large fraction of fully-developed land. Cells that were in strongly anthropogenic cover types (such as structures, parking lots, and roads) were also excluded, as were areas where inundation was not dominated by the river (such as permanent ponds created by gravel mining). Further details of these calculations are given in Appendix B.

Rejuvenating Mosaic Condition

Many riparian species do well near the river because they have adaptations, tolerances, or requirements for a moist, moveable, and frequently disturbed environment. These communities and species tend to decline in the absence of disturbances, channel movement, and periodic turnover of near channel substrates. The clearest example of this in Fort Collins is plains cottonwood, whose regeneration from seed is highly dependent upon new bare, moist disturbance patches (Mahoney and Rood, 1998; Scott and Auble, 2002; Rood *et al*., 2007). Once established, plains cottonwood trees can survive well in the absence of disturbance, but are very unlikely to be replaced in undisturbed locations by subsequent generations of plains cottonwood.

Floodplain turnover creates new disturbance patches for the rejuvenation of riparian forests, but can also have deleterious effects on human infrastructure. Floodplain turnover and channel movement tend to be episodic and are difficult to predict. There is a strong temptation to avoid considering floodplain turnover or channel migration at all, because that is difficult to do with confidence. However, this reluctance needs to be balanced against the limitations of any analysis that ignores what is known to be a critical driving variable. Some of the primary controlling factors of floodplain turnover are topographic constraints that define the low-lying area of most likely channel movement, the ability of the river to mobilize and transport sediment, and the natural and human-hardened resistance of the banks and sediment to mobilization. The Rejuvenating Mosaic variable combines these factors as an index to the relative potential for a rejuvenating riparian mosaic. The result is an index of relative potential, rather than a prediction of the extent, timing, or location of channel change.

The Rejuvenating Mosaic index is calculated as the product of:

a. area (expressed as average width) of potential floodplain turnover (low-lying, occasionally flooded area where movement is most likely)
b. the ability of the flow regime to mobilize substrate based on shear stresses associated with a flow regime
c. a fractional reduction due to extent of bank stabilization

The area of potential floodplain turnover is estimated using maximum daily flows (partial duration series of all days in the years), excluding area below the 200 cfs flow line (corresponding to the upper edge of the primarily aquatic zone). These areas, and corresponding average widths, are calculated using

exceedance probability of annual maximum daily flows and the same reach-specific area to discharge relationships used for the Riverine Wetlands and Functional Riparian Zone variables.

Widths of potential floodplain turnover are grouped into four classes of Minimal (0–15 m), Narrow (15–45 m), Moderate (45–90 m), and Wide (>90 m). Midpoints of these potential width classes (120 m for the Wide class) are multiplied by a measure of capacity of a flow regime to mobilize reach-specific bed sediment. This is expressed as the average expected days per year of channel movement, with the daily probability of channel movement estimated as a modified power function of the dimensionless shear stress produced by a given flow relative to the dimensionless critical shear stress associated with reach-specific bed sediment (as detailed in Appendices B2 and B5). Average expected days per year of channel movement are grouped into four classes of None, Rare (> 0–0.05), Infrequent (0.05–2), and Occasional (> 2), with midpoints of classes used in the multiplication. The resulting product is fractionally reduced according to the reach-specific class of bank stabilization (Table II.28).

Table II.28: Classes of channel stabilization.

Class	Description – based on length of stabilizing features relative to bank length (twice the channel length)
Minimal	Stabilized length occurring at any distance from channel center line is < 5% of bank length.
Altered	Stabilized length > 5% of bank length and stabilized length occurring < 50 m from channel center line is < 15% of bank length.
Protected	Stabilized length occurring < 50 m from channel center line is 15–30% of bank length.
Stabilized	Stabilized length occurring < 50 m from channel center line is > 30% of bank length.

Note: Current values for Reaches 3a, 3b, and 7 are Protected, Protected, and Altered, respectively.

This calculation produces a single value ranking the relative extent and likelihood of floodplain turnover. Units of this index are average expected days of channel movement per year times the width of floodplain subject to turnover in m. Uncertainty (and a partial correction for underestimation from both unequal bin widths and using the lower bound of the discharge classes in the application of the width-discharge tables) is incorporated using the same general logic used for the Riverine Wetlands and Functional Riparian Zone variables described above. A uniform probability distribution from 0.2–2.2 times the point estimate is used to estimate probabilities across the four discrete states of Minimal, Small, Moderate, and Substantial (Table II.29).

Table II.29: Description of four states of a Rejuvenating Mosaic of riparian vegetation that depend on channel movement.

Rejuvenating Mosaic states	Index of potential floodplain turnover (days * m / yr)	Selected examples
Minimal	0–0.2	(a) No shear stress competent to move bed, (b) combinations of minimal 1 in 5-yr floodplain, stabilized or protected channel, and rare or infrequent channel movement (low average shear stress)
Small	0.2–2	(a) Wide or moderate 5-yr floodplain, protected or altered channel and rare or infrequent channel movement, (b) minimal 5-yr floodplain, altered or protected channel, and occasional channel movement
Moderate	2–5	(a) Narrow 5-yr floodplain, protected or altered channel, and occasional channel movement, (b) moderate 5-yr floodplain, altered channel, and infrequent channel movement
Substantial	> 5	a) Wide 5-yr floodplain, minimal channel stabilization, occasional channel movement (high average shear stress)

In the Bayesian network model, the results of these calculations are represented as a large table with class probabilities for combinations of reach, 1 in 5-year daily high flow, class of channel stabilization, and average days of expected channel movement calculated from daily shear stresses (Appendix B).

The Rejuvenating Mosaic index responds in the right directions to the main controlling factors. However, specific predictions of channel movement on these scales are extremely difficult and uncertain, even in those rare situations when they can be empirically based on extensive, site-specific data sets and models. Thus, the index should be interpreted as an approximate, relative scoring of alternative flow regimes.

Functional Riparian Zone Condition

Riparian areas in general exhibit a strong pattern of species and community change along elevation and moisture gradients from the river to surrounding uplands. This pattern was evident in the Poudre River transect vegetation data provided by the City of Fort Collins. There was not, however, a clear break or threshold in these distributions, the lack of which reflects a combination of multiple influential factors including sample size, relatively short transects not extending far into uplands, and blurring of the riparian-upland transition by a combination of planting and clearing, application and storage of water in the uplands, human land uses, and natural turnover of plant species along such moisture gradients.

Thus, a measure of Functional Riparian Zone was defined as the area inundated by the river at least one day in two years of growing season days (growing season exceedance of 0.0033). Area below the 200 cfs flow line was excluded (in channel). The Functioning Riparian Zone will include the narrower, more frequently inundated Riverine Wetlands described below. The Functioning Riparian Zone variable is formulated as width classes (Table II.30) with uncertainty around the point estimates incorporated using the same approach described below for the Riverine Wetlands variable. A large table relates 0.0033 growing season exceedance flows to Functional Riparian Zone width classes in the Bayesian network model (Appendix B).

Table II.30: Description of four states of width that depend on inundation by the river at least one day in the two years of growing season days.

Functional Riparian Ecosystem states	Average width in m (total area / channel length)
Minimal	< 15
Narrow	15–45
Moderate	45–90
Wide	> 90

Note: Widths include both sides of the channel and represent total area divided by channel length.

Data from the vegetation transect plots did indicate a significant difference in plant species composition above (drier) compared to below (wetter) the stage of the 0.0033 exceedance flow (ANOSIM, $p = 0.004$). However, the Functional Riparian Ecosystem variable is not focused on specific and abrupt vegetation differences. Rather it is intended to provide an index of the area of connected floodplain that occasionally provides functions such as organic matter exchange, sediment trapping, nutrient and contaminant processing, expansion of aquatic habitat, and flood peak attenuation.

Riverine Wetlands Condition

This Bayesian network indicator estimates the area where inundation from the river is sufficient to support plant communities dominated by species that tend to occur in wetlands. The variable represents the average width of this zone (total area in a reach divided by length of channel in a reach) summarized in four width classes (Table II.31). Because they are defined as total area divided by length, the states include area on either side of the channel (for example, 5 m on one side and 15 m on the other side would be a width of 20 m, classified as Moderate).

Table II.31: Description of four states of Riverine Wetlands extent that depend on inundation for 5% of the growing season.

Riparian Wetlands states	Average width in m (total area / channel length)
Minimal	< 5
Narrow	5–15
Moderate	15–30
Wide	> 30

Note: Widths include both sides of channel and represent total area divided by channel length.

The upper, higher elevation edge of this zone is defined as land that is inundated 5% of the growing season. Current regulatory procedures (Environmental Laboratory, 1987–201, online version) for the wetland hydrology criterion specify continuous inundation or saturation for at least 5% of the growing season in most (50%) years. The Natural Research Council (NRC, 1995) recommended a hydrology threshold of two growing season weeks of soil saturation (to within 0.3 m of surface) at least every other year (an overall frequency of approximately 0.05 of May–September days) for supporting hydrophytes. The ERM includes a threshold value of 0.05 of all growing season (May–September) days of surface inundation. This hydrologic threshold of 0.05 of growing season days closely corresponds to the flow exceedance value associated with a 50% (prevalence) probability of occurrence of the hydrophytic vegetation guild from the field data and geospatial probability of occurrence modeling (Figure II.9 and Appendix B5). The lower (streamward) edge of the Riverine Wetlands zone was assumed to be the 200-cfs flow line.

Calculation of this indicator begins with the discharge that is equal to or exceeds the 0.05 fraction of the growing season in a given flow scenario and reach. This value is used to access area-discharge relationships that summarize the area, and corresponding average width, inundated by different discharges as determined by hydraulic model output. Flows intermediate between the discrete discharges used in the hydraulic model are assigned the width at the lower end of the range. This point estimate of width is unreasonably precise and somewhat biased to underrepresent the width by using the width associated with the lower end of each flow range. Thus, each point estimate of width (*w*) was expanded to a width range of 0.6*w* to 1.6*w* (addressing both uncertainty in the exact value and bias toward lower values). This range of widths was then converted to probabilities for the discrete width classes (Table II.24) by assuming a uniform probability across the range and considering how much of the range fell within different width classes. The results of these calculations are represented in the Bayesian network model as a table discretely relating 0.05 growing season exceedance flows to width class probabilities for each reach. The portions of this table corresponding to the focal Reaches 3a, 3b, and 7 are presented in Appendix B5 (Table B.12).

Geospatial Probabilities of Occurrence

In addition to the three riparian indicators used in the Bayesian network model, the same underlying formulation of the relationship between streamflow and physical conditions in the bottomland—streamflow sequence apportioned across reaches, hydraulic model of water surfaces across discharges, and topography—was used to model probabilities of occurrence of select plant species and species groups (Appendix B). The resulting models are computationally intensive and geographically detailed, and thus not directly incorporated into the ERM. Rather, they represent an alternative and corroborating formulation of the relationship between streamflow regime and riparian vegetation response.

In order to calibrate probability of occurrence models, global positioning system (GPS) coordinates of the vegetation transects and the spacing of plots along those transects was used to determine geospatial coordinates of vegetation plots sampled in 2009. Their location on the grid coverage allowed an estimate of their elevation and inundating discharge from detailed digital elevation models. Their location in a specific reach, in combination with the flow partitioning algorithm applied to the historic flow record, produced a history of inundation at each of these plots. Fitting observed occurrence associated with historic inundation at the sampled plots yielded response curves (logistic regression models) relating probability of occurrence to a given inundation duration. As illustrated in Appendix B (Subsection B5), these curves could then be used to project probabilities of occurrence throughout the study area from the patterns of inundation associated with an alternative flow scenario for every grid cell across the area of interest. To project change in response to various future water scenarios, the ERM team then predicted probability of occurrence of several cover types as a function of exceedance probability, determined the number of grid cells with probabilities of occurrence of 60% or higher, and then calculated the areas of high probability occurrence.

Figure II.9 shows the model-predicting probability of occurrence of a hydrophytic vegetation guild as a function of growing season inundation. Prevalence of hydrophytic vegetation is a wetland delineation criterion that should correspond to the hydrologic criterion used in the Riverine Wetlands indicator. The model fit to Poudre River data (Figure II.9) predicts a 50% probability of occurrence of hydrophytic vegetation very near the 0.05 growing season inundation value, providing strong corroboration of the simpler Bayesian network indicator. More detailed descriptions and results from these probability-of-occurrence models are presented in Appendix B (Subsection B5).

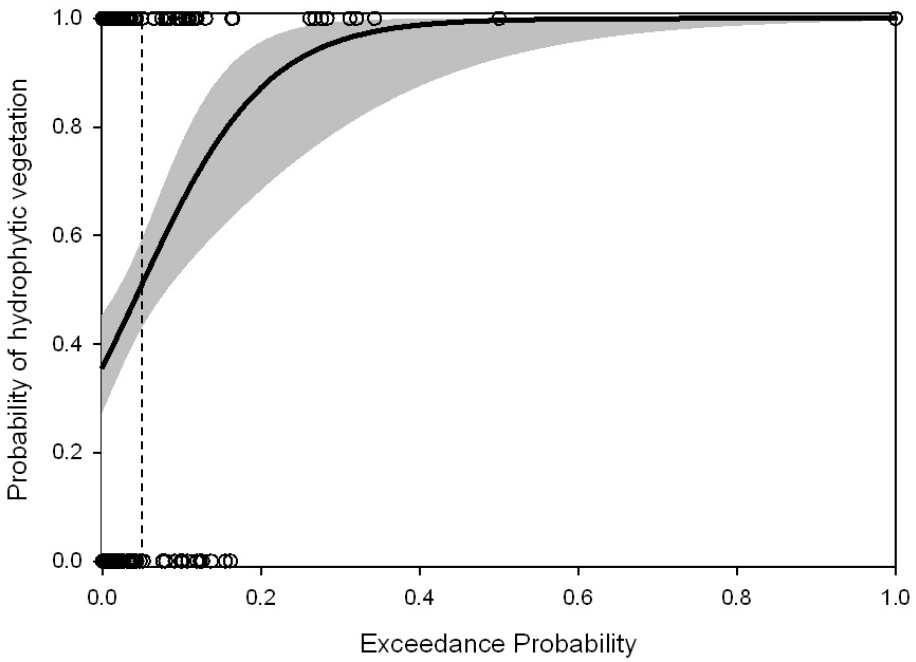


Figure II.9. Probability of herbaceous hydrophytic species guild as a function of inundation fit to 2009 Poudre River riparian plot data using logistic regression.

Note: Exceedance probability is fraction of growing season that the plot is inundated (higher values are wetter). Circles are individual plots where presence=1 or absence=0. Shaded zone is the 95% confidence interval. The dashed vertical line is the 0.05 exceedance value used for the Riverine Wetlands indicator.

SUMMARY OF COMPONENTS ANALYSES

The ERM was modelled to represent the multi-dimensional character for the modern, urban Poudre river landscape. Table II.32 provides an at-a-glance summary for all the analyses conducted for model components to assist in understanding this project.

Table II.32: Summary of analytical approach and data availability for each model component.

Model component	Analytical approaches	Availability of data for each reach
Channel Structure	Hydraulic modeling of reach-specific shear stresses and sediment mobility, effective discharge analysis, and historical analysis of aerial images.	Channel geometry, sediment size distributions, and hydrologic data available for all three reaches (3a, 3b, and 7).
Algae and Nutrients	Algae based upon estimates and observations. Nutrients concentrations converted to probabilities of annual loading.	Algae; no data Nutrients; Reaches 3a and 3b have single nutrient data source (Lincoln Street gage) Boxelder gage provided data for Reach 7
Aquatic Insects	Percent EPT (percent sensitive species).	Available for all three reaches.
Fish - Brown Trout	Compared abundance of young trout to important flow parameters, including those during reproductive periods. Categorized data that showed a positive relationship between young trout abundance and flow the previous winter.	Reaches 3a and 3b treated together with data from site near McMurray Natural Area/Martinez Park. Reach 7 used data from Environmental Learning Center (ELC).
Fish –Native Species	Explored relationships between mean, peak, and base flow levels to fish species richness, abundance, and biomass. Trends and spatial patterns observed were weak so species habitat use patterns and expert judgment were used to hypothesize population responses to flow and management actions.	Reaches 3a and 3b treated together with data from site near McMurray Natural Area/Martinez Park. Reach 7 data provided from samples at ELC.
Riparian Vegetation - Rejuvenating Mosaic	Potential zone of movement reduced by shear stress and extent of bank stabilization.	Hydraulic, topographic, and channel stabilization data available for entire study area. Little empirical data on actual rates of channel movement.
Riparian Vegetation - Functioning Riparian Zone	Area inundated by the river at least one day out of every two growing seasons and supported by a significant difference in plant species composition above (drier) compared to below (wetter) that elevation	Hydraulic, topographic, and vegetation transect plot data available for entire study area.
Riparian Vegetation - Riparian Wetlands	Threshold based in inundation duration during growing season corroborated by probability of occurrence of hydrophytic (water loving) vegetation guild.	Hydraulic, topographic, and vegetation transect plot data available for entire study area.

SECTION III: RESULTS AND DISCUSSION

OVERVIEW

Section III describes the estimated ecological response to each hydrology scenario and examines differences among flow scenarios for each of the three reaches studied through the ERM. As discussed in Section II, each indicator was scaled on a spectrum from *higher functioning condition* to *most degraded condition*. The results presented in this section are appropriately interpreted in comparative terms. The relative differences for indicators across scenarios and reaches, and the patterns of indicator responses, are considered more important than the absolute value of any indicator in isolation.

Section III provides indicator results for all nine hydrological scenarios (five core and four test) over the three river reaches (Figures III.1–III.8). Graphical results are preceded by state definition tables (as reproduced from Section II) along with explanations that link back to the Bayesian model structure to facilitate interpretation of the figures.

Next, the same complete set of results is presented as a single expected value (the mean of the full probability distribution) in Figures III.9-III.12.

BAYESIAN MODEL RESULTS

The following series of graphs and figures demonstrates the ERM results for each indicator, along with a discussion of their relative relevance.

Channel Structure Results

Table III.1 is presented below (as reproduced from Section II: Channel Structure) as a useful reference for interpreting the results for Channel Structure that follow.

Table III.1: Description of four states of Channel Structure that depend on the combined status of flushing flows, coarse substrate mobilization, channel migration flows, and extent of armoring.

State	Description
Clean and diverse	Flushing and bed mobility flow functions intact, substrate clean on surface, interstitial space open, vegetation encroachment not advancing, channel has wide variety of depth, velocity, substrate combinations with morphologically diverse features such as side channels, chutes, bars owing to substantial removal of lateral armoring.
Partially mobile and diverse	All three flow functions at least partially intact, flushing occurs at least every few years, interstitial space open in high-stress zones such as riffles, vegetation encroachment slowly advancing in low-stress zones, habitat diversity flows may be intact but lateral armoring partially limiting channel complexity.
Largely immobile and homogeneous	Bed mobilization and/or channel migration flows not intact, flushing partially or not intact, vegetation encroachment likely advancing, river increasingly canal-like with homogeneous habitat until partially reset by an extreme event that overcomes riprap armoring in isolated locations, substrate flushing at least partially intact, habitat diversity flows could be intact but lateral armor present
Entrenched	Partial to no substrate cleaning, channel maintenance absent, interstitial space not opened > 3–5 years, extensive lateral armoring, canal-like homogeneous channel.

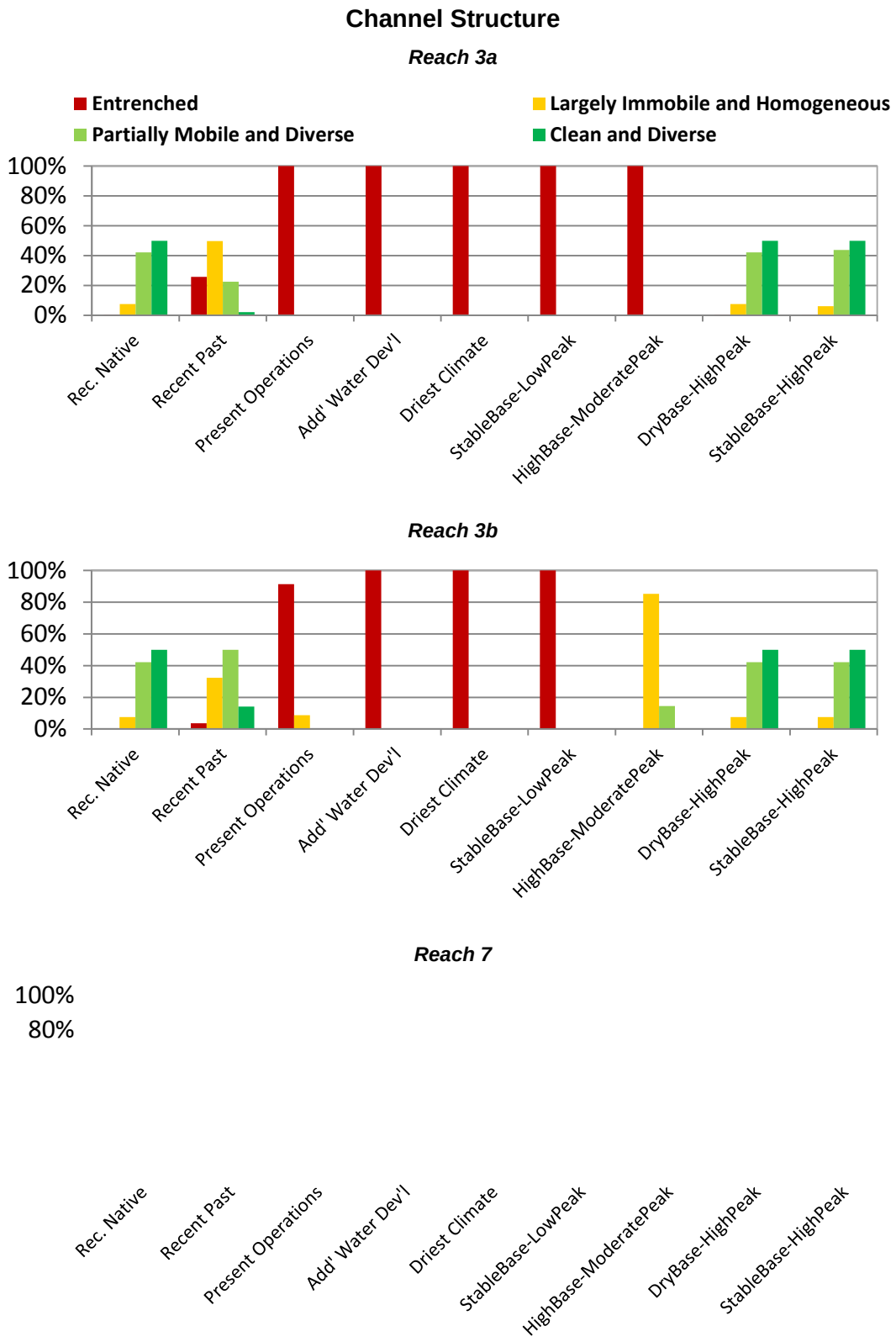


Figure III.1: Relative likelihood of four states of Channel Structure associated with nine flow scenarios.

Note: Plots for each of the three focal river reaches are arranged from upstream to downstream (Reach 3a on top, Reach 3b in the middle and Reach 7 at the bottom).

The ERM thus suggests the following regarding Channel Structure:

- Channel condition reflects both the geomorphic work performed by high flows in rejuvenating habitats, as well as direct human influences, such as leveeing and bank armoring. Geomorphic work is the balance between available hydraulic power (flow velocity and shear stress) and bed sediment size. The median sediment size in our three reaches decreases more rapidly than channel slope moving downstream (d_{50} in Reach 3a = 56mm, 3b = 52mm, 7 = 36mm). Hence, the flow required to achieve the same degree of work and habitat maintenance also decreases in a downstream direction (see Table III.2). This sediment size reduction more than counteracts the subtle decrease in flow between Reaches 3 and 7 to result in comparable amounts of geomorphic work being performed at lower flow rates in Reach 7.
- Historically, the river bed sediment was probably finer when the channel had larger peak flows, was less laterally constrained, and had access to sources of gravel stored in the floodplain. Reduced high flows, channel straightening, and bank stabilization have reduced habitat quality resulting in conditions that only occasionally flush sand and silt. Substantial reductions in the high flows (magnitude, frequency, and duration) that loosen gravels and cobbles have caused the riverbed to coarsen and interstitial spaces between cobbles to become clogged with finer sediment. This coarsening of the bed sediment size, also known as *armoring*, is particularly evident in Reach 3a. While reach 3a has the same flow as Reach 3b,the armoring and confinement cause 3a to have lower condition values for all scenarios (with the exception of the Driest Climate scenario, where all reaches are in the lowest state).
- The test scenarios demonstrate the same effects of downstream fining (a steady decrease in cobble size such that the river bed is composed of a much greater proportion of finer sediments in the downstream reaches) relative to channel slope as the base scenarios (i.e., Reach 7 generally has a greater probability of a higher geomorphic condition than Reach 3a). It is worth noting that all flows above the base flow in DryBase-HighPeak and StableBase-HighPeak scenarios are the same; hence, their effect on Channel Structure is identical.
- The HighBase-ModeratePeak scenario has an adequate frequency and magnitude of flushing flows, but lacks peak flows that can move coarse bed sediment. Hence, its channel condition scores moderately well, but the peak flows will not likely reset bed sediment armoring and limit channel vegetation encroachment.

Table III.2: Discharge (cfs) corresponding to three thresholds of dimensionless shear stress at the three study locations (as reproduced from Section II: Channel Structure).

Location	$\tau_* = 0.021$	$\tau_* = 0.03$	$\tau_* = 0.035$	$\tau_* = 0.06$
Reach 3a: Taft to Shields	1,750	2,700	3,300	6,900
Reach 3b: Shields to College	1,400	2,500	3,200	8,000
Reach 7: Boxelder Gage to I-25	900	1,550	2,100	9,200

Algae Results

Table III.3 is presented below (as reproduced from Section II: Algae) as a useful reference for interpreting the results for Algae that follow.

Table III.3: Description of three states of Algae that depend on dilution flows, temperature, and flushing flows.

State	Definition
Less than today	Less frequent and/or less severe algal blooms than have been typical in recent years.
About the same as today	About the same frequency and severity of algal blooms as have been typical in recent years.
More than today	More frequent and/or more severe algal blooms than have been typical in recent years.

ERM data surrounding the Algae indicator suggest the following.

- The risk of excessive production of Algae generally increases with increases in nutrient concentrations, bed stability, and light. Based on current loading of nitrogen and phosphorus, reduced flow results in higher nutrient concentrations. Conversely, higher flows result in lower nutrient concentrations and more scouring of Algae.
- Nutrient monitoring performed by the City of Fort Collins from 2006–2011 shows no clear trend in nutrient concentrations between the Lincoln Street gage (data used for calculations in Reaches 3a and 3b) and the Boxelder gage (data used for Reach 7). This results in minimal differences between the three reaches in algal indicator values.
- With decreasing flows, the ERM indicates a substantially increased risk of proliferation of Algae (compared to today's levels) between the Present Operations scenario and Additional Water Development scenario above College Avenue. In Reach 7, this shift occurs after the anticipated flow reductions are combined with Driest Climate.
- Algae production is linked primarily to the scouring function of higher flows and secondarily to the proliferation that occurs during low flows (and higher temperatures and nutrient concentrations). This is reflected with the improvement of HighBase-ModeratePeak over StableBase-LowPeak, and with a slightly greater improvement expected from the DryBase-HighPeak scenario.
- Similar to the riparian indicators described below, no change occurs between the Recent Past and Present Operations scenarios, because a critical high-flow threshold is missed in both scenarios.

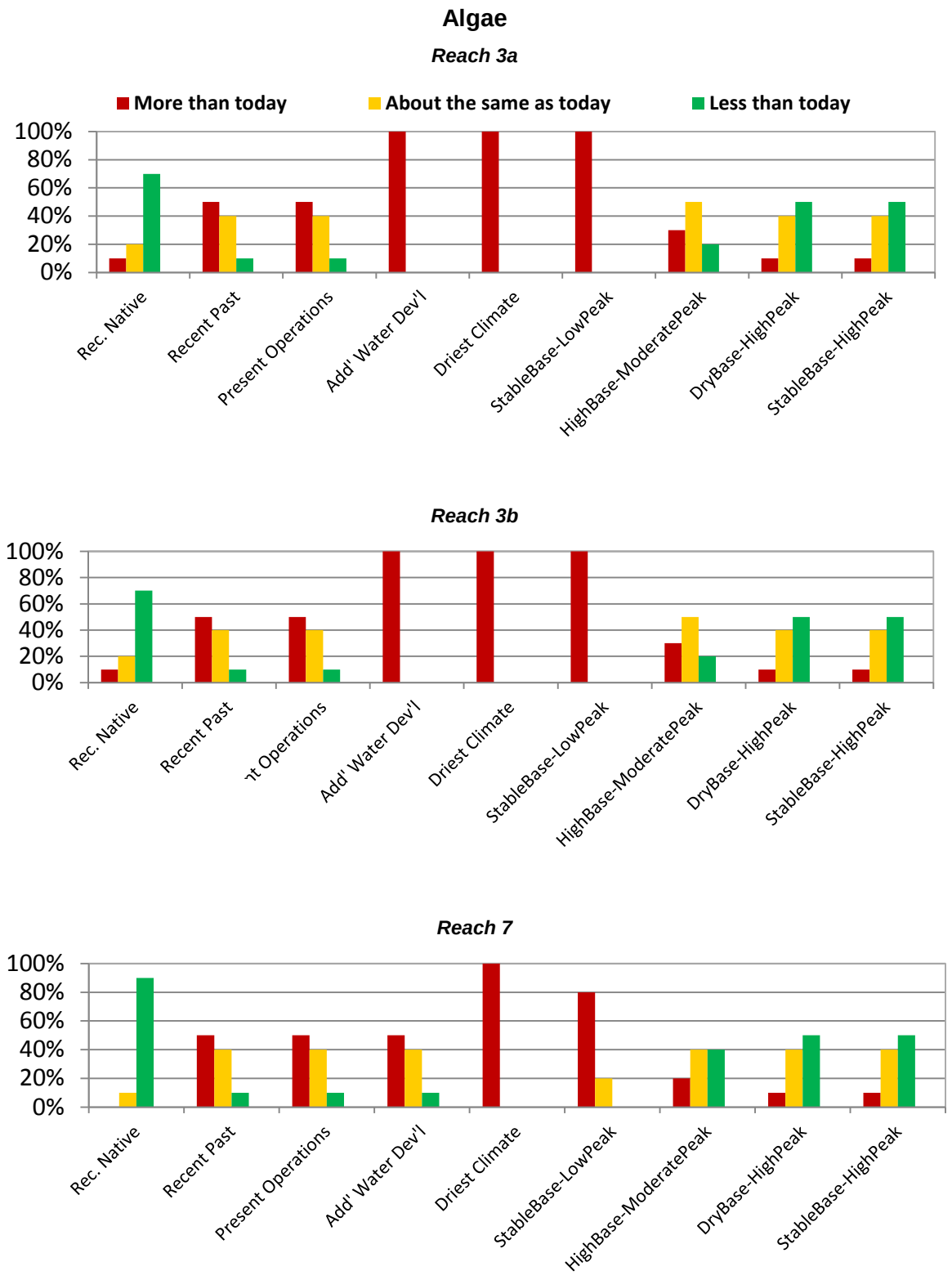


Figure III.2. Relative likelihood of three states of Algae associated with nine flow scenarios.

Note: Plots for each of the three focal river reaches are arranged from upstream to downstream (Reach 3a on top, Reach 3b in the middle and Reach 7 at the bottom).

Aquatic Insects Results

Table III.4 is presented below (as reproduced from Section II: Aquatic Insects) as a useful reference for interpreting the results for aquatic insects that follow.

Table III.4: Description of three states of Aquatic Insects that depend on scouring flows that cleanse streambed and check algal proliferation, and on summer baseflows.

State	Definition
+	Presence of species that take one (univoltine) to two (semivoltine) years to complete life cycles; semivoltine species present in all size classes, indicating successful annual reproduction and similar abundance to upstream/canyon areas; similar overall diversity to upstream/canyon reaches.
0	Mostly univoltine taxa present; reproduction during favorable conditions; less abundant than upstream/canyon areas; low diversity compared to upstream/canyon reaches.
-	Mostly univoltine taxa present; low abundance or high abundance dominated by tolerant taxa such as oligochaete worms, Turbellaria (flatworms), and chironomid worms.

The following points are relevant to the Aquatic Insects results.

- As a result of a long legacy of flow extraction and human development, the most sensitive species of Aquatic Insects became locally extinct in the system long ago. Thus, the remaining species do not exhibit as much sensitivity to flow alteration. Because empirical data describing response to flow alteration are sparse and inconclusive, probabilities within the model were developed with a more conservative approach such that relatively large changes in flow and other inputs are required to shift ecological states. The subtle responses observed for Aquatic Insects reflect this conservative approach and relative uncertainty in the absence of adequate data.
- For Aquatic Insect conditions, the StableBase-HighPeak test scenario (with both high- and low-flow improvements) consistently outperformed the test scenarios with only a single type of flow (high or low) improved. This is due to the positive response of Aquatic Insects to both improved channel substrate conditions and consistent summer base flows.
- The urban corridor of the river, because of its position in the transition zone from the mountains to the plains, has the potential to support overall high diversity of species given the overlapping mix of plains and montane biological communities. The Reconstructed Native and StableBase-HighPeak scenarios show the best possible results for aquatic insects, but a positive response would still be limited by the existing pool of species. Under improved conditions, recolonization of sensitive species would depend on both the degree of improvement and proximity of a species pool.

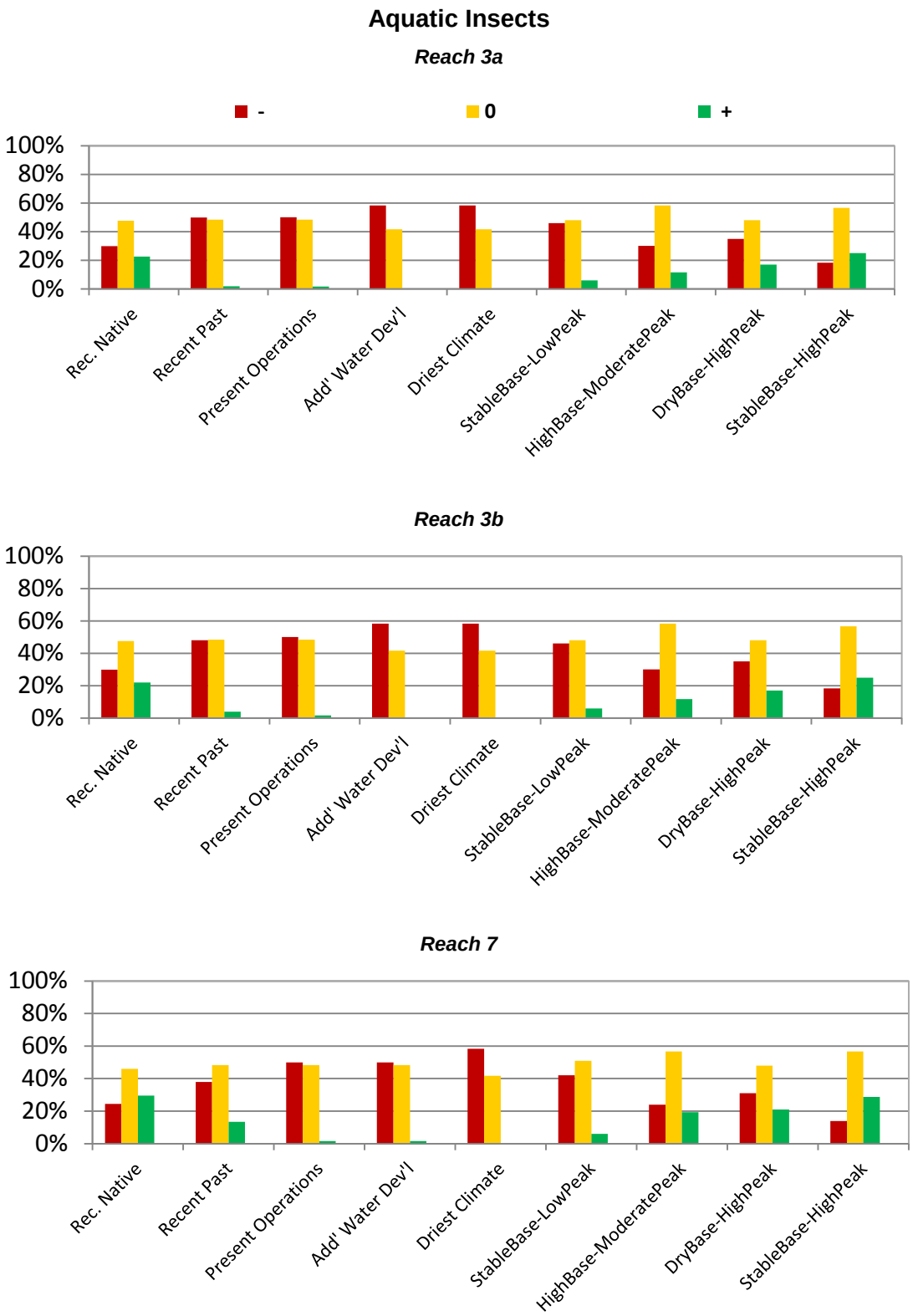


Figure III.3. Relative likelihood of three states of Aquatic Insects associated with nine flow scenarios.

Note: Plots for each of the three focal river reaches are arranged from upstream to downstream (Reach 3a on top, Reach 3b in the middle and Reach 7 at the bottom).

Native Fish Results

Table III.5 is presented below (as reproduced from Section II: Native Fish) as a useful reference for interpreting the results for Native Fish that follow.

Table III.5: Description of four states of Native Fish that depend on summer baseflow, summer temperature, Brown Trout predation, Aquatic Insects, and Channel Structure.

State	Definition
+	High diversity (> 12 taxa in warm-water streams) and high abundance (> 1,000 individuals total), multiple life stages.
0	Moderate diversity (7–12 taxa in warm-water streams) and abundance (100 –1,000 individuals total in standard sampling effort), two or more life stages per species.
-	Low diversity (six or fewer taxa in warm-water streams) or abundance (< 100 individuals total) in a standard sampling effort, single life stage for many species.
- -	Low diversity (four or fewer taxa in warm-water streams) and abundance (< 100 individuals total) in standard sampling effort, single life stages for most species.

ERM data on the Native Fish indicator lead to the following discussion points.

- Very low flows are stressful for fish; therefore, the test scenarios with consistent base flows (StableBase-LowPeak, HighBase-ModeratePeak and StableBase-HighPeak) improve the success of Native Fish over Current Operations. This improvement is particularly notable in Reach 7 because the model incorporates the lack of predatory trout in Reach 7 by giving it higher baseline potential than 3a and 3b for the vulnerable fish populations.
  As with many of the biological indicators, a combination of stable base flows and high peak flows of sufficient magnitude and frequency to maintain physical habitat favors the highest likelihood of increased native fish diversity and abundance.
- The Recent Past scenario (based on daily gage data and diversion records) has notably fewer days of zero flow in the low-flow months as compared with all the scenarios that were disaggregated from monthly average data (the City of Fort Collins' MODSIM model). This possible overestimation of days of zero flow may help to explain why even StableBase-LowPeak is an improvement for Native Fish in the both the Recent Past and Present Operations scenarios. Thus, the varying input data sources could lead to misinterpretation of conditions in the Recent Past for Native Fish communities compared to today's conditions. It is anticipated that future data from the Common Technical Platform (CTP) for the NISP and HSWMP EIS processes will help to rectify this issue.
- Native Fish are influenced by several factors in the model, including four variables that are directly linked to the Native Fish response without intervening variables. With few data to link states of native fish populations with these factors, many of the relationships were based on scientific literature, biological theory and expert judgment gained via long-term sampling experience with native fishes in the Poudre River.

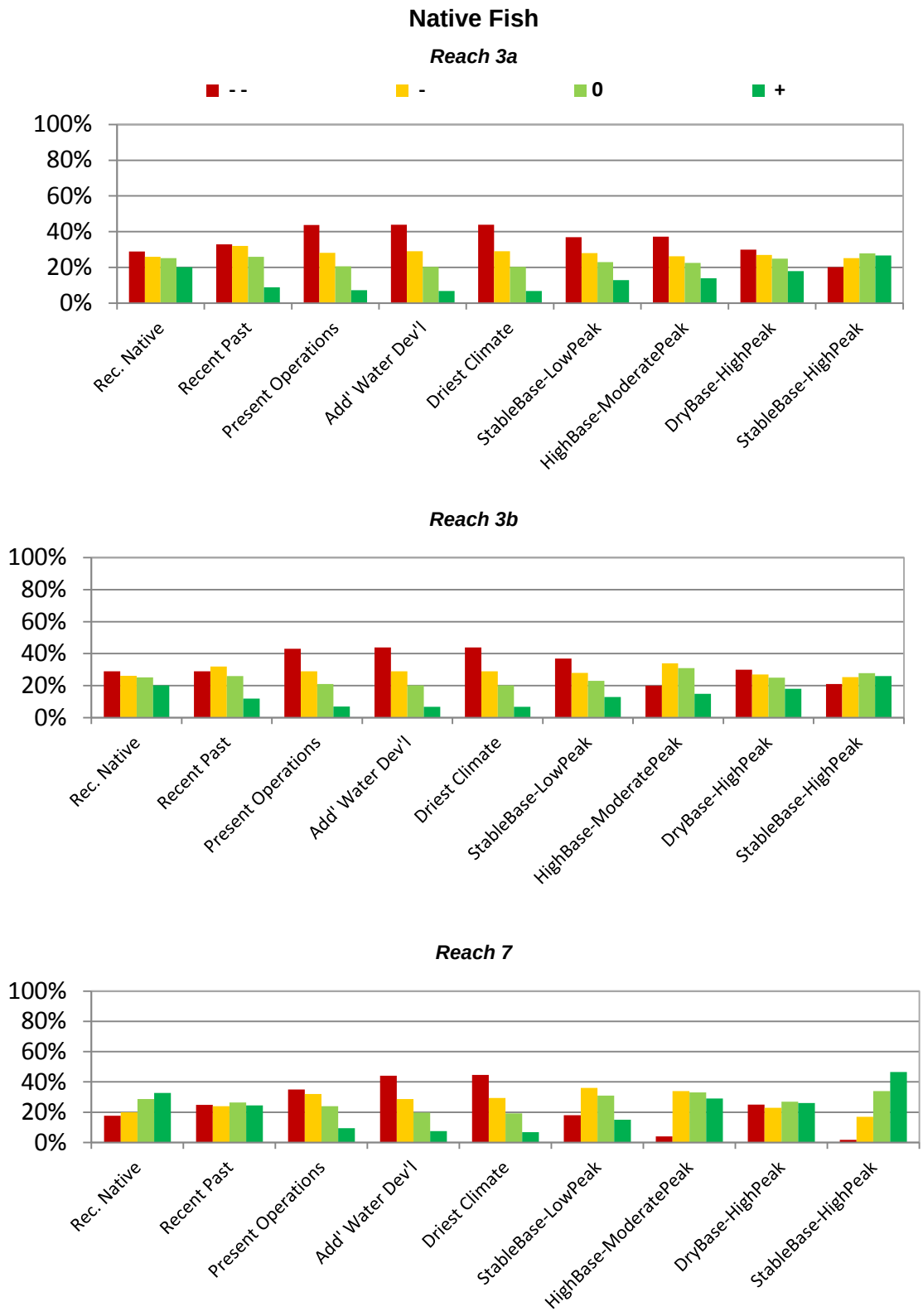


Figure III.4: Relative likelihood of four states of Native Fish associated with nine flow scenarios.

Note: Plots for each of the three focal river reaches are arranged from upstream to downstream (Reach 3a on top, Reach 3b in the middle and Reach 7 at the bottom).

Brown Trout Results

Table III.6 is presented below (as reproduced from Section II: Brown Trout) as a useful reference for interpreting the results for Brown Trout that follow.

Table III.6: Description of four states of Brown Trout that depend on summer temperature, summer baseflow, winter baseflow, Aquatic Insects and Channel Structure.

State	Definition
+	Multiple (3–4 or more) age classes; successful annual reproduction; high total biomass; resilient to multiple detrimental events/years; viable recreational fishery, many adult fish.
0	Three age classes; more variability across years in terms of biomass and reproduction; variable as a recreational fishery from year to year, occasional years with moderate numbers of adult fish.
-	Dominated by a single age class, others may be present; reproduction minimal; recovery from stressor events would take several years; generally poor fishery, inconsistent from to year to year.
- -	Single age class present; very sporadic reproduction; low abundance, population vulnerable to one detrimental event/year, the poor fishery is in danger of collapse; many years of good conditions needed for recovery.

An interpretation of the above data leads to the following:

- In the ERM model, Brown Trout are directly influenced by five factors (Figure I.4), with a heavier influence by the low-flow conditions than by other biological indicators (due to incorporation of both critical summer and winter base flows). High flows remain important for creation of clean substrates and diverse channel structure, but Brown Trout are strongly affected by extreme low flows, elevated water temperature, and depleted oxygen levels.
- Due to the influence of both summer and winter baseflows, the likelihood of improving the state of Brown Trout is much higher in the HighBase-ModeratePeak scenario compared to the DryBase-HighPeak scenario. All four test scenarios yield higher likelihoods of Brown Trout improvement relative to the three present and future flow scenarios (Present Operations, Additional Water Development, and Driest Climate). This reflects the erratic low flows and reduced peak flows that rarely exceed thresholds for maintaining physical habitat in drier core flow scenarios. Similarly, even the StableBase-HighPeak test scenario outperforms Reconstructed Native due to consistent base flows.
- The language in the highest condition class, *resilient to multiple detrimental events/years,* is even more important under the future climate scenarios that predict more extreme flow and water conditions. Trout can survive through cycles of extremes if they have a healthy population prior to the extreme. Brown Trout are known to be relatively tolerant and able to thrive in diverse conditions. (Note that the Brown Trout node in the model can act as a surrogate for rainbow trout – a species that is also desired for recreational purposes – although local populations have recently been eliminated by whirling disease. Spring spawning rainbow trout would be more sensitive to peak flows.)

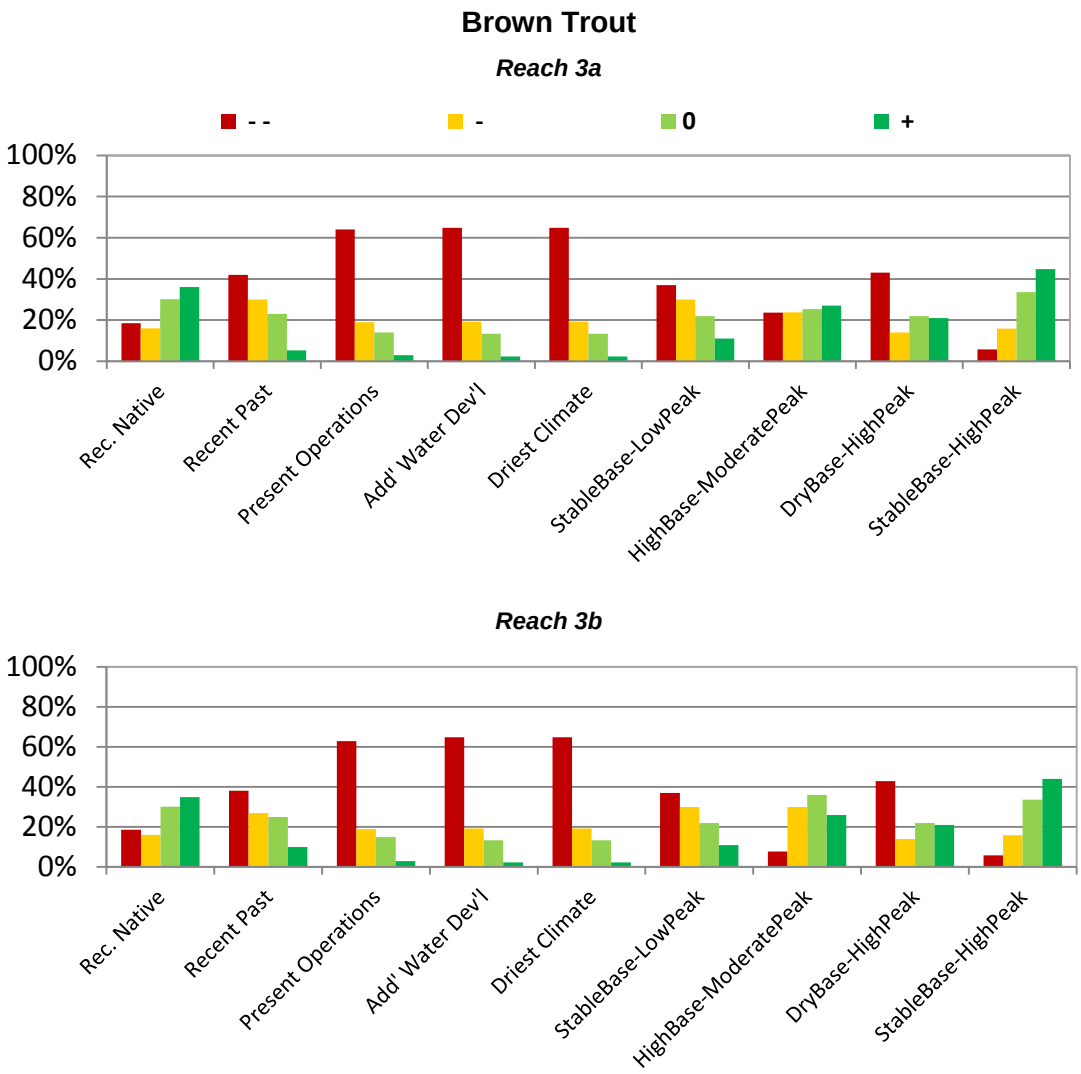


Figure III.5. Relative likelihood of four states of Brown Trout associated with nine flow scenarios.

Note: Plots for the two relevant focal river reaches are arranged from upstream to downstream (Reach 3a on top, Reach 3b at the bottom). Note: the downstream Reach 7 is typically too warm to support trout.

Rejuvenating Mosaic Results

Table III.7 is presented below (as reproduced from Section II: Rejuvenating Mosaic) as a useful reference for interpreting the results for rejuvenating mosaic that follow.

Table III.7: Description of four states of a Rejuvenating Mosaic of riparian vegetation that depend on channel movement.

Rejuvenating Mosaic states	Index of potential floodplain turnover (days * m / yr)	Selected examples
Minimal	0–0.2	(a) No shear stress competent to move bed; (b) combinations of minimal 1 in 5-yr floodplain, stabilized or protected channel, and rare or infrequent channel movement (low average shear stress)
Small	0.2–2	(a) Wide or moderate 5-yr floodplain, protected or altered channel and rare or infrequent channel movement; (b) minimal 5-yr floodplain, altered or protected channel, and occasional channel movement
Moderate	2–5	(a) Narrow 5-yr floodplain, protected or altered channel, and occasional channel movement; (b) moderate 5-yr floodplain, altered channel, and infrequent channel movement
Substantial	> 5	(a) Wide 5-yr floodplain, minimal channel stabilization, occasional channel movement (high average shear stress)

This data leads to the following key discussion points.

- The reduction in native Rejuvenating Mosaic forests may be one of the most notable shifts of the Poudre River toward a trajectory that is a different (novel) ecosystem compared to pre-development conditions.
- Riparian forests turn over (produce new generations) on the multi-decadal to century time scale, which reflects the lifespan of deciduous trees such as cottonwood. Therefore, there is a significant lag time in the condition of this indicator. The Present Operations scenario has likely set the course for future narrowing beyond what today's field observations indicate, because recruitment of young trees to the riparian forest is currently not occurring.
- The Rejuvenating Mosaic variable is driven primarily by high flows generally in excess of the flows needed to mobilize sediment in the channel and large enough to create channel movement in the absence of channel armoring. The ERM construct incorporates (as a limitation) the extent of river banks that are armored against channel erosion and migration. The basic requirements for riparian inundation (high flows, gently sloping and relatively low elevation stream banks) and the opportunity for riparian zone migration are rarely found combined in the urban environment. However, Reach 7 represents the best potential to support a forest with native ecosystem functions, if land managers can identify safe zones for channel migration induced by flood flows.

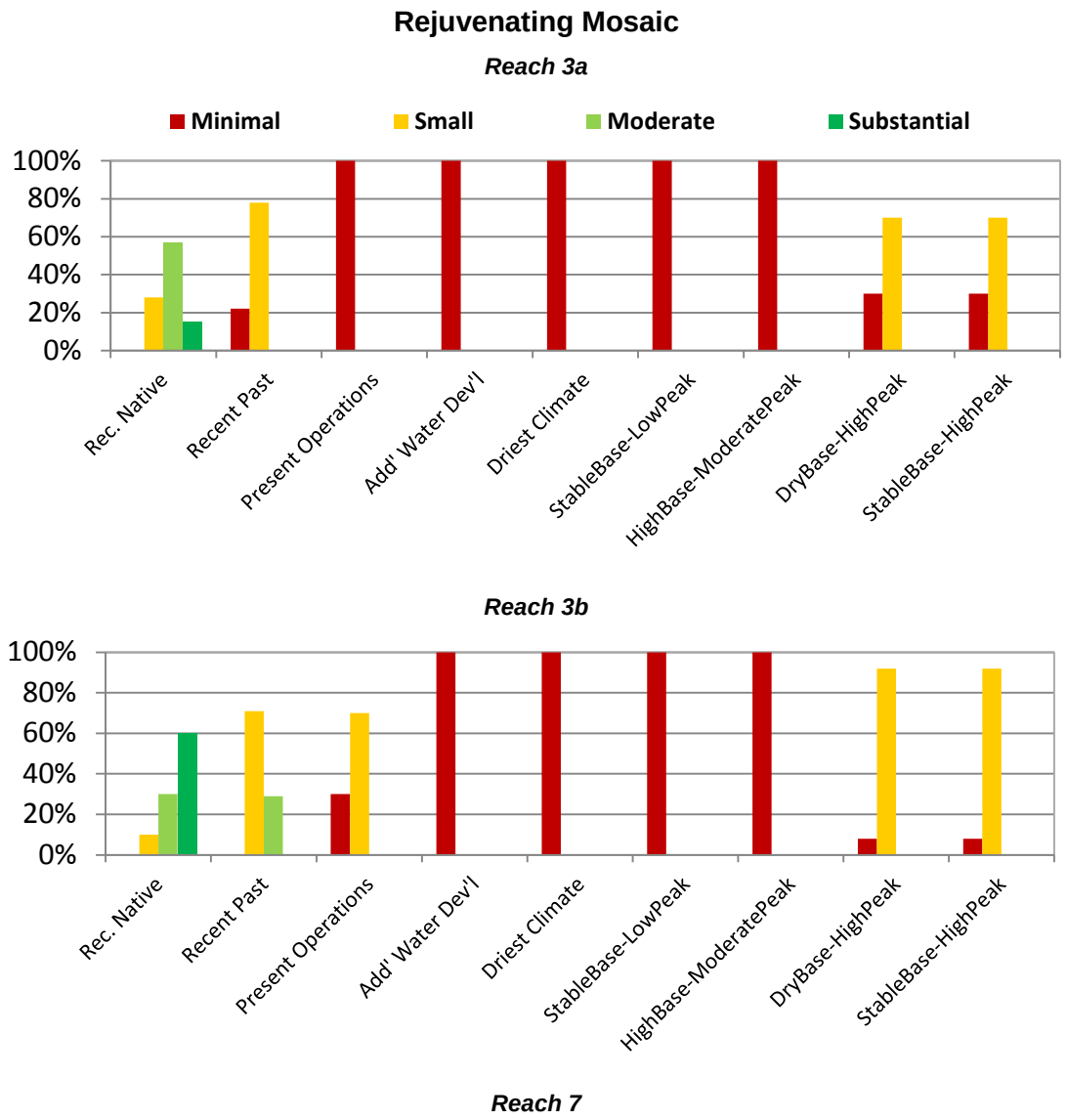


Figure III.6: Relative likelihood of four states of the Rejuvenating Mosaic associated with nine flow scenarios.

Note: Plots for each of the three focal river reaches are arranged from upstream to downstream (Reach 3a (confined) on top, Reach 3b (intermediate) in the middle and Reach 7 (unconfined) at the bottom).

Functional Riparian Zone Results

Table III.8 is presented below (as reproduced from Section II: Functional Riparian Ecosystem) as a useful reference for interpreting the results that follow.

Table II.8: Description of four states of width that depend on inundation by the river at least one day in the two years of growing season days.

Functional Riparian Ecosystem states	Average width in m (total area / channel length)
Minimal	< 15
Narrow	15–45
Moderate	45–90
Wide	> 90

Note: Widths include both sides of channel and represent total area divided by channel length.

The following interpretations can be made from these results.

- When the river is highly confined, as in Reach 3a, the potential zone for a Functional Riparian Ecosystem is limited.
- Results indicate Reaches 3b and 7 consistently provide more suitable conditions for riparian development and function than Reach 3a. This demonstrates the importance of gently sloping and relatively low-elevation stream banks for riparian inundation.
- The DryBase-HighPeak and StableBase-HighPeak test scenarios substantially increase the likelihood of maintaining a relatively wide functional riparian extent compared to Present Operations and Additional Water Development scenarios.
- Test scenarios that improve base flows have little or no benefit for the riparian forest in the ERM model.
- The results for both test scenarios that improve the base flows (StableBase-LowPeak and HighBase-ModeratePeak) area relatively poorer than the two test scenarios that improve the peak flows (DryBase-HighPeak and StableBase-HighPeak). This is based upon a functional riparian zone's dependence on peak flows to provide hydrologic connectivity to the river.

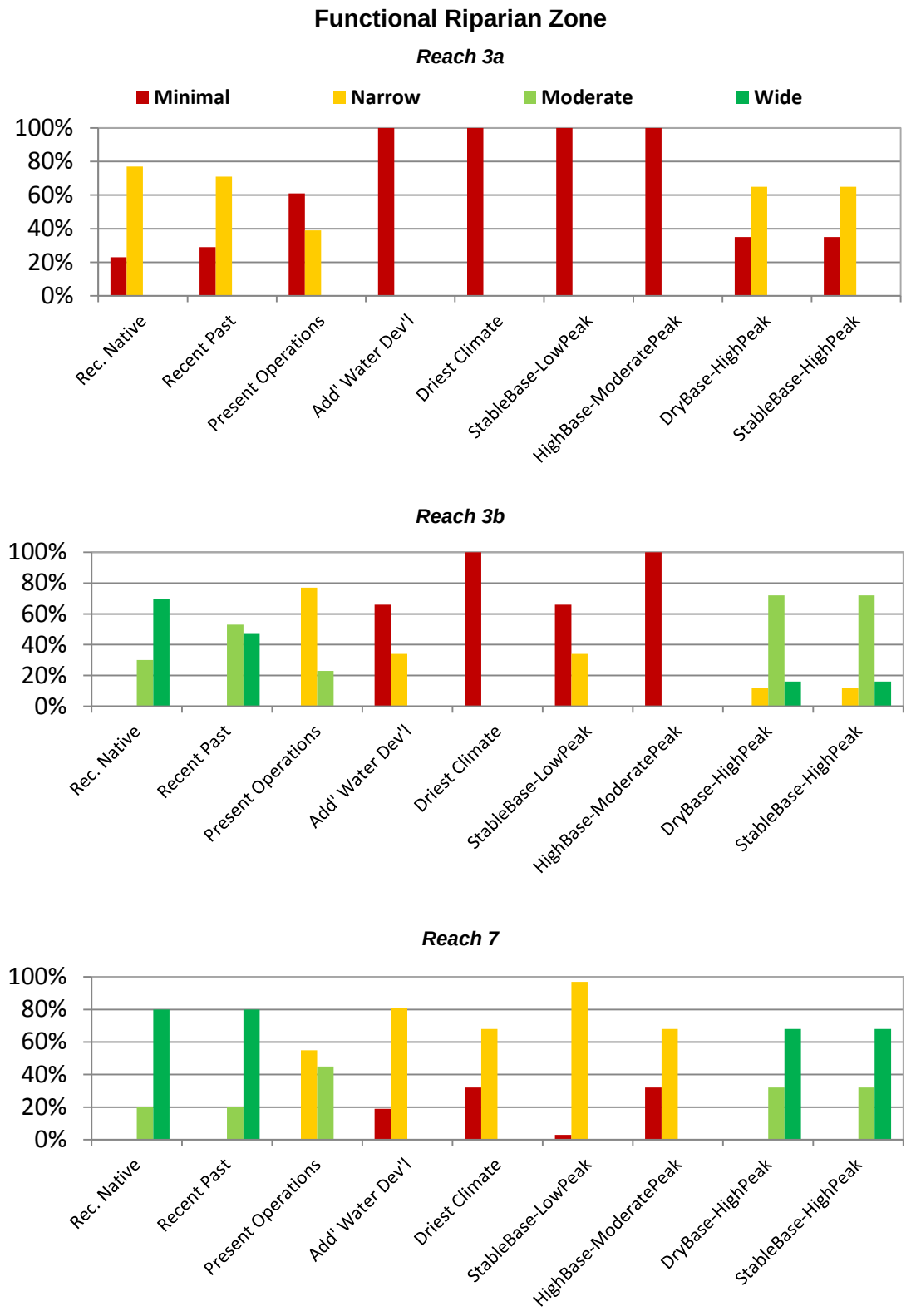


Figure III.7: Relative likelihood of four states of Functional Riparian Zone width associated with nine flow scenarios.

Note: Plots for each of the three focal river reaches are arranged from upstream to downstream (Reach 3a on top, Reach 3b in the middle and Reach 7 at the bottom).

Riverine Wetlands Results

Table III.10 is presented below (as reproduced from Section II: Riparian Wetlands) as a useful reference for interpreting the results for Riparian Wetlands that follow.

Table III.10: Description of four states of Riparian Wetlands extent that depend on inundation for 5% of the growing season. Widths include both sides of channel and represent total area divided by channel length.

Riparian Wetlands states	Average width in m (total area / channel length)
Minimal	< 5
Narrow	5–15
Moderate	15–30
Wide	> 30

Riverine Wetlands results can be summarized as follows.

- Results suggest the extent of Riparian Wetlands would likely be reduced with each scenario that further depletes high flows (such as Additional Water Development and Driest Climate). Similarly, results demonstrate a likely increase in wetland width the test scenarios that have higher peak flows.
- There is a notable difference in wetland width across the three reaches. The prevalence of steep banks and channel entrenchment in Reach 3a significantly limits wetland development almost regardless of flow scenario. Reach 7 has the greatest potential for wetland development because of low-lying topography in the riparian zone, and it shows marked decreases in riparian wetland width with additional water development (Present Operations vs. Additional Water Development). Comparison of results across the three reaches suggests that a potential increase in wetlands habitat could occur if steep banks were sloped back to re-establish connectivity with the river channel and floodplain.
- Riparian Wetlands show sensitivity to changes from the Present Operations scenario to the Additional Water Development and Driest Climate scenarios. The Additional Water Development scenario indicates the river would have less than 5 m of wetlands, combined for both sides of the river, essentially meaning a narrow band of wetland habitat along the water's edge.
- Note that the highest width classes for this indicator only require more than 30 m of wetlands combined for both banks. Width classes were developed based on the overall spread of results and do not include potential wetlands occurring around floodplain ponds; therefore, this width represents wetlands resulting from a direct link between river overbank flows and the adjacent floodplain.
- Wetlands are defined as requiring two weeks of saturation every other year during the growing season, and this value decreases steadily across the five core flow scenarios. Further, for these scenarios wetland width increases generally from upstream (constrained) to downstream (less constrained) reaches.

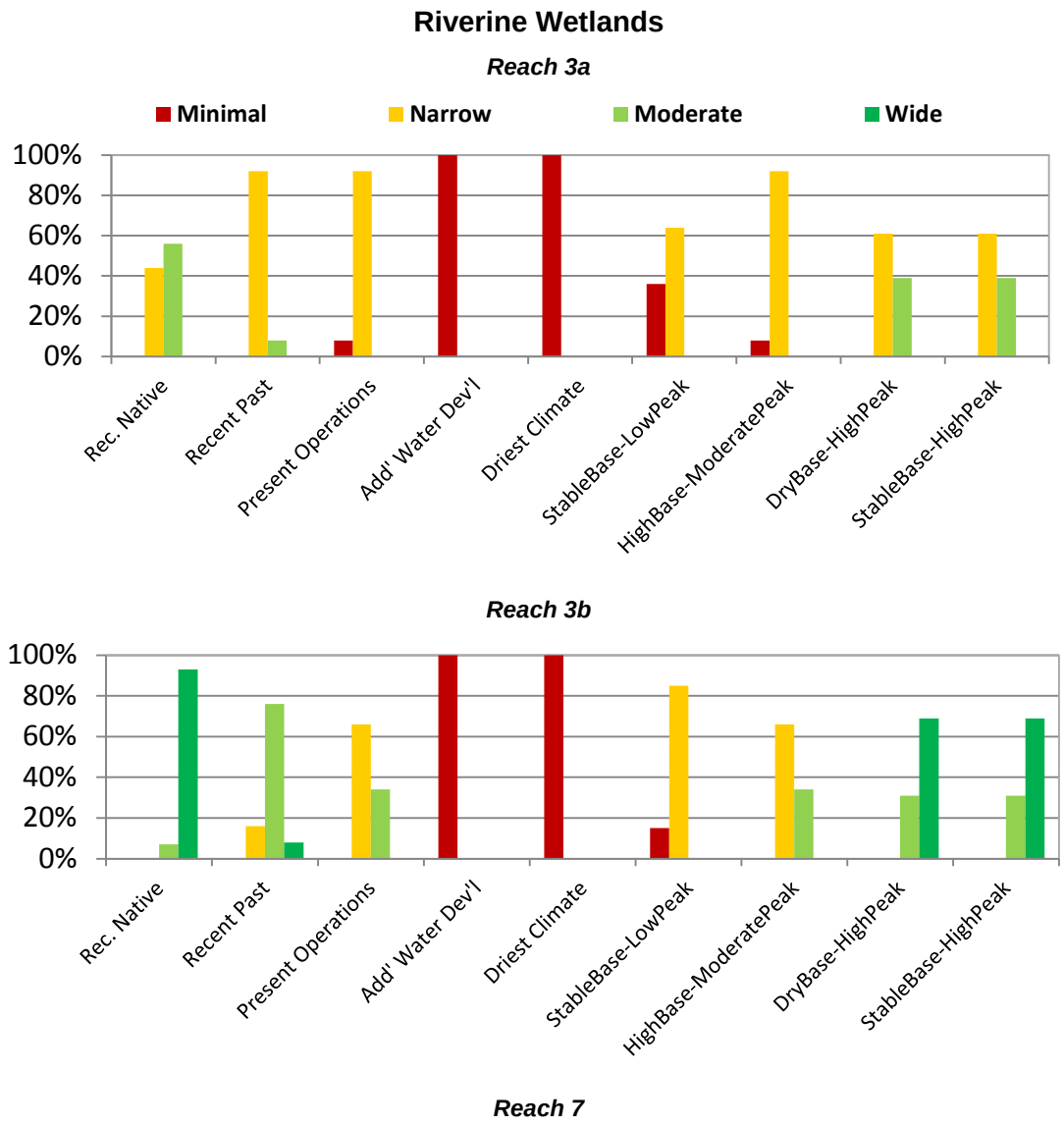


Figure III.8. Relative likelihood of four states of Riverine Wetlands associated with nine flow scenarios.

Note: Plots for each of the three focal river reaches are arranged from upstream to downstream (Reach 3a on top, Reach 3b in the middle and Reach 7 at the bottom).

DEVELOPMENT OF A SINGLE METRIC TO PROVIDE EXPECTED CONDITION

Results for each indicator variable were computed as the full distribution of probabilities across all states (as presented in all the previous results Figures III.1 – III.8) and, additionally, as a single expected value (the mean of the full probability distribution) presented below in Figures III.9-III.12. This single expected value was used to communicate a wide range of outputs into a single figure. The expected value was computed by:

1. Assigning linearly-scaled weights from 0 (most degraded condition) to 1 (highest functioning condition) to each of the state categories
2. Multiplying the outcome probabilities by these weights for each state (A*B = C)
3. Summing the result for the final relative condition

This summed score represents a synthesis of the probable condition for each indicator. As seen in the example below (Table III.10), the original distribution of outcome probabilities for Native Fish is 7%, 20%, 29%, and 44%. After weighting these outcomes, the aggregated metric describing relative condition has a value near 0.3, which approximates the "-" condition (defined as low diversity or abundance with a single life stage for many species). This average weighted value provides a straightforward means of comparing the relative condition of all eight indicators across flow scenarios and reaches using a composite variable.

Table III.10: Example computation of relative condition for Native Fish in Reach 3a under the Additional Water Development scenario.

Native Fish categories	(A) Outcome probabilities	(B) Linearly-scaled weights		(C) Product (probability * weight)[a]
+	7%	1.00		0.07
0	20%	0.66		0.13
-	29%	0.33		0.10
--	44%	0.00		0.00
Sum	100%	1.00	(D)	0.30

[a] Rounded to two decimal places.

This single metric describes all results on a scale of 0–1, where a 100% probability of the *lowest* state of river condition corresponds to a value of zero (for example, Channel Structure outcome at all three reaches for the Driest Climate scenario) and a 100% probability of the *highest* state of river condition corresponds to a value of one. Figures III.9–III.12 summarize the probable condition of each of the eight indicators on this common scale where green to red represents 0 to 1, respectively. It is important to note the green to red scale represents the continuum of state definition categories the is unique for each indicator.

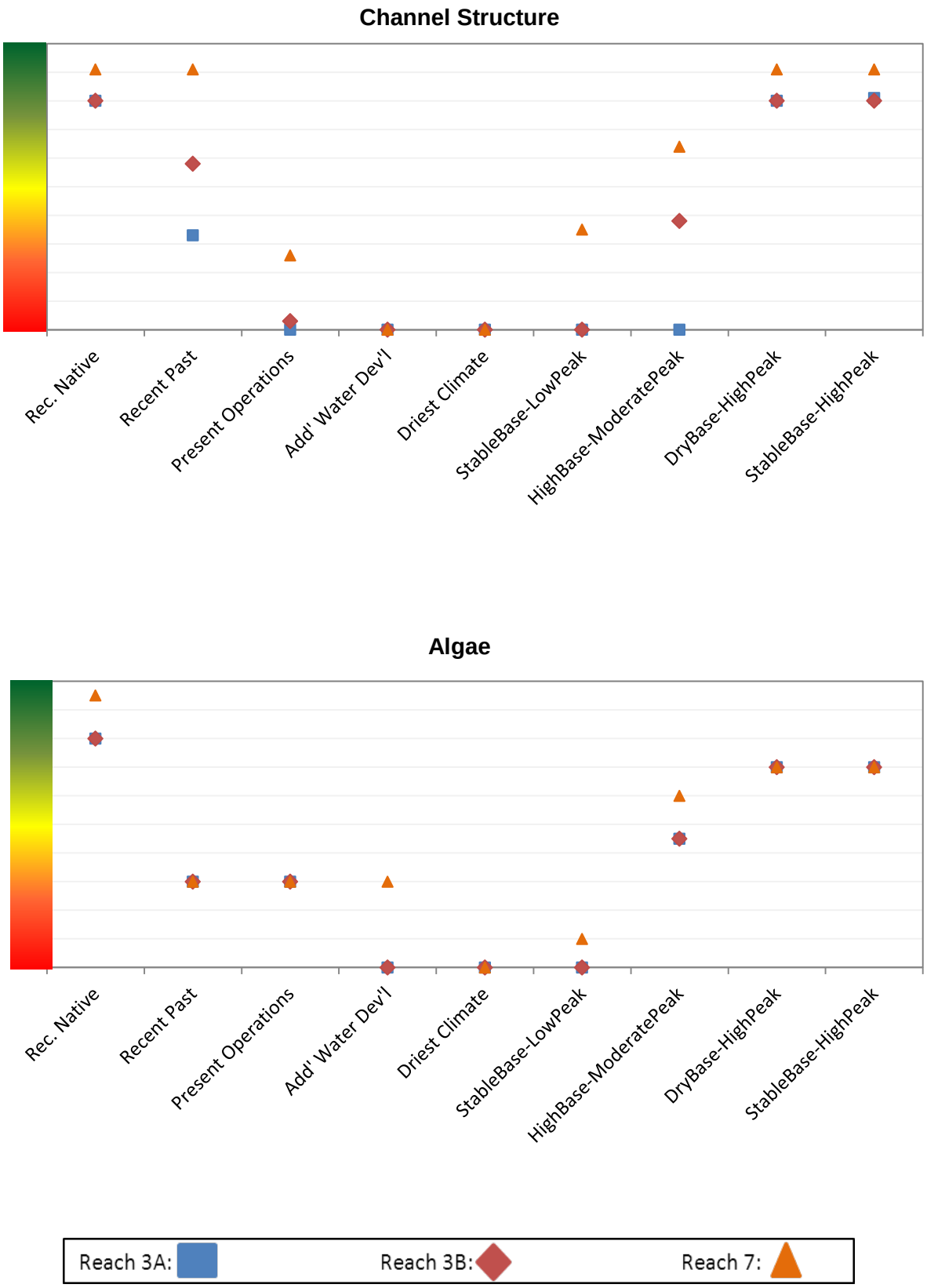


Figure III.9: Results presented in single metric form for all hydrologic scenarios for Channel Structure (above) and Algae (below) for all three reaches (distinguished by symbol).

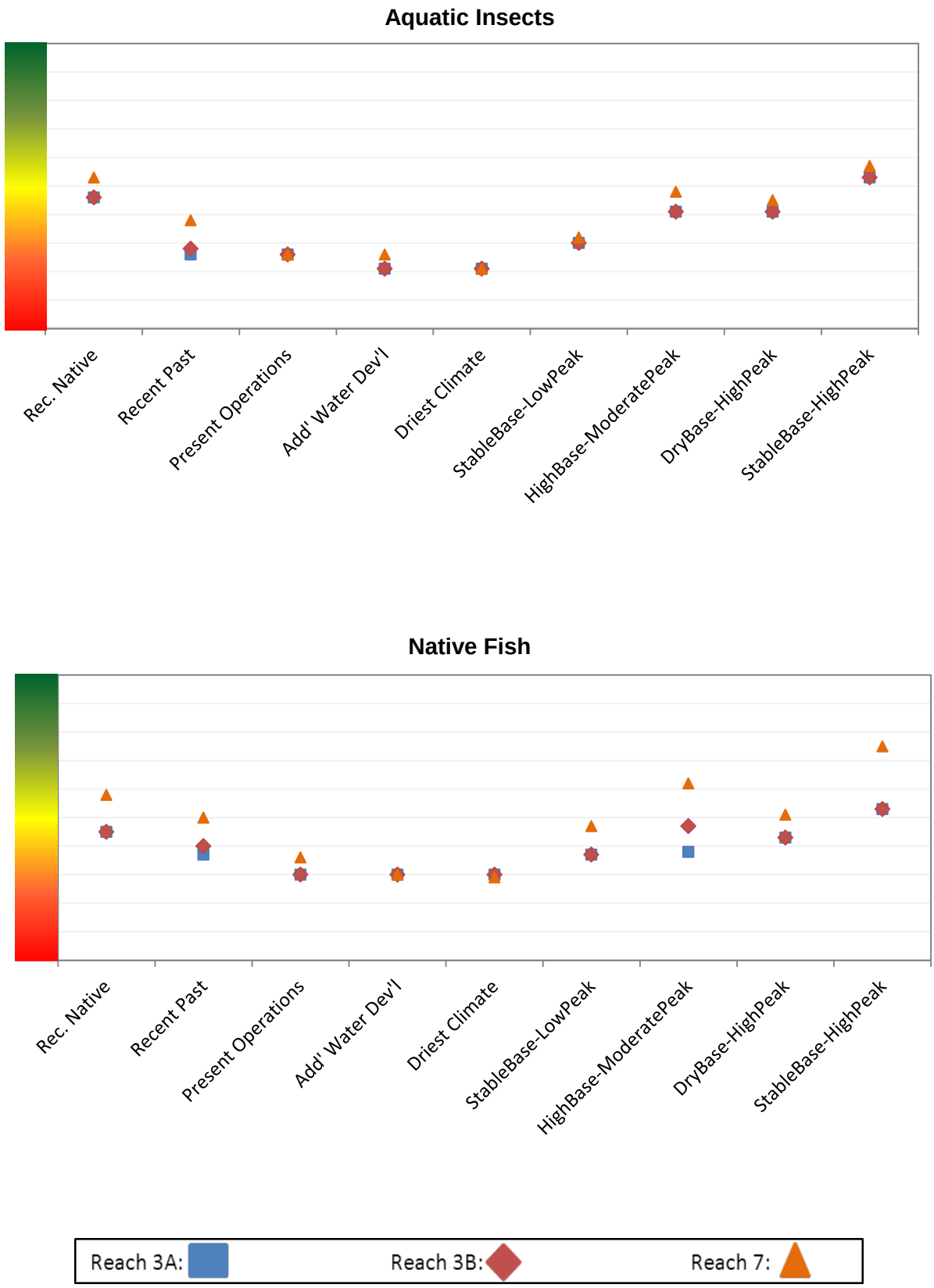


Figure III.10 Results presented in single metric form for all hydrologic scenarios for Aquatic Insects (above) and Native Fish (below) for all three reaches (distinguished by symbol).

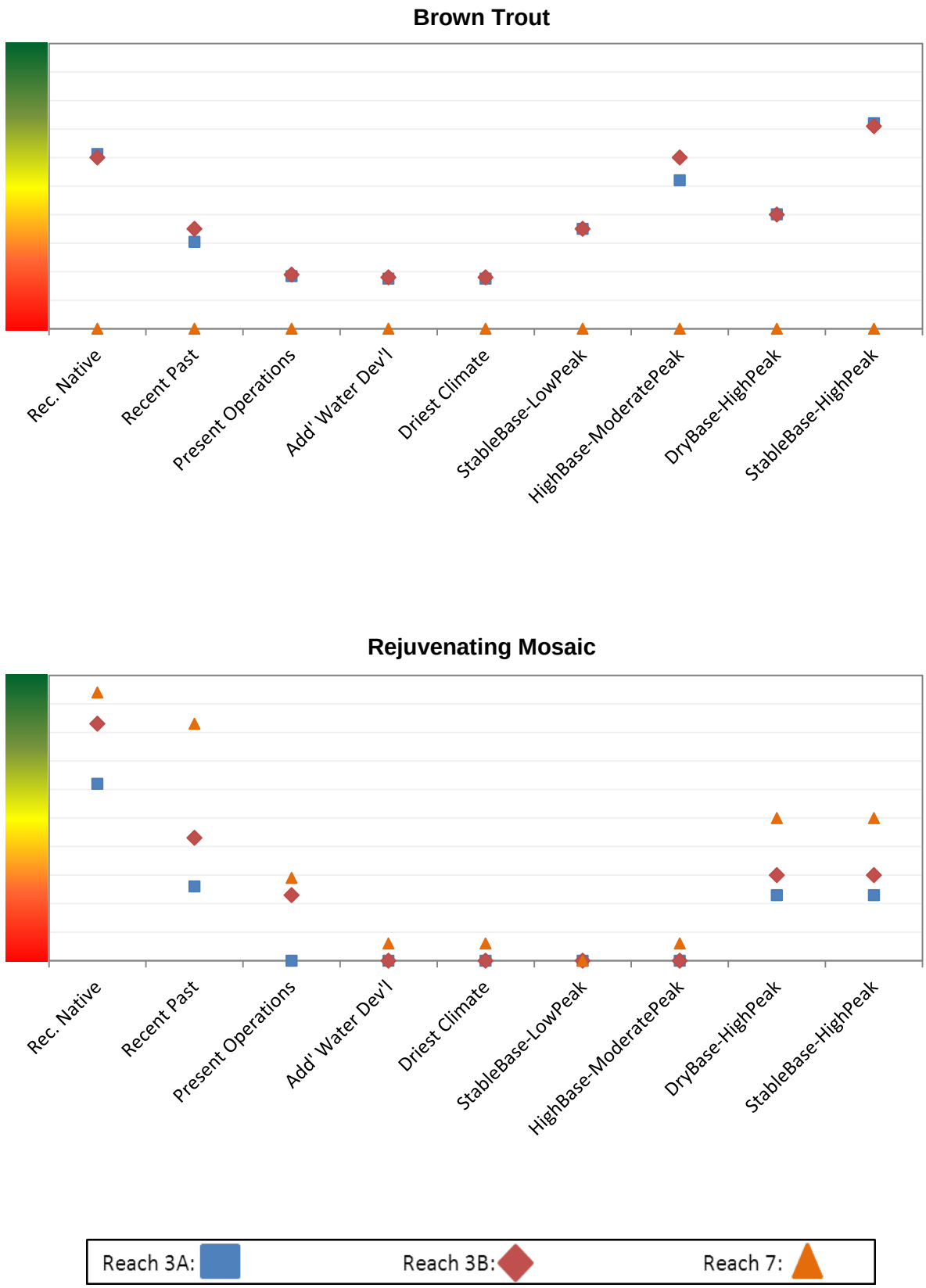


Figure III.11 Results presented in single metric form for all hydrologic scenarios for Brown Trout (above) and Rejuvenating Mosaic (below) for all three reaches (distinguished by symbol).

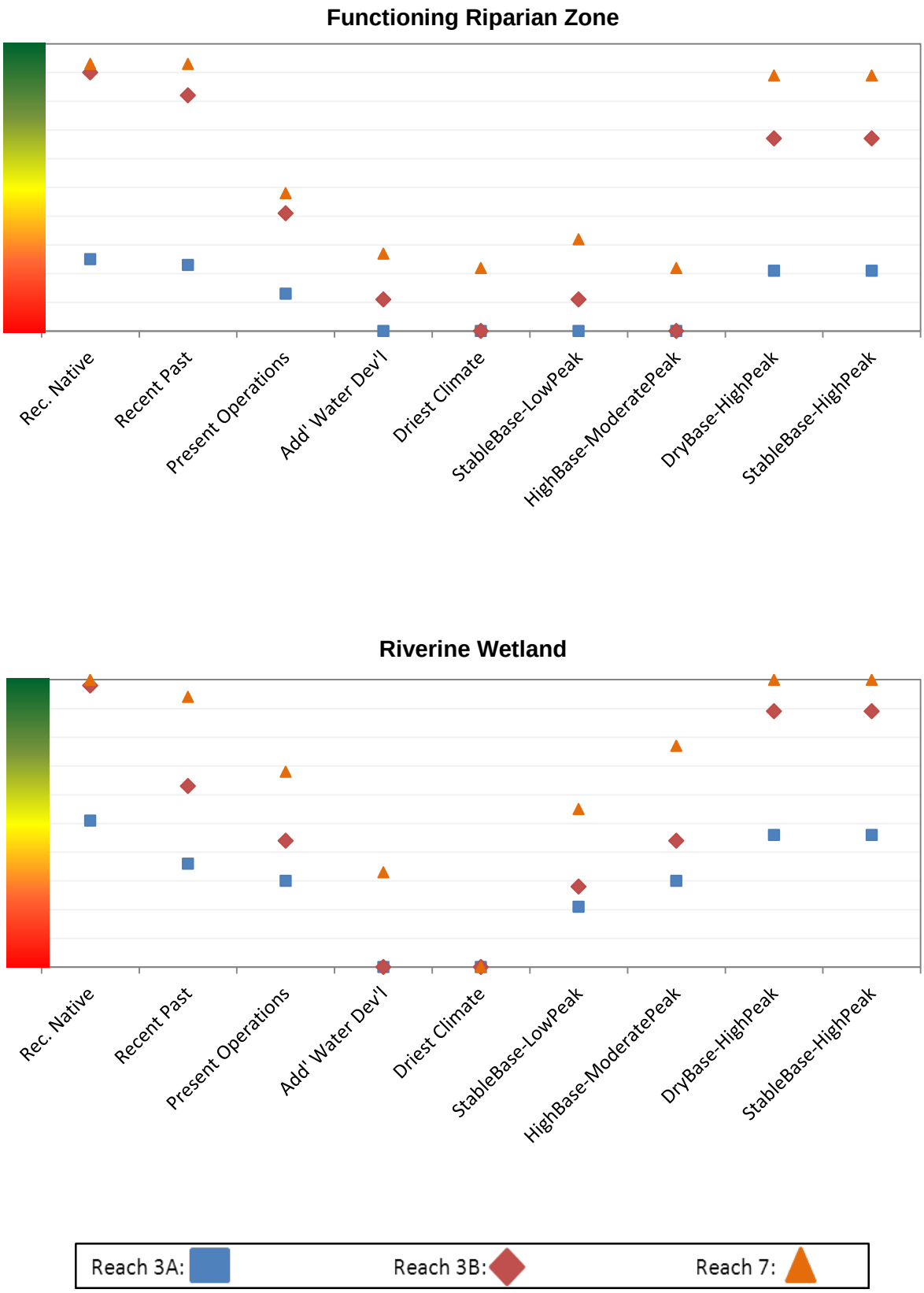


Figure III.12 Results presented in single metric form for all hydrologic scenarios for Functional Riparian Zone (above) and Riverine Wetland (below) for all three reaches (distinguished by symbol).

SUMMARY OF RIVER CONDITION BY FLOW SCENARIO

Reconstructed Native. As expected, this flow scenario yields the highest-predicted condition for all indicators; however, it does not optimize outcomes for all indicators or reaches. Flows are the primary factor determining river health, yet human-induced changes to this system have resulted in a reduced ability of the system to reach potential natural flow benefits. For example, for all three riparian indicators the steep and stabilized banks of Reach 3a lead to a substantially lower condition compared to Reaches 3b and 7, which are less confined. For Aquatic Insects and Native Fish, there appears to be a limit on potential improvement from the changing of flow alone. While this is in part due to the inherent conservatism of a theory-based relationship, it is also limited by irreversible alterations to the ecosystem (such as local extinctions of the most sensitive insects and fishes, and introduction of non-native, warm-water fishes).

Recent Past. These flows reflect conditions as they existed over the past 40 years; they were developed from historic gage and operations data. Over this time period, flow was increasingly diverted from the river, and thus there has been a consistent decrease in flows (beyond any climactic variability). Ecological conditions that we observe in the river today reflect the time-integrated response to these declining flow levels over this historical period. For example, the lack of young trees in the riparian zone reflects a lack of overbank flooding and channel movement, and it portends a future riparian zone that will continue to shift from cottonwood trees to upland trees (including non-natives) in the absence of high flows that exceed recruitment thresholds.

Present Operations. This scenario refers to the application of today's operations over the 40-year historical record; thus, the sustained increase in operational demands are likely to result in ecological decline relative to the Recent Past scenario. ERM results support this hypothesis, indicating that, had flow levels been consistently reduced over this entire period, the ecological status of the river would likely be in a more degraded state. Given the lag time in ecosystem indicators to reduced flow levels, a projection of the Present Operations into the future suggests that the river ecosystem will degrade further in the coming years if climate, hydrology, and current operations continue. A further degradation in ecological indicators would reflect a likely loss in system resilience in the face of extreme disturbance events, such as prolonged drought.

Additional Water Development. The impact of proposed additional water development is represented in this scenario, together with projected future water demands. ERM results indicate that this scenario will further deplete flows in the Poudre River through Fort Collins. Additional depletions will likely come from both low and high flows. The ERM suggests that the increased depletions associated with new projects and future diversions are likely to produce substantial reductions in river health from the current condition. With few exceptions, most of the ERM indicators in all three reaches yield their lowest results with this scenario. The ERM predicts increased risk of excessive Algae, a substantial narrowing of the Functional Riparian Zone and Riverine Wetlands, diminished Aquatic Insect communities, and reduced Brown Trout and Native Fish. The Additional Water Development scenario also misses critical flow thresholds, causing wetland and riparian functions to decline substantially.

The Additional Water Development scenario is based on preliminary information, and may not represent hydrologic conditions expected to be shown in the various project EISs. Results for this scenario may change with the more refined low flow and daily disaggregated data from the upcoming EISs.

Driest Climate. This scenario projects similarly degraded ecological conditions. It also generates flows that fail to reach critical thresholds for wetland and riparian function. In Reach 7, where there is a gently

sloping channel and relatively low elevation stream banks, Riverine Wetlands reach the narrowest category and are almost completely lost.

Within the following ERM *test* scenarios, a combination of stable base flows and rejuvenating high flows are shown to improve all indicators of river health relative to current conditions.

StableBase-LowPeak. When low flows alone are restored, as in this scenario, very little improvement is seen compared to Present Operations in aquatic or wetland/riparian indicators. This is due to the absence of high flows that rejuvenate the bed or inundate the floodplain.

HighBase-ModeratePeak. This scenario also fails to improve wetland and riparian functions because the peak flows remain at lower levels. However, the aquatic indicators do improve as stable base flows, combined with streambed scouring flows, improve habitat quality for these aquatic species.

DryBase-HighPeak. All indicators are improved relative to Present Operations by exceeding thresholds of moderate and high flows that prevent excessive accumulation of fine sediments and perform important geomorphic and ecological functions (including maintenance of channel habitat for fish and insects, scouring of excess algal biomass, and inundation of riparian areas to promote wetland and riparian function and vegetation mosaics). However, the very low flows in this test scenario act to limit the potential of some aquatic indicators, especially Brown Trout, as can be seen in comparing the HighBase-ModeratePeak and DryBase-HighPeak scenarios.

StableBase-HighPeak. This scenario provides similar peak flow conditions to the DryBase-HighPeak scenario, and thus it supports similarly high values for the aquatic and wetland/riparian indicators. The stable base flows in this scenario exceed the threshold necessary to sustain more robust Brown Trout populations, and this indicator reaches its maximum value in this scenario. Based on the results of the StableBase-HighPeak scenario, it is estimated with confidence that a combination of stable base flows and habitat-rejuvenating high flows provides synergistic benefits for the Poudre River ecosystem that substantially exceed the benefits provided by improvements in only one type of flow.

ERM EVALUATION

Testing the ERM

In the development phase, each indicator was individually evaluated and tested against available empirical data and current scientific understanding. Some indicators had a large amount of available data (such as Riparian Wetlands) while others had very little (Native Fish) and thus had to be more reliant on expert judgment. As discussed in Section I, one way to account for uncertainty associated with expert judgment is to be more conservative with the assignment of conditional probabilities based upon expert judgment instead of empirical data. While this conservatism may lead to less variation in the absolute expected values of each indicator, the relative differences across the flow scenarios remain robust.

The ERM will be further refined as new biologic, geomorphic, and hydrologic data become available. One of the strengths of the Bayesian model is its ability to refine the conditional probabilities as scientific understanding is refined or additional empirical data produced. This may lead to expert judgment relationships being replaced by empirical relationships, continually improving the tool.

After the model was developed for the core hydrologic scenarios, it was additionally tested through the formation and evaluation of the four test hydrologic scenarios. Additional test scenarios could also be developed to answer a broader range of questions related to a water development or augmentation proposal.

Elements Not Included in the Model

Other endpoints could certainly be included in an ecosystem-scale model. For the ERM the number of nodes was limited to those shown in Figure II.2 because the team concurred that a) these are key components that capture the major dimensions of the Poudre River ecosystem, and b) there was sufficient data or data-informed expert knowledge available for modeling these elements. Certainly, additional linkages can be imagined in an ecosystem model, such as additional ecological feedback loops, numerous anthropogenic influences, or potential future management actions. However, adding additional elements for which no data and/or expert judgment exist is more problematic and would carry with it a penalty of increasing the model's complexity with no benefit of additional insight. Therefore, the final ERM is viewed as one that balances representation of system complexity with available knowledge base. This model construction generates results that meaningfully contrast system responses to different water management and climate scenarios. The purpose of the model is to facilitate a comparison of diverse, plausible trajectories of the Poudre River ecosystem, rather than producing precise predictions of future ecosystem states under some specific management or climate scenario.

The following is a list of ecosystem linkages that were intentionally <u>not</u> captured in the model for the reasons stated above:

- The time sequence of flows that control vegetation encroachment through mechanical removal and inundation (e.g., a high flow period that build bars following by a drought) are not accounted for in the models. Similarly, mechanisms that control bar and island formation are not explicitly incorporated into the models. Both of these phenomena have the potential to alter baseline conditions of channel geometry, sediment transport capacity, lateral erodibility, and/or degree of overbank flooding and ultimately affect the risk of channel miniaturization which would have wide-ranging effects on the system.
- Input of terrestrial food resources for fish
- Implications of water temperature beyond the 23C threshold (for Brown Trout, Native Fish, and Aquatic Insects) related to nutrient processing and algae growth
- Interaction between riparian shading and water temperature
- Impacts of the hyporheic zone and alluvial groundwater on surface hydrology, water temperature, and/or biotic refuges
- Short-term deviation from average conditions (for example, the large fires in the upper watershed in 2012 that caused numerous short-term impacts and could potentially alter the long-term trajectory of the system including short-term increases in flows, turbidity, and sediment that could lead to degraded water quality for aquatic wildlife and accelerated channel narrowing)
- Impact of increased presence of aggressive, non-native (or newly introduced) species on desired species, including predation or utilization of resources (especially with regard to riparian vegetation), disease (for example, whirling disease, chytrid fungus, and emerald ash borer), and migration of undesirable filamentous algae into the reach
- Effects of hourly scale flow fluctuations caused by diversion operations on aquatic organisms

Management actions, current or potential, that were <u>not</u> included in the model include the following:

- Hard or soft engineering approaches to riparian restoration and bank erosion (such as lowering banks to increase the width of overbank flooding on the 2-year return interval, but with hardened structures underneath)
- Management of non-native riparian species (for example, extensive Russian olive management)

- Further bank alterations including changes to topography or new lateral constraints, or, conversely, the reduction of existing lateral constraints to allow for expansion of aquatic and riparian areas and channel movement into areas currently isolated from the river
- Local sediment balance/imbalance as a result of many anthropogenic activities locally and fires in the upper watershed

Influence of Low-Flow Data on Modelling Process and Results

Accurate characterization of low-flow hydrology is very important for understanding aquatic habitat conditions and biological responses in river systems. The ERM is sensitive to the accuracy of hydrologic input data in describing low-flow characteristics. Model results for trout, native fishes, and invertebrates are influenced by the occurrence of zero- and extreme low-flow days in the input series of daily flows. Differences for the low-flow months between disaggregated monthly data versus daily gage data can represent either an exaggeration of zero-flow days or minimization of extreme low-flow days due to basing daily variability off monthly averages and consequential loss of accurate portrayal of the minimum flow days. Hence, the ERM underestimates negative consequences for biological indicators when extreme low flows are under-represented as a result of erroneous smoothing, errors in disaggregation, or other modeling errors. Conversely, the ERM overestimates the biological effects of flow extraction when extreme low flows are over-represented. Improving the accuracy of current hydrologic models in predicting key low-flow characteristics (magnitude, frequency, duration, timing and rate of change) at daily and sub-daily time intervals would substantially enhance our predictive ability.

ENHANCING PREDICTIVE ABILITY IN THE FUTURE

Through the development of a Bayesian network model, the ERM effort has facilitated analysis of multiple flow scenarios and reach types to assess relative influences on key ecosystem functions and attributes.

The results of this study illustrate broad trends in the overall ecosystem and individual components without overestimating precision. In other words, the ERM provides comparisons of outcomes across scenarios to draw conclusions about which direction the ecosystem is likely to trend and the relative magnitude of such change. Despite the uncertainty inherent in ecosystem modeling, this approach provides a systematic means of estimating likely trends in ecosystem response that can then inform educational efforts, goal setting, decision making, and adaptive management.

Decision makers can consider a variety of stakeholder interests and the engineering, ecological, economic, and societal consequences associated with all policy options. The probabilistic scientific predictions provided by the ERM provide a rational and transparent basis for decision making by explicitly recognizing uncertainty and helping managers understand the likely consequences of their policy choices.

The team's experts were purposely conservative in their construction of these relationships and probabilities. Transitions between indicator states required very large changes in driving variables (flows), so that an indicator that registered the "best" or "worst" condition was difficult to achieve. This conservatism in indicator response provides a desirable stability given the uncertainties of assigning indicator probabilities. This conservatism also is reflected in the subtle differences between scenarios in many of these aquatic indicators, but it does allow confidence that where relatively large differences occur among scenarios, these differences are robust. Again, however, the *absolute* values of the indicators are not of greatest interest. Rather, it is the *relative change* in indicators across scenarios that are most informative. The consistent patterns that emerge for the many aquatic indicators across the scenarios add additional confidence to the results and our interpretations.

There is higher confidence for indicators that were derived from relatively strong empirical relationships and analysis, and they are more responsive to flow differences across the scenarios. For example, Channel Structure and the three wetland/riparian relationships are formulated mainly from empirical analysis. Similarly, the relationship between winter low flows and Brown Trout is empirically derived and modelled with confidence.

Examples of additional information that would improve predictive capability of the ERM would include the following:

Flows

- Improve empirical basis for understanding low-flow variability, low-flow days, and the impact of future water depletions on low flows.
- Derive data from daily or hourly gage data rather than disaggregated monthly data, which is not well suited to daily time-scales.

Channel Structure

- Improve the accuracy and resolution of hydraulic and sediment-transport models through additional calibration and validation with field data.
- Improve the spatial resolution of the hydraulic models to account for longitudinal variability in sediment sizes, shear stress/discharge relationships, and lateral armoring among segments throughout the corridor.
- Monitor fine sediment to understand flushing flows needed to provide a clean substrate under different levels of sediment delivery and watershed disturbance.
- Develop a river sediment budget to aid in understanding how habitat could be enhanced through changes in channel form and gravel supply.
- Identify potential safe locations for re-establishing dynamic connectivity between the channel and its floodplain.

Algae and Aquatic Insects

- Initiate a systematic approach toward monitoring streambed algae and pair these data with other water-quality parameters, especially nutrient concentrations. This information can be very helpful in projecting future river conditions in the face of increasing nutrient loading and/or reduced summer base flows.

Fish

- Seek a more complete understanding of the complex interplay between fish habitat, channel structure, streamflow, and native fish and trout population response to better predict the future state of these resources in the Poudre River.
- Continue monitoring aquatic resources, including Native Fish and Brown Trout populations, to better understand their dynamics and response to disturbances such as habitat change or further streamflow modifications.

Riparian Forest and Wetlands

- Develop better understanding of the characteristics and composition of the Functional Riparian Zone
- Improve current methods by incorporating new HEC-RAS hydraulic models.
- Develop better understanding and estimates of likely channel movement in context of altered topography, bank stability, and flow regimes.

In summary, the ERM team has confidence in the model outputs. It also acknowledges that improved understanding of relationships between indicators and river flow conditions would be desirable to better develop some of the more conservatively modeled indicators in the ERM. A strength of the ERM is that future data can be incorporated to further validate and improve it.

SECTION IV: CONCLUSIONS

OVERVIEW

The ERM team developed an integrated model of the urban Poudre River ecosystem to better understand how key environmental drivers interact to shape river condition. Recognizing that flow regime is fundamental to riverine ecosystem function and services, this project provides a new perspective on the consequences of changing flow patterns to important indicators of ecosystem condition. The ERM is an adaptive tool that can foster and inform dialog on river management through a scientifically grounded understanding of how future changes in river flow are likely to be reflected in physical and ecological adjustments of the contemporary ecosystem. Specifically, the ERM illustrates the role that particular flow parameters play in sustaining and achieving desired biological and ecological outcomes. For example, results from this modelling effort demonstrate fish and aquatic insects depend on both high flows to rejuvenate critical river bed habitats and on low flows that maintain a minimum wetted habitat required for daily survival. Similarly, the model illustrates a clear relationship between the width of the functioning riparian forest and riverine wetlands with the magnitude and frequency of overbanking flows.

The model has revealed that although the Poudre River continues to support several functioning remnants of native riparian and aquatic communities, this urbanized ecosystem has experienced broad and significant changes over the last 150 years. The combination of land use and water management has substantially modified native aquatic and riparian communities, greatly altering the current ecological function of the Poudre River through the City. Indicators of this altered function include moderate or poor condition for trout populations, lost or diminished populations of native fishes, and limited ability of valued native plants along the river (especially native plains cottonwood trees) to reproduce and replace decadent stands of mature trees.

While the ERM models flow as the primary driver of river condition, several other parameters (such as physical topography and sediment balance, fragmentation of habitats, species composition, and pollutants loads) also fundamentally influence river condition and are therefore incorporated as secondary drivers into the model.

Figure IV.1 Secondary drivers of river condition including fragmentation of aquatic habitat from diversion dams (left) and pollutant loading as occurs when oil is dumped directly into storm drains (right).

This study suggests ecological conditions are likely to shift further in the coming decades, even under current flow management practices. This trajectory is likely to accelerate with further water development in the basin or with a drying climate. Further reductions in abundance and diversity of sensitive aquatic insects (such as mayflies and stoneflies) can be expected. These species will likely be replaced by

species that are more tolerant of heavy siltation and poor water quality (such as worms and midges). Trout and native fish populations will likely decline further and could become more vulnerable to disturbances and human pressures. The abundance of riparian species that require overbank flows are expected to decline over time and the riparian forest is expected to narrow, followed by replacement by upland species. Nuisance algal blooms are likely to increase under current nutrient loading levels, and there is a high probability that nuisance algae will further increase under water-development scenarios that reduce scouring flows.

The current and likely future flow scenarios of the ERM paint a future of changing river conditions that represent a substantial departure from the City of Fort Collins' goal of a healthy and resilient river. Despite this possibility, model results based on the best available local data, fundamental ecological theory, and data-informed expert judgment of the interdisciplinary team have revealed that this departure away from a biologically thriving river is not a foregone conclusion. The ERM modeling effort indicates that carefully designed environmental flows could improve the state of the Poudre River ecosystem.

Environmental flows that combine stable and adequate base flows in low-flow months with occasional rejuvenating high flows that meet thresholds levels defined in this study are likely to synergistically improve all biological indicators across the system. Specifically the StableBase-HighPeak test scenario suggests some gains are to be made across the system from following such a flow management strategy. This test scenario indicates substantial improvements in the river ecosystem can be achieved with flow volumes similar to those observed in the river over the last half century of intensive water development. These results underscore the possibility that the river ecosystem can be improved through active management while still maintaining the economic benefits and the Poudre's role as a working river.

Significant ecological benefits from environmental flows are most likely to occur if flow management is strategically combined with other management actions that promote upstream-downstream and channel-floodplain connectivity along the river corridor. With respect to sustaining riparian vegetation, the comparison of results across three geomorphically distinct reaches suggests that flow management alone will not be adequate. Land-use policy and practices have combined to effectively narrowing the river corridor through hardening of riverbanks with structural stabilization and creation of levees. With heavily reinforced streambanks along much of the river, even the restoration of high flows (which could otherwise maintain aquatic and riparian habitats) will have limited ability to re-establish desirable riparian conditions and aquatic habitat diversity.

Therefore intentional management of high flows would need to be in conjunction with other management actions that reconnect the riparian zone with the channel and assist the river in moving laterally in safe and feasible locations. For example, lowering unnaturally high berms in conjunction with setting back armoring and riprap to the margins of the floodplain or high terrace in selected locations could allow the channel to be reshaped in response to more frequent overbank flooding aimed to maintain native riparian flora. Such actions would allow for more frequent overbank flooding and connectivity between the river and its floodplain support the underlying processes that promotes native riparian vegetation and reduce establishment and root reinforcement by non-native dry-land species. Additionally human encroachment in the floodplain could be gradually decreased over the long term through planning and floodplain management efforts. These management actions also have the potential to simultaneously improve flood conveyance and mitigate flooding to adjacent properties.

The ERM has illuminated the fact that the contemporary Poudre River ecosystem has lost much biological diversity, habitat heterogeneity and habitat continuity over the last century. Model results for native fish, which do not under any scenario reach the highest condition category, provide a clear demonstration of the ecosystem's limited potential under current conditions. Local species extinctions, introduction of

predacious trout and carp, and the fragmentation by small dams that prevent upstream-downstream movement of aquatic species were all important considerations in the model construct for native fish.

Similarly, as development of the ERM included an in-depth exploration of available data and extensive discussions on relationships and interactions required to build this integrated ecosystem model, the team repeatedly encountered concepts and issues that are unique to this system, thus underscoring the notion that the Poudre is a *novel* ecosystem. Such a system is not characterized simply through common river theory, relationships, and native species compositions. Instead, this contemporary ecosystem is characterized by a patchwork-like set of physical conditions and an evolving biological makeup. Furthermore, it is likely to have a reduced ecological resilience to both human and natural stressors. Fundamental elements of the novel ecosystem, while not directly drawn from the predictive domain of the model, but that were considered important during model development and interpretation of the results include:

- The river's altered geomorphic and physical environment (including the river bed, banks and floodplain topography) cannot respond naturally to flows that shape the river and its potential for habitat. The discontinuous patchwork of bank stabilization and associated river bed armoring, pinch points (bridges), and truncated sediment flux have largely eliminated the river's capacity to self-adjust, and create and maintain a time varying diversity of habitats. A consequence is that maintenance of instream and riparian habitats will likely require mechanical manipulation by river managers as human alterations have largely rendered the river incapable of performing these functions itself as it did in the past.
- Low-flow rates vary along the river profile and riverbed dry-ups occur during extreme periods of low flow. For example, in reaches 3a and 3b more than 12% of days in the Recent Past scenario, constructed from gage data, are estimated to have zero flow. Periods of no flow are detrimental to aquatic species.
- The presence of non-native species throughout the system adds degrees of complexity in the form of additional feedback loops. For example, non-native trout are highly desirable for recreation, but as predators they have an adverse impact on native fish species. This adds a layer of complexity when trying to manage for healthy populations of both native and sport fishes.
- The ERM results suggest the riparian forest has undergone a fundamental shift that has rendered the system unable to self-sustain populations of plains cottonwood – its flagship species. In this void it appears that green ash will likely become an important component of the future forest. However, the recent arrival of the exotic emerald-ash borer (which is likely to decimate green ash populations) makes the future forest composition uncertain. Without a healthy forest canopy along the river's fringe, normal riparian functions and amenities like nutrient filtration, wildlife habitat, and even shade for recreation will be altered.
- Insofar as future river conditions comprise extended periods of low water, elevated temperatures, greater nutrient concentrations, and reduced frequency of scouring flows, a proliferation of nuisance algae is likely in the coming decades. This makes it difficult to provide a clean riverbed with an aesthetically pleasing water column.

Figure IV.2 Recent lowering of a high berm (remnant from gravel mining activity) between the Poudre River and Sterling Pond upstream of Shields St. allowed high spring flows in June 2014 to overtop its banks, inundate a wider riparian area, and flow into the pond.

Note: A substantial amount of deposition can be seen on the left side of Sterling Pond as well as the creation of an outflow stream on the downstream end (right side of the pond). Cottonwood seedlings were observed in establishing in patches throughout the area illustrating the river's inherent resilience and potential to respond quickly and positively to favorable conditions and restoration efforts.

Figure IV.3 Bank stabilization, confinement at bridge underpasses, and development encroachment into the floodplain is observed where the Poudre travels under Mulberry St. and Lemay Ave. bridges and parallel to Riverside Ave.

Note: This is one of many locations where physical changes to the floodplain limit habitat potential and ecological functionality.

The ERM assists managers in identifying specific and potentially obtainable goals and in linking management actions to the attainment of those goals for specific indicators of river health. The findings of this project are not recommendations for water resource and operations managers. The findings do, however, provide a scientific foundation to identify flow targets needed to achieve desired ecosystem functions and biological outcomes.

The purpose of the model was to consider likely biophysical and ecological responses to the range of possible futures, with little restraint as to what is likely, affordable, or administratively possible. Accordingly, the ERM team recognizes the challenge of integrating the ERM with legal, jurisdictional, fiscal, and managerial constraints. Decision makers must ultimately weigh a variety of stakeholder interests and the ecological, economic, and societal consequences associated with all policy options in an atmosphere of some uncertainty, whether acknowledged or otherwise. Probabilistic scientific assessments like those provided in this study can provide a rational, science-based and transparent basis for prediction and decision making by explicitly recognizing uncertainty and helping clarify the likely consequences of policy choices.

POSSIBLE NEXT STEPS

The ERM is a flexible tool that allows the incorporation of new information over time. The model's design team recommends consideration of the following steps.

- Input new hydrologic data and scenarios as they become available from the EIS or other studies to the ERM to refine results and improve prediction confidence.
- Review system understanding and consider possible adjustment of baseline conditions and thresholds in light of recent fires and flooding.
- Develop long-term monitoring and reporting protocol of key indicators to enable the community to track trends in river health and update knowledge underpinning the ERM. Consider additional data collection, analysis, and incorporation as described in Section III to fill important gaps in the understanding of the river system.
- Share these results beyond the scientific and management communities.

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AN ECOLOGICAL RESPONSE MODEL FOR THE CACHE LA POUDRE RIVER THROUGH FORT COLLINS

APPENDIXES

ECOLOGICAL RESPONSE MODELING TEAM

DECEMBER 2014

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APPENDIX A: ABBREVIATED BIOS FOR ERM TEAM MEMBERS (LISTEDALPHABETICALLY)

Gregor Auble is a research ecologist with the U.S. Geological Survey at the Fort Collins Science Center. Greg has more than 30 years of experience as an ecologist in the areas of ecological modelling, wetlands, and riparian ecosystems. For the last 20 years, his work has focused on responses of western riparian vegetation to flow alteration, channel modification, and herbivory. His studies have encompassed formal models projecting likely future vegetation as well as long-term field studies at sites including the upper Missouri, Gunnison, upper Green, Judith, Marias, and Illinois rivers. Greg earned a BA from Indiana University and a PhD in ecology from the University of Georgia. He holds professional certifications of Senior Ecologist from the Ecological Society of America and Professional Wetland Scientist from the Society of Wetlands Scientists.

Daniel Baker is a research scientist at Colorado State University (CSU). In the summer of 2012 Dan completed a postdoctoral fellowship at Johns Hopkins University, working with the National Science Foundation-funded National Center for Earth Surface Dynamics and the Intermountain Center for River Rehabilitation and Restoration based at Utah State University. He completed his PhD in civil and environmental engineering in 2009 at CSU, with a focus on river engineering and stream restoration. Dan's research focuses on the interaction between physical and biochemical processes in streams, the effects of flow extraction on stream geomorphology and sediment dynamics, and the application of Geographic Information Systems (GIS) technology to evaluate reach-scale conditions from digital elevation models. Other current projects focus on developing urban stream restoration guidance with the USACE and monitoring post-fire sediments and aquatic insects on the Poudre River.

Kevin Bestgen is the director of the Larval Fish Laboratory in the Department of Fish, Wildlife, and Conservation Biology at Colorado State University, where he is also a senior research scientist and faculty member. He has conducted research on ecology of stream fishes in the western U.S. for the past 30 years and focuses on flow and temperature needs of fishes and their conservation and restoration in altered stream systems. He has conducted biannual monitoring of fishes in Front Range streams, including the Poudre River, since 1992.

Brian Bledsoe is a professor of Civil and Environmental Engineering at Colorado State University. Brian has more than 25 years of experience as an engineer and environmental scientist in the private and public sectors, including more than 20 years of experience in stream and wetland restoration. Brian's research and teaching are focused on watershed and river processes at the interface of hydrology and aquatic ecology. He has worked in the private sector as a consulting engineer and surveyor, and for the state of North Carolina as a stream and wetland restoration specialist and nonpoint source program coordinator. Brian has served as a peer reviewer on recovery programs for the Platte and San Juan Rivers, the U.S. Environmental Protection Agency's Environmental Monitoring and Assessment Program (EMAP), as well as on numerous large-scale restoration projects including the Everglades and Louisiana coastal areas. Brian is a licensed professional engineer in Colorado and North Carolina.

Boris Kondratieff is a professor of entomology and director of the 3-million specimen C. P. Gillette Museum of Arthropod Diversity at Colorado State University (CSU). His current interests include insect biodiversity surveys of wild lands and other landscapes, especially military lands; aquatic insect ecology; taxonomic revisions and descriptions of new or poorly known species, especially Ephemeroptera (mayflies), Plecoptera (stoneflies), and Diptera (flies); forensic entomology; and management and curatorial work in the museum he directs. He has published 200 peer-reviewed scientific papers and

coauthored four books. He currently teaches six or seven different courses in bioagricultural sciences and pest management at CSU during an academic year. He received his PhD from Virginia Tech in 1982.

Mark Lorie is a water resources planner with Abt Associates in Bethesda, Maryland. He specializes in collaborative planning and decision-making processes for water resources management, decision-support modeling, and water resources policy analysis. Mark started his career with the Institute for Water Resources of the USACE and gained expertise in planning principles, multi-objective theory, decision-support modeling, and facilitation methods while working on major studies around the country. He played a key role in USACE's Shared Vision Planning (SVP) water management effort for the International Lake Ontario–St. Lawrence River Study, and supported districts and state agencies in implementing SVP for reservoir operations, water supply and other purposes. Mark worked for two years to improve water management processes in the Potomac River Basin before becoming an independent consultant. He led the SVP process for water supply projects in northern Colorado in connection with Clean Water Act permitting, the first study of its kind in the nation. Mark has played a key role in developing a national community of practice on methods such as SVP and has worked on various collaborative processes, including long-term management of the Poudre River. Mark has a bachelor's degree from the University of Connecticut and master's degree from Johns Hopkins University.

David Merritt is a riparian plant ecologist with the National Watershed, Fish and Wildlife Program of the U.S. Forest Service in Fort Collins, Colorado. The main focus of his work is to understand the role of river flow regime in structuring plant communities and maintaining diversity in riparian areas; to characterize the influences of dams and diversions on riparian vegetation; and to understand the mechanisms associated with the invasion of riparian areas by non-native plant species. In his current position, David serves as a liaison between the research community and National Forest managers on water resource-related issues.

LeRoy Poff is a professor of biology and director of the graduate degree program in ecology at Colorado State University. He teaches courses in aquatic ecology, trains and mentors graduate students, and conducts externally funded research on aquatic and riparian ecosystems in diverse settings that include Colorado, Australia, and Ecuador. Since receiving his PhD in 1989, his research has specialized on the ecological consequences of how natural and human-caused hydrologic variability regulates the interactions among species and the structure and function of riverine ecosystems. His work has contributed directly to the development of the science of environmental flows, which aims to support sustainable management of streams and rivers – at local to regional to global scales – in the face of competing water demands. He has more than 100 peer-reviewed publications and is named a Highly Cited Researcher. He was elected president of the Society of Freshwater Science in 2007, and is a fellow in the Aldo Leopold Leadership Program of the Ecological Society of America.

John Sanderson, Director of Conservation Science for The Nature Conservancy (TNC) of Colorado, manages a staff of scientists and project directors to deliver conservation outcomes on a wide range of topics. These include ensuring adequate streamflow for endangered fish in the Yampa River, making energy development compatible with sage grouse on protected lands in northern Colorado, and keeping hundreds of thousands of acres on the Great Plains intact to support native wildlife. John holds a bachelor's degree in engineering from Purdue University, a master's degree in botany from the University of Vermont, and a PhD in ecology from Colorado State University.

Jennifer Shanahan is an environmental planner for the City of Fort Collins, Natural Areas Department. Jen participates in a variety of planning processes related to management of the city's 42 natural areas. Her position focuses on a spectrum of issues surrounding the Poudre River that include landscape-level planning, application of science to policy and management, technical communications between numerous projects, and communication of technical topics to the broader community. She holds a master's degree from the Department of Forest Rangeland and Watershed Stewardship at Colorado State University, with a research focus in riparian restoration.

John Stokes began his career more than 20 years ago with the Appalachian Trail Conference, a non-profit organization that oversees management and conservation of the Appalachian National Scenic Trail. John accepted a position with The Nature Conservancy (TNC) of Texas in 1993 and moved to Fort Collins in 1996 to work with TNC in Colorado. He left in 2003 as the director of TNC's eastern Colorado programs. John then became Director of Natural Resources for the City of Fort Collins, in charge of operations for environmental services and natural areas programs. In 2012, John transitioned to become the director of the currently named Natural Areas Department and serves in a new role as the City's point person on Poudre River issues. John holds a master's degree in urban and environmental planning from the University of Virginia.

APPENDIX B: TECHNICAL BASIS OF MODEL COMPONENTS

Appendices B1–B2 Contributed By:

Daniel Baker, PhD, Hydrologist, Research Scientist, Department of Civil and Environmental Engineering, Colorado State University

Brian Bledsoe, PhD, Hydrologist, Professor, Department of Civil and Environmental Engineering and Graduate Degree Program in Ecology, Colorado State University

AppendixB3 Contributed By:

Boris Kondratieff, Ph.D., Entomologist, Department of Bioagricultural Sciences and Pest Management, Colorado State University

Appendix B4 Contributed By:

Kevin Bestgen, Ph.D., Director and Senior Research Scientist, Larval Fish Laboratory, Department of Fish, Wildlife and Conservation Biology, Colorado State University

LeRoy Poff, Ph.D., Aquatic Biologist, Department of Biology, and Director, Graduate Degree Program in Ecology, Colorado State University

Appendix B5 Contributed By:

Gregor Auble, PhD, Riparian Ecologist, United States Geological Survey

David Merritt, PhD, Riparian Ecologist, United States Forest Service

Vernon Bevan, Biological Technician, United States Forest Service

APPENDIX B1: CHANNEL STRUCTURE

METHODS

As an extension of the work presented in Section II of this report, this section further develops the technical basis for the development of the CMFI computations and thresholds associated with the Channel Structure indicator. First, the grain-size distributions used in the analysis will be discussed. Next, the three primary lines of evidence which helped inform the geomorphic/physical habitat components of the ERM will be examined in more detail, namely:

1) Dimensionless shear stress analyses that quantify the frequency and duration of flows that perform sediment flushing, river bed rejuvenation, and channel maintenance,
2) Effective discharge analysis of cumulative sediment transport capacity over the full spectrum of streamflows under historical conditions, and
3) Historical analysis of aerial images of the river planform and evidence of lateral migration.

Grain-size Distributions

The site-specific, grain-size distributions of the bed material used in the analyses were taken from a report by Ayres Associates (2001) and their sampling locations are provided in Table B.1 and Figure B.1, respectively. Not every site number had a sample that was deemed representative by Ayres Associates; therefore, surface gradations were based on their Wolman pebble counts and estimated substrate gradations on their grab sample gradation statistics. To define surface gradation in ERM Reach 3a, a representative sample of the upper portion of Ayres Reach 5 were used. Substrate gradation in this reach is based off a sample in Ayres Reach 4. The average of two samples closer to the end of Ayres Reach 5 is used for surface conditions in the ERM Reach 3b. For this reach, no single appropriate substrate sample exists, so samples from Ayres Reaches 4, 7, and 8 were averaged. The ERM Reach 7 uses a sample from Ayres Reach 15 for both the surface and substrate. The resulting values were similar to values estimated by CSU engineering students during laboratory exercises and recent CSU data collected as part of the post-2012 fire monitoring of the Poudre River (Daniel Baker, 2013, pers. comm.). These grain-size distributions were used for both the shear stress and effective discharge analyses. Pebble counts can tend to overestimate grain sizes because of measurement bias toward coarser particles (Bunte and Abt, 2001) but there are ways to decrease this bias (e.g. sampling frames).

Table B1.1. Sediment gradations (mm) used in the shear stress and effective discharge analyses.

	D5	D16	D35	D50	D65	D84	D95
Reach 3a							
Surface	16.0	30.8	43.2	52.6	63.9	84.7	110
Substrate	0.764	3.75	31.5	47.6	65.3	76.6	79.2
Reach 3b							
Surface	26.9	40.8	58.5	72.2	89.9	109	130
Substrate	0.554	2.85	18.8	29.4	50.3	63.2	70.8
Reach 7							
Surface	5.6	25.3	46.1	54.3	63.9	81.9	94.3
Substrate	1.38	5.63	29.8	50.3	54.9	62.9	77.7

Source: Ayres Associates, 2001.

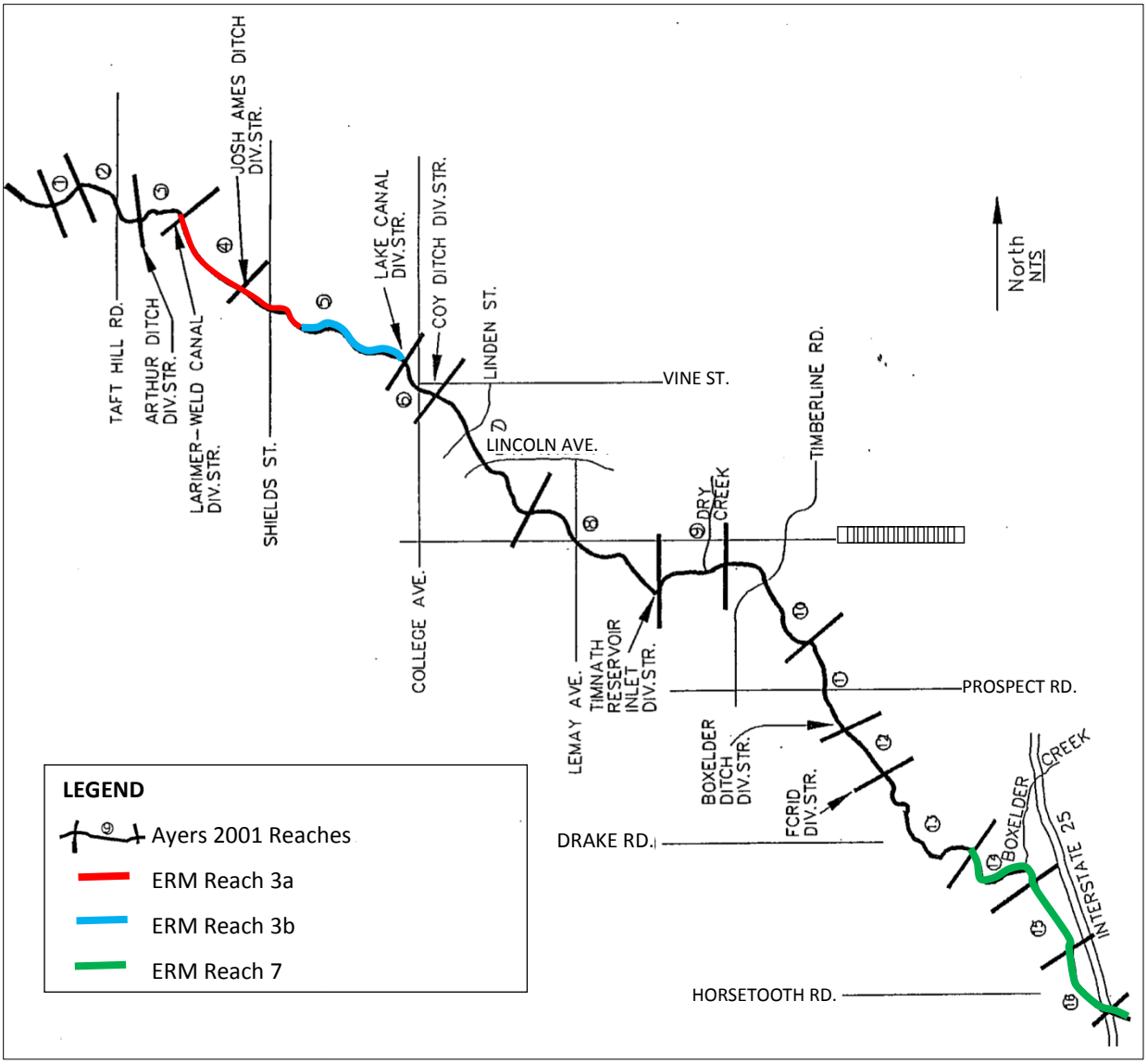

Figure B1.1: Sediment sample locations, in which red, blue and green lines indicate Reach 3a, Reach 3b, and Reach 7, respectively (adapted from Ayres, 2001).

Dimensionless Shear Stress Analysis

Dimensionless shear stress (τ_*) is a fundamental hydraulic parameter representing a ratio of erosive forces to resisting forces. It is commonly used in river mechanics to characterize the mobility of various sizes of sediment particles on the river bed. Dimensionless shear stress is defined as:

$$\tau_* = \frac{RS}{(G-1)d}$$

where *R* is hydraulic radius, *S* is slope, *G* is specific gravity of sediment (estimated at 2.65), and *d* represents grain diameter.

Most of the parameters needed to quantify shear stress at representative locations along the river corridor were generated using HEC-RAS 4.1 (USACE, 2010). The HEC-RAS model used in these analyses was provided by Anderson Consulting (Brad Anderson, 2011, pers. comm.; USACE, 2008), using cross sections measured by King Surveyors in 2007 as well as additional cross sections added by Anderson Consulting using other means (i.e., interpolation, repeated cross-sections, and photogrammetry). The model domain extends from the mouth of the canyon west of Fort Collins downstream past Greeley near the confluence with the South Platte River. A Manning *n* value of 0.035 used in the original model was maintained for the channel bed throughout Fort Collins. The HEC-RAS model already contained values for Manning *n* in overbank and impervious regions as approximately 0.05 and 0.025 with variation along the channel. These values were also retained. With these geometric inputs and a downstream boundary condition, HEC-RAS can calculate a water-surface profile, along with other corresponding parameters, for any given discharge. For this analysis, the downstream boundary condition was set as normal depth for a slope of 0.0036, which is the average bed-slope in the lower portion of the model domain. It is also important to note that model domain is much larger than the scale of this project; thus, the reaches in question are not sensitive to the selection of the downstream boundary condition.

Fifty-three different discharge values were modeled, ranging from 50 cfs up to 9,000 cfs using HEC-RAS, examining how main-channel shear stress, hydraulic radius of the channel, hydraulic depth of the channel, friction slope, and energy slope varied with streamflow. Although energy slope and friction slope are typically synonymous descriptions of the slope of the energy grade line in open channel flow, HEC-RAS provides different values because energy slope is estimated at a single cross-section, whereas friction slope is averaged over two cross-sections. Five different methods of calculating in-channel shear stress (τ) were compared (γ = specific weight of water):

1. main channel shear as calculated by the 1D HEC-RAS hydraulic model,
2. as estimated by $\tau = \gamma D S_e$, where D = hydraulic depth and S_e = energy slope
3. as estimated by $\tau = \gamma R S_e$, where R = hydraulic radius and S_e = energy slope
4. as estimated by $\tau = \gamma D S_f$, where D = hydraulic depth and S_f = friction slope
5. as estimated by $\tau = \gamma R S_f$, where R = hydraulic radius and S_f = friction slope

Visual inspection (see Figure B.2) of rating relationships indicated that using the product of hydraulic radius R and friction slope S_f provided the most physically realistic results in terms of how shear stress varies with discharge. Then, piecewise at-a-station hydraulic geometry relationships for shear stress, hydraulic radius, and friction slope as functions of discharge were developed. An example of a characteristic set of piecewise functions is shown in Figure B.3. After running the steady flow analyses, cross sections that were in close proximity to structures (such as weirs and bridges) and heavily influenced by backwater effects were removed from the HEC-RAS output before averaging reach-wide hydraulic characteristics. There is significant variation in these parameters among cross sections due to both inherent variability in channel forms and floodplain encroachment.

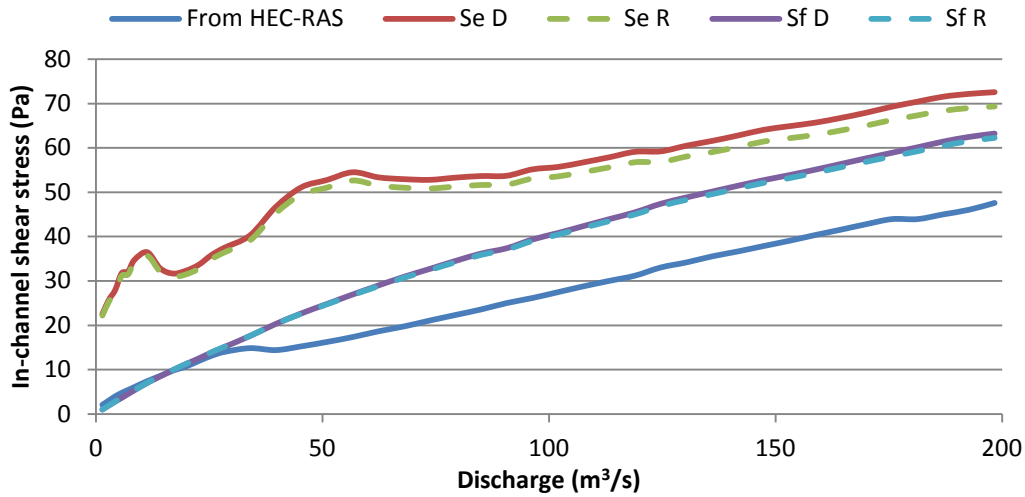

Figure B1.2: Reach-averaged relationships between shear stress and discharge in Reach 3a using various combinations of energy slope, friction slope, hydraulic radius, and depth.

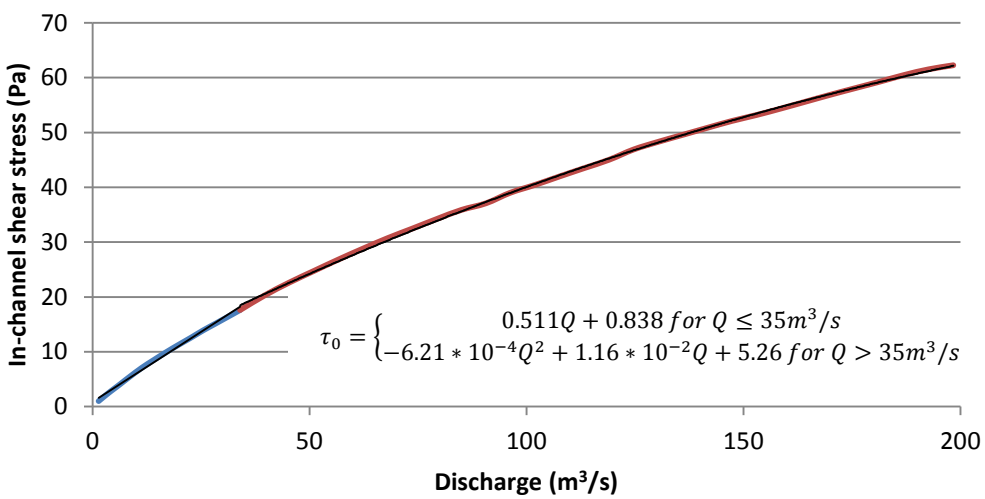

Figure B1.3. Piecewise at-a-station hydraulic geometry relationships between shear stress and discharge in Reach 3a.

Thresholds of dimensionless shear stress referenced to the median grain size of the river surface (D50) are associated with important geomorphic and ecological processes (e.g., ASCE, 1992; Milhous, 2000, 2003). These processes include the following.

- Algae scour/disturbance
- Sand/fine sediment flushing
- Limiting encroaching vegetation
- Armor breakup/full transport of bedload

Sediment movement in low gradient gravel-bed rivers can be described in terms of five general states (Table B.2).

Table B1.2: Interpretation of dimensionless shear stress values in terms of states of fine sediment flushing and coarse substrate mobilization.

	Dimensionless shear stress (τ_*) referenced to d_{50}	
Sediment movement state	**Lower bound**	**Upper bound**
Fines and sand are stored		0.009
Fines and sand in motion	0.009	0.021
Surface cleaning and removal of fines	0.021	0.035
Initial movement of armor and substrate cleaning	0.035	0.06
General movement of and cleaning of substrate	0.06–0.084	–

Source: Adapted from Milhous, 2000, 2003.

For the dimensionless shear stress analysis, spreadsheet tools were developed to quantify the frequency and average number of days per year that hydraulic conditions exceed incremental values of dimensionless shear stress (0.021, 0.030, 0.035, 0.040, 0.047, 0.053, and 0.060) referenced to estimated median grain size (D50) for any input streamflow series. These increments of dimensionless shear stress span varying degrees of river bed cleaning starting with removal of surficial deposits of fine sediments (0.021), to both surface cleaning and partial substrate cleaning (0.035), through increasingly thorough general cleaning of the substrate (0.040-0.06).

Results – Dimensionless Shear Stress Analysis

Using the main channel hydraulic radii and friction slopes from HEC-RAS (USACE, 2008; Brad Anderson, 2011, pers. comm.) in conjunction with site-specific grain-size distributions, estimates of discharges were calculated that correspond to ecologically-relevant thresholds of dimensionless shear stress for each reach (Table B.5).

Table B1.3: Discharge (cfs) corresponding to four thresholds of dimensionless shear stress at the three study locations.

Location	$\tau_* = 0.021$	$\tau_* = 0.03$	$\tau_* = 0.035$	$\tau_* = 0.06$
Reach 3a: Taft to Shields	1,750	2,700	3,300	6,900
Reach 3b: Shields to College Ave	1,400	2,500	3,200	8,000
Reach 7: Boxelder Gage to I-25	900	1,550	2,100	9,200

It is important to note that these values approximate the lower bound of the ranges in Table B.5 for flushing and substrate mobilization, and could potentially underestimate the flows required to perform these geomorphic functions. In general, substrate flushing and mobilization is a patchy and dynamic phenomenon; thus, conceptualizing substrate flushing and mobilization as a sort of on/off switch is erroneous. For example, a dimensionless shear stress of 0.03, based on cross-section averaged hydraulic characteristics, results in patches of the river bed that range from little or no transport to those experiencing intense transport with τ_* exceeding 0.06 in many cross sections. Values of critical dimensionless shear stress (referenced to D50) in the range of 0.01 to 0.03 are commonly observed in low-gradient, gravel-bed rivers like the Poudre (Buffington and Montgomery, 1997; Ferguson, 2012). This reflects the fact the cross-section averaged hydraulic characteristics tend to bias the actual shear stress and transport downward in irregular sections with zones of greater depth that produce nonlinear increases in transport.

Effective Discharge Analyses

For several decades, geomorphologists and engineers have recognized the value of coupling continuous flow series with sediment-transport relationships to quantify the combined effects of flow and sediment regime using Magnitude-Frequency Analysis (MFA) (Wolman and Miller, 1960). In this approach, the estimated geomorphic "effectiveness" (i.e., long-term sediment-transport capacity) of different flow levels is multiplied by the likelihood of occurrence (Pickup and Warner, 1976; Andrews, 1980; Emmett and Wolman, 2001). The flow with the largest product of sediment transport capacity and frequency is deemed the "effective discharge." For gravel bed snowmelt rivers like the Poudre, the effective discharge generally corresponds to range of flows that is most influential in performing geomorphic work and maintaining the channel over a period of years (Andrews, 1980; Emmett and Wolman, 2001).

In practical applications of MFA, discharge values are typically arranged into a specified number of discrete classes, referred to henceforth as "bins." The number of observations in each bin represents a flow frequency relative to the total number of flows recorded. The product of the sediment-transport capacity of a representative flow from each bin and its flow frequency produces an estimate of how much sediment can be transported by each bin. This procedure results in a series of discrete product values that form an effectiveness curve, with the highest point in an effectiveness curve representing an estimate of the effective discharge, the flow that transports the largest portion of the annual sediment yield the period of record (Andrews, 1980). The area under the effectiveness curve represents the time-integrated capacity to transport sediment through the channel.

Effective discharge analyses were performed using methods recommended by the USACE (Biedenharn et al., 2000; Soar and Thorne, 2001) to develop a second line of evidence for quantifying channel maintenance flows in the ERM. Twenty-five arithmetic flow bins and two bedload functions that bracket the hydraulic conditions and substrate characteristics of the Poudre River were used: 1) the Parker *et al*. (1982) bedload equation, and 2) the Wilcock and Crowe (2003) bedload equations. A description of these sediment-transport relationships follows.

Parker et al. (1982) Surface-based Relation

The bedload relation of Parker *et al*. (1982) is widely used in analyses of gravel-bed rivers. It is based solely on field data, mostly from Oak Creek, Oregon but also several other streams. The shear stresses were computed from depth-slope products, and it was assumed that drag at gravel-transporting flows was negligible:

For $\phi_i > 1.65$ $$q_{bv_i} = f_i g^{1/2}(G-1)^{-1}\left[11.2\left(1-\frac{0.822}{\phi_i}\right)^{4.5}\right](RS)^{3/2}$$

For $0.95 \le \phi_i \le 1.65$ $$q_{bv_i} = f_i g^{1/2}(G-1)^{-1}[0.0025\exp[14.2(\phi_i-1)-9.28(\phi_i-1)^2]](RS)^{3/2}$$

$$\phi_i = \frac{\tau_{*_i}}{\tau_{*_{ri}}}$$

Where ϕ_i is the ratio of dimensionless shear stress to reference dimensionless shear for a particular grain size class; *g* is acceleration due to gravity; *G* is specific gravity of sediment estimated at 2.65; and f_i

is a number between 0 and 1, representing the fraction of sediments in grain-size class *i*. Dimensionless shear stress for a given size class is defined as:

$$\tau_{*_i} = \frac{RS}{1.65 d_i}$$

Where d_i is geometric average grain diameter of fraction *i*. The volumetric bedload transport per time per channel width for a given bed-material size fraction is represented by q_{bvi}. The q_{bvi} for each size fraction are summed and multiplied by the channel width available for transport to calculate the sediment-transport capacity. Characteristic transport widths of 24.4 m, 21.3 m, and 12.2 m were used for the Reaches 3a, 3b, and 7, respectively. The Parker (1990) transport relation was also used for ϕ < 0.95 following Wilcock *et al*. (2009) and the U. S. Forest Service BAGS software package.

In the absence of a relationship calibrated at the specific site of interest, the following surface relationship developed by Andrews and Nankervis (1995) using field data from the Poudre River near Rustic, Colorado, provides a reasonable estimate of reference shear stress:

$$\tau_{ri}^* = 0.035(d_i/d_{50})^{-0.942}$$

Andrews (1984) also provided a reference dimensionless shear stress equation based on subsurface data from the East Fork River in Wyoming, and the Snake and Clear Water Rivers in Idaho:

$$\tau_{ci}^* = 0.0834(d_i/d_{u50})^{-0.872}$$

Wilcock and Crowe (2003)

The Wilcock and Crowe (2003) equation defines reference dimensionless shear stress as a function of sand content. The hiding function is taken to be a function of grain size *i* and the median grain size:

$$\tau_{r50}^* = 0.021 \pm .015\exp[-20F_s]$$

Where F_s is the fraction of sand on the bed surface:

$$\frac{\tau_{ri}^*}{\tau_{r50}^*} = \left(\frac{d_i}{d_{50}}\right)^b, \qquad b = \frac{0.67}{1 + \exp\left(1.5 - \frac{d_i}{d_{50}}\right)}$$

$$W_i^* = \frac{(G-1)gq_{bvi}}{f_i\left(\tau/\rho\right)^{3/2}} = \begin{cases} 0.002\phi^{7.5} & for\ \phi < 1.35 \\ 14\left(1 - \frac{0.894}{\phi^{0.5}}\right)^{4.5} & for\ \phi \geq 1.35 \end{cases}$$

Where W_i* is the dimensionless transport rate of size fraction *i* and τ is shear stress (in Pa).

Flow Records – Effective Discharge

The effective discharge analyses were based on the Recent Past flow scenario (water years 1970-2010) (see Section II for more details[1]) representing flow conditions at the Lincoln Street in Fort Collins (USGS gage 06752260) with flow adjusted through the city based on operations of diversions and additions (Donnie Dustin, 2011, pers. comm.; Andy Pineda, 2011, pers. comm.) The Poudre River is primarily a

[1] Note that USGS gage 06752260 began operations in April 1975. Data prior to that date is based upon the point-flow model further described in Table II.3 of the ERM Report

snowmelt-driven river, thus the rate of the change of flows is low, and use of daily average flows (as compared to 15 minute flows) provides acceptable results (Biedenharn *et al*., 2000). The differences between peak annual stream flow and corresponding daily average for the last 13 years in the record, as provided by the USGS gage 06752260, are presented in Table B.3. This indicates that daily average peak flow values provide a reasonably good representation of sub-daily flow peaks.

Table B1.4: Difference in peak and daily average flow conditions 1983-1995.

Date	Peak flow (cfs)	Daily average flow (cfs)	Difference (%)
6/21/1983	6674	6080	10%
5/25/1984	3426	2890	18%
6/9/1985	2260	1870	21%
6/7/1986	3426	3020	14%
6/9/1987	883	316	182%
6/11/1988	1236	933	33%
5/30/1989	706	492	46%
6/9/1990	1801	1190	51%
6/2/1991	3270	2430	39%
6/24/1992	953	429	124%
6/19/1993	2684	2470	9%
6/1/1994	1377	937	48%
6/18/1995	3500	3500	0%
Total average			46%
Average of flows above 2472 m^3/s			15%

In 1983, the Poudre River watershed experienced an extreme snowpack that provided not only the highest daily maximum (in the 1970-2010 period) of 6080 cfs, but also 28 of the top 30 daily average flows for the recent past flow record and the top 16 daily average flows for the native flow record. Peak stream flow for the 1983 event has a 19-year return interval based on the 37-year (1975–2011) peak annual stream flow record provided by the USGS at the Lincoln Street gage (Table B.4). More importantly, this event had an extremely long duration, and as a result, is very influential in determining the frequency distribution of high flows. Average stream flow for 1983 was 779 cfs, which is 490% higher than the average annual stream flow in the same 37-year period (1975–2011), 88% higher than the second highest year (1980 at 413 cfs), and is even higher than the peak stream flow of 1989. Due to these factors, the top 35 flow days from the 1983 water year were dropped to reduce the skew introduced to the effective discharge curves provided by a large number of high-flow days in 1983 and to determine the geomorphic effectiveness of flows other than the extreme 1983 event. This resulted in a 39% reduction(6074 to 3708 cfs) in the largest daily-averaged flow in the record of calculation, November 1, 1969–October 31, 2010, for the Recent Past scenario. The average annual discharge was reduced down to the level of most of the other high-flow years (from 777 to 346 cfs), which would make it the fourth highest annual average flow year in the 38-year record.

Table B1.5: Return interval analysis of instantaneous peak flows at the USGS Lincoln Street gage.

Flow (cfs)	Return interval
4767	10
3355	5
2649	2.5
1413	1.5
≈706	1

Sensitivity Analyses – Effective Discharge

For the effective discharge computations, two types of sensitivity analyses were performed by varying: 1) reference shear stress relationships, and 2) the number of flow bins used to discretize the flow records (following Biedenharn *et al*., 2000).

The substrate of the Poudre River through Fort Collins is armored in many locations and this generally reduces the sediment transport and increases the effective discharge. To better understand the magnitude of change in effective discharge if the armor layer was mobilized, substrate gradations were also used, as well as proportions of the surface gradation, in the surface relation of Parker *et al*. (1982). In addition, it was estimated the effective discharge were estimated based on the Andrews (1984) substrate equation, substrate gradation for Parker surface composite, substrate gradation for Parker substrate equation, as well as 2.5% and 5% surface sand in the Wilcock and Crowe (2003) equation.

Sensitivity to the number of flow bins used in the analysis was also examined. Using the effective discharge estimated with the entire flow distribution, the range of flows were narrowed incrementally to investigate how the effective discharge would change. Particular interest was given to the smallest bin size that avoided zero frequencies following Biedenharn *et al*., (2000).

Results – Effective Discharge Analysis

Ranges of effective discharges for each of these methods and for each reach are provided In Table B.6. The effective discharge values, based on the Parker surface composite method, closely match (within 2–8%) the discharge corresponding to a dimensionless shear stress value of 0.035 in each of the three river segments and are insensitive to the binning method and modest changes in reference shear stress and substrate characteristics. The convergence of results from the dimensionless shear stress analyses and the various effective discharge computations indicate that the discharges selected for substrate rejuvenation/channel maintenance are reasonable estimates until more detailed, site-specific monitoring can be performed.

Table B1.6: Effective discharge values (in cfs) under all methods for current conditions.

	Parker *et al*. surface composite		Parker *et al*. subsurface equation			Wilcock and Crowe		
	Gradation		Andrews modification	Gradation		Percent sand		
	Surface	Substrate		Surface	Substrate	0%	2.5%	5%
Reach 3a	3350	3350	3350	3350	3350	2120	2120	2120
Reach 3b	3350	3350	3350	3350	3350	2470	2120	2120
Reach 7	2650	2650	3710	3710	3710	2650	2650	2650

Although variations in reference shear method examined do not change the value of effective discharge values, they do produce a large variation in the amount of sediment transported at all ranges of discharges as is typical when utilizing diverse sediment-transport relations. The Parker surface composite, under both gradations, is always equal to the mode of estimated discharge values. For Reach 3a, removal of the top flows of 1983 reduces the range of flows by 39%; however, there is a consistent local maximum in all graphs around 3350 cfs. Results of the analysis of sensitivity to the number of flow bins are provided in Table B.7.

Table B1.7: Effective discharge by bin size for the current flow record using Parker surface composite.

Bin Size (cfs)	Effective discharge (cfs)		
	Reach 3a	Reach 3b	Reach 7
39	3320	3320	2966
49	3320	3567	2966
60	3602	3320	3002
71	3355	3355	3002
81	3320	3320	2613
92	3284	3284	3002
99	3320	3320	3002
109	3284	3284	2966
120	3284	3284	3037
Median	3320	3320	3002

Historical Analysis of Aerial Images

To explore historical changes in river planform and identify flow magnitudes associated with channel migration and creation of potential recruitment areas for plains cottonwood, maps and aerial imagery was examined from several time periods. Data sources included a detailed survey of Fort Collins from 1874 and available aerial photographs from 1937, 1984, 1999, 2002, and 2005. USGS historic photographs were also examined (though most were of poor quality) as well as images available through Google Earth, which has 11 sets of photographs from October 3, 1999–October 27, 2011. The time series of aerial photographs were examined in the context of the flow record at the USGS gage on the Poudre River at Lincoln Street (1975–2010) in an effort to estimate or bracket the magnitude of flows that have resulted in channel migration or areas of the river corridor that have partial or no lateral armoring.

Results – Historical Analysis of Aerial Images

The Poudre has experienced considerable channel migration from 1874 to the present, but most of this migration occurred before 1972. The exact mechanisms of planform adjustment are uncertain, though it appears that many of the significant changes were the result of direct human manipulation of the channel. The 1937 aerials provide the first high-quality images, and there is evidence of active channel migration due to natural processes at that time; however, with the exception of somewhat isolated changes in 1999, subsequent adjustments in channel planform depicted in the available photographs correlate directly to changes in human land uses along the corridor.

The ERM team was not able to locate suitable pre- and post-1983 imagery to assess the effects of the large and extended duration runoff event in that year. Therefore, the response to the 1999 high-flow event was primarily used to make inferences about the flow magnitudes that are associated with the type of channel adjustments and scour needed to maintain channel complexity for habitat and support recruitment of plains cottonwood in the riparian corridor. The flashy high flow of April 30, 1999 is somewhat anomalous in that it was generated by a rain on snow event that resulted in an instantaneous peak flow of 7,700 cfs, a value 2,000 cfs higher than the average daily flow of 5,640 cfs. In contrast to the long-duration 1983 event, the 1999 event exceeded 4,000 cfs for only three days. Despite its relatively short duration, the flow in April 1999 provided substantial scouring of point bars, newly-deposited lateral bars, and lateral migration in several locations with relatively low amounts of bank armoring (e.g., segment downstream of Shields Avenue). An additional short-duration, high-intensity flooding event occurred in September 2013. This rainfall-driven event peaked near 8,000 cfs, yet was only above 4,000

cfs for two days. The 2013 event created newly deposited lateral bars and caused minor lateral migration, but failed to mobilize vegetation on point bars last scoured in the 1999 event. In contrast to the 1999 event, a 2010 event with instantaneous and daily averaged peaks of 4,570 and 3,700 cfs, respectively, induced little detectable change in terms of bar formation or channel migration. Accordingly, it appears that daily averaged flows in the vicinity of 5,000 to 6,000 cfs may be required to produce substantial bar formation and scouring in locations lacking effective bank armoring. Depending on location, such flows would correspond to a τ_* exceeding 0.06 (referenced to D50 of the channel substrate).

As described above, it appears that occasional flows exceeding 5,000 to 6,000 cfs are necessary to induce channel adjustments that support plains cottonwood recruitment and maintenance of habitat complexity (e.g., pool-riffle sequences). However, such adjustments are only likely to occur in locations with minimal lateral armoring, or armoring that is set back from the channel banks. In many locations along the river, it is difficult to discern the extent of armoring because mature vegetation has developed on top of riprap that was emplaced decades ago. To better understand the extent of lateral armoring throughout the urban corridor, city staff compiled a map of lateral armoring and riprapped locations as described in the Riparian Methods in Section II. The map reveals that there are relatively few locations along the river that lack substantial armoring; this indicates that it is necessary to account for lateral armoring in the ERM to mediate the potential for high flows to induce channel adjustments that would create new habitats and opportunities for recruitment of plains cottonwood.

Extensive armoring is not unexpected in locations with infrastructure and human encroachment into the floodplain; however, there are a few segments along the urban corridor where natural river migration would not threaten human safety and infrastructure. These segments are the focus of the channel migration/habitat diversity flow analysis in that they could represent potential safe locations for cottonwood recruitment with reduced or setback armoring.

Initial Probability Development for Channel Structure

Building upon the above analyses, our initial probability construct attempted to bring together dimensionless shear stress exceedance with duration and frequency in a single table (Table B.8).

Table B1.8: Probabilities of three states of sediment flushing and bed mobilization based on dimensionless shear stress values, frequency of occurrence, and duration within a year.

Surface flushing	**Clean and diverse[2]**	**Marginally mobile[3]**	**Entrenched[4]**
τ_* exceeds 0.021 for 5+ days in 3 of 4 years	0.8	0.2	0
τ_* exceeds 0.021 for 3+ days in 2 of 3 years	0.4	0.5	0.1
τ_* exceeds 0.021 for 2+ days in 1 of 2 years	0	0.4	0.6
less than above	0	0	1
Bed mobilization / substrate rejuvenation			
τ_* exceeds 0.035 for 3+ days in 1 of 2 years	0.8	0.2	0
τ_* exceeds 0.035 for 3+ days in 1 of 3 years	0.5	0.4	0.1
τ_* exceeds 0.03 for 3+ days in 1 of 2 years	0.3	0.5	0.2
τ_* exceeds 0.03 for 1+ days in 1 of 3 years	0	0.3	0.7
less than above	0	0	1

NOTE: The information in this table was not directly used in the final model, but was used to inform the development of the CMFI metric

The primary challenge we faced when using these discretized shear thresholds was that they were not sensitive to differences among scenarios. For example, two flow scenarios that generate τ_* of 0.022 and 0.029 would be placed in the same probability bin, despite the fact that one has substantially greater potential to mobilize bed material. We therefore resolved to create a continuous variable which factored in both the magnitude and duration of shear stress exceedance events – the channel maintenance flow index (CMFI).

[2]Substrate clean on surface, interstitial space open, vegetation encroachment not advancing, channel has wide variety of depth, velocity, substrate combinations with morphologically diverse features such as side channels, chutes, bars owing to substantial removal of lateral bank stabilization.

[3] Flushing occurs at least every few years, interstitial space open in high-stress zones such as riffles, vegetation encroachment slowly advancing in low-stress zones, habitat diversity flows may be intact but bank stabilization partially limiting channel complexity.

[4] Partial to no substrate cleaning, channel maintenance absent, interstitial space not opened > 3–5 years, extensive bank stabilization, canal-like homogeneous channel.

CMFI development

Building off all the previous analyses we created a magnitude and duration metric, called the channel maintenance flow index (CMFI). The CMFI provides a continuous metric of channel maintenance effectiveness based on excess shear stress and its duration; therefore, it avoids issues associated with discretization approaches based on categorical thresholds of shear stress that are relatively insensitive to differences among similar scenarios. The CMFI equation is:

$$CMFI = \sum_{i=1,n} \left(\frac{\tau_{*i}}{\tau_{*R}}\right)^{1.5} \left(\frac{D}{D_c}\right)$$

Wherein:

τ_*	=	dimensionless shear stress
τ_{*R}	=	dimensionless reference shear stress capable of initiating geomorphic processes of interest
D	=	duration (days)
D_c	=	duration ceiling above which no additional geomorphic benefit is calculated
n	=	number of days during a year of record in which $\tau_{*R}$is exceeded

The CMFI metric essentially integrates how intensely, long, and often flushing occurs into a single continuous score for each flow scenario. This metric combines an excess shear ratio (non-linearized by raising the ratio to the 1.5 power after Wong and Parker (2006) and others) with a duration ratio. Two separate CMFI scores are computed; one for flushing (CMFI-F) and another for bed mobilization (CMFI-M) using the reference shear and duration ceiling values found in Table B1.9. Yearly CMFI scores were then averaged by summing the CMFI values across all years and dividing by the years in the analysis period.

Table B1.9: Summary of the reference shear (τ_{*R}) and duration ceiling (D_c) for the computation of CMFI-F (fine sediment flushing) and CMFI-M (coarse substrate mobilization).

Function	τ_{*R}	D_c
Fine sediment flushing (CMFI-F)	0.021	5
Bed mobility (CMFI-M)	0.030	5

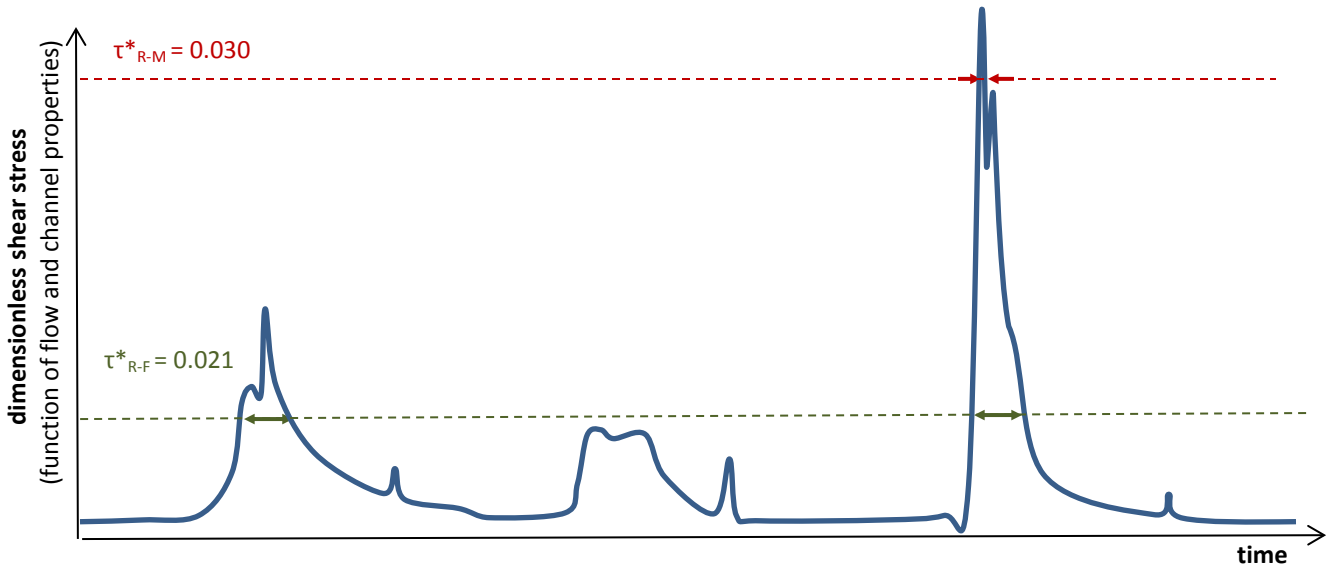

Figure B1.4: Visual explanation of the influences of magnitude, duration, frequency on Channel Structure over a hypothetical three year period.

Note:

Magnitude (height over thresholds): *The channel maintenance flow index (CMFI) computation is dependent on flow levels increasing the dimensionless shear stress (τ*) of the channel above a critical dimensionless shear stress of* $\tau^*_{R\text{-}F} = 0.021$ *for fine sediment flushing and* $\tau^*_{R\text{-}M} = 0.030$ *for bed mobility. The higher the flow, the higher the CMFI value, as indicated by the ratio of the actual τ* to the reference raised to the 1.5 power.*

Duration (time over thresholds): *The duration of shear stress above the critical value is a secondary contributor to the overall effectiveness of peak flows to improve channel structure. The CMFI equation demonstrates a linear scale to this duration term with a 5 day cap. Thus, 2 days of flow over the critical value gives you just 2/5 of the benefit of 5 days. Greater than 5 days does not improve the benefit over the 5 day cap.*

Frequency (fraction of years over thresholds): *Frequency enters the computations in the transition of CMFI values to the final Channel Structure probabilities. The more often flushing or mobility events occur, the more they will positively influence Channel structure. Flushing is desired 2 out of 3 years and bed mobility 1 out of 3 years (matching the frequencies of this figure).*

The end product is a physically-based and intuitive equation for quantifying flows associated with sedimentation processes such as surface flushing of fine sediments and coarse substrate mobilization. Convergence of results from previous analyses (shear and Qeff) informed thresholds used in the CMFI approach.

The analysis steps to convert the CMFI values to their final distributions were as follows.

A. <u>Determine controlling process</u> (flushing fines or bed mobilization). As flow rate increases, the channel maintenance functions transition from a state of no maintenance, gradually into surface flushing only, and finally to full flushing and substrate mobility. Using Table B1.8 as a basis, we found flushing to be fully engaged at a value of CMFI-F = 1.0 (τ_* = 0.021 for 5 days). Again using Table B1.8 as a basis, we found the lower limit of bed mobility at a CMFI-M = 0.34 (τ_* = 0.03 for 1 day). Comparing CMFI-F and CMFI-M values across flow scenarios, it was found that this pair of values coincided with each other. Thus, scenarios with CMFI-F ≤ 1.0 are deemed to only involve flushing of surficial deposits of fine sediment. For CMFI-F > 1.0 (and hence CMFI-

M > approx. 0.34), shear stresses transition into the flushing plus bed mobility range and CMFI-M is used.

B. Normalize CMFI values. As the goal of the Channel Maintenance analysis was a single probability distribution for each flow scenario based its intensity, duration, and frequency of both flushing and substrate cleaning, it was then necessary to collapse the CMFI-F and CMFI-M variables into a single linear function. As indicated above, CMFI-F = 1.0 and CMFI-M = 0.34 coincided, thus we used those values as a cross-over point in creating an index function with a minimum value of 0 and a maximum of 1 (Figure B1.4).

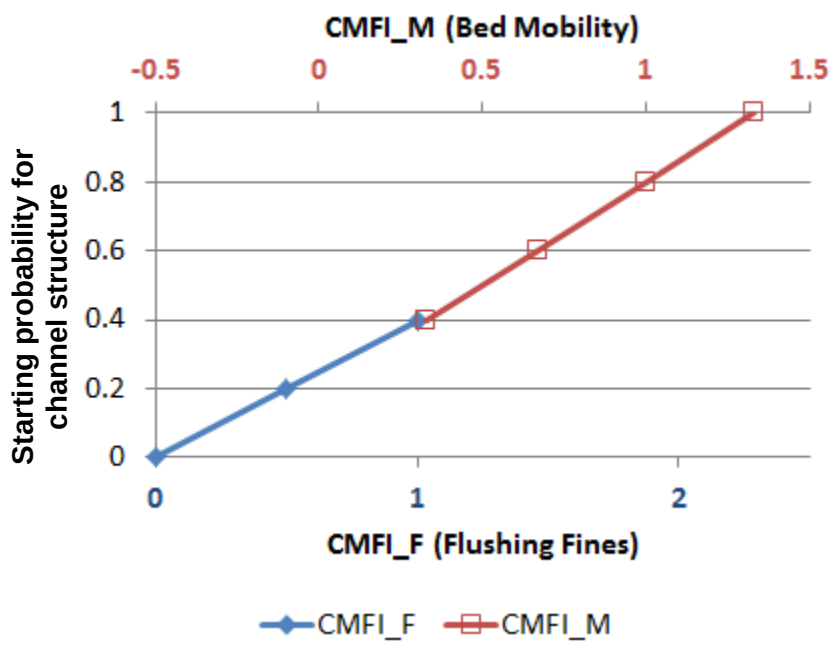

Figure B1.5: This figure demonstrates which process (flushing fines or bed mobility) controls the computation of the starting value for developing channel structure probabilities.

Note: It also assigns a value function to the continuous values of CMFI_F and CMFI_M. Note the equivalence of CMFI_F= 1.0 and CMFI_M = 0.34 (Step B above)

C. Assign uncertainty. It was then assumed that the uncertainty of the resulting normalized starting value was 25% of its original value (analogous to a coefficient of variation equal to 0.25). This uncertainty could be adjusted in future iterations of the model, given more in-depth information.

D. Adjust for frequency. If the fine sediment flushing and bed mobility occur less frequently, the resulting channel condition will likely degrade and the uncertainty about that condition is likely to increase. The inverse is also true; higher frequency equates to improved condition and less uncertainty. Thus the channel condition probability was adjusted linearly, using the following benchmarks (Table B 1.10). Benchmarks and channel states were established by eliciting expert judgment from Peter Wilcock (Johns Hopkins University) and Robert Milhous (USGS Retired), as well as from review of literature from similar systems, and return intervals were informed by ecological and sediment transport theory.

Table B1.10: Summary table of adjustment factors for flushing and bed mobility frequency intervals

Level	Flushing return interval (yrs)	Bed mobility return interval (yrs)	Multiplier for mean probability	Multiplier for standard deviation of probability
Minimum*	1.3	2.0	1.2	0.7
Mean	1.5	3.0	1	1
Maximum**	5.0	7.0	0.3	2

*Return intervals less than the minimum were held to the multipliers for the minimum level
*if the return intervals were greater than the Max value, then the mean probability was set to zero and the standard deviation multiplied by 3.

E. Limit by bank stabilization (armoring). Bank stabilization was then able to limit the mean channel condition according to the following rules:

Table B1.11: Bank stabilization category definitions and adjustments to mean channel condition

Bank stability category	Definition	Adjustment to mean channel condition
Minimal	Stabilized length occurring at any distance from channel center line is < 5% of bank length.	None
Altered	Stabilized length > 5% of bank length and stabilized length occurring < 50 m from channel center line is < 15% of bank length.	Limit state probability to 0.875
Protected	Stabilized length occurring < 50 m from channel center line is 15– 30% of bank length.	Limit state probability to 0.75
Stabilized	Stabilized length occurring < 50 m from channel center line is > 30% of bank length.	Limit state probability to 0.625

F. Compute distribution and bin. Lastly, the final weighted mean and standard deviation were used to develop a normal curve for the probability of channel condition for each flow scenario. The probabilities were then binned into the states in Table II.4.

Table B1.12: Description of four states of Channel Structure that depend on the combined status of flushing flows, coarse substrate mobilization, channel migration flows, and extent of armoring.

Likely State	Channel Condition Values	Description
Clean and diverse	0.75-1.00	Flushing and bed mobility flow functions intact, substrate clean on surface, interstitial space open, vegetation encroachment not advancing, channel has wide variety of depth, velocity, substrate combinations with morphologically diverse features such as side channels, chutes, bars owing to substantial removal of lateral armoring.
Partially mobile and diverse	0.50-0.75	All three flow functions at least partially intact, flushing occurs at least every few years, interstitial space open in high-stress zones such as riffles, vegetation encroachment slowly advancing in low-stress zones, habitat diversity flows may be intact but lateral armoring partially limiting channel complexity.

Largely immobile and homogeneous	0.25-0.50	Bed mobilization and/or channel migration flows not intact, flushing partially or not intact, vegetation encroachment likely advancing, river increasingly canal-like with homogeneous habitat until partially reset by an extreme event that overcomes riprap armoring in isolated locations, substrate flushing at least partially intact, habitat diversity flows could be intact but lateral armor present.
Entrenched	0.00-0.25	Partial to no substrate cleaning, channel maintenance absent, interstitial space not opened > 3–5 years, extensive lateral armoring, canal-like homogeneous channel.

The CMFI was applied to the full period of record for all flow scenarios.

APPENDIX B2: ALGAE AND NUTRIENTS

The following graphs summarize the exceedance probability of likely nutrient concentrations over the six hydrologic scenarios (see Figures B.4 through B.7). They can be interpreted as the percent of the time flows (y-axis) will likely have nutrient concentrations of a given value (x-axis). Also displayed on the graphs as vertical red-dashed lines are estimated threshold values for increased levels of algae growth; in the case of nitrogen this is around 0.4 mg/L (Dodds *et al*., 1997, 2002) and for phosphorus 0.11 (proposed cold-water standard for total phosphorus from Elmund *et al*. (2011)). As a demonstration of how you could read these graphs:

> Q: What is the fraction of time the total nitrogen concentration at Lincoln Street (Figure B.4) is above the threshold during the reconstructed natural scenario?
>
> A: By observing that the reconstructed native flow scenario crosses the 0.4-mg/L threshold at around 10%, one can deduce that the nutrient concentrations of the natural flow scenario are estimated to be above the threshold 10% of the time.

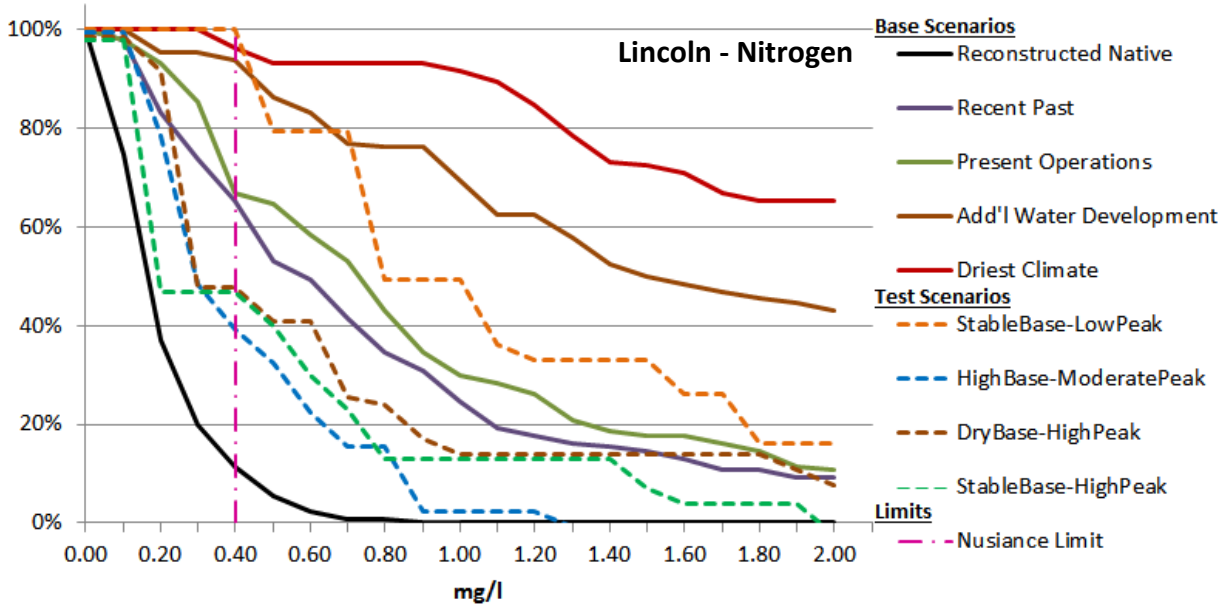

Figure B2.1: Exceedance probabilities of Base Scenarios and Test Scenarios for total nitrogen at Lincoln Street estimated for the period of record WYs 1970–1995 across multiple hydrologic scenarios.

Note: Also shows the 0.4-mg/L threshold for nuisance growth of algae (Dodds et al., 1997, 2002).

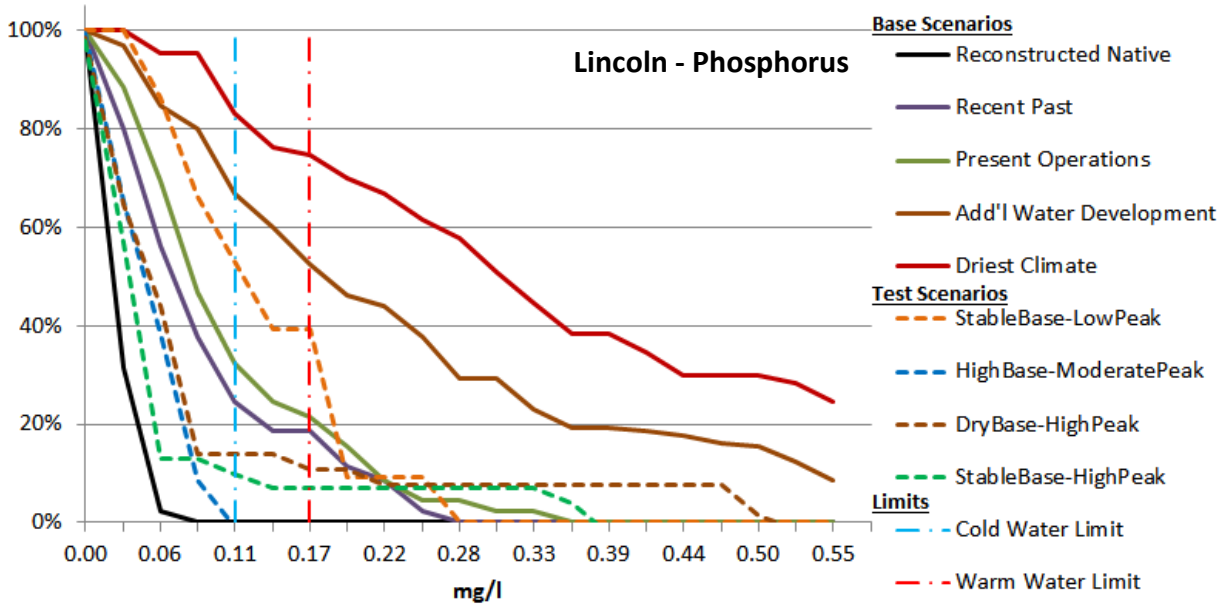

Figure B2.2: Exceedance probabilities of Base Scenarios and Test Scenarios for total phosphorus at Lincoln Street estimated for the period of record WYs 1970–1995 across multiple hydrologic scenarios.

Note: As a point of reference related to the nuisance growth of algae, the graph also displays the proposed median annual limits for both cold and warm water (Lincoln will be classified as a warm water reach as of March 2013), which can only be exceeded one in five years (Elmund et al., 2011).

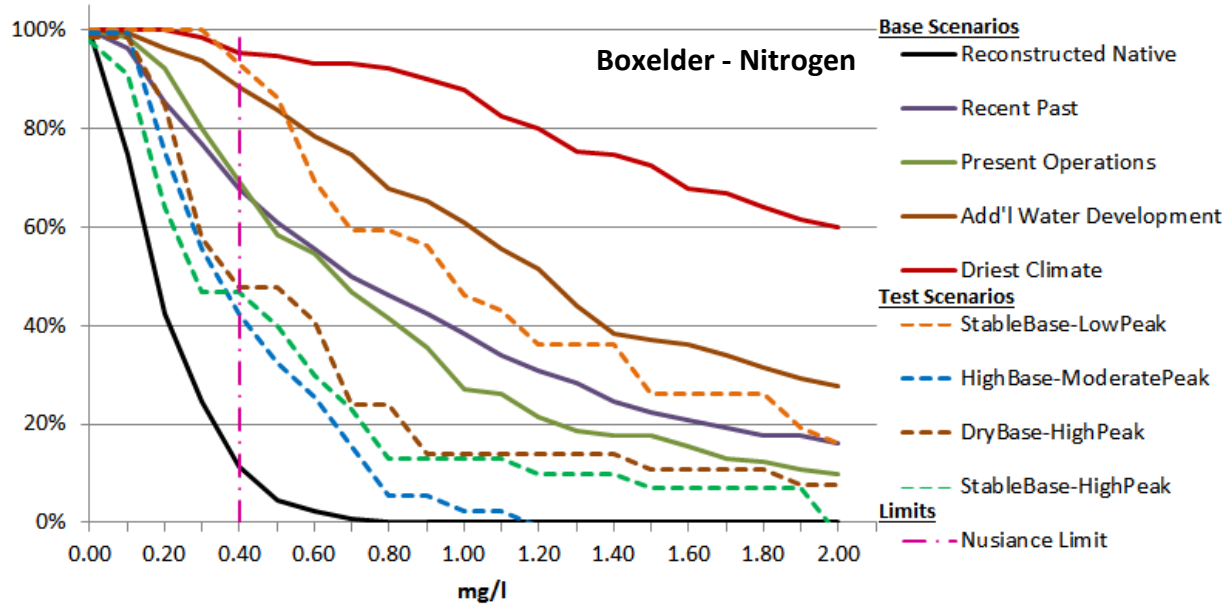

Figure B2.3: Exceedance probabilities of Base Scenarios and Test Scenarios for total nitrogen at Boxelder Creek estimated for the period of record WYs 1970–1995 across multiple hydrologic scenarios.

Note: Also shows the 0.4-mg/L threshold for nuisance growth of algae (Dodds et al., 1997, 2002).

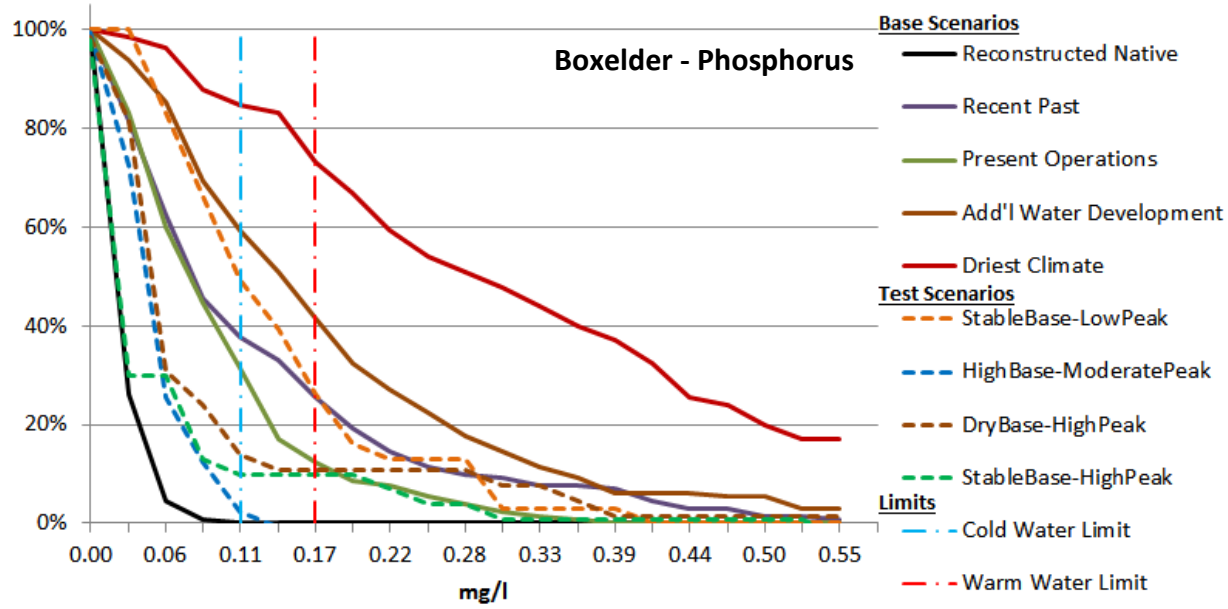

Figure B2.4: Exceedance probabilities of Base Scenarios and Test Scenarios for total phosphorus at Boxelder estimated for the period of record WYs 1970–1995 across multiple hydrologic scenarios.

Note: As a point of reference related to the nuisance growth of algae, the graph also displays the proposed median annual limits for both cold and warm water (Boxelder will be classified as a warm water reach as of March 2013), which can only be exceeded one in five years (Elmund et al., 2011; CDPHE, 2012).

Table B2.1: Probabilities for the impacts of nutrient enrichment and scouring flows on Algae.

Total nitrogen (NO3+NO2+TKN) – relative enrichment as compared to Recent Past scenario	Dissolved phosphorus (PO_4) – relative enrichment as compared to Recent Past scenario	Algae-flushing flow function	Probabilities for Algae		
			Less than today	About the same as today	More than today
Significant improvement	Significant improvement	Intact	0.9	0.1	0
Significant improvement	Significant improvement	Partially intact	0.6	0.3	0.1
Significant improvement	Significant improvement	Absent	0.4	0.4	0.2
Significant improvement	About the same	Intact	0.7	0.2	0.1
Significant improvement	About the same	Partially intact	0.4	0.4	0.2
Significant improvement	About the same	Absent	0.2	0.5	0.3
Significant improvement	Significant enrichment	Intact	0.5	0.4	0.1
Significant improvement	Significant enrichment	Partially intact	0.3	0.4	0.3
Significant improvement	Significant enrichment	Absent	0.1	0.4	0.5
About the same	Significant improvement	Intact	0.7	0.2	0.1
About the same	Significant improvement	Partially intact	0.4	0.4	0.2
About the same	Significant improvement	Absent	0.2	0.5	0.3
About the same	About the same	Intact	0.5	0.4	0.1
About the same	About the same	Partially intact	0.3	0.4	0.3
About the same	About the same	Absent	0.1	0.4	0.5
About the same	Significant enrichment	Intact	0.3	0.4	0.3
About the same	Significant enrichment	Partially intact	0.2	0.3	0.5
About the same	Significant enrichment	Absent	0	0.2	0.8
Significant enrichment	Significant improvement	Intact	0.5	0.4	0.1
Significant enrichment	Significant improvement	Partially intact	0.3	0.4	0.3
Significant enrichment	Significant improvement	Absent	0.1	0.4	0.5
Significant enrichment	About the same	Intact	0.3	0.4	0.3
Significant enrichment	About the same	Partially intact	0.2	0.3	0.5
Significant enrichment	About the same	Absent	0	0.2	0.8
Significant enrichment	Significant enrichment	Intact	0.1	0.2	0.7
Significant enrichment	Significant enrichment	Partially intact	0	0.2	0.8
Significant enrichment	Significant enrichment	Absent	0	0	1

APPENDIX B3: AQUATIC INSECTS

Table B3.1is a master list of taxa used in the ERM and their designation as sensitive taxa (EPT). This list is a compilation of data from Grotheer *et al*. (1994), Shieh *et al*. (1999, 2002), Voelz *et al*. (2000, 2005), USGS (2003), and Rice and Bestgen (2006).

Table B3.1: A master list for the taxa of Aquatic Insects.

TAXA	EPT (y/n)	TAXA	EPT (y/n)	TAXA	EPT (y/n)
Acentrella	y	Eukiefferiella		OLIGOCHAETA	
Agraylea	y	Euparyphus		Ophiogomphus s	
Amphiagrion		Fallceon quilleri	y	Optioservus	
Antocha		Ferrissia		Orthocladius	
Arctopsyche grandis	y	Glossosoma	y	Palpomyia	
Asellus		Glyptotendipes		Parachironomus	
Atherix		Gyraulus		Paraleptophlebia	y
Baetis	y	Helicopsyche borealis	y	Pentaneura	
Berosus		Hemerodromia		Pericoma	
Brachycentrus	y	Heptagenia	y	Petrophila	
Brillia		Hesperoperla pacifica	y	Phaenopsectra	
Caenis	y	Heterlimnius corpulentus		Physella	
Capnia	y	Hexagenia limbata	y	Pisidium	
Cardiocladius		Hexatoma		Polypedilum	
Chelifera		Hyalella		Procladius	
Cheumatopsyche	y	HYDRACARINA		Psectrocladius	
Chironomus		Hydropsyche	y	Pseudochironomus	
Cinygmula	y	Hydroptila	y	Psychomyia flavida	y
Claassenia subulosa	y	Isoperla	y	Rhithrogena	y
Clinocera		Isotomurus		Rhyacophila	y
Corynoneura		Kiefferulus		Serratella micheneri	y
Crangonyx		Lepidostoma	y	Simulium	
Cricotopus		Leptophlebia cupida	y	Skwala americana	y
Cryptochironomus		Limnophora		Stictochironomus	
Cultus aestivalis	y	Lopescladius		Sweltsa	y
Diamesa		Lymnaea		Tanypus	
Dicranota		Mesovelia		Tanytarsus	
Diplocladius		Microtendipes		Thienemanniella	
Drunella	y	Microvelia		Tipula	
Dugesia		Narpus concolor		Trichocorixa	
Endochironomus		Nectopsyche	y	Tricorythodes	y
Epeorus	y	Ecdyonurus	y	Triznaka signata	y
Ephemerella	y	NEMATODA		Zaitzevia parvula	
Erpobdella		Oecetis	y	Zapada	y

APPENDIX B4: BROWN TROUT AND NATIVE FISH

Background

The Poudre River originates in high-elevation mountains of the Front Range near Cameron Pass about 68 km west of Fort Collins, Colorado. The stream flows in a mostly easterly direction downstream to the foothills area. In high-elevation areas (> 1,900 m above sea level), the Poudre River is primarily a high-velocity, cold, high-gradient, and rocky-bottomed stream. Few fish species in the region are adapted to cold-water temperatures, so high-elevation mountain streams support primarily cold-water fishes such as trout. As the Poudre River emerges from the foothills, the character of the river changes to one that meanders more broadly, and water velocity is slower in wider, lower gradient valley reaches of this transition zone (approximately 1,600 to 1,900 m altitude; Propst (1982)). The fish community of a typical transition reach in the South Platte River Basin of Colorado includes brown trout (*Salmo trutta*), suckers (*Catostomus* sp.), and various minnows such as longnose dace (*Rhinichthys cataractae*). Stream substrate is still predominantly rocky, but water temperatures warm as the river passes through the transition zone. Associated with these physical habitat changes is a concurrent change in the fish community to species that tolerate cool (not cold) water temperature regimes. The transition zone continues downstream from the foothills to the vicinity of Fort Collins. The portion of the river that supports cool-water salmonids shifts downstream during years of higher and colder flows (e.g., since about 2008), such that brown trout may be relatively common as far downstream as Prospect Bridge. In warmer years, distribution of brown trout may be restricted mainly to the reach upstream of College Avenue.

Downstream from Fort Collins, the Poudre River enters the plains reach. In its natural (non-channelized) state, it meandered broadly across a wider floodplain, had relatively low gradient and current velocity, and probably had substrate composed of smaller particles such as sand and small gravel. Water temperatures in the plains reach are warmer than those in the transition zone and the Poudre River supports fish communities that are composed primarily of minnows, suckers, and darters; trout have been documented downstream into some plains reaches, but that likely occurred only in years with higher cooler flows.

The primary study area of concern in this report was the Poudre River from just west of College Avenue, Fort Collins, downstream to the ELC near the eastern terminus of Horsetooth Avenue. This section of the Poudre River is mostly in the transition zone and supports a mixture of cool- and warm-water fishes.

Study Sites

Inference was drawn to fish data gathered at two main sites in the study area. The first site is just upstream of College Avenue and adjacent the McMurray Natural Area and just upstream of Martinez Park (Site #1 in Bestgen and Fausch,1993). Collections at this site were initiated in 1990 and extended through 2006, with the exception of 1997 when no sampling occurred. After 2006, sampling was moved downstream to a site just upstream of the Lincoln Street Bridge; some inferences will be made to those data as well. The river at this site meanders slightly within channelized banks, but generally retains some of its natural character because some stream banks that have intact riparian trees are undercut but stable. Channelization, levees, and bank stabilization (e.g. riprap) at this site prevent the river from eroding into adjacent gravel-pit ponds, work which was apparently done prior to initiating collections. Habitat is diverse and consists primarily of deep runs and pools, and shallow riffles; substrate is predominantly cobble and gravel. The downstream half of the site is shaded by riparian trees that stabilize moderately undercut banks. Bank vegetation in the upstream half of the site consists of grasses

and sedges, and small trees. Large woody debris created habitat instream for large-bodied fishes at various times during sampling but is often removed, which simplifies habitat and reduces holding cover for large-bodied fishes including trout and suckers. This river reach is isolated upstream and downstream by nearby diversion dams. Discharge was normally higher at this site than at others, presumably due to increased downstream diversion, but generally reflects the discharge patterns at the Lincoln Street USGS gage (#06752260).

The second site (ELC) (Site #3 in Bestgen and Fausch, 1993) is located between Fort Collins Wastewater Treatment Plant #2 and the Boxelder Sanitation District effluent discharges. Sampling began here in spring 1981, and the site has not been moved during the study period. The river meandered slightly in this reach within incised and channelized banks. Habitat was somewhat diverse and included deep pools, shallow riffles, and a backwater. Substrate in deep pools and backwaters was generally thick, anaerobic silt over cobble. Riffle substrate was cobble and gravel, but was usually embedded with fine sediments. Riparian vegetation in the form of large cottonwoods and other trees was abundant and banks were generally stable and grass covered. This site was adjacent to gravel-pit ponds on the north side and to the Fort Collins ELC on the south side of the channel. The river has been severely channelized and the left bank armored since about 2005, presumably for protection of infrastructure at Boxelder Sanitation District, which eliminated much of the deep pool habitat and instream cover in the form of large woody debris. Flows at this site are typical of those at the USGS gage above Boxelder Creek (#06752280), which is located at the upstream end of the study area.

Several locations were also sampled between the Mulberry and Prospect Street bridges from 1990 until present (e.g., Site #2 in Bestgen and Fausch,1993). Some inferences are made to the fish communities there as well when defining probability states related to various model-driving variables.

Fish Collections

Fish collections were made at the Poudre River mostly using bank-based electrofishing gear, though in some years fine-mesh seines were used to supplement sampling effort. The same locations were sampled each year so that consistency of habitat was ensured unless sites were permanently changed due to proximity of bridges, channelization, or other unavoidable factors. Sampling times at sites were standardized to 45 minutes. Although samples were available from a variety of seasons, late summer or autumn samples were mostly used to maintain consistency (especially to determine year-class strength of brown trout produced the winter before). Typically one to two passes through the site were made, depending on the complexity of the habitat and the number of fish caught. Two persons electrofished and netted fish while two to four additional people netted and transported fish. All fishes were then identified to species, counted, and weighed (all individuals of a species combined, except trout where individual lengths and weights were usually taken), and returned to the river. Habitat and river conditions and sampling efficiency were also recorded.

Overall, during low-flow conditions, electrofishing was thought to obtain a representative sample of the fishes of a given reach. Tests of sampling efficiency of electrofishing gear were conducted at one simple site (Site #7) and one moderately complex site due to habitat diversity (Site #10) in the Poudre River. During repeated electrofishing passes at both sites, all but one of the fish species eventually caught in four passes was caught on the first pass. In each case, the remaining species caught was represented by a single individual that was caught on the second pass. Since one to two passes were generally made at each site in the Poudre River, most species at the site were probably caught by this method. That same evaluation of electrofishing efficiency also indicated that nearly half of the fish eventually caught in four passes were caught in the first pass, so that a good representation of fish numbers was also achieved by this method.

APPENDIX B5: RIPARIAN VEGETATION

POUDRE RIVER RIPARIAN VEGETATION PROBABILISTIC MODELING

Objectives

The objective of modeling riparian vegetation as a function of present flow regime along the Poudre River was to develop the ability to predict probability of change in vegetation attributes as a function of possible future changes in river flow regime. Vegetation data provided by the City of Fort Collins (Shanahan, 2009) served as the basis for the vegetation component of this work. Hydraulic models and an interdiversion flow portioning algorithm were provided by Anderson Consulting Engineers, Inc. (ACOE, 2008; Brad Anderson, 2011, pers. comm.). Vegetation attributes of interest in this work included presence/absence of: 1) hydrophytic (wetland) vegetation, 2) *Salix exigua* (sandbar willow), 3) *Populus deltoides* (plains cottonwood), and 4) *P. deltoides* seedlings. Hydrophytic vegetation closely corresponds to the Riverine Wetlands indicator in the Bayesian model and the long-term presence of *S. exigua*, *P. deltoides*, and *P. deltoides* seedlings are associated with the Rejuvenating Mosaic indicator in the Bayesian model.

Methods

The City of Fort Collins provided an ArcGIS shapefile of vegetation transects along the Poudre River and a triangulated irregular network (TIN) of elevations (±1 m) for the study segment of interest. Vegetation plot (N = 194) locations were derived from field-measured distances along 55 transects. Many transects were short and the generally occupied only one side of the river. A point coverage was generated to include each vegetation plot. Vegetation data included presence-absence and cover of all woody species in the plots and hydrophytic herbaceous vegetation. Presence-absence of seedlings of woody species was also recorded. The elevation TIN was converted to raster format and used to extract elevations for the vegetation transect endpoints and the center points of vegetation plots.

An ArcGIS shapefile of channel cross-sectional data and a HEC-RAS hydraulic model of the Poudre River were obtained from ACOE. Flows were modeled on the Poudre River between the town of Laporte and Interstate-25. Discharge at which vegetation plots became inundated was calculated using rating curves developed from these hydraulic models. Water-surfaces were generated using a range of flows at each HEC-RAS transect. Inundating discharge for each vegetation plot was determined through iteratively increasing discharge modeled until plot center points were inundated. Water-surface elevation of vegetation transects at various flows was calculated by interpolating between the water surface elevations of the upstream and downstream HEC-RAS transects at the respective flows. Two vegetation plots at Cottonwood Hollow and 16 plots at the Environmental learning Center (Reach 6) were excluded due to insufficient hydraulic data at those sites.

Maps in raster format showing the area and probability of inundation were created in ArcGIS for the following flows: 200, 300, 400, 500, 600, 700, 800, 900, 1,000, 1,500, 2,000, 2,500, 3,000, 3,500, 4,000, 4,500, 5,000, 5,500, 6,000, 6,500, and 7,000 cfs. The data to create these maps came from the HEC-RAS model and from exceedance probabilities of these flows occurring during the growing season (May–September). Exceedance probabilities were calculated from reconstructed flow data for seven inter-diversion reaches of the Poudre River. This output was also used to create the tables of inundated width (area divided by channel length) as a function of discharge used in riparian Bayesian network variables.

Grids of exceedance probabilities were initially created for the entire Poudre River between Laporte and Interstate-25, and were based on the width of the HEC-RAS transects. For final analysis, the area of interest was confined to the area inundated at a flow of 7,000 cfs. The river water surface at 200 cfs,

water bodies adjacent to the stream, and hardened structures (e.g., buildings, roads, and parking lots) were clipped from the area of interest and excluded from modeling results.

To calibrate exceedance probability models, data from Poudre River diversions and inputs were used to calculate exceedance probabilities during the growing season for seven reaches between the town of Laporte and Interstate-25. Presence and absence of each of the riparian vegetation attributes of interest were modeled as a function of Recent Past (Section II) exceedance probabilities using realized niche modeling (Jongman *et al*., 1995; Guisan and Zimmermann, 2000). Logistic regression model fit and significance were determined using Hosmer-Lemeshow (HL) goodness of fit tests and -2 log likelihood (LL). When significant, models were then used to predict the probability of occurrence in each 1 m x 1 m grid cell of each of the four vegetation attributes in the entire area of interest in ArcGIS. Model predictions of measured values were evaluated using cross validation error rates.

To examine possible future climate conditions and water development actions, nine different flow scenarios were developed (Hydrologic Scenarios, Section II). Exceedance probabilities for these scenarios were calculated and grids of exceedance probabilities were generated. Raster probability maps were created for the entire Poudre River study area for each flow scenario using ArcGIS.

Results

The model for *hydrophytic (wetland) vegetation* was significant (LL $p < 0.0001$) and the goodness of fit test indicated that model fit to the data was excellent (HL $p = 0.28$,where values < 0.05 would indicate a significant lack of fit). Cross validation indicated that the model correctly predicted presence of observed hydrophytic vegetation 68% of the time. The model for *Salix exigua* (sandbar willow) was also significant (LL $p < 0.0001$) and the goodness of fit test indicated that model fit to the data was excellent (HL $p = 0.36$). Cross validation indicated that the model correctly predicted presence of hydrophytic vegetation 73% of the time.

Results for the *hydrophytic (wetland) vegetation* model are presented in Figures B5.1, B5.3, B5.4, B5.5, B5.6, B5.7, B5.9, and B5.15.

Results for the *Salix exigua* (sandbar willow) model are presented in Figures B5.1, B5.8, B5.10, B5.11, B5.12, B5.13, B5.14 and B5.16.

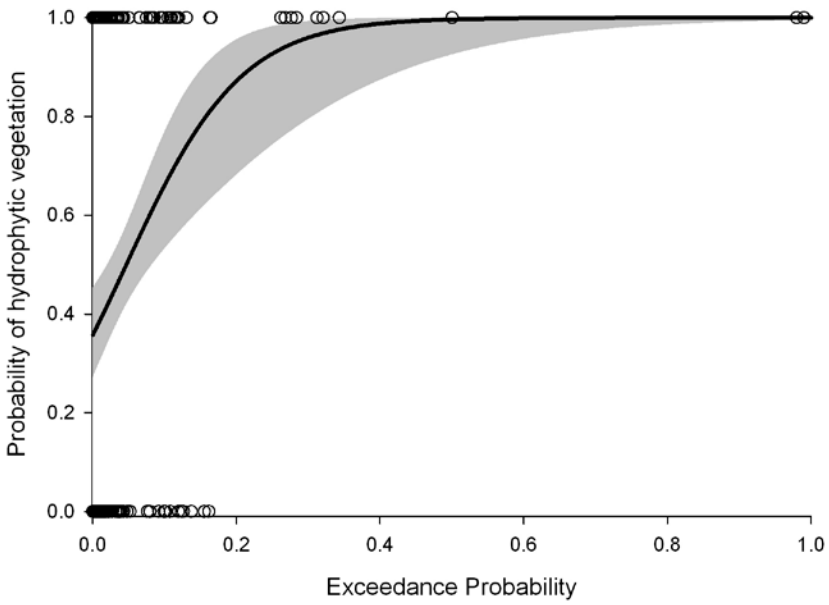

Figure B5.1: Probability of herbaceous hydrophytic (wetland) vegetation occurrence as a function of inundation.

Note: Exceedance probability is the fraction of the growing season that the vegetation plot is inundated (higher values are wetter). Circles are individual plots where presence=1 or absence=0. The model fit was significant (p < 0.0001) and predictions of measured data were 68% correct. The shaded zone is the 95% confidence interval.

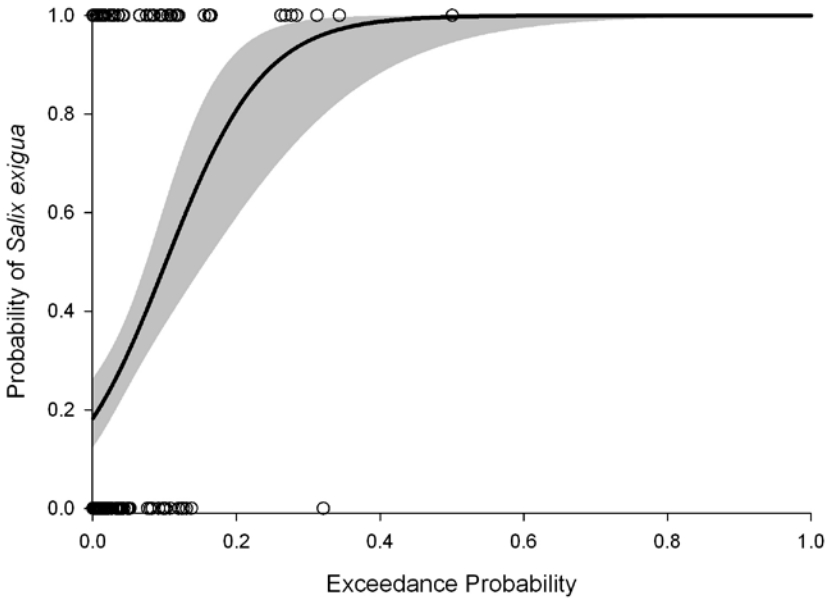

Figure B5.2: Probability of *Salix exigua* (sandbar willow) occurrence as a function of inundation.

Note: Exceedance probability is the fraction of the growing season that the vegetation plot is inundated (higher values are wetter). Circles are individual plots where presence=1 or absence=0. The model fit was significant (p < 0.0001) and predictions of measured data were 73 % correct. The shaded zone is the 95% confidence interval.

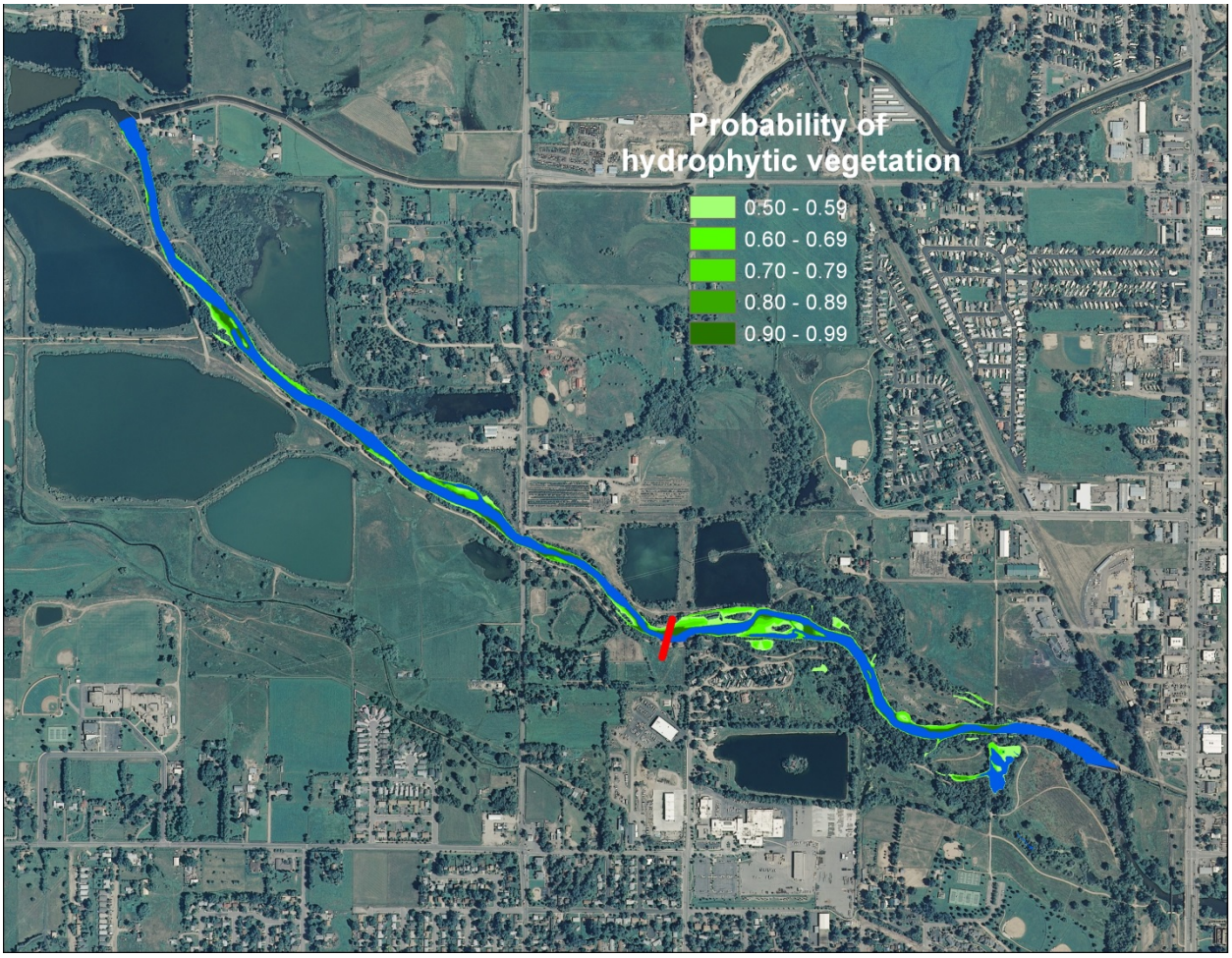

Figure B5.3: Probability of hydrophytic vegetation along Poudre River Reaches 3a and 3b as a function of exceedance probability for Recent Past flows.

Note: Reach 3a is to the left of the red line and Reach 3b is to the right. Along Reach 3a, 1.4 ha (7 m average width) of wetland vegetation is predicted under the Recent Past regime and 2.9 ha (23 m average width) is predicted for Reach 3b.

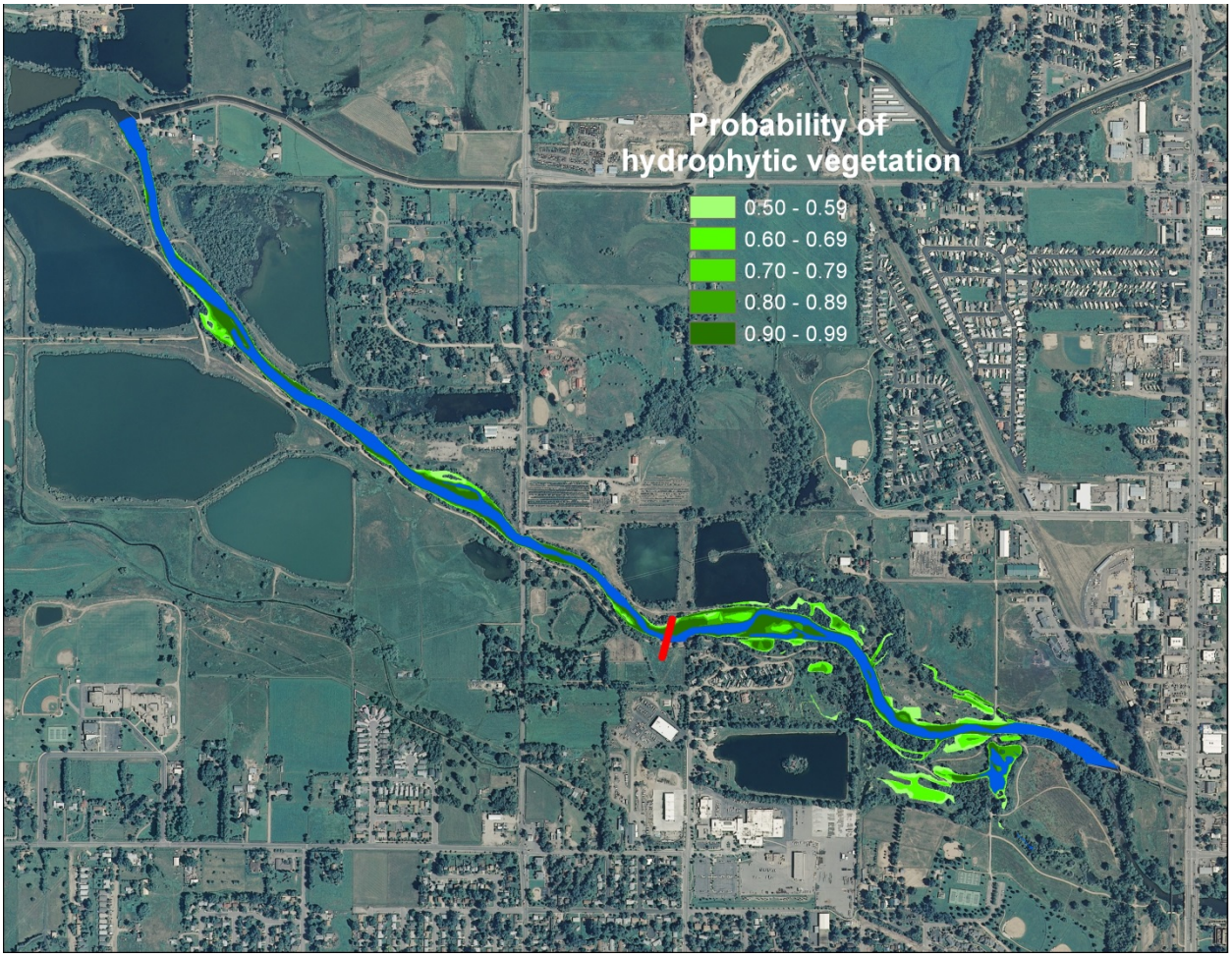

Figure B5.4: Probability of hydrophytic vegetation along Poudre River Reaches 3a and 3b as a function of exceedance probability for Reconstructed Native flows (reconstructed flow record without water diversions).

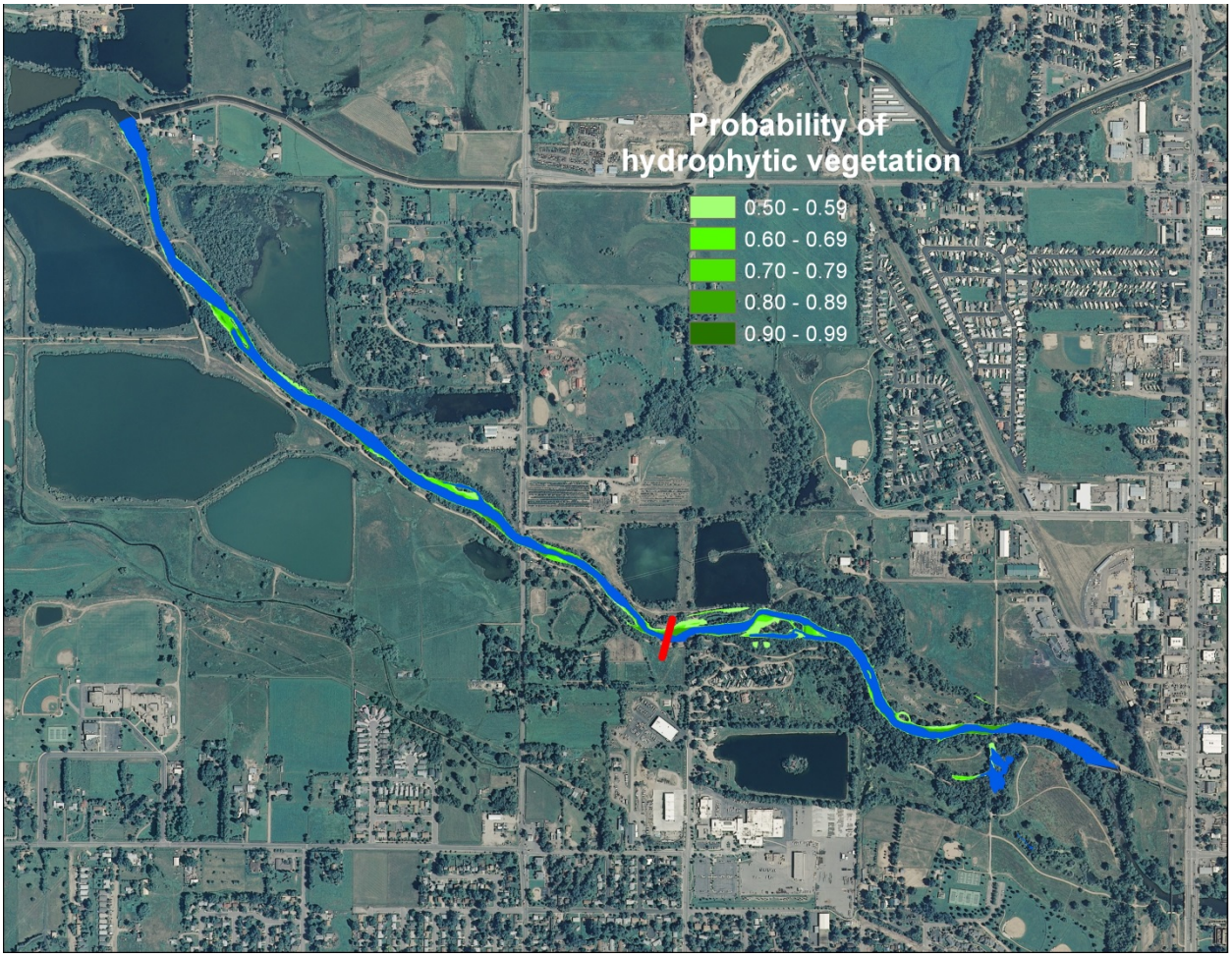

Figure B5.5: Probability of hydrophytic vegetation along Poudre River Reaches 3a and 3b as a function of exceedance probability for Present Operations continued flow scenario.

Note: Reach 3a is to the left of the red line and Reach 3b is to the right. Along Reach 3a, 0.8 ha (4 m average width) of wetland vegetation is predicted under the Recent Past regime and 1.5 ha (12 m average width) is predicted for Reach 3b.

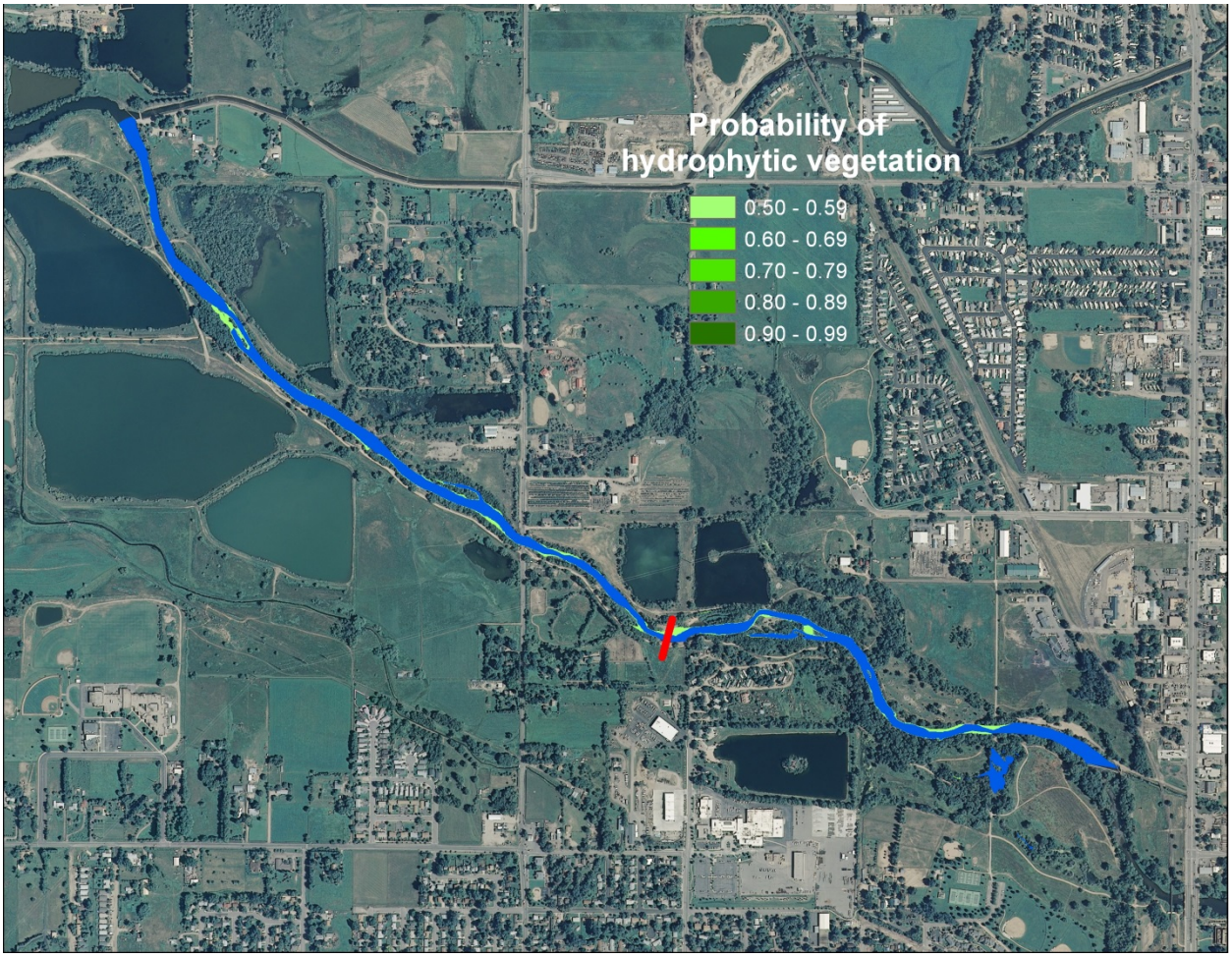

Figure B5.6: Probability of hydrophytic vegetation along Poudre River Reaches 3a and 3b as a function of exceedance probability for Additional Water Development flow scenario.

Note: Reach 3a is to the left of the red line and Reach 3b is to the right. No wetland vegetation was predicted (> 0.6 probability) along Reaches 3a or 3b under the Additional Water Development scenario. The light green areas all had probabilities ranging from 0.5–0.59.

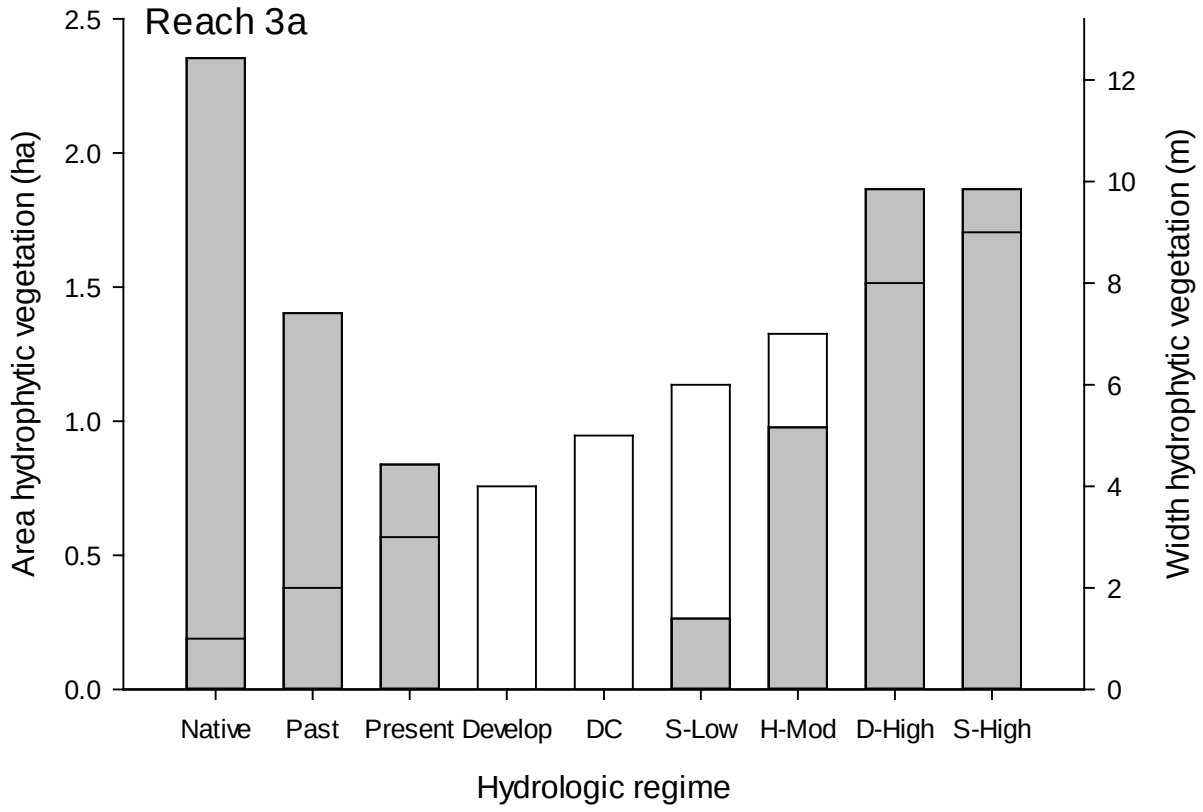

Figure B5.7: Predicted areal extent (in hectares) and average width (areal extent divided by reach length in meters) for hydrophytic vegetation in Reach 3a.

Note: Abbreviated scenario names represent: Reconstructed Native (Native), Recent Past (Past), Present Operations (Present), Additional Water Development (Develop), Driest Climate (DC), StableBase-LowPeak (S-Low), HighBase-ModeratePeak (H-Mod), DryBase-HighPeak (D-High), and StableBase-HighPeak (S-High) scenarios (refer to text for full descriptions of scenarios).

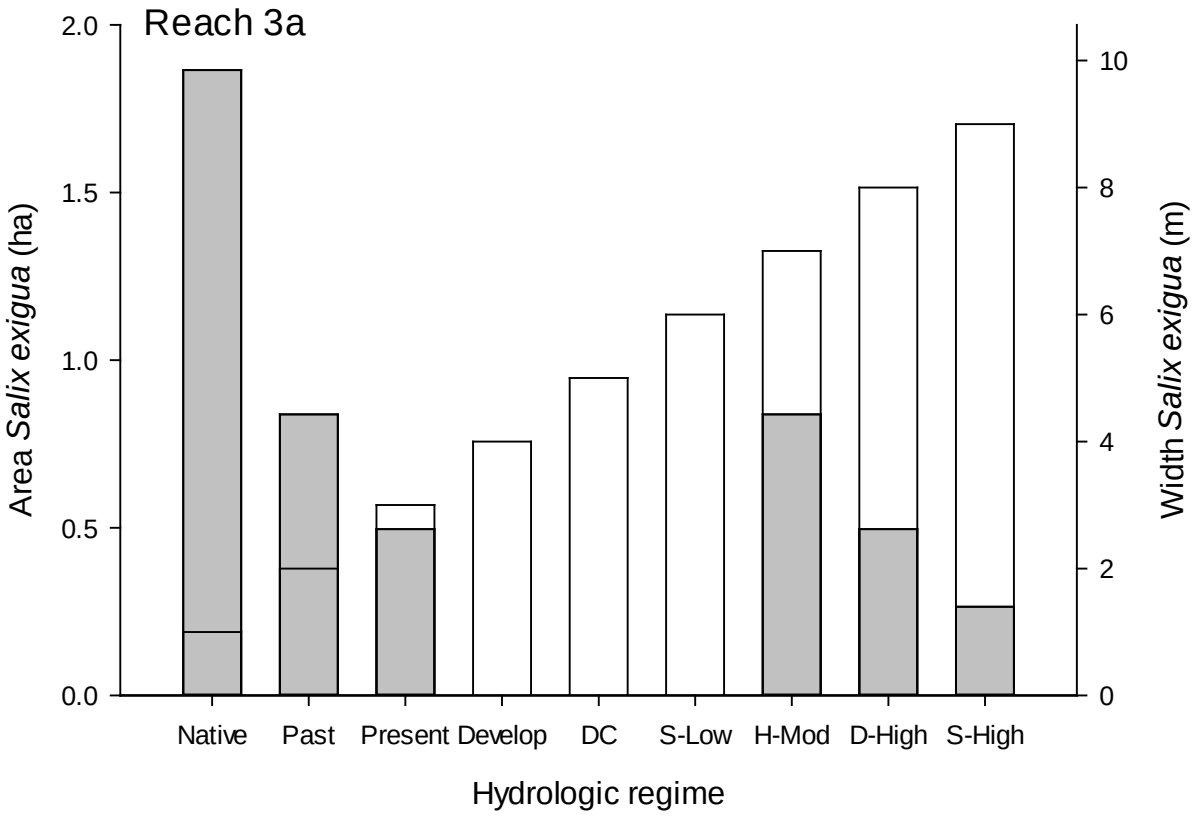

Figure B5.8: Predicted areal extent (in hectares) and average width (area divided by reach length in meters) for *Salix exigua* in Reach 3b.

Note: Abbreviated scenario names represent: Reconstructed Native (Native), Recent Past (Past), Present Operations (Present), Additional Water Development (Develop), Driest Climate (DC), StableBase-LowPeak (S-Low), HighBase-ModeratePeak (H-Mod), DryBase-HighPeak (D-High), and StableBase-HighPeak (S-High) scenarios (refer to text for full descriptions of scenarios).

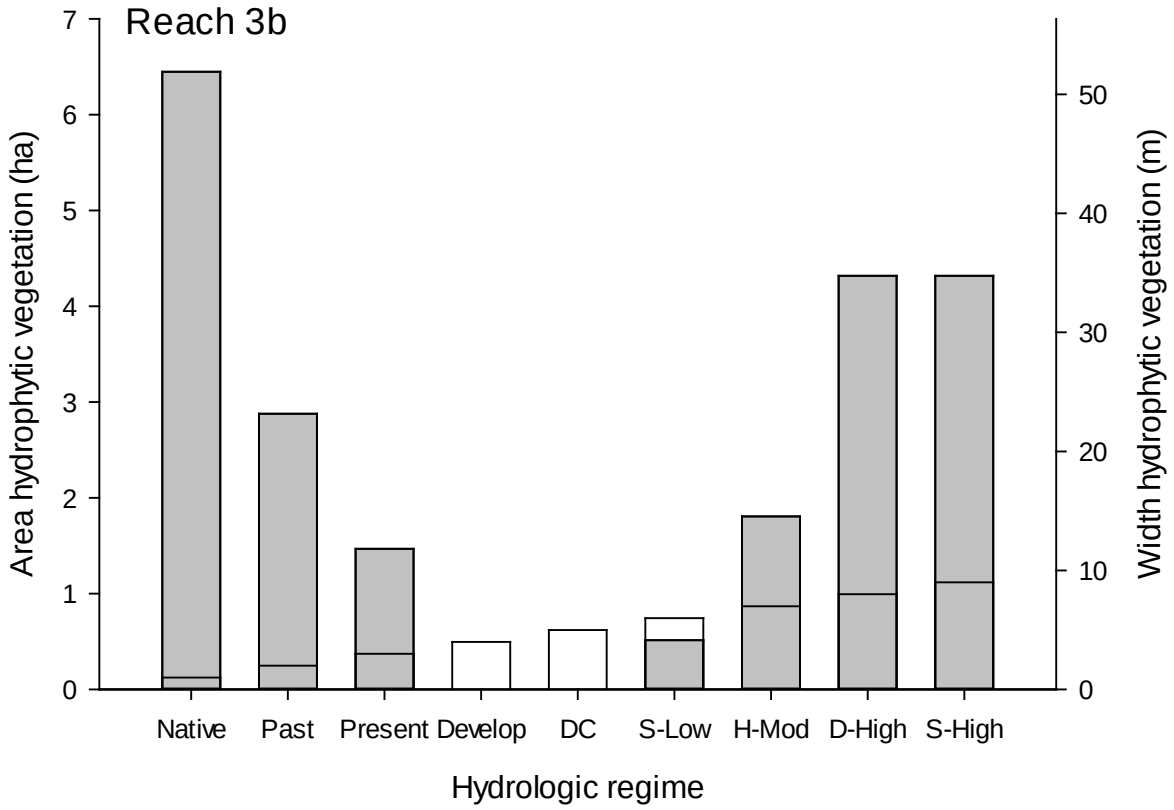

Figure B5.9: Predicted areal extent (in hectares) and average width (areal extent divided by reach length in meters) for hydrophytic vegetation in Reach 3b.

Note: Abbreviated scenario names represent: Reconstructed Native (Native), Recent Past (Past), Present Operations (Present), Additional Water Development (Develop), Driest Climate (DC), StableBase-LowPeak (S-Low), HighBase-ModeratePeak (H-Mod), DryBase-HighPeak (D-High), and StableBase-HighPeak (S-High) scenarios (refer to text for full descriptions of scenarios).

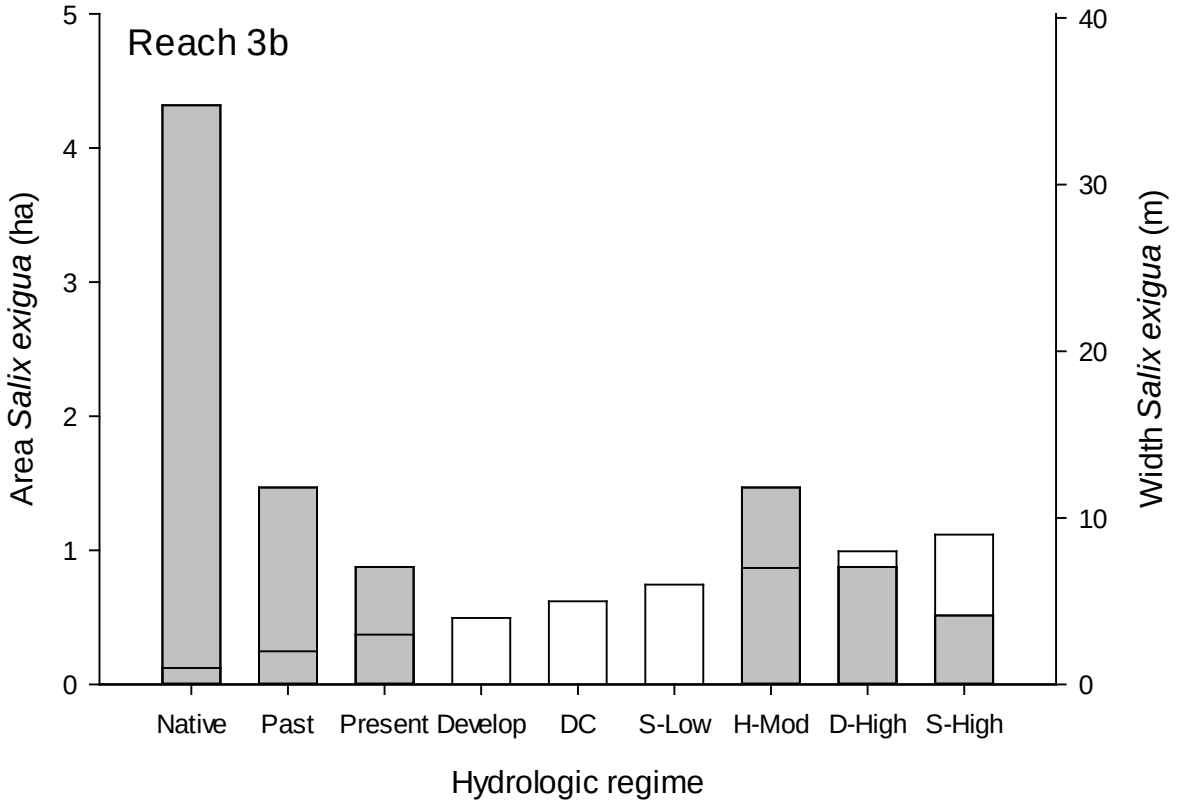

Figure B5.10: Predicted areal extent (in hectares) and average width (areal extent divided by reach length in meters) for *Salix exigua* in Reach 3b

Note: Abbreviated scenario names represent: Reconstructed Native (Native), Recent Past (Past), Present Operations (Present), Additional Water Development (Develop), Driest Climate (DC), StableBase-LowPeak (S-Low), HighBase-ModeratePeak (H-Mod), DryBase-HighPeak (D-High), and StableBase-HighPeak (S-High) scenarios (refer to text for full descriptions of scenarios).

Figure B5.11: Probability of *Salix exigua* (sandbar willow) along the Poudre River Reach 7 as a function of exceedance probability for Recent Past (baseline) flow.

Note: Predicted occurrence of S. exigua is 5.1 ha (14 m wide) along Reach 7 under the historic flow regime.

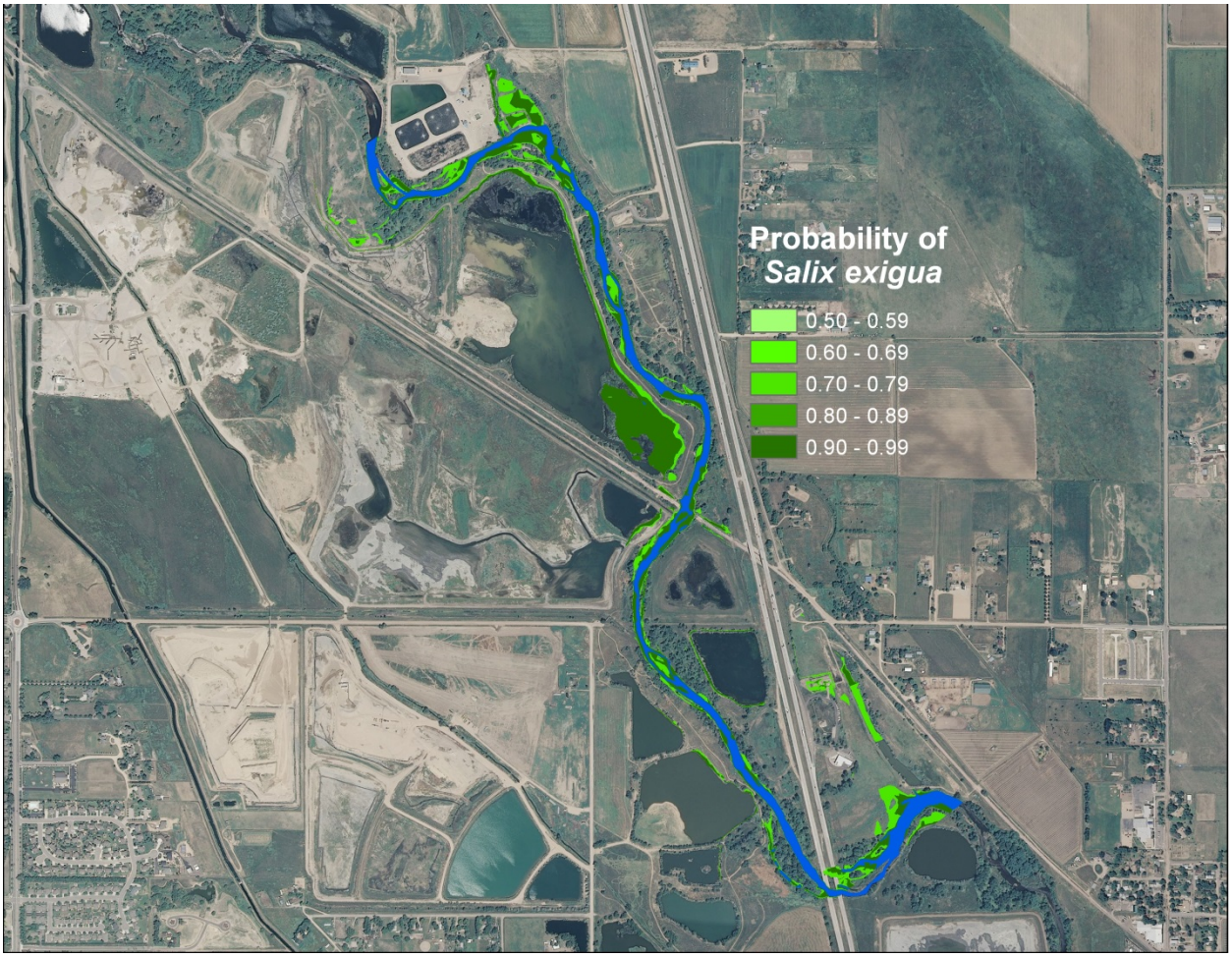

Figure B5.12: Probability of *Salix exigua* along Poudre River Reach 7 as a function of exceedance probability for Reconstructed Native flows (reconstructed flow record without flow diversions).

Note: Predicted occurrence of* S. exigua *is 14.1 ha (39 m average width) along Reach 7 under the Recent Past regime.

Figure B5.13: Probability of *Salix exigua* along Poudre River Reach 7 as a function of exceedance probability for Reconstructed Native flow.

Note: Predicted occurrence of* S. exigua *is 1.4 ha (3.8 m average width) along Reach 7 under the Recent Past regime.

Figure B5.14: Probability of *Salix exigua* along Poudre River Reach 7 as a function of exceedance probability for Additional Water Development flow.

Note: No* S. exigua *cover is predicted along Reach 7 for this scenario; the highest predicted probability of occurrence was 0.51 (7.5 ha).

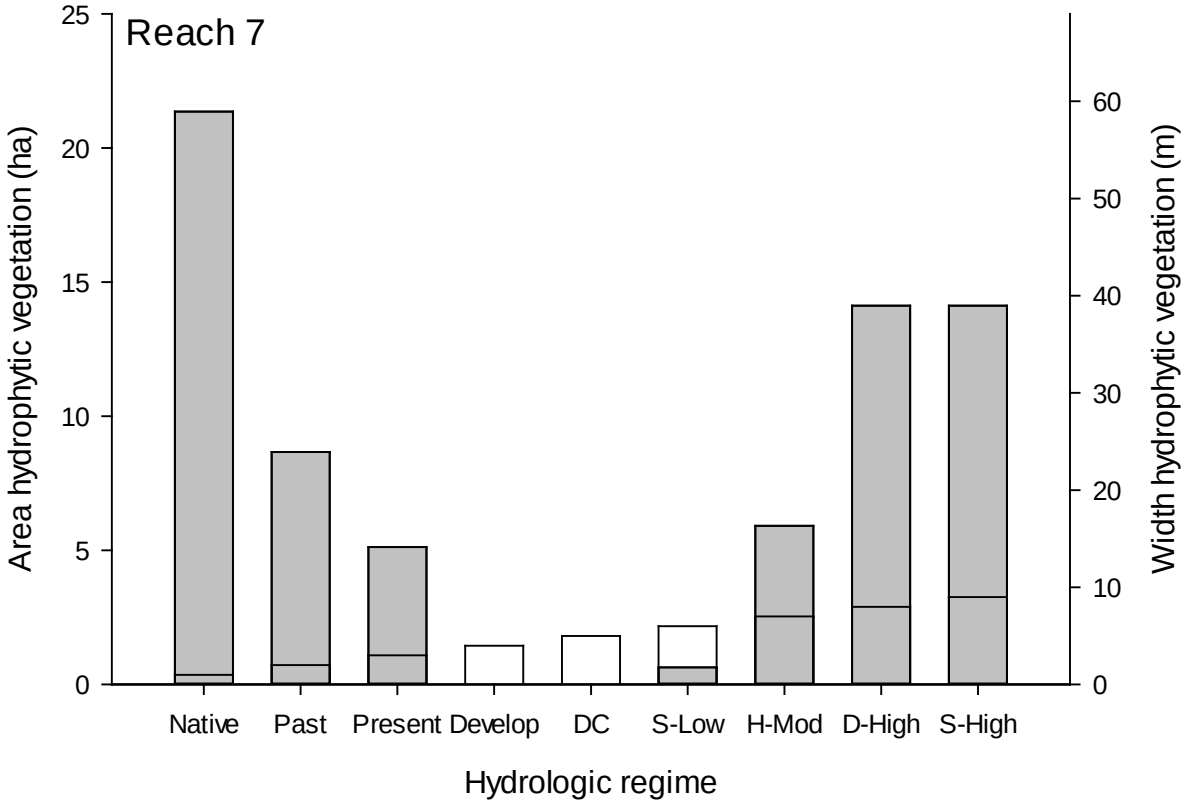

Figure B5.15: Predicted areal extent (in hectares) and average width (areal extent divided by reach length in meters) for hydrophytic vegetation in Reach 7.

Note: Abbreviated scenario names represent: Reconstructed Native (Native), Recent Past (Past), Present Operations (Present), Additional Water Development (Develop), Driest Climate (DC), StableBase-LowPeak (S-Low), HighBase-ModeratePeak (H-Mod), DryBase-HighPeak (D-High), and StableBase-HighPeak (S-High) scenarios (refer to text for full descriptions of scenarios).

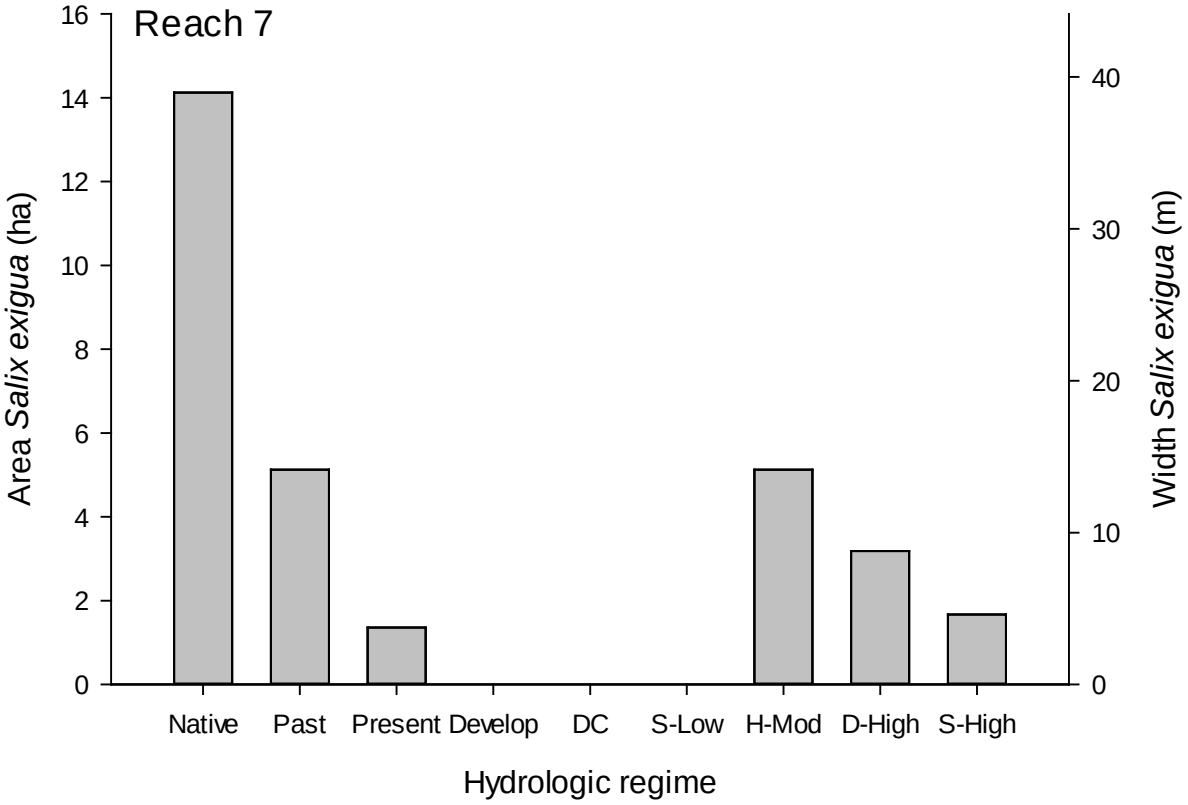

Figure B5.16: Predicted areal extent (in hectares) and average width (areal extent divided by reach length in meters) for *Salix exigua* in Reach 7

Note: Abbreviated scenario names represent: Reconstructed Native (Native), Recent Past (Past), Present Operations (Present), Additional Water Development (Develop), Driest Climate (DC), StableBase-LowPeak (S-Low), HighBase-ModeratePeak (H-Mod), DryBase-HighPeak (D-High), and StableBase-HighPeak (S-High) scenarios (refer to text for full descriptions of scenarios).

Conclusions for the Riparian Vegetation Probabilistic Modeling

Exceedance probability was a good predictor of the presence-absence of both hydrophytic vegetation (riverine wetland) and *Salix exigua*, as it provides a meaningful measure of water availability to riparian vegetation, as well as the probability of extreme high- and low-flow events. In most all cases, vegetation cover types were predicted to be highest in areal extent and average width in the Reconstructed Native flow scenario, followed by Recent Past (baseline), HighBase-ModeratePeak, DryBase-HighPeak, StableBase-HighPeak, Present Operations and Additional Water Development flow scenarios (descending cover). The most extreme cases were those of *S. exigua* in Reach 7 that completely disappeared from the reach under Additional Water Development (Figures B.21 and B.23) and hydrophytic cover in Additional Water Development and Driest Climate scenarios (no predicted cover). It is clear that the area of available habitat for both hydrophytic vegetation and *S. exigua* is greater along less constrained Reach 7 (Figures B.19 and B.23). Reaches 3a and 3b are more confined by levees and armored banks, so the area of available habitat is limited; changes in *S. exigua* cover as a function of flow are correspondingly lower. Predicted cover of hydrophytic vegetation was higher along all the reaches under the Reconstructed Native flow scenario, increasing from 68 to 146% from Recent Past. Present Operations resulted in decreases in wetland area of 40, 49, and 41% along Reaches 3a, 3b, and 7, respectively. Driest Climate resulted in elimination of hydrophytic and *Salix exigua* cover along all reaches. *S. exigua* was predicted to decrease along reach 3a (-40%) in comparing the Recent Past scenario to Present Operations, and *S. exigua* declined significantly along Reach 3b (-49%) and Reach 7 (-73%). Both cover types declined 100% in cover under Additional Water Development. Additional Water Development and Driest Climate had the most negative consequences for both riparian cover types evaluated, given all nine scenarios. Clearly, reduced magnitude and duration of peak flow and reduced low flow during the growing season lead to reduced cover and extent of hydrophytes and disturbance-adapted species such as *S. exigua*. The DryBase-HighPeak scenario and the StableBase-HighPeak scenario both improved conditions for wetland cover over Recent Past (and Present Operations, Additional Water Development, and Driest Climate), but these improvements were much more significant for the less-confined Reaches 3b and 7 compared to confined Reach 3a. *S. exigua* maintained cover relative to historic flows under the HighBase-ModeratePeak flow regime, but declined under all other modeled flow regimes.

Both low and high flows are important for riparian tree establishment and maintenance as well as for other important floodplain processes. High flows play an important role in creating and maintaining the channel and channel forms as well as maintaining dynamic and heterogeneous physical habitat for vegetation and wildlife in riparian areas (Stromberg *et al*., 2007). High flows create and maintain bare, exposed sites for seedlings of disturbance-adapted, native riparian species (e.g., *P. deltoides* and *S. exigua*). Occasional high flows mediate regeneration, are necessary for maintenance of growth and vigor of vegetation, and support the long-term sustainability of the riparian forests along the Poudre River. High flows also recharge groundwater, moisten the soil column, maintain fine roots of vegetation in the soil column, and facilitate decomposition, nutrient cycling, and nutrient availability to plants (Molles *et al*., 1998). Through moistening the soil column and elevating groundwater levels, high flows serve to exclude upland species from riparian areas, reducing competition with native riparian species and maintaining riparian areas that are distinct from adjacent uplands (Molles *et al*., 1998; Merritt and Bateman, 2012).

Sufficient low flows capable of supporting shallow water tables can increase the likelihood of establishment of disturbance-adapted species following scouring floods and support root development, growth, and survival to reproductive age (Mahoney and Rood, 1998; Merritt *et al*., 2010).

Reaches that are unconfined by riprap, bank armoring, and other structures may experience beneficial flooding of the floodplain during higher (even moderately high) flows. Appropriately timed high-flow

pulses (e.g., in the spring when native riparian forest species are dispersing seed) and gradually receding flows are important biologically. Spring and summer flow pulses result in brief rises in groundwater levels which recharge and moisten the soil column and the plant roots within it, and enhance transpiration and growth of riparian vegetation.

Prolonged periods without overbank flooding along the Poudre River would lead to accumulation of organic material on the floodplain (litter and wood), increased fuel accumulation and potential for intense wildfires, nutrient limitations for some species, drier soils, lowering of water tables, and amplified water stress for phreatophytic and wetland vegetation during periods of low streamflow. Lack of flooding would also result in higher probability of shifts towards shrub-dominated vegetation in areas nearer the channel. Occasional high flows are necessary for maintenance of growth and vigor as well as the long-term sustainability of the riparian forests along the Poudre River.

The ERM's probabilistic models use existing relationships between riparian vegetation cover types to predict probable changes in these cover types as a function of changes in flow scenarios in the Poudre River. Though only nine scenarios were presented in this work, these models may be used to predict areal extent and average width of hydrophytic (riparian wetland) vegetation and *S. exigua* (dynamic mosaic) for any scenario for which exceedance probability can be calculated.

RIPARIAN BAYESIAN MODEL VARIABLES: METHODS

The structure of the integrated Bayesian model dictated categorical variables and calculations that could be easily represented by combinations of tables. The definitions and general logic of those riparian variables are presented in Section II. This appendix provides more detail on the calculations and intermediate tables. Although the Bayesian network variables and calculations are structured differently than the geospatial probability models described above, both approaches have the same foundation – application of a hydraulic model to flow sequences in order to overlay water surfaces on a channel and bottomland topography followed by estimation of the resulting pattern of physical characteristics and consequent vegetation distribution.

Rejuvenating Mosaic

This index of the creation of fluvial disturbance patches supporting establishment of new pioneer species is the product of three components: area of high potential for turnover (1 in 5-year floodplain); expected average days per year of channel movement based on dimensionless critical shear stress; and a reduction factor for anthropogenic bank stabilization. The area of high potential is obtained by the flow-width relationships applied to the 1 in 5-year annual maximum daily flows and is summarized based on four classes (Tables B.9 and B.10).

Table B5.1: Classes of 1 in 5-year floodplain width.

1 in 5-year floodplain width class	Average width in m (total area / channel length)
Minimal	<15
Narrow	15–45
Moderate	45–90
Wide	>90

Note: Widths include both sides of channel and represent total area divided by channel length.

Table B5.2: Relationship of 1 in 5-year annual maximum daily discharge and class of 1 in 5-year floodplain width.

1 in 5-year maximum daily discharge	Reach		
	3a	3b	7
<200	Minimal	Minimal	Minimal
200	Minimal	Minimal	Minimal
300	Minimal	Minimal	Minimal
400	Minimal	Minimal	Minimal
500	Minimal	Minimal	Minimal
600	Minimal	Minimal	Minimal
700	Minimal	Minimal	Minimal
800	Minimal	Minimal	Minimal
900	Minimal	Minimal	Minimal
1000	Minimal	Minimal	Narrow
1500	Minimal	Narrow	Narrow
2000	Minimal	Narrow	Moderate
2500	Minimal	Narrow	Moderate
3000	Narrow	Moderate	Wide
3500	Narrow	Moderate	Wide
4000	Narrow	Wide	Wide
4500	Narrow	Wide	Wide
5000	Narrow	Wide	Wide
5500	Narrow	Wide	Wide
6000	Narrow	Wide	Wide
6500	Moderate	Wide	Wide
7000	Moderate	Wide	Wide

Average expected days per year of channel movement is based on reach-specific daily values of dimensionless shear stress (τ_*) following calculations described in Appendix B1. A piecewise non-linear function relates daily dimensionless shear stress to daily probability of channel movement (Figure B.24). Probability of channel movement is zero for $\tau_* < 0.03$ and a minimal 0.001 for τ_* between 0.03 and 0.045. Above the threshold of $\tau_* = 0.045$, probability of movement increases from 0.1 at $\tau_* = 0.045$ to a maximum of 1.0 at $\tau_* = 0.06$. The non-linear increase is proportional to $(\tau_* / 0.045)^3$. Individual daily probabilities of channel movement are then used to calculate the average expected days of channel movement per year.

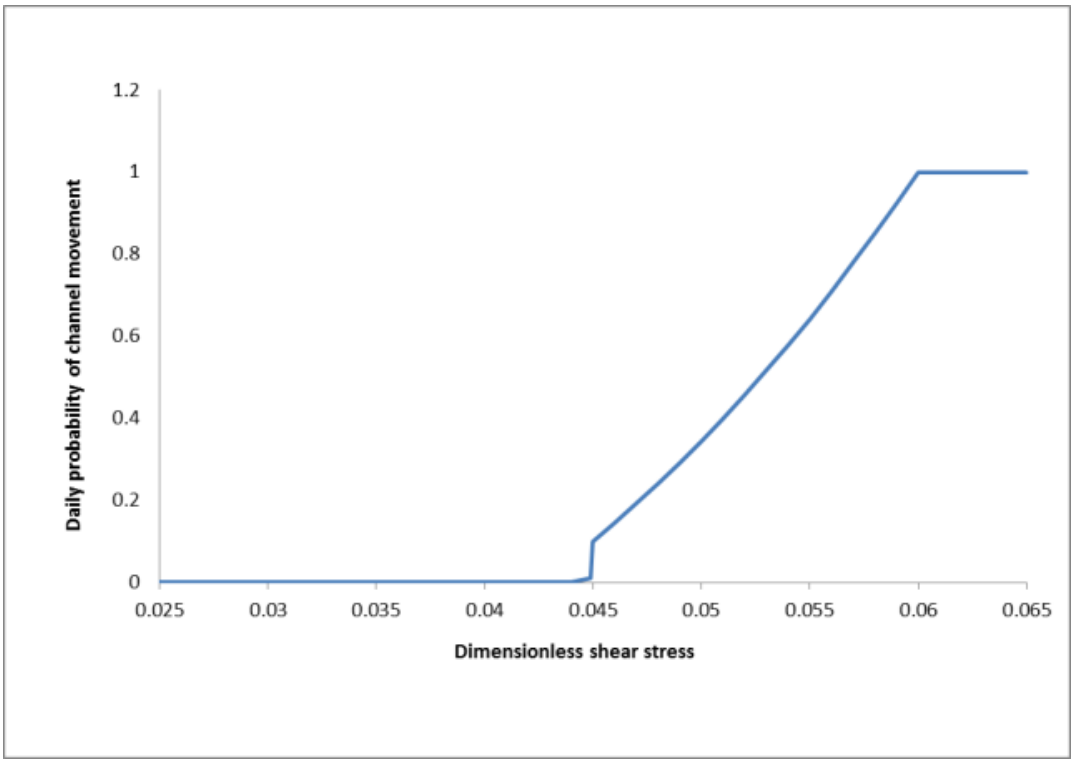

Figure B5.17: Relationship between daily probability of channel movement and dimensionless shear stress used in Bayesian Rejuvenating Mosaic calculation.

Reduction factors due to class of channel stabilization are presented in Table B.11.

Table B5.3: Reduction factor due to channel stabilization.

Class	Fractional reduction in width of Rejuvenating Mosaic
Minimal	0.92
Altered	0.58
Protected	0.33
Stabilized	0.04

Note: Current values for Reaches 3a, 3b, and 7 are Protected, Protected, and Altered, respectively.

In the Bayesian model, three factors are combined in a reach-specific table relating output state of Rejuvenating Mosaic to width class of potential turnover: the 1 in 5-year floodplain; class of likely channel movement (as determined by dimensionless shear stresses); and class of channel stabilization (Table B.12).

Table B5.4: Bayesian network table for Rejuvenating Mosaic.

Class of expected annual days of movement	Class of channel stabilization	Class of 5-yr floodplain width	Probabilities of Rejuvenating Mosaic class			
			Minimal	Small	Moderate	Substantial
None	Minimal	Minimal	1	0	0	0
None	Minimal	Narrow	1	0	0	0
None	Minimal	Moderate	1	0	0	0
None	Minimal	Wide	1	0	0	0
None	Altered	Minimal	1	0	0	0
None	Altered	Narrow	1	0	0	0
None	Altered	Moderate	1	0	0	0
None	Altered	Wide	1	0	0	0
None	Protected	Minimal	1	0	0	0
None	Protected	Narrow	1	0	0	0
None	Protected	Moderate	1	0	0	0
None	Protected	Wide	1	0	0	0
None	Stabilized	Minimal	1	0	0	0
None	Stabilized	Narrow	1	0	0	0
None	Stabilized	Moderate	1	0	0	0
None	Stabilized	Wide	1	0	0	0
Rare	Minimal	Minimal	0.48	0.52	0	0
Rare	Minimal	Narrow	0.04	0.96	0	0
Rare	Minimal	Moderate	0	0.54	0.46	0
Rare	Minimal	Wide	0	0.25	0.52	0.23
Rare	Altered	Minimal	0.82	0.18	0	0
Rare	Altered	Narrow	0.13	0.87	0	0
Rare	Altered	Moderate	0	0.92	0.08	0
Rare	Altered	Wide	0	0.47	0.53	0
Rare	Protected	Minimal	1	0	0	0
Rare	Protected	Narrow	0.3	0.7	0	0
Rare	Protected	Moderate	0.08	0.92	0	0
Rare	Protected	Wide	0	0.91	0.09	0
Rare	Stabilized	Minimal	1	0	0	0
Rare	Stabilized	Narrow	1	0	0	0
Rare	Stabilized	Moderate	1	0	0	0
Rare	Stabilized	Wide	0.73	0.27	0	0
Infrequent	Minimal	Minimal	0.02	0.98	0	0
Infrequent	Minimal	Narrow	0	0.19	0.43	0.38
Infrequent	Minimal	Moderate	0	0.03	0.19	0.78

Table B5.4: Bayesian network table for Rejuvenating Mosaic.

Class of expected annual days of movement	Class of channel stabilization	Class of 5-yr floodplain width	Probabilities of Rejuvenating Mosaic class			
			Minimal	Small	Moderate	Substantial
Infrequent	Minimal	Wide	0	0	0.07	0.93
Infrequent	Altered	Minimal	0.08	0.92	0	0
Infrequent	Altered	Narrow	0	0.36	0.64	0
Infrequent	Altered	Moderate	0	0.1	0.31	0.59
Infrequent	Altered	Wide	0	0.01	0.17	0.82
Infrequent	Protected	Minimal	0.22	0.78	0	0
Infrequent	Protected	Narrow	0	0.71	0.29	0
Infrequent	Protected	Moderate	0	0.26	0.54	0.2
Infrequent	Protected	Wide	0	0.1	0.3	0.6
Infrequent	Stabilized	Minimal	1	0	0	0
Infrequent	Stabilized	Narrow	0.57	0.43	0	0
Infrequent	Stabilized	Moderate	0.2	0.8	0	0
Infrequent	Stabilized	Wide	0.07	0.93	0	0
Occasional	Minimal	Minimal	0	0.45	0.55	0
Occasional	Minimal	Narrow	0	0.04	0.21	0.75
Occasional	Minimal	Moderate	0	0	0.05	0.95
Occasional	Minimal	Wide	0	0	0	1
Occasional	Altered	Minimal	0	0.77	0.23	0
Occasional	Altered	Narrow	0	0.12	0.33	0.55
Occasional	Altered	Moderate	0	0	0.14	0.86
Occasional	Altered	Wide	0	0	0.04	0.96
Occasional	Protected	Minimal	0.05	0.95	0	0
Occasional	Protected	Narrow	0	0.28	0.57	0.15
Occasional	Protected	Moderate	0	0.07	0.25	0.68
Occasional	Protected	Wide	0	0	0.14	0.86
Occasional	Stabilized	Minimal	0.53	0.47	0	0
Occasional	Stabilized	Narrow	0.21	0.79	0	0
Occasional	Stabilized	Moderate	0.04	0.96	0	0
Occasional	Stabilized	Wide	0	0.69	0.31	0

Functional Riparian Zone

Table B.13 summarizes the relationship between discharge exceeded one day in two years of growing season days (0.0033 exceedance) and class of Functional Riparian Ecosystem area.

Table B5.5: Bayesian network table relating discharge to states of Functional Riparian Ecosystem (width classes) by selected reach.

Reach	Discharge (cfs)	Probability by width class[a]			
		Minimal	Narrow	Moderate	Wide
3a	200	1	0	0	0
3a	300	1	0	0	0
3a	400	1	0	0	0
3a	500	1	0	0	0
3a	600	1	0	0	0
3a	700	1	0	0	0
3a	800	1	0	0	0
3a	900	1	0	0	0
3a	1000	1	0	0	0
3a	1500	0.92	0.08	0	0
3a	2000	0.61	0.39	0	0
3a	2500	0.44	0.56	0	0
3a	3000	0.35	0.65	0	0
3a	3500	0.29	0.71	0	0
3a	4000	0.23	0.77	0	0
3a	4500	0.15	0.85	0	0
3a	5000	0.02	0.98	0	0
3a	5500	0	0.95	0.05	0
3a	6000	0	0.64	0.36	0
3a	6500	0	0.38	0.62	0
3a	7000	0	0.22	0.78	0
3b	200	1	0	0	0
3b	300	1	0	0	0
3b	400	1	0	0	0
3b	500	1	0	0	0
3b	600	1	0	0	0
3b	700	1	0	0	0
3b	800	1	0	0	0
3b	900	0.89	0.11	0	0
3b	1000	0.66	0.34	0	0
3b	1500	0.16	0.84	0	0
3b	2000	0	0.77	0.23	0
3b	2500	0	0.4	0.6	0
3b	3000	0	0.12	0.72	0.16
3b	3500	0	0	0.53	0.47
3b	4000	0	0	0.3	0.7
3b	4500	0	0	0.16	0.84
3b	5000	0	0	0.04	0.96
3b	5500	0	0	0	1

Table B5.5: Bayesian network table relating discharge to states of Functional Riparian Ecosystem (width classes) by selected reach.

Reach	Discharge (cfs)	Probability by width class[a]			
		Minimal	Narrow	Moderate	Wide
3b	6000	0	0	0	1
3b	6500	0	0	0	1
3b	7000	0	0	0	1
7	200	1	0	0	0
7	300	1	0	0	0
7	400	1	0	0	0
7	500	0.69	0.31	0	0
7	600	0.46	0.54	0	0
7	700	0.32	0.68	0	0
7	800	0.19	0.81	0	0
7	900	0.11	0.89	0	0
7	1000	0.03	0.97	0	0
7	1500	0	0.55	0.45	0
7	2000	0	0.16	0.76	0.08
7	2500	0	0	0.54	0.46
7	3000	0	0	0.32	0.68
7	3500	0	0	0.2	0.8
7	4000	0	0	0.12	0.88
7	4500	0	0	0.05	0.95
7	5000	0	0	0	1
7	5500	0	0	0	1
7	6000	0	0	0	1
7	6500	0	0	0	1
7	7000	0	0	0	1

[a] Width classes: Minimal (< 15 m); Narrow (15–45 m); Moderate (45–90 m); and Wide (> 90 m).

Riverine Wetland

Table B.14 summarizes the relationship between discharge exceeded 5% of the growing season and class of Riverine Wetland area (expressed as width to normalize for different channel lengths).

Table B5.6: Bayesian network table relating discharge to Riverine Wetland states (width classes) by selected reach.

		Probability by width class[a]			
Reach	**Discharge (cfs)**	**Minimal**	**Narrow**	**Moderate**	**Wide**
3a	200	1	0	0	0
3a	300	1	0	0	0
3a	400	1	0	0	0
3a	500	0.83	0.17	0	0
3a	600	0.54	0.46	0	0
3a	700	0.36	0.64	0	0
3a	800	0.23	0.77	0	0
3a	900	0.14	0.86	0	0
3a	1000	0.08	0.92	0	0
3a	1500	0	0.92	0.08	0
3a	2000	0	0.61	0.39	0
3a	2500	0	0.44	0.56	0
3a	3000	0	0.35	0.65	0
3a	3500	0	0.29	0.71	0
3a	4000	0	0.23	0.77	0
3a	4500	0	0.15	0.75	0.09
3a	5000	0	0.03	0.62	0.35
3a	5500	0	0	0.43	0.57
3a	6000	0	0	0.22	0.78
3a	6500	0	0	0.05	0.95
3a	7000	0	0	0	1
3b	200	1	0	0	0
3b	300	1	0	0	0
3b	400	1	0	0	0
3b	500	0.65	0.35	0	0
3b	600	0.38	0.62	0	0
3b	700	0.15	0.85	0	0
3b	800	0	1	0	0
3b	900	0	0.89	0.11	0
3b	1000	0	0.66	0.34	0
3b	1500	0	0.16	0.76	0.08
3b	2000	0	0	0.31	0.69
3b	2500	0	0	0.07	0.93
3b	3000	0	0	0	1
3b	3500	0	0	0	1
3b	4000	0	0	0	1
3b	4500	0	0	0	1
3b	5000	0	0	0	1
3b	5500	0	0	0	1
3b	6000	0	0	0	1
3b	6500	0	0	0	1
3b	7000	0	0	0	1

Table B5.6: Bayesian network table relating discharge to Riverine Wetland states (width classes) by selected reach.

		Probability by width class[a]			
Reach	**Discharge (cfs)**	**Minimal**	**Narrow**	**Moderate**	**Wide**
7	200	1	0	0	0
7	300	0.49	0.51	0	0
7	400	0	1	0	0
7	500	0	0.69	0.31	0
7	600	0	0.46	0.54	0
7	700	0	0.32	0.68	0
7	800	0	0.20	0.79	0.01
7	900	0	0.11	0.71	0.18
7	1000	0	0.03	0.63	0.34
7	1500	0	0	0.17	0.83
7	2000	0	0	0	1
7	2500	0	0	0	1
7	3000	0	0	0	1
7	3500	0	0	0	1
7	4000	0	0	0	1
7	4500	0	0	0	1
7	5000	0	0	0	1
7	5500	0	0	0	1
7	6000	0	0	0	1
7	6500	0	0	0	1
7	7000	0	0	0	1

[a] Width classes: Minimal (< 5 m); Narrow (5–15 m); Moderate (15–30 m); and Wide (> 30 m).

APPENDIX C: MODEL RESULTS

Tables C.1–C.8 display the comprehensive set of results for each of eight biological indicators in relation to the various hydrology scenarios studied through the ERM.

Table C.1: Comprehensive results for Channel Structure in each scenario, separated by the reach of the river.

CHANNEL STRUCTURE										
Reach	**Scenario →** / **Condition ↓**	*Rec. Native*	*Recent Past*	*Present Operations*	*Add' Water Dev'l*	*Driest Climate*	*StableBase-LowPeak*	*HighBase-ModeratePeak*	*DryBase-HighPeak*	*StableBase-HighPeak*
3A	- -	0%	26%	100%	100%	100%	100%	100%	0%	0%
	-	8%	50%	0%	0%	0%	0%	0%	8%	6%
	0	42%	22%	0%	0%	0%	0%	0%	42%	44%
	+	50%	2%	0%	0%	0%	0%	0%	50%	50%
3B	- -	0%	4%	91%	100%	100%	100%	0%	0%	0%
	-	8%	32%	9%	0%	0%	0%	85%	8%	8%
	0	42%	50%	0%	0%	0%	0%	14%	42%	42%
	+	50%	14%	0%	0%	0%	0%	0%	50%	50%
7	- -	0%	0%	38%	99%	100%	1%	0%	0%	0%
	-	2%	2%	46%	1%	0%	93%	11%	2%	2%
	0	22%	22%	15%	0%	0%	6%	83%	22%	22%
	+	76%	76%	1%	0%	0%	0%	6%	76%	76%

Table C.2: Comprehensive results for Algae in each scenario, separated by the reach of river.

ALGAE										
Reach	**Scenario →** / **Condition ↓**	*Rec. Native*	*Recent Past*	*Present Operations*	*Add' Water Dev'l*	*Driest Climate*	*StableBase-LowPeak*	*HighBase-ModeratePeak*	*DryBase-HighPeak*	*StableBase-HighPeak*
3A	-	10%	50%	50%	100%	100%	100%	30%	10%	10%
	0	20%	40%	40%	0%	0%	0%	50%	40%	40%
	+	70%	10%	10%	0%	0%	0%	20%	50%	50%
3B	-	10%	50%	50%	100%	100%	100%	30%	10%	10%
	0	20%	40%	40%	0%	0%	0%	50%	40%	40%
	+	70%	10%	10%	0%	0%	0%	20%	50%	50%
7	-	0%	50%	50%	50%	100%	80%	20%	10%	10%
	0	10%	40%	40%	40%	0%	20%	40%	40%	40%
	+	90%	10%	10%	10%	0%	0%	40%	50%	50%

Table C.3: Comprehensive results for Aquatic Insects in each scenario, separated by the reach of river.

AQUATIC INVERTEBRATES										
Reach	Scenario → Condition ↓	*Rec. Native*	*Recent Past*	*Present Operations*	*Add' Water Dev'l*	*Driest Climate*	*StableBase-LowPeak*	*HighBase-ModeratePeak*	*DryBase-HighPeak*	*StableBase-HighPeak*
3A	-	30%	50%	50%	58%	58%	46%	30%	35%	18%
	0	48%	48%	48%	42%	42%	48%	58%	48%	57%
	+	23%	2%	2%	0%	0%	6%	12%	17%	25%
3B	-	30%	48%	50%	58%	58%	46%	30%	35%	18%
	0	48%	48%	48%	42%	42%	48%	58%	48%	57%
	+	22%	4%	2%	0%	0%	6%	12%	17%	25%
7	-	25%	38%	50%	50%	58%	42%	24%	31%	14%
	0	46%	48%	48%	48%	42%	51%	57%	48%	57%
	+	30%	14%	2%	2%	0%	6%	19%	21%	29%

Table C.4: Comprehensive results for Native Fish in each scenario, separated by the reach of river.

NATIVE FISH										
Reach	Scenario → Condition ↓	*Rec. Native*	*Recent Past*	*Present Operations*	*Add' Water Dev'l*	*Driest Climate*	*StableBase-LowPeak*	*HighBase-ModeratePeak*	*DryBase-HighPeak*	*StableBase-HighPeak*
3A	- -	29%	33%	44%	44%	44%	37%	37%	30%	20%
	-	26%	32%	28%	29%	29%	28%	26%	27%	25%
	0	25%	26%	21%	20%	20%	23%	23%	25%	28%
	+	20%	9%	7%	7%	7%	13%	14%	18%	27%
3B	- -	29%	29%	43%	44%	44%	37%	20%	30%	21%
	-	26%	32%	29%	29%	29%	28%	34%	27%	25%
	0	25%	26%	21%	20%	20%	23%	31%	25%	28%
	+	20%	12%	7%	7%	7%	13%	15%	18%	26%
7	- -	18%	25%	35%	44%	45%	18%	4%	25%	2%
	-	20%	24%	32%	29%	29%	36%	34%	23%	17%
	0	29%	26%	24%	20%	19%	31%	33%	27%	34%
	+	33%	25%	9%	7%	7%	15%	29%	26%	47%

Table C.5: Comprehensive results for Brown Trout in each scenario, separated by the reach of river.

TROUT										
Reach	Scenario → Condition ↓	*Rec. Native*	*Recent Past*	*Present Operations*	*Add' Water Dev'l*	*Driest Climate*	*StableBase-LowPeak*	*HighBase-ModeratePeak*	*DryBase-HighPeak*	*StableBase-HighPeak*
3A	- -	19%	42%	64%	65%	65%	37%	24%	43%	6%
	-	16%	30%	19%	19%	19%	30%	24%	14%	16%
	0	30%	23%	14%	13%	13%	22%	25%	22%	34%
	+	36%	5%	3%	2%	2%	11%	27%	21%	45%
3B	- -	19%	38%	63%	65%	65%	37%	8%	43%	6%
	-	16%	27%	19%	19%	19%	30%	30%	14%	16%
	0	30%	25%	15%	13%	13%	22%	36%	22%	34%
	+	35%	10%	3%	2%	2%	11%	26%	21%	44%
7	- -	100%	100%	100%	100%	100%	100%	100%	100%	100%
	-	0%	0%	0%	0%	0%	0%	0%	0%	0%
	0	0%	0%	0%	0%	0%	0%	0%	0%	0%
	+	0%	0%	0%	0%	0%	0%	0%	0%	0%

Table C.6: Comprehensive results for Rejuvenating Mosaic in each scenario, separated by the reach of the river.

REJUVENATING MOSAIC RIPARIAN FOREST										
Reach	Scenario → Condition ↓	*Rec. Native*	*Recent Past*	*Present Operations*	*Add' Water Dev'l*	*Driest Climate*	*StableBase-LowPeak*	*HighBase-ModeratePeak*	*DryBase-HighPeak*	*StableBase-HighPeak*
3A	- -	0%	22%	100%	100%	100%	100%	100%	30%	30%
	-	28%	78%	0%	0%	0%	0%	0%	70%	70%
	0	57%	0%	0%	0%	0%	0%	0%	0%	0%
	+	15%	0%	0%	0%	0%	0%	0%	0%	0%
3B	- -	0%	0%	30%	100%	100%	100%	100%	8%	8%
	-	10%	71%	70%	0%	0%	0%	0%	92%	92%
	0	30%	29%	0%	0%	0%	0%	0%	0%	0%
	+	60%	0%	0%	0%	0%	0%	0%	0%	0%
7	- -	0%	0%	13%	82%	82%	100%	82%	0%	0%
	-	1%	10%	87%	18%	18%	0%	18%	47%	47%
	0	17%	31%	0%	0%	0%	0%	0%	53%	53%
	+	82%	59%	0%	0%	0%	0%	0%	0%	0%

Table C.7: Comprehensive results for Functional Riparian Ecosystem in each scenario, separated by the reach of the river.

WIDTH OF FUNCTIONING RIPARIAN ZONE										
Reach	**Scenario →** / **Condition ↓**	*Rec. Native*	*Recent Past*	*Present Operations*	*Add' Water Dev'l*	*Driest Climate*	*StableBase-LowPeak*	*HighBase-ModeratePeak*	*DryBase-HighPeak*	*StableBase-HighPeak*
3A	- -	23%	29%	61%	100%	100%	100%	100%	35%	35%
	-	77%	71%	39%	0%	0%	0%	0%	65%	65%
	0	0%	0%	0%	0%	0%	0%	0%	0%	0%
	+	0%	0%	0%	0%	0%	0%	0%	0%	0%
3B	- -	0%	0%	0%	66%	100%	66%	100%	0%	0%
	-	0%	0%	77%	34%	0%	34%	0%	12%	12%
	0	30%	53%	23%	0%	0%	0%	0%	72%	72%
	+	70%	47%	0%	0%	0%	0%	0%	16%	16%
7	- -	0%	0%	0%	19%	32%	3%	32%	0%	0%
	-	0%	0%	55%	81%	68%	97%	68%	0%	0%
	0	20%	20%	45%	0%	0%	0%	0%	32%	32%
	+	80%	80%	0%	0%	0%	0%	0%	68%	68%

Table C.8: Comprehensive results for Riparian Wetlands in each scenario, separated by the reach of the river.

RIPARIAN WETLAND WIDTH OF RIVER DOMINATED ZONE										
Reach	**Scenario →** / **Condition ↓**	*Rec. Native*	*Recent Past*	*Present Operations*	*Add' Water Dev'l*	*Driest Climate*	*StableBase-LowPeak*	*HighBase-ModeratePeak*	*DryBase-HighPeak*	*StableBase-HighPeak*
3A	- -	0%	0%	8%	100%	100%	36%	8%	0%	0%
	-	44%	92%	92%	0%	0%	64%	92%	61%	61%
	0	56%	8%	0%	0%	0%	0%	0%	39%	39%
	+	0%	0%	0%	0%	0%	0%	0%	0%	0%
3B	- -	0%	0%	0%	100%	100%	15%	0%	0%	0%
	-	0%	16%	66%	0%	0%	85%	66%	0%	0%
	0	7%	76%	34%	0%	0%	0%	34%	31%	31%
	+	93%	8%	0%	0%	0%	0%	0%	69%	69%
7	- -	0%	0%	0%	0%	100%	0%	0%	0%	0%
	-	0%	0%	11%	100%	0%	32%	3%	0%	0%
	0	0%	17%	71%	0%	0%	68%	63%	0%	0%
	+	100%	83%	18%	0%	0%	0%	34%	100%	100%

APPENDIX D: PEER REVIEW

In November of 2012 the City of Fort Collins hosted a review discussion on the ERM with the team and over twenty individuals from local agencies with expertise on Poudre River including staff from other departments within the City of Fort Collins, Colorado Parks and Wildlife, Colorado State University, and local non-profits and consulting firms. The reviewers were provided with a preliminary ERM report and the comments received through that process is presented below along with responses from the ERM team. Please note, the preliminary report was, in many aspects, considerably different from this final report.

OVERARCHING CONSIDERATIONS

Comment 1: The report does not address the most critical and pressing question across all audiences. Namely, what does this mean and what can we do about it? What potential actions must the City take to successfully manage resources under the various scenarios? There should be a social element on top of this science to inform water managers.

> ***Response 1:*** The purpose of this report is to document the process of model development and offer full results of each element of the model. Thus, the overall structure of the report will not change. Model results do not lead directly to management recommendations or to the development of specific educational messages for managers. However, considering the interest in management recommendations and the need for a simpler description of the project, a subgroup of the ERM team – lead by City staff who have management rather than science as their primary charge – may develop an independent document geared toward the management audience.

Comment 2: The tone of the report is defensive. Limitations are reported in depth and repeatedly. The report should be shorter to be more interesting and accessible to a wider audience.

> ***Response 2:*** This may have occurred as a result of nine authors trying to capture a very large modeling effort. The tone of the report has been edited as appropriate to reflect the team's confidence in the model, with duplicate statements of caveats eliminated. This report serves as a comprehensive documentation of the project and each element (hydrology input data, analyses of sub-models, formation of expert opinion into probabilities, the structure of the Bayesian model, and reporting of extensive results) and each has specific, relevant limitations. As mentioned in *Response 1*, a stand-alone summary aimed at a wider audience may be developed.

Comment 3: The authors need to be cognizant when making statements contrary to City policy and current practices. For example, the concept of anchoring large, woody debris in the river to increase habitat is contrary to several City policies and regulations. The City of Fort Collins Utilities has a policy to remove woody debris from the river to prevent the buildup of debris on bridges. The debris would have to be strategically placed to avoid flooding adjacent properties or causing unexpected erosion. Similarly, the concept of allowing channel movement in some areas of the river needs additional exploration. This concept could be workable in specific reaches of the river, but the City would need to comprehensively address and plan for constraints of private property, permitting and flood issues.

Response 3: The final report will explicitly acknowledge those recommendations or ideas that run against City policy. The report will still include the ideas because they merit consideration if the City wants to improve conditions on the river.

Comment 4: Many of the public see the existing Poudre River as a good deal better than these results indicate.

Response 4: The hydrology and landscape of the Poudre River through Fort Collins have been vastly altered since pre-settlement times. These changes affect the river both in space and time time. While the proximity of Fort Collins to Poudre Canyon does help to improve the health of the river through town, noteworthy shifts exist in water quality, temperature, and fish in the few short miles that the Poudre runs through Fort Collins. Second, some elements of the ecosystems such as the riparian forest respond to changing conditions on the multi-decadal to century time scale, which reflects the lifespan of deciduous trees such as cottonwood. Therefore, there is a significant lag time in the condition of this indicator in response to input parameters. For example the Present Operations scenario indicates a course of future narrowing beyond what today's field observations indicate. This becomes evident through field observations that reveal a scarcity of young native riparian trees with increasing distance from the river's edge.

Comment 5: What is the baseline? In an earlier version of the report, all the results were displayed against the poorest possible condition for each indicator. It may be a good idea to portray the current baseline in more neutral terms. Could you compare the results for all scenarios against the Reconstructed Native scenario? Or could you display the results against the baseline of Present Operations scenario?

Response 5: There is reluctance to reference all the results on the Reconstructed Native condition because there is a significant change to the indicators under all scenarios when compared to the results for Reconstructed Native.

Therefore, under such a comparison it would be hard to distinguish the differences across the scenarios most likely to occur in our future because the changes are minimized when compared to the Reconstructed Native.

Comment 6: Some biological indicators (Algae and Aquatic Insects) are presented based on a change from today's condition; the rest of the indicators are presented by a description, and the reader does not know in which state they are currently.

Response 6: The modeling team has developed these categories based on each specific discipline, and based on data availability. All indicators were designed to cover a range of conditions which are described to the extent possible as allowed by data availability...

Comment 7: Is it correct to categorize this as a change model as opposed to an absolute results model?

Response 7: Yes and no. The greatest confidence lies in the comparison for results between reaches and scenarios. However, the model was developed with the best available data for both input and nodes with the intention of characterizing the states for each indicator. The weakness and imprecision of the absolute results is due the process of categorizing each sub-node and the output into four "bins". This should not discount the value of the absolute results. When better

hydrologic data becomes available from EISs for the NISP and HSWSP projects, the ERM will show a parallel improvement in the absolute results.

Comment 8: Climatologists seem to concur that as climates continue to change, fires will start to become the norm rather than a temporary aberration. This report suggests fires as a short-term deviation. Maybe fires and the subsequent sediment loading of the river are not a temporary issue. The wilderness areas within national forests will not be seeded for soil stabilization; therefore, they will continue to deliver additional sediment to the Poudre for many years – even after the lower portions of the watershed have been stabilized through efforts by the cities of Fort Collins, Greeley, and others. Finally, the High Park Fire and its impact on water quality in the Poudre, specifically in regard to nutrient loading, will be very significant in both the short- and long-term. Maybe an additional paragraph on the anticipated impact in relation to the nutrient control regulations would be in order. There is more nutrient data for 2013 at several sites on the Poudre, from the mouth of the canyon to Greeley. The data includes values captured during post-fire stormwater runoff conditions.

Response 8: Fire is only one of a series of human and natural changes to the watershed that would have a profound impact on the ecological condition of the river. The ERM team could consider adding modules to address effects of perturbations like fire (for example the changes in watershed sediment supply or size, water quality alterations other than nutrients, etc.). The reality is that the data available to make probabilistic forecasts for these drivers is sparse and thus it is challenging to insert them at this time. A comprehensive list of those drivers not included in the model can be found in Section III.

Comment 9: Reducing the effect of "turning the tap on and off" to smooth out the low flows would be beneficial. The variability of low flows not only harms aquatic organisms but also is detrimental to the recreational boating and tubing experience. This important flow issue on the Poudre is not in the model but was brought up repeatedly during the peer review workshop. Coordination between the several water managers on the river to better manage its flows could possibly reduce the flashiness of the peaks on the river. There are cases where the river flows can vary by hundreds of cfs in a matter of hours.

Response 9: The model does not incorporate the impact of hourly low flow volatility on the condition of the aquatic indicators. It is unlikely that the ERM can accurately incorporate this element, and this will probably not be attempted to maintain existing level of confidence. The City of Fort Collins is working on a study directed specifically at understanding the administration, timing, and location of Poudre water rights to identify feasible solutions to dry up points and low flow volatility. The goal of that study is to explore possible simple operational changes (innocuous to water users) that could reduce the erratic behavior in the low flow months.

This topic is also discussed further towards the end of Section III on page 83 under the subtitle Influence of Low Flow Data on Modelling Process and Results

Comment 10: The Poudre provides other benefits to the surrounding communities (drinking water, agriculture, food production, etc.). The report ignores these other benefits. It needs to be made clear that it is ecosystem needs, not human needs, being discussed.

Response 10: The earlier report did not acknowledge this sufficiently, as noted by this comment. The introduction of the final report has been edited to acknowledge these benefits explicitly in the Introduction.

Comment 11: Longitudinal connectivity is not accounted for in the model and it should be if this is to be called a holistic model. Does the city view each project in isolation? For example, how might widening it in one place affect channel downstream? How does money spent on one treatment affect other treatments? How does the model deal with sediment delivery, influence of diversion structures on the dispersal of aquatic species? If not thought through carefully in advance, small-scale changes to the channel without a more global perspective can degrade fish habitat.

> ***Response 11:*** This will be noted within the City as an important consideration for its planning, local modeling needs, and evaluation of restoration projects. The ERM itself it is not structured to evaluate local changes and impacts. However, it does significantly contribute to the discussion (including the importance and role of the physical context at the local level) occurring within the City and the greater Poudre River community. This type of comment could provoke greater communication between localized projects to help assure that specific concerns are considered.

MODEL STRUCTURE

Comment 12: The model indicates there is only one main driver of river condition, namely water volume and duration, and so the discussion appears directed solely at water users. Discussion needs to be aimed at a broader audience and to highlight other inputs to the river. The model should be used to illustrate the combination of influences of hydrology with land use and development, the influence of microsite softening, land management techniques, nutrient inputs, and daily water management, to demonstrate the non-water diversion aspects of the current condition of the river. How could you characterize the return on investment given the same water flow and find other avenues for small wins? Doing so will make the model much more useful, interest a larger group of stakeholders, and make it easier to engage the water management community.

> ***Response 12:*** The project and discussion is not directed only at water users, but the project is based on the theory that flows are the master variable of river systems and the primary driver of ecosystem condition. The team and the model structure does recognize a broad spectrum of influential factors on this highly altered system, yet flows remain the primary input. The team may expand the explore ways to demonstrate the importance of a broader set of inputs. Specifically, the riparian element could be expanded to demonstrate a variety of static but low-lying bank management techniques and their impact on riparian outcomes.

Comment 13: Several important ecological interactions are not included in the model structure. Missing relationships include:

- The influence of riparian trees proximate to the channel for shading water, reducing temperatures, providing microhabitats for fish, insects and associated allochthonous inputs,
- Wetland macro-invertebrate inputs or model consideration,
- Scour of vegetation from higher flows and channel maintenance preventing encroachment and channel shrinkage, and
- The predatory interaction between Brown Trout and Native Species.

> ***Response 13:*** The model was structured to include the most influential relationships referred to in the report as primary influencers. The above list includes many important ecological connections that were acknowledged in the text of the report (see Section III, page 82), but excluded from the model because they were considered secondary influencers of condition.

Additionally, many of these relationships are not as well informed by empirical data in the broader knowledgebase of ecosystem science or in the Poudre basin. Thus, it was felt that inclusion would decrease the overall strength of the model.

Comment 14: Show the model algorithms. The reader cannot see the actual model calculations.

Response 14: The ERM runs on SMILE (Structural Modeling, Inference, and Learning Engine) running within the GeNIe (Graphical Network Interface) both found at http://genie.sis.pitt.edu/. As the SMILE-GeNIe model is currently set up, results are simply conditional probabilities of the categorical input data through each step of the model using the general form:

$$P(A_i|B) = \frac{P(B|A_i)P(A_i)}{P(B)} = \frac{P(B|A_i)P(A_i)}{\sum_{i=1}^{n} P(B|A_i)P(A_i)}$$

Where A and B are possible outcomes and $P(A_i|B)$ is interpreted as the conditional probability of A_i given B.

MODEL TESTING

Comment 15: Is there any way to calibrate the results to known, observed parameters?

Response 15: In short, yes. The model can be calibrated to observed conditions as that data becomes available. The probabilities developed for each sub-model also contain varying proportions of data and expert opinion. For example, the Riparian Wetlands and Brown Trout models were based on field data, while the Algae model was based on scientific understanding of the drivers of algae growth and no actual field data.

Comment 16: Is there a plan to add validation (sampling) to those areas that are based on expert opinion when empirical data is limited? How will this be tested?

Response 16: A field campaign to provide validation data is currently outside the scope and budget of this project, although the input data, methodology, and relationships have been thoroughly vetted by scientific experts in each respective field. Project managers are open to such validation as the data and/or funding becomes available.

Comment 17: How will you test the model?

Response 17: See responses to Comments15 and 16, above. Further, robust testing of each component of the model is not currently possible given data limitations. Greater confidence exists in the relative trend-prediction capabilities of the model than in its acute accuracy.

Comment 18: Using historic flows to test against current conditions is a possible test. Have you considered the results of the Recent Past scenario to current condition observed on the river?

Response 18: Yes, managers have considered (and evaluated) contrasting the projected conditions against the historic flows. One present challenge is variation (in period of record) of

the available flow scenarios. Once comparable flow scenarios from the USACE's Common Technical Platform become available, this type of contrasting will hold more validity.

HYDROLOGY INPUT DATA AND SCENARIOS

Comment 19: You are really projecting future flow years based on 1970–2010 Recent Past flow data. You should model the accounts better for quantity of water as opposed to timing of flows.

Response 19: Correct, potential changes to the timing of flows (such as timing of spring peak as it may be affected by changes in climate) have not been incorporated. While it would be possible to add this to the model, it would further stretch the current understanding of cause-effect relationships in the ecosystem.

Comment 20: The terms "Historic" and "Reconstructed Native" are very confusing. I recommend striving to find titles that are more descriptive of these conditions. When I hear Historic, I picture pre-European settlement conditions. Reconstructed Native to me means rebuilding back to pre-settlement conditions.

Response 20: This has been one of the most contentious discussions among the team. There is no perfect, simple title to capture these important details in the various flows scenarios. The tables and text associated provide the complete description of these scenarios and data sources.

The scenario titles were changed, however, as follows.

Previous scenario naming convention	Current naming convention
N – Reconstructed Native	Reconstructed Native
H – Historic Gage Data	Recent Past
S1 – Current Operations	Present Operations
S2 – Additional Water Development	Additional Water Development
S3 – Drier Climate	Driest Climate
S5 – Wetter Climate	(no longer used)

Comment 21: Does the absence of significant flood flows in the historical record skew any of the results? The Poudre has not experienced a major flood (100-year or greater) since the early 1900s. Does this pattern affect any of the model results?

Response 21: Yes, it is possible, but the model is limited to the available gage records. There is no way to know if the major floods of the past will occur again or if long-term climate shifts in the watershed are being observed.

Comment 22: The disaggregation of monthly flow data to daily flow does not contain variability. How does the model represent the daily and hourly variability?

Response 22: The disaggregated daily flow is patterned off of the actual daily discharge record of the Canyon Gage; thus, the daily variability of each flow scenario is scaled from the actual flow variability of the river at the Canyon Gage. The best temporal resolution of input to the model is the daily time-step of the input from the Recent Past scenario. It does not represent hourly variability.

NUTRIENTS

Comment 23: Nutrient Control Regulations were passed by the Colorado Water Quality Control Commission on June 11, 2012 so are no longer "proposed" as it reads in the report. Monitoring requirements and continued implementation of the regulations start in March 2013.

> ***Response 23:*** Updated in Section II.

Comment 24: Regarding graphs in an early report, compliance with the regulated nutrient standards will be based on the concentrations of specific nutrient parameters and not loads (kg/year) as depicted in the graphs or TMDL loads as discussed in the text.

> ***Response 24:*** The final text does not indicate the calculated annual loads are the same as the specific nutrient standards.

Comment 25: Biological Nutrient Removal (BNR) processes are already in place and operating at the Mulberry Water Reclamation Facility (MWRF). These processes removed key nutrients: total phosphorus, total inorganic nitrogen, and total nitrogen. A primary goal of that multi-million dollar renovation was to ensure full compliance with the new regulations and treatment processes are being optimized to ensure full compliance. During renovation, discharge to the Poudre stopped in September of 2008. After renovation, discharge to the Poudre began again after Labor Day of 2011. Do the bar graphs depict a "no discharge" condition on the Poudre for the MWRF during that time period as shown by nutrient levels at the Boxelder gage above Boxelder Creek?

> ***Response 25:*** Computations are based upon actual nutrient concentrations from river grab samples, not potential nutrients from waste water contributions.

Comment 26: As required by the Colorado Department of Health, redundant BNR systems have been installed at the Drake Water Reclamation Facility (DWRF), again at a cost of several million dollars to ensure full compliance with the nutrient regulations.

> ***Response 26:*** While this is relevant to the contribution of nutrients from the Fort Collins Wastewater Treatment plant, it does not directly impact the current model.

Comment 27: It should be noted in the text that only the MWRF discharges directly into the Poudre. The DWRF discharges into Fossil Creek Ditch and that, in turn, makes its way some five miles downstream to Fossil Creek Reservoir. The discharge from Fossil Creek Reservoir is to the Poudre is just above the New Cache Irrigation Canal and near where the Poudre crosses below County Road 32E. The reservoir's discharge location is in Segment 12 of the Poudre, downstream of the ERM study area.

> ***Response 27:*** Noted, though outside the scope of this report.

Comment 28: There could be better interaction between hydrology and nutrient processing instead of the current analysis that simply looks at dilution.

> ***Response 28:*** Agreed. The current dilution-based model does not capture the full extent of interaction between nutrients and the compartments of the river system capable of transforming and/or removing them.

AQUATIC

Comment 30: Why is the non-native brown trout species important enough to represent a key indicator? Is not the purpose of this project to evaluate the condition of the natural (native) river ecosystem?

> ***Response 30:*** Cold water fishes are recognized as sensitive indicators of river health regardless of the species. Given that trout were a native component of the fishery at one time, but that native cold water fish declined in large part for reasons other than flows, using brown trout was justified. Brown trout are also recognized as an important part of today's Poudre River because they are a highly valued recreational asset. Native cutthroat trout may be a more natural component of the fish community, but – in their absence – brown trout provide a reasonable surrogate to describe the health of the cold water fish community and there was data available to portray their abundance patterns. Thus, if one portrays brown trout as a surrogate for cold water salmonids in general, and fishes are a major component of the model, inclusion of the Brown Trout indicator is justified.

Comment 31: Is there a model representation of the predatory interaction between the brown trout and native fish? Rainbow trout have a different relationship with native species, as well as unique timing of spawning. Using rainbow trout as the indicator may be beneficial due to the decreased predatory relationship. Using flows that benefit rainbows over brown may have increased improvement for native fisheries.

> ***Response 31:*** Yes, a variable, trout impact on native fishes was included, because at high abundance levels, trout can suppress diversity and abundance of native fishes via predation. Probability values for that metric reflect that even if physical habitat conditions are good for native fishes, a healthy trout population has the ability to suppress native fishes to a relatively low state. Conversely, if physical habitat conditions are good and trout abundance is low, the native fish community (at least the elements that now remain) has a moderate to high probability of achieving a "0" or "+" state.
>
> Rainbows definitely have a different relationship with native fishes than brown trout, but are still predators on other fishes. And yes, they have different needs in terms of spawning success and flows, with rainbow trout being spring spawners. But populations of rainbow trout do not exist in the Poudre River in any numbers; this is mostly due not to flows but to whirling disease. Using cold water species other than brown trout was considered, but – since there is not data to represent them – it seemed an unjustified approach. Brown trout also require spawning gravel for successful reproduction, so some of the same processes that would benefit rainbow trout should also benefit brown trout but in different seasons.
>
> It was also unclear what flow regimes would necessarily benefit rainbow trout over brown trout in this system. Brown trout are mostly negatively affected by higher late-winter and spring scouring flows that reduce survival of early life stages. The Poudre does not seem to have such events in its natural or present, semi-altered state. Even if brown trout were reduced, it is not clear how rainbow trout would benefit given their presently reduced state and apparent lack of reproduction in this system. That may change in the future.
>
> Representing the Poudre River coldwater fish community with rainbow (Hofer hybrid strains) trout rather than brown trout is discussed in part above. It may be that, if reestablishment of rainbow trout is successful, the model could be recalibrated to represent either rainbow or brown trout.

Comment 32: Diversion dams on the Poudre fragment the system and can especially prevent movement by fishes.

> ***Response 32:*** This issue is recognized in the report as an important factor influencing the health of fish populations in highly altered rivers. This is especially true in flow-depleted systems like the Poudre River. However, explicit modeling of fish movement among reaches dissected by diversion dams, as well as a thorough understanding of the effects of dams and restricted movement on distribution and abundance of fishes in an affected reach, are questions for which there are few data in the science literature. This is also especially true for the Poudre River. (See *Response 11*, which discusses spatial model limitations.)

Comment 33: Kurt Davies of Colorado Parks and Wildlife indicated he had more trout data we might want to see to extend the time coverage of our model.

> ***Response 33:*** Unfortunately the data was derived using different methods and slightly different locations, and is therefore difficult to incorporate appropriately.

Comment 34: It was implied that there is better native fish habitat near Interstate 25, but the ERM doesn't include that reach. It would be nice to include this reach.

> ***Response 34:*** The current plan is not to expand the model to more reaches, such as the reach downstream by Interstate 25. Better warm water fish habitat may have existed historically in that area, especially since it is more truly a warm water reach. However, that reach is presently highly confined in channel structure and other attributes, and as a result has less native fish habitat than the reach that was used near the Environmental Learning Center (ELC) property. Inferences about management actions that may enhance native fish habitat could be had by comparing the ELC reach with the one upstream, which is more confined and similar to the Interstate 25 reach.

Comment 35: Impoundments behind dams provide brown trout with suitable habitat in winter when flow conditions are very low.

> ***Response 35:*** Noted. Impoundments do provide habitat for brown trout and other fishes during low flows. They essentially act similar to deep pools in more naturally flowing sections of the river. However, those impoundments are few and are not spatially well-distributed like natural pools in a stream channel. Such pools also collect sediment in low flow periods and do not necessarily support abundant invertebrate communities that support brown trout and other insect-eating fishes.

Comment 36: Someone suggested that new floodplain aquatic habitat would benefit not only native fish but also non-native fish, which might proliferate.

> ***Response 36:*** The ERM team has discussed the issue that any new connections made between ponds and the river would have to be carefully evaluated for the possible undesirable release of new non-natives into the river. Providing habitat is a first step toward supporting more diverse and healthy native fish communities. However, such habitat may support non-native fishes as well, such as western mosquitofish, which compete with and prey upon native fishes that also occur in such habitat. It would also behoove management agencies responsible for mosquito control to

evaluate use of native fishes rather than non-native ones, as the native species are also effective predators on mosquito larvae.

Comment 37: Wood in the channel improves cover for fish, trout and natives.

Response 37: This is noted by the team as a positive possible management technique but, as noted in *Comment 3*, it runs against City policy for stormwater management.

RIPARIAN

Comment 38: The definition of *wetland* used in the Riparian Wetland indicator is out of date (14 days of inundation during the growing season; 0.05 exceedance probability). The new USACE definition is 14 consecutive days during the growing season. The report indicates the wetlands target is similar to the regulatory wetlands, but it does not consider the need for the 14 days of inundation to be consecutive.

Response 38: The final report will stay consistent with the original previous regulatory definition of wetlands by using the definition of 14 days, not necessarily consecutive per the recent change in Corps regulations. The purpose of the project is not necessarily to be comparable to the very specific, legally binding definitions like that of regulated wetlands. Nevertheless, by using the previous version it will serve as a parallel or proxy.

Comment 39: Could groundwater be incorporated into the model? Return flow could be an alternative source of water for the riparian forest and wetlands.

Response 39: Groundwater could have been incorporated into these models if there were sufficient data. Individual wells tell little about the direction of movement and the slopes of groundwater surfaces; they offer a depth to the water table at a point in time. Return flow could be an important source of water for riparian forest in this type of environment where much water is used in agriculture and landscaping in the urban environment, however it is not a constant or predictable pattern. The ERM was built on the excepted assumption that groundwater and surface water fluctuate together in the near channel areas of the Poudre (particularly those that are within the area flooded by a flow of 7000 cfs).

Comment 40: Another valuable response variable, in addition to Riparian Wetlands and Rejuvenating Mosaic, is the relict forest (the old deciduous forest that persists via access to groundwater).

Response 40: It is recognized that the extant mature riparian forests rely on groundwater, and may in fact be more responsive to lateral sources of groundwater independent of water supplied by instream flow along the Poudre. In addition, these forests are well established and likely to persist even after conditions shift away from optimal for the trees. This is why realized niche modeling was performed, the output of which is probabilistic. Based upon where a particular species or cover type is now, this is the most probable outcome if conditions change. Such outcomes vary based upon the resistance and resilience of the species/cover types in question and other factors (grazing, vegetation removal, floods, droughts, etc.).

Comment 41: The desirable forest species (native cottonwood versus non-native maple or green ash) is a social question rather than a scientific one.

Response 41: Indeed, many non-native species also provide habitat (cover, food, shade, nest sites, etc.). Cottonwood per se was not singled out as the only riparian forest species. Several non-native species were included in our models.

Comment 42: How does laying banks back (removing constraints) and widening a channel affect critical shear stress? Could laying banks back for "restoration" conflict with aquatic habitat maintenance?

Response 42: Certainly a wider and shallower channel will result in more flow to achieve the shear stress necessary to mobilize the bed. This could result in more fine sediment in the interstitial spaces and habitat degradation in the channel.

Comment 43: How would the loss of willow cover (as per riparian probabilistic models under drying scenarios) affect bank stability? Could the loss of willow under dry scenarios result in a wide, shallow, active channel?

Response 43: Yes, if willow and other woody species were removed or lost due to drought, there could be bank erosion and channel widening in areas that are not riprapped.

Comment 44: Wetland and dynamic mosaic occurs primarily in narrow zones near the channel within riprap. These areas could be better managed and widened within confined zones or if the zone were expanded.

Response 44: Certainly, and this is a good thought. In- and near-channel wetlands could be expanded through removal of constraints such as riprap and abutments, bike paths, roads, etc. Laying back channel margins, creating a topographic gradient, and then managing flows to support desired vegetation types would be ecologically important.

Comment 45: Why focus only on flow and current geometry? The ERM should consider channel movement, restoration, and reforming topography.

Response 45: By evaluating three different reaches with distinct geometry and flow combinations, it was possible to cross compare the benefits and limitations of various degrees of channel constraint, topographies, and channel forms.

Comment 46: What is a "good" value for a Hosmer-Lemeshow p-value? Both models purportedly had excellent fit, but – to the untrained eye – 0.7 and 0.14 are very different values.

Response 46: Clarification will be added to the report. The null hypothesis being tested in the Hosmer-Lemeshow goodness of fit test is that the model fits the data well. Higher p-values (>0.05) do not allow this hypothesis to be rejected, thus indicating a good model fit.

Comment 47: Much of the riparian zone area is inundated via groundwater during the high flow stage, but the model is based only on surface flows. Why is depth to groundwater not a component in the model? What could be a good proxy for groundwater flow?

Response 47: Addressed above. Also, there is a strong relationship between surface water level (stage) and groundwater levels along streams, though these relationships change over the

course of a seasonal hydrograph. Precise information about groundwater levels relative to each of the vegetation plots would have enabled the incorporation of such information into the model, but such data was not available. Because elevation above the channel is often highly inversely correlated with water availability, and is highly correlated to depth of water table, this was used as the master variable. This indeed explained a significant proportion of the variability in plant community composition and the presence or absence of certain species and cover types.

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